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Failure Analysis

I. INTRODUCTION

Despite the great strides forward that have been made in technology, failures continue to occur, often accompanied by great human and economic loss. This text is intended to provide an introduction to the subject of failure analysis. It cannot deal specifically with each and every failure that may be encountered, as new situations are continually arising, but the general methodologies involved in carrying out an analysis are illustrated by a number of case studies. Failure analysis can be an absorbing subject to those involved in investigating the cause of an accident, but the capable investigator must have a thorough understanding of the mode of operation of the components of the system involved, as well as a knowledge of the possible failure modes, if a correct conclusion is to be reached. Since the investigator may be called upon to present and defend opinions before highly critical bodies, it is essential that opinions be based upon a sound factual basis and reflect a thorough grasp of the subject. A properly carried out investigation should lead to a rational scenario of the sequence of events involved in the failure as well as to an assignment of responsibility, either to the operator, the manufacturer, or the maintenance and inspection organization involved. A successful investigation may also result in improvements in design, manufacturing, and inspection procedures, improvements that preclude a recurrence of a particular type of failure.

The analysis of mechanical and structural failures might initially seem to be a relatively recent area of investigation, but upon reflection, it is clear the topic has been an active one for millenia. Since prehistoric times, failures have often resulted in taking one step back and two steps forward, but often with severe consequences for the designers and builders. For example, according to the Code of Hammurabi, which was written in about 2250 BC (1):

> If a builder build a house for a man and do not make its construction firm, and the house which he has built collapse and cause the death of the owner of the house, that builder shall be put to death. If it cause the death of a son of the owner of the house, they shall put to death a son of that builder. If it destroy property, he shall restore what ever it destroyed, and because he did not make the house which he built firm and it collapsed, he shall rebuild the house which collapsed at his own expense.

The failure of bridges, viaducts, cathedrals, and so on, resulted in better designs, better materials, and better construction procedures. Mechanical devices, such as wheels and axles, were improved through empirical insights gained through experience, and these improvements often worked out quite well. For example, a recent program in India was directed at improving the design of wheels for bullock-drawn carts. However, after much study, it was found that improvements in the design over that which had evolved over a long period of time were not economically feasible.

An example of an evolved design that did not work out well is related to the earthquake that struck Kobe, Japan, in 1995. That area of Japan had been free of damaging earthquakes for some time, but had been visited frequently by typhoons. To stabilize homes against the ravages of typhoons, the local building practice was to use a rather heavy roof structure. Unfortunately, when the earthquake struck, the collapse of these heavy roofs caused considerable loss of life as well as property damage. The current design codes for this area have been revised to reflect a concern for both typhoons and earthquakes.

The designs of commonplace products have often evolved rapidly to make them safer. For example, consider the carbonated soft-drink bottle cap. At one time, a metal cap was firmly crimped to a glass bottle, requiring a bottle opener for removal. Then came the easy-opening, twist-off metal cap. These caps were made of a thin, circular piece of aluminum that was shaped by a tool at the bottling plant to conform to the threads of the glass bottle. If the threads were worn, or if the shaping tool did not maintain proper alignment, then the connection between cap and bottle would be weak and the cap might spontaneously blow off the bottle, for example, on the supermarket shelf. Worse than that, there were a number of cases where, during the twisting-off process, the expanding gas suddenly propelled a weakly attached cap from the bottle and caused eye damage. To guard against this danger, the metal caps were redesigned to have a series of closely spaced perforations along the upper side of the cap, so that as the seal between the cap and bottle was broken at the start of the twisting action, the gas pressure was vented, and the possibility of causing an eye injury was minimized. The next stage in the evolution of bottle cap design has been to use plastic bottles and plastic caps. In a current design, the threads on the plastic bottle are slotted, so that, as in the case of the perforated metal cap, as the cap is twisted the CO_2 gas is vented, and the danger of causing eye damage is reduced.

Stress analysis plays an important role both in design and in failure analysis. Ever since the advent of the industrial revolution, concern about the safety of structures has resulted in significant advances in stress analysis. The concepts of stress and strain developed from the work of Hooke in 1678, and were firmly established by Cauchy and Saint-Venant early in the nineteenth century. Since then, the field of stress analysis has grown to encompass strength of materials, and the theories of elasticity, viscoelasticity, and plasticity. The advent of the high-speed computer has led to further rapid advances in the use of numerical methods of stress analysis by means of the finite element method (FEM), and improved knowledge of material behavior has led to advances in development of constitutive relations based upon dislocation theory, plasticity, and mechanisms of fracture. Design philosophies such as safe-life and fail-safe have also been developed, particularly in the aerospace field.

In a safe-life design, a structure is designed as a statically determinant structure that is intended to last without failure for the design lifetime of the structure. To guard against premature failure, the component should be inspected at intervals during its in-service lifetime.

In the fail-safe approach, the structure is designed such that if one member of the structure were to fail, there would be enough redundancy built into the structure that an alternate load path would be available to support the loads, at least until the time of the next inspection. (The use of both suspenders and a belt to support trousers is an example of a fail-safe, redundant approach.) Consideration must also be given to the spectrum of loading that a structure will be called upon to withstand in relation to the scatter in the ability of materials to sustain these loads. As indicated in Fig. 1-1, danger of failure is present when these two distributions overlap.

In addition, new fields such as fracture mechanics, fatigue research, corrosion science, and nondestructive testing have emerged. Important advances have also been made in improving the resistance of materials to fracture. In the metallurgical field, these advances have been brought about through improvements in alloy design, better control of alloy chemistry, and improvements in metal processing and heat treatment. The failure analyst often has to determine the nature of a failure; for example,

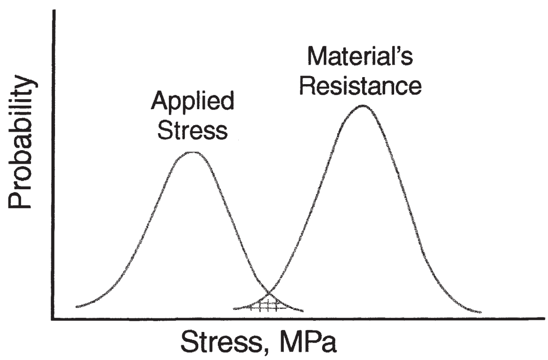


Fig. 1-1. Schematic frequency distributions showing the applied stresses and the resistance of the material.

was it due to fatigue or to an overload? In many cases, a simple visual examination may suffice to provide the answer. In other cases, however, the examination of a fracture surface (fractography) may be more involved and may require the use of laboratory instruments such as the light microscope, the transmission electron microscope, and the scanning electron microscope.

Many of today's investigations are quite costly and complex, and require a broad range of expertise as well as the use of sophisticated laboratory equipment. In some instances, the investigations are carried out by federal investigators, as in the case of the TWA Flight 800 disaster (center fuel tank explosion), where both the Federal Bureau of Investigation (FBI) and the National Transportation Safety Board (NTSB) had to determine if the cause of the failure was due to a missile attack, sabotage, mechanical failure, or an electrical-spark-ignited fuel tank explosion. The case of the Three Mile Island accident (faulty valve) involved the Nuclear Regulatory Commission (NRC), and the Challenger space shuttle disaster (O-ring) involved the National Aeronautics and Space Administration (NASA). Many investigations are also carried out by manufacturers to ensure that their products perform reliably. In addition, a number of companies now exist for the purpose of carrying out failure analyses to assist manufacturers and power plant owners, as well as to aid in litigation. The results of many of these investigations are made public, and thus provide useful information as to the nature and cause of failures. Unfortunately, the results of some investigations are sealed as part of a pretrial settlement to litigation, and the general public is deprived of an opportunity to learn that certain products may have dangers associated with them. A company may decide on the basis of costs versus benefits that is cheaper to settle a number of claims rather than to issue a recall. This policy can sometimes be disastrous, as in the case of the recent rash of tire failures. Another example involved a brand of cigarette lighter that repeatedly malfunctioned and caused serious burn injuries. It was only after some fifty of these events had occurred and the cases had been settled that the dangers associated with this item were brought to light in a public trial.

An important outcome of failure analyses has been the development of building codes and specifications governing materials [the American Society for Testing and Materials (ASTM)], manufacturing procedures [the Occupational Safety and Health Administration (OHSA)], design [the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Codes, the Federal Aviation Administration (FAA), NASA, American Petroleum Institute (API)], construction (state and municipal codes), and operating codes (NASA, NRC, FAA). These codes and standards have often been developed to prevent a repetition of past failures, as well as to guard against potentially new types of failure, as in the case of nuclear reactors. Advances in steel making, nondestructive examination, and analytical procedures have led to a reduction of the material design factor (safety factor) for power boilers and pressure vessels from 4 to 3.5 (2). (Allowable stress values based upon the tensile strength are obtained by dividing the tensile strength by the material design factor.) Today, the reliability of engineered products and structures is at an all-time high, but this reliability often comes with a high cost. In fact, in the nuclear industry, compliance with regulations intended to maximize safety may be so costly as to warrant the taking of a reactor out of service. It is also important for manufacturers to be aware of the state of the art as well as the latest standards. The number of manufacturers of small planes has dwindled because of product liability losses incurred when it was shown that their manufacturing procedures did not meet the current state-of-the-art safety standards. To guard against product failures, a number of firms now are organized in such a way that failure analysis is a line function rather than a staff function, and a member of the failure analysis group has to sign off on all new designs before they enter the manufacturing stage.

II. EXAMPLES OF CASE STUDIES IN FAILURE ANALYSIS

A. Problems with Loads and Design

1. Problems with Wind Loadings The Tay Bridge was a 10,300 foot long single track railroad bridge built in 1878 to span the Firth of Tay in Scotland (3). A portion of the bridge consisted of 13 wrought iron spans, each 240 feet in length and 88 feet above the water, which were supported by cast iron piers. On the fateful day of December 28, 1879, a gale developed with wind speeds up to 75 mph. That evening a passenger train, while making a scheduled crossing, plunged into the Firth, together with the 13 center spans, and 75 passengers and crew members lost their lives.

The subsequent investigation revealed that a major cause of the disaster was that the gale force winds produced lateral forces on the passenger cars that were transmitted to the bridge structure and led to its collapse. Such wind loading had not been properly taken into account in the design stage. This disaster underscored the obvious fact that all potential loading conditions must be considered in order to design safe and reliable structures.

Today, we are much more aware of the importance of wind loading in structural design. Nevertheless, from time to time, problems still arise. For example, the Citicorp Tower in New York City was built in 1977 in accord with the building code, which required calculations for winds perpendicular to the building faces. However, this was a unique structure in that a church occupies one corner of the building site, and the CiticorpTower is built over and around it. In 1978, it was discovered that the building was unstable in the presence of gale-force quartering winds, that is, winds that come in at a 45° angle and hit two sides of the building simultaneously. The building was quickly reinforced to insure its safety in the event of all types of wind loading, and a potential disaster was averted.

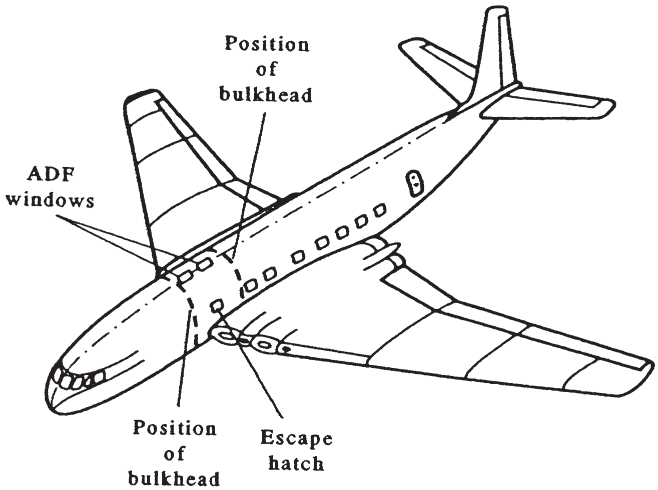
An instance where wind loading did result in a spectacular failure was that of the Tacoma Narrows suspension bridge, which failed in 1940 after only four months of service. The bridge, which connected the Olympic peninsula with the mainland of Washington, had a narrow, two-lane center span over a half mile in length. The design was unusual in that a stiffened-girder, which caught the wind, was used, rather than a deep open truss, which would have allowed the wind to pass through. The design resulted in low torsional stiffness and so much flexibility in the wind that the bridge was known as "Galloping Gertie." As the wind's intensity increased to 42 mph, the bridge's rolling, corkscrewing motion also increased, until it finally tore the bridge apart. The ultimate cause of the failure was the violent oscillations, which were attributed to forced vibrations excited by the random action of turbulent winds as well as to the formation and shedding of vortices created as the wind passed by the bridge.

2. Comet Aircraft Crashes In the early 1950s, the Comet aircraft was the first jet transport introduced into commercial passenger service. The plane was so superior to propeller-driven transports that it soon captured a large share of the market for future transport planes. However, not long after coming into service, two planes of the Comet fleet, on climbing to cruise altitude, underwent explosive decompressions of the fuselage (as shown by subsequent investigation), which resulted in the loss of the planes as well as the lives of all aboard. Intensive investigation revealed that these crashes were due to fatigue cracking of the fuselage at regions of high stress adjacent to corners of more-or-less square (rather than round) windows, as shown in Fig. 1-2. The fatigue loading was due to the pressurization and depressurization of the cabin, which occurred in each takeoff and landing cycle. The presence of fatigue cracking was confirmed through study of the fracture surfaces of critical parts of the wreckage. These surfaces were found to contain fractographic markings, which are characteristic of fatigue crack growth (4).

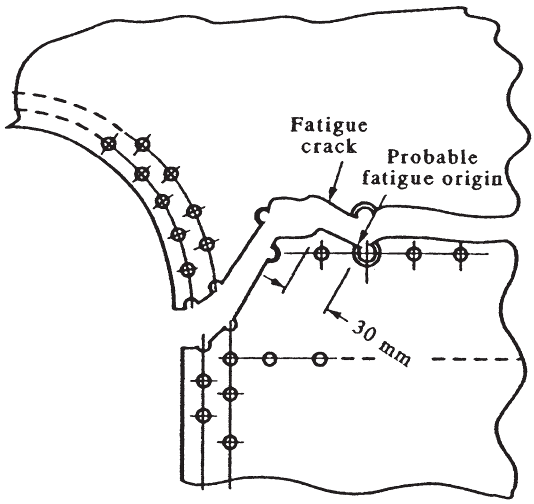
The results of these crashes were significant. First of all, the Comet fleet was grounded and orders for new aircraft were canceled. Secondly, the crashes drew attention to the importance of fatigue crack growth in aircraft structures. Thirdly, it was realized that pressurized fuselages had to be designed so as to avoid catastrophic depressurization in the presence of damage such as fatigue cracking or penetration by debris should an engine explode. As a result of these crashes, significant steps to improve the reliability of aircraft structures were taken in terms of design philosophy, consideration of the effects of fatigue crack growth, and inspection procedures.

As underscored by the Comet crashes, fatigue must be an important consideration in the design of aircraft. Certain components such as turbine blades, which may experience 10^{10} stress cycles over their lifetimes, are designed such that the stresses are well below the fatigue strengths of the materials. The design objective for such components is that fatigue cracks never develop within the design lifetime, for if a crack were to form in a turbine blade, it would rapidly grow to critical size, and hence periodic inspection would not detect it in time to avert disaster. The situation with respect to the aircraft structure is different. Here cycles are accumulated at a slower rate than in engine components, and if a fatigue crack were to form, the critical size for fracture would be measured in terms of centimeters rather than millimeters, as in the case of a small turbine blade. This means that with proper inspection it is possible to detect fatigue cracks in a structure before they have grown to critical size.

Aluminum alloys are widely used in the construction of aircraft structures. Their high strength-to-density ratio makes them attractive for this application. However, these alloys are characterized by relatively low fatigue strengths. If an aircraft struc-



(*a*)



(*b*)

Fig. 1-2. (*a*) The Comet aircraft. (*b*) The location of fatigue cracking near an aft corner of the ADF (automatic direction finder) window. (After Jones, 3, reprinted by permission.)

ture were to be designed such that all repeated stresses were below the fatigue limit, the aircraft would be too heavy for economical flight. To reduce the weight of the structure, the design cyclic stresses are set at levels above the fatigue strength in what is referred to as the finite life range. This means that if the cyclic stresses are repeated often enough, fatigue cracks would eventually develop. Because of the statistical variation in fatigue lifetimes, as well as uncertainty with respect to the actual loading conditions, the designer must consider the possibility that fatigue cracks may appear within the lifetime of the structure. If cyclic tests are carried out on full-scale prototypes, the results will provide some knowledge of the fatigue strength of the structure as well as information about where fatigue cracks are likely to be located. However, actual structures in service may experience different cyclic loading conditions than the prototype, and in addition, as in the case of aging aircraft, long-time effects associated with corrosion and fretting-corrosion may take place, effects that would not have been reflected in the prototype tests.

As mentioned earlier, two different design approaches have been developed in order to deal with the problem of fatigue cracking in aircraft structures. When the structure is designed to be statically determinant, a safe-life design approach is used. In this approach, the components of the structure are designed to have sufficient fatigue life to exceed the design lifetime of the aircraft, but inspections for fatigue cracks are required to insure the safety of the aircraft structure. The other approach is known as fail-safe. In this approach, there is sufficient redundancy in the structure such that if a structural component failed, other structural members would have enough strength to carry the redistributed load. Further, these now more highly stressed surviving members should themselves not be in danger of failing prior to the next scheduled inspection. In principle this approach is more reliable than safe-life, but it entails a weight penalty.

3. Dan Air Boeing 707 Crash (5) The following case study illustrates an instance where the fail-safe approach did not work out as planned. In 1977, a Boeing 707-300C aircraft on a scheduled cargo flight from London to Zambia was preparing to land when the right horizontal stabilizer and elevator separated in flight, causing the aircraft to pitch rapidly nose down and dive into the ground about two miles short of the runway. The pilot, copilot, and flight engineer were killed. This plane was the first off the B-707-300C series convertible passenger/freighter production line, and had accumulated a total of 47,621 airframe hours and had made a total of 16,723 landings. It had made 50 landings since its last inspection. The horizontal stabilizer, as well as other components of this aircraft, had been designed using the fail-safe approach, but full-scale fatigue testing of the B-707-300C stabilizer had not been done.

However, a fail-safe design is only fail-safe if after the failure of one component the remaining components have sufficient residual strength to support the applied loads. A singly redundant structure (as in this case) is only fail-safe while the primary structure is intact. Once this has failed, the principle of safe-life obtains, and it becomes necessary to find the failure in the primary structure before the fail-safe members themselves can be weakened by fatigue, corrosion, or any other mechanism. Because the strength reserves in the fail-safe mode are usually well below those of the intact structure, this means that, in practice, the failure must be found and appropriate action taken within a short time compared with the normal life of the structure. In order to maintain the safety of a fail-safe structure, an adequate inspection program must be an integral part of the total design to insure that a failure in any part of the primary structure is identified well before any erosion of the strength of the fail-safe structure can occur.

Postaccident examination of the detached stabilizer revealed a failure of the top chord of the rear spar of the stabilizer due to the growth of a fatigue crack from a fastener hole. (The word chord has two different meanings in aircraft structural terminology. It is defined as the straight line joining the leading and trailing edges of an airfoil, and also as either of the two outside members of a truss connected and braced by web members. The latter definition is applicable here, i.e., the chords of the stabilizer ran in the span-wise direction.) The rear spar consisted of a top chord, a middle chord, and a bottom chord, which were joined by an aluminum web. The purpose of the nominally unstressed middle chord was to act as a crack arrestor in the event that a fatigue crack propagated in the rear spar web from the top chord. There was evidence that the fracture of the web between the upper chord and the center chord had also failed prior to the crash. There was some fatigue cracking of the center chord, and both the center chord and lower chord had failed due to overload. This was not an isolated case, for a survey of 521 B-707 aircraft equipped with this type of horizontal stabilizer revealed that 7% had rear spar cracks of varying sizes.

The investigation was directed at the establishment of (a) the reason for and age of the fatigue failure, and (b) the reason why the fail-safe structure in the rear spar had failed to carry the flight loads once the top chord had fractured as a result of fatigue. The examination indicated that the total number of flights between the initiation of the fatigue crack and final failure of the upper chord was on the order of 7200. The study concluded that additional fatigue crack growth had occurred after the top chord failure, and that there were probably up to 100 flights between top chord failure and stabilizer separation.

The recommended time to be spent in inspecting the horizontal stabilizer was of such a duration, 24 minutes, as to suggest that a visual inspection rather than a more detailed examination was intended. The rear top and bottom spar chords had been designed to permit them to be inspected externally, and the recommended inspection should have been adequate to detect a crack in the top chord provided the crack was reasonably visible. It was known from those cracks detected as a result of the postaccident fleet inspection that partial cracks on the top chord, although visible to the naked eye when their precise location was known, were for all practical purposes undetectable visually. The recommended inspection could not therefore detect the crack in the spar chord unless the inspection occurred during the interval between top chord severance and total spar failure, which was not so in this case.

The investigators concluded that following the failure of the stabilizer rear spar top chord, the structure could not sustain the flight loads imposed upon it long enough to enable the failure to be detected by the then existing inspection schedule. Although the manufacturer had designed the horizontal stabilizer to be fail-safe, in practice it was not, because of the inadequacy of the inspection procedure. The inspections were not adequate to detect partial cracks in the horizontal stabilizer rear spar top chord, but would have been adequate for the detection of a completely fractured top chord.

Horizontal stabilizers remain prone to fatigue. A British Concorde was recently grounded when a growing fatigue crack in the left rear wing spar had propagated to 76 mm (6).

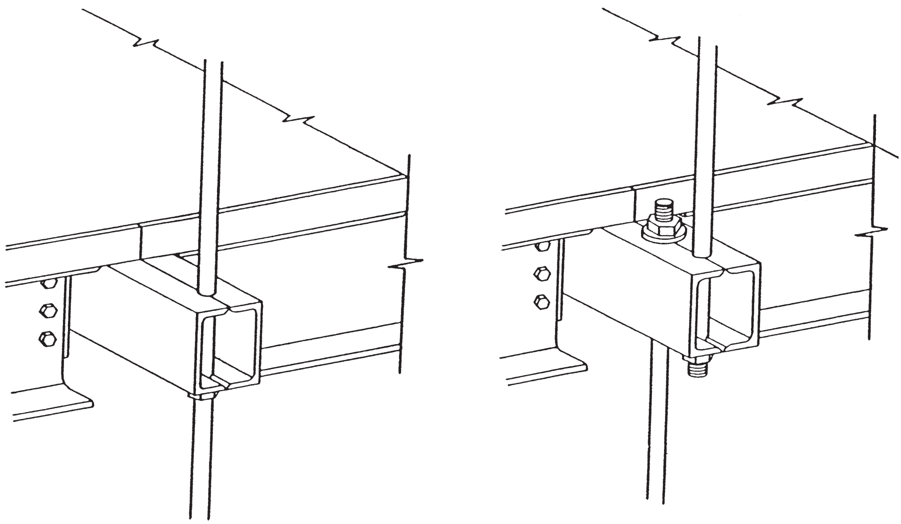
4. Hartford Coliseum Roof Collapse The roof of this three-year-old structure collapsed at 4:00 am on January in 1978 during a freezing rainstorm after a period of snow. A triangular lattice steel space grid, 360 feet by 300 feet, supported on four reinforced concrete pylons giving spans of 270 feet and 210 feet, was used to support the roof. Smith and Epstein (7) concluded that the interaction of top chord compression members and their bracing played an important role in the redistribution of load and the eventual collapse. They noted that certain compression members were braced against buckling only in one plane. As loads increased, these members buckled out of plane and redistributed load to other members. Over a period of time, more chords buckled and fewer and fewer members carried the load. This situation worsened until the remaining members were unable to withstand the added stress due to the loads present that night, and the final, sudden collapse took place.

This is an instance primarily of inadequate structural design.

5. Kansas City Hyatt Regency Walkways Collapse (8) On July 20, 1981, two suspended walkways within the atrium area of the Hyatt Regency Hotel in Kansas City, MO, collapsed, leaving 113 people dead and 186 people injured. In terms of loss of life and injuries, this was the most devastating structural collapse ever to take place in the United States. The second floor walkway was suspended from the fourth floor walkway, which was directly above it. In turn this fourth walkway was suspended from the atrium roof framing by three pairs of hanger rods. In the collapse, the second and fourth floor walkways fell to the atrium floor, with the fourth floor walkway coming to rest on top of the lower walkway. Most of those killed or injured were either on the first floor level of the atrium or on the second floor walkway.

As originally approved for construction, the plans for the walkways called for the hanger rods to pass through the fourth floor box beams and on through the second floor box beams. The box beams were made up of a pair of 8-inch steel channels with the flanges welded toe-to-toe. The beams were to rest on hanger-rod washers and nuts below each set of beams, Fig. 1-3*a*. Under this arrangement, each box beam would separately transfer its load directly into the hanger rods.

However, during construction, drawings were prepared by the steel fabricator that called for discontinuous rather than continuous hanger rods, Fig. 1-3*b*. In this modified design, three pairs of hanger rods extended from the fourth floor box beams to the roof framing, and three pairs of hanger rods extended from the second floor box beams to the fourth floor box beams. Under this arrangement, all of the second floor walkway load was first transferred to the fourth floor box beams, where both that load and the fourth floor walkway load were transmitted through the box beam hanger rod connections to the ceiling hanger rods. This change essentially doubled the load to be transferred by the fourth floor box beam-hanger rod assembly connections.



(*a*) (*b*)

Fig. 1-3. A comparison of the Kansas City Hyatt walkway connectors. (*a*) As originally designed. (*b*) As built. (From National Bureau of Standards, 8.)

Postcollapse failure analysis indicated that the failure of the walkway system initiated in one of the box beam-hanger rod connections. In this instance, the fabricator, structural engineer, and the architect, each of whom had approved the design change, had not appreciated the consequences of the design change.

B. Problems with Inspection, Maintenance, and Repair

6. Mianus River Bridge Failure Demers and Fisher (9) provide a description of the collapse of a portion of this bridge. A six-lane interstate highway supported by six sets of piers, which are skewed to run parallel to the river, spans the Mianus River in Greenwich, CT. The bridge is composed of a number of individual spans, each supported on the outer edges by longitudinal girders. The bridge had been in service for 24 years when, on June 28, 1983, in the early hours of the morning—fortunately an hour when traffic was light—one of the eastbound spans completely separated from the bridge and fell to the river below, causing several fatalities. The span that failed had been suspended, as indicated in Fig. 1-4*a*, between adjacent spans that were cantilevered out from supporting piers. The failed span was a statically determinant structure, which meant that the failure of one main structural member of a span would lead to collapse of that span. Recall that a redundant structure is one in which failure of a structural component leads to a redistribution of loads to other members, but not complete collapse. The span that failed employed pin-and-hanger assemblies at its eastern corners to connect the girders of adjacent

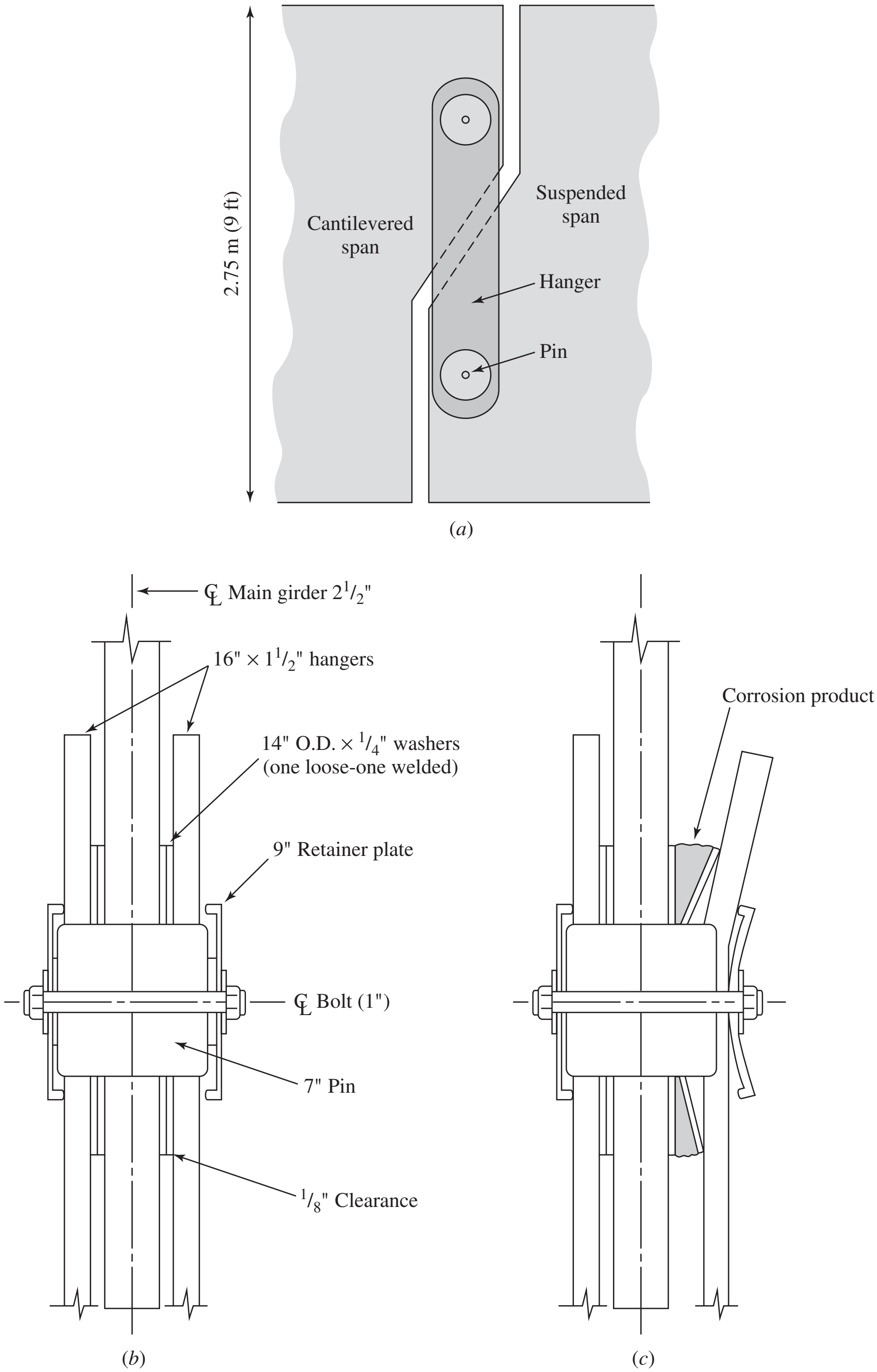


Fig. 1-4. The Myannis River bridge hangers. (*a*) Method of supporting failed suspended span. (*b*) Pin-hanger assembly as built. (*c*) Pin-hanger assembly after 24 years of service. (Fig. 1-4 b and c, after Demers and Fisher, 9.)

components of the bridge. Collapse started at the southeast corner as deduced from the postfailure position of the span. After the collapse, the southeast corner inside hanger was found to be straight and attached to the upper pin, whereas other connectors had been severely deformed. It was concluded that since the inside hanger was straight, the lower pin had separated from it prior to the collapse and had moved in the direction of the outer hanger. This unloading of the inner hanger doubled the load on the outer hanger. The resulting high bearing pressure at the upper surface of the upper pin led to the formation of a fatigue crack in the pin, which caused a portion of the upper pin to separate from the pin, thereby allowing the hanger to slip off the upper pin to bring about the final collapse of the span.

Postaccident inspection revealed that the bearing surface of the southeast corner inside hanger at the lower hole was severely corroded. The inside end of the lower pin was severely corroded and tapered, and the bottom edge had broken off. Movement of the lower pin required the failure of the restraining bolt through the pin. Extensive corrosion packout (compare Figures 1-4*b* and 1-4*c*) between the outer washers was found on the outer side of both upper and lower assemblies, which resulted in plastic deformation of the retainer plate and high tensile stresses in the bolt, which led to its fracture. It was concluded that failure was the result of a progressive process that occurred over a period of time, and that corrosion packout was primarily responsible for the hanger displacement on the pin, which led to the collapse.

This failure underscored the importance of maintaining effective corrosion prevention and inspection programs to maintain the integrity of such structures.

7. Aloha Airlines Boeing 737-200 Accident (10) In 1988, a Boeing 737-200 operated by Aloha Airlines, while en route from Hilo to Honolulu, HI, experienced an explosive decompression and structural failure as the plane leveled at 24,000 feet. Approximately 18 feet of the cabin skin and structure aft of the cabin entrance door and above the passenger floor had separated from the airplane, Fig. 1-5. There were 89 passengers and 6 crewmembers on board. One flight attendant was swept overboard and seven passengers and one flight attendant received serious injuries. An emergency landing was made on the island of Maui. As a result of the accident the airplane was damaged beyond repair and was dismantled and sold for scrap.

The B-737 involved had been manufactured in 1969. At the time of the accident it had acquired 35,496 flight hours and 89,680 flight cycles (landings), the second highest number of cycles in the worldwide 737 fleet. Due to the short distance between destinations on some Aloha Airlines routes, the full pressurization of 52 kPa (7.5 psi) was not reached on every flight. Therefore, the number of full pressure cycles was significantly less than 89,680. The plane had also been exposed to warm, humid, maritime air, which promoted corrosion.

Failure was found to have initiated along a fuselage skin longitudinal lap joint that had been "cold bonded." The cold bonding process utilizes an epoxy-impregnated woven "scrim" cloth to join the longitudinal edges of the single-thickness 0.036-inch skin panels together. In addition, the joint contained three rows of

Fig. 1-5. General view showing the damage sustained by the Aloha Airlines 737. (From NTSB, 10.)

countersunk rivets. Fuselage hoop loads were intended to be transferred through the bonded joint, rather than through the rivets, allowing for thinner skin with no degradation in fatigue life. However, early service history with production B-737 airplanes revealed that difficulties were encountered with the bonding process, and it was discontinued after 1972. In order to safeguard those B-737 planes that had been "cold bonded," Boeing issued a number of service bulletins over a period of time directing the attention of operators to the problem of disbonding and providing information on how to check for disbonding using the eddy current nondestructive examination (NDE) method. In 1987, the FAA issued an airworthiness directive (AD) requiring that eddy current inspections of the bonds and repairs, if needed, be carried out in compliance with the Boeing service bulletins. Some of the bonds had low environmental durability, with susceptibility to corrosion. Some areas of the lap joints did not bond at all, and moisture and corrosion could contribute to further disbonding. When disbonding did occur, the hoop load transfer though the joint was borne by the three rows of countersunk rivets. However, the countersinking extended through the entire thickness of the 0.036-inch sheet, which resulted in a knife edge being created at the bottom of the hole, which concentrated stress and promoted fatigue crack nucleation, Fig. 1-6. For this reason, fatigue cracking would be expected to begin in the outer layer of the skin along the lap joint along the upper, more highly stressed, row of rivet holes.

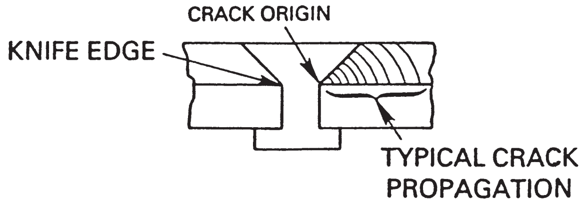


Fig. 1-6. A sketch of a countersunk rivet and an associated fatigue crack observed in Aloha Airlines 737. (From NTSB, 10.)

The NTSB believed that the top rivet row was cracked at the critical lap joint before the accident flight takeoff, and determined that the probable cause of the accident was the failure of the Aloha Airlines maintenance program to detect the presence of the significant disbonding and fatigue damage that ultimately led to the failure of the lap joint and the separation of the fuselage upper lobe. This accident was significant in that it brought attention to some of the corrosion and fatigue problems that could develop in *aging aircraft*. It also focused attention on the problem of multiple-site damage (MSD), that is, the formation and possible linking up of fatigue cracks formed at adjacent rivet holes.

8. Chicago DC-10-10 Crash (11) On May 25, 1979, as American Airlines Flight 191, a McDonnell-Douglas DC 10-10 aircraft, was taking off from the Chicago-O'Hare International Airport, the left engine and pylon assembly separated from the aircraft, went over the top of the wing, and fell to the runway. The plane continued to climb to about 325 feet off the ground and then rolled to the left and crashed. The aircraft was destroyed in the crash and subsequent fire, and the 271 persons on board were killed, as were two others on the ground, the worst loss of life in U.S. aviation history. The accident aircraft had entered service in 1972. It had accumulated a total of 19,871 flight hours, 341 of which had come since a maintenance procedure in Tulsa, OK.

The cause of the separation of the engine from the wing was found to be cracking of the aft bulkhead of the pylon, a problem created during the maintenance procedure in Tulsa. Figure 1-7 shows the pylon assembly. Note that the upper spar is attached to a flange (not shown) on the forward side of the aft bulkhead. This flange turned out to be a critical element in the accident sequence. McDonald-Douglas had issued a service bulletin calling for the replacement of the upper and lower spherical bearings that attached the pylon to the wing. In this procedure, McDonald-Douglas indicated that the 13,477-lb engine was to be removed from the 1865-lb pylon before the pylon was removed from the wing. Procedures for accomplishing this maintenance were also described. However, in contrast to the maintenance procedure advocated by McDonald-Douglas, American Airlines decided to lower and raise the engine and pylon assembly using a forklift-type supporting device, since this procedure would save about 200 man-hours per aircraft and would reduce the

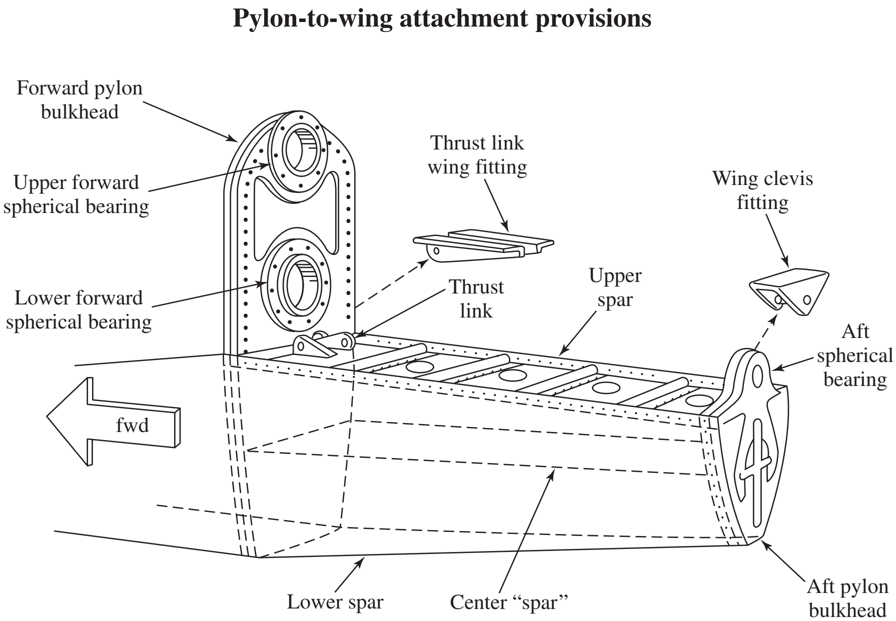


Fig. 1-7. The pylon assembly of a DC-10. The upper spars and sheet metal are attached to the critical forward flange of the aft bulkhead. (From NTSB, 11.)

number of disconnects from 79 to 27. An engineering change order (ECO) was issued by American Airlines in 1978 prescribing this maintenance procedure, and in March 29 through 31, 1979, the accident aircraft underwent the spherical bearing modification using this procedure. It is noted that McDonald-Douglas had discouraged the use of this procedure because of the risk involved in remating the engine-pylon assembly to the wing attach points, but lacked the authority to either approve or disapprove the maintenance procedures of its customers. Also, members of the American Airlines engineering department did not witness the removal of the wing to pylon attachment assemblies, and consequently, they were not aware of difficulties such as controlling the forklift accurately.

Postaccident investigation revealed that a portion of the upper forward flange of the aft bulkhead had been fractured by overload in the inboard-outboard direction just forward of the radius between the flange and the bulkhead plane. The fracture had been initiated by a downward bending moment at the center section of the flange just forward of the fracture plane due to contact between the clevis and the flange. As a result of this contact, the aft fracture surface of the upper flange was deformed into a crescent shape that matched the shape of the lower end of the wing clevis. The length of this overload fracture was 10 inches. Fatigue cracking was present at both ends of the overload fracture, and the total length of the crack due to both overload and fatigue was 13 inches.

In postaccident inspections of the DC-10 fleet, four American Airlines planes and two Continental Airlines planes were found to have cracked upper flanges on the pylon aft bulkheads, with the longest of these cracks being 6 inches. In addition, it was discovered that two Continental Airlines DC-10s, one in December 1978 and the other in February 1979, had had fractures on their upper flanges. These two flanges had been damaged during this same maintenance operation, but they had been repaired and returned to service. McDonald-Douglas had been informed of these problems, but neither the FAA nor other airlines had been informed because the events were considered to have been maintenance errors.

An examination of the maintenance procedure disclosed numerous possibilities for the upper flange of the aft bulkhead to be brought into contact with the wing-mounted clevis. A fracture-producing load could be applied during or after removal of the attaching hardware in the aft bulkhead fitting. Because of the close fit between the pylon to wing attachments and the minimal clearance between the structural elements, maintenance personnel had to be extremely cautious when they detached or attached the pylon. A minor mistake by the forklift operator could easily damage the aft bulkhead and its upper flange.

The structural separation of the pylon was caused by a complete failure of the forward flange of the aft bulkhead after its residual strength had been reduced by the fracture induced during the maintenance operation as well as by additional fatigue crack growth in service. It is also clear the poor communications between engineering and maintenance personnel, and between the FAA, the manufacturer, and the airlines contributed to this accident.

9. Japan Airlines Boeing 747SR, Crash 1985 (12) In August of 1985 a Japan Airlines Boeing 747SR (short range) jet aircraft was on a flight from Tokyo to Osaka. On climbing through 24,000 feet, the rear pressure bulkhead failed, and as a result, there was an explosive decompression, which led to loss of hydraulic power and of the pilot's ability to control the aircraft. Thirty minutes later the aircraft crashed into a mountain. This was the worst single-plane accident in aviation history, for of the 524 people on board, only 4 survived.

This aircraft had been in a takeoff mishap in June of 1978 in which the tail section struck the runway, causing damage to the lower half of the rear pressure bulkhead. This bulkhead is in the shape of a hemisphere and is made of thin-gauge aluminum alloy sheets. At a joint between sheets the sheets overlap, and an additional piece of sheet material, known as a doubler, spans the riveted joint to provide extra strength. To repair the damage after the 1978 accident, a new lower half bulkhead was riveted to the upper half. However, the two halves were not properly spliced together. On the upper side of the joint, there was a doubler and a stiffener on the inner side of the bulkhead, Fig. 1-8. On the lower side of the joint there was a doubler, but the doubler was not continuous with the upper doubler, so that a gap existed between the doublers, with only the sheet material carrying the load. In addition, the centroid of the load-bearing material was now on the inner side of the bulkhead. Therefore, the load on the sheet spanning the gap consisted not only of that due to the hoop tension, but also that due to bending because of the eccentric loading condition created by the doublers and the stiffener. Each time the cabin was

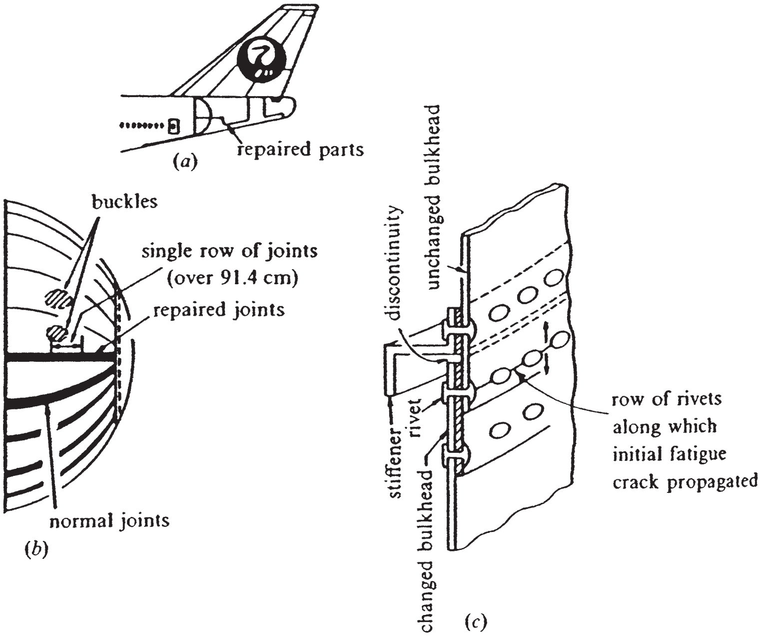


Fig. 1.8. The rear bulkhead of the JAL 747 SR. (After Kobayashi, 12.)

pressurized, there was an increase in stress in the aluminum sheet spanning the gap over that expected. As a result of this stress increase, fatigue cracks were formed at each of the rivet holes on the lower half of the bulkhead just below the gap, another example of MSD. These fatigue cracks eventually linked up, and the resultant long crack led to the explosive decompression.

C. Other Problems

10. Air France Concorde Crash, July 25, 2000 The crash of Air France Flight 4590, a supersonic Concorde (SST), moments after takeoff from the Charles de Gaulle Airport near Paris, resulted in the deaths of 109 people aboard the jet and 5 people on the ground. This accident is currently under investigation, but the preliminary evidence, as well as a past history of similar, but fortunately not catastrophic, events, indicate that the bursting of a tire on the left side of the plane while the plane was accelerating during its takeoff run was critical. A 16-inch piece of metal that fell to the runway from the engine of a plane that had taken off shortly before the Concorde may have caused the tire to burst. The metal strip matched a gash found in one of the Concorde's left tires, and it is probable that this piece caused the cut. There have been 57 cases of burst tires on Concordes, and in 7 instances these bursts have led to the rupture of fuel tanks, the severing of hydraulic lines, and the damaging of engines. French investigators believe that in the Paris crash, after the tire burst, an 8-lb piece of rubber penetrated the fuel tank, thereby releasing a plume of fuel that, being in close proximity to the two left side engines, ignited. Both British and French aviation authorities have grounded the Concordes pending further assessment of their fail-safe capabilities in the event of a tire burst. The addition of fuel-tank liners to minimize damage related to tire bursts is being considered

11. TWA Flight 800 Crash In July of 1996, TWA Flight 800, a Boeing 747, crashed into the Atlantic off Long Island, NY, killing 230 people. A leading theory as to the cause of this accident is that fuel vapors in the empty center fuel tank may have been explosively ignited by a spark between two elements of a terminal strip that was part of a fuel probe. Moments before the explosion, a fuel gauge behaved erratically, an indication of a wiring problem. The potential difference between the elements of the terminal strip was 170 volts, which ordinarily would not be a cause for concern. However, the plane was 25 years old and over time a semiconducting sulfur compound had built up on the terminal strip, which allowed current to flow between the elements. As a result, the compound may have "burned" and triggered a spark that caused the explosive ignition of the fuel vapors.

III. SUMMARY

These eleven examples indicate the range of design, maintenance, environmental, and inspection problems that can arise and endanger the integrity of structures. In the following chapters, the failure mechanisms and investigative procedures are discussed in greater detail, and additional case studies are presented.

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