METAL FAILURES

MECHANISMS, ANALYSIS, PREVENTION

ARTHUR J. McEVILY

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Metal Failures:
Mechanisms, Analysis, Prevention

To
Geoff, Allysha, Keith, Joey, Ryan, Kyle, and Courtney

Preface

This book is intended for use by senior engineering students in a one-semester course, as well as by graduate engineers who are seeking further information concerning the analysis of failures. The book is the outcome of teaching a 14-week course to both undergraduates and graduates for more than ten years. By dealing with a wide scope of types of failures, the book provides the information usually found in a course on mechanical metallurgy. A large number of case studies, often based upon the author's experience of over 50 years, are used to illustrate many of the basic principles involved, both in metallurgy and in failure analysis. These case studies are intended to demonstrate how basic principles are applied to real-world situations. There are 14 chapters, of varying lengths, and it is expected that an instructor will balance the time spent on each to cover the material in a semester as suits his or her interests and those of the students.

My appreciation is expressed to my colleagues Mark Aindow, Martin Blackburn, Steven Boggs, Maurice Gell, Jorge Gonzalez, Yoshiyuki Kondo, Iain Le May, Gary Marquis, John Morral, Yukitaka Murakami, Nitin Padture, and Leon Shaw for their helpful comments and encouragement.

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Storrs, CT
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Metal Failures:
Mechanisms, Analysis, Prevention

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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,

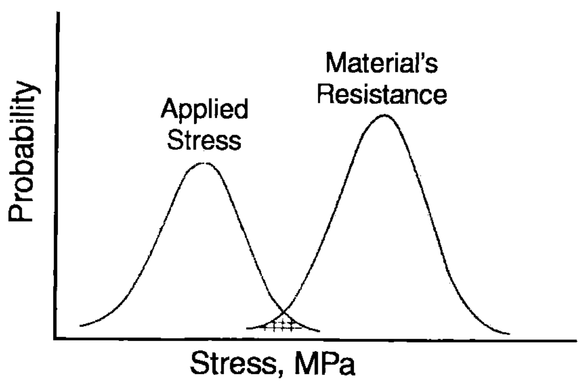

Fig. 1-1. Schematic frequency distributions showing the applied stresses and the resistance of the material.

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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-

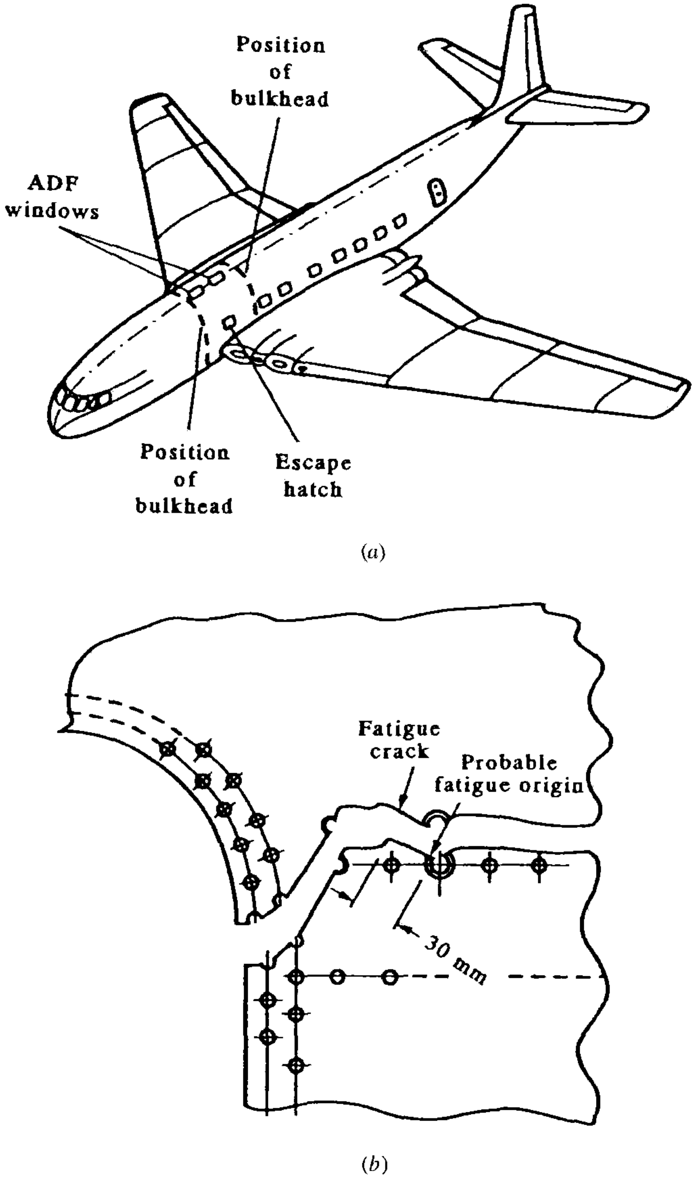

Fig. 1-2. (*a*) The Comet aircraft. (*b*) The location of fatigue cracking near an aft corner of the ADF (automatic direction finder) window. (After Jones, 3, reprinted by permission.)

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.

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