Failure Analysis
of Engineering Structures
Methodology and Case Histories

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Foreword

By B.R. Pai

Machines and structures have failed in service without warning and with disastrous consequences. Collapse of bridges and buildings, massive splitting of ships and tankers, explosions in chemical factories, in-flight disintegration of aircraft and space vehicles, and other such major disasters have become history. The consequential damages of these mishaps are humanly unforgivable and can never be forgotten by mankind. Needless it is to emphasize the importance of the prompt investigation of these failures in order to ascertain their causes, inform the public, and to take remedial action to prevent their recurrence.

Investigation of service failures and accidents is a formidable, complex, and challenging task, very startling even to start with. In the case of aviation accidents, location of the wreckage itself is a major task, especially if the wreckage is distributed on a mountainous terrain or on the ocean floor. A wreckage distribution map and an inventory of the pieces recovered from the wreckage and their documentation go a long way in reconstruction of the scene just prior to the mishap. The analytical part of the investigation of the damaged structure and its components is a multidisciplinary activity. It demands tremendous responsibility and coordination on the part of the analyst and a thorough knowledge of materials science supplemented with appreciation and application of related engineering disciplines.

Failures are a fact of life. A failure-free system is more a myth than a reality. The engineering profession and the industries aim at design and manufacture of products with the probability of service failure at the absolute minimum. Realizing the significance of failures, especially in aerospace systems, National Aerospace Laboratories nurtured the failure analysis activity from its inception. The Failure Analysis and Accident Investigation Group in the Materials Science Division of this laboratory has been very active in this field for over four decades. Several hundred investigations have been carried out by this group for various organizations, industries, and institutions and remedial actions suggested. The members of this group have assisted in various commissions of inquiry appointed by the government for investigating failures and accidents that took place in India and elsewhere. The feedback received from the clientele has been very satisfying.

Failure Analysis of Engineering Structures: Methodology and Case Histories, by these scientists, is a culmination of years of their experience in the field. The authors have meticulously compiled lots of information on the subject. Chapters in the book cover, inter alia, the common causes of failures with numerous examples; methodology of failure analysis, including some advanced techniques; various mechanisms of failures; and characteristic macroscopic and microscopic features on failed components, which provide significant clues to their causes. Deliberate damage to structures caused by the use of explosives today is a global threat. The authors have provided useful information on the detection and identification of explosive damages. Treatment of this topic with a detailed description of aircraft accidents due to explosive sabotage is exemplary. The authors' sharing of their personal experiences of the investigation of the major aircraft accident to the Boeing 747 aircraft Kanishka of Air India over the Atlantic Ocean is commendable. Keeping in mind that failures and accidents often lead to serious litigations, the authors have also provided a chapter on forensic failure analysis.

Service failure is the ultimate test for the integrity of a machine, though a very expensive and destructive test. It is now a well-known adage that one learns more from failures than from successes. A detailed and faithful account of service failures and accidents and their in-depth analysis provide very valuable lessons for future designers, manufacturers, users, and maintenance personnel. Failure awareness, anticipation of failures and proactive failure analysis form a good part of successful engineering. It is in this context that the study of case histories of failures assume great importance. The authors of this book have thoughtfully added a complete section on case histories.

This book is a good archive of information for failure analysts, practicing engineers, and students of engineering. I compliment the authors for this effort.

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October, 2004

Foreword

By V.S. Arunachalam

Why does a material fail? There can be only four reasons: the material is subject to an environment beyond its design envelope; it is an inappropriate choice for the design and operating conditions; the material, to start with, is defective; or the design itself is wrong. It is vital to know the reasons as component failures can lead to catastrophic accidents causing heavy loss of life and property. Such accidents can slow down or even temporarily stunt the development of new artifacts and systems that appeared so promising. An inappropriate gasket design, of all things, delayed the space shuttle program by many years.

Every failure leaves its own telltale signs in the macrostructure and microstructure of the failed component. It is not always easy to read those signs because the accident could have destroyed the evidence irreversibly, and the failed component itself could present conflicting evidence. In spite of these difficulties, failure analysis has grown to be an important tool in the design and manufacture of engineering parts.

Materials derive their properties from the structure they exhibit, and when they fail, the structure shows that as well. That is why microscopes have become essential tools in failure analysis. Increasing resolution, improved depth of focus, simultaneous chemical analysis at molecular levels, and imaging of imperfections have now become commonplace, thanks to advances in electron, x-ray, and laser optics. Some of the most recent work in hydrogen embrittlement has been made possible because of the availability of sophisticated analytical tools.

Can we simulate a failure in laboratory conditions? Interestingly, an early account of such a simulation where a failure was recreated came out of Nevil Shute's novel, *No Highway* (Amereon Limited, 1988). Since then, the fiction was made real when the Comet aircraft crash was simulated in a specially built water tank. Nowadays, mechanical, physical, and chemical testing of materials and components, in addition to modeling of parts and simulation of components in service, have become commonplace. Thanks to the availability of powerful computers, large computer memory, and impressive processing speeds, computer simulations today provide the verisimilitude of components in service with realistic operating and environmental conditions—all without actually breaking the component. The ubiquitous computer has given us other tools as well, such as fault tree analysis, information, and data mining of past accidents.

Why is the past so important? Psychologists tell us we learn from experience, especially from failures. Every experience adds more information to memory so that our cognitive skills become less bound, and reasoning becomes more logical. That is why we have to document our experiences properly and derive lessons from them. In spite of such efforts, accidents will unfortunately continue to happen because of deliberate acts such as sabotage, or the lessons learned of the past instances have not diffused well, or even for reasons that are beyond our control and past learning. But their numbers will continue to reduce, making our lives safer and property more secure; look at the earthquake-proof structures or the pressure vessels that engineers have built today.

The Bangalore National Aerospace Laboratories (NAL) Failure Analysis Centre has grown to become India's foremost group for this area of analysis. The scientists and engineers working in this group have built a rich repertoire of experiences in failure analysis. The procedures they follow, the techniques they use, and the inferences they draw from the observations make this book a very useful contribution to the study of failure analysis. They have not limited themselves to run-of-the-mill engineering failures, but share their rich and varied experiences in such areas as sabotage with explosives and also litigations that inevitably follow accidents. I have had the privilege of working with the authors of this book and have marveled often at their professional skills and the commitment they brought to their work. ASM International is to be congratulated for publishing this book and thus enabling the NAL group to share their experiences with the global engineering community.

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Preface

Service failures of machines and structures without warning have been experienced in many industries with varying degrees of consequential damages. Systematic analysis of such failures has generated a fund of useful information for designers, manufacturers, and users of industrial hardware. With an understanding of failures and their causes, technical remedies were incorporated at various stages and, thus, recurrence of failures prevented. National Aerospace Laboratories (NAL), Bangalore, has been involved in failure analysis and accident investigations for over four decades. Though initially the clientele was mainly from the aerospace sector, several other organizations have taken advantage of this service. The experience gained over the years has culminated in the compilation of this book, *Failure Analysis of Engineering Structures: Methodology and Case Histories.* The book comprises two parts. The first part is a treatment of various aspects of failure analysis with emphasis on techniques. The second part deals with failure case studies analyzed by the Failure Analysis and Accident Investigation Group in the authors' laboratories.

The introductory chapter cites a few major industrial catastrophes encountered in the last century. The importance, philosophy, and the beneficiaries of failure analysis are covered. The failure rate in the life span of machines is comparable to the geriatric curve, high in the initial and final stages and minimum in between. The philosophy of failure analysis is to bring down the failure rate and to extend the span of minimum failure rate.

Chapter 2 covers the common causes of failures. Various failures encountered in industries could ultimately be attributed to some deficiency introduced, though inadvertently, during the various stages of manufacture and operation. These stages include design, production (which covers materials selection, processing operations, treatments, assembly, and inspection), maintenance, service abnormalities, abuses, and environmental effects. Failure cases are described with examples from various industries such as chemical, mining, aviation, power generation, and so forth to illustrate how the deficiencies ultimately led to serious failures.

The success of failure analysis depends on the use of proper analytical techniques in proper sequence. Chapter 3 describes the techniques with which every analyst should be familiar. The techniques described include collecting background information; survey of wreckage; collection and preservation of samples for further laboratory examination; tests such as chemical analysis at various levels, mechanical tests, nondestructive inspection, microscopy, fractography, simulation tests; and final analysis of results to pinpoint the cause of the failure and the sequence of events. Simulation tests often help in clinching specific issues.

Vital information about failures is provided by microscopic examination of samples at various levels of resolution and magnification. A separate chapter is thus devoted to microscopy in failure analysis. Microstructural examination with the metallurgical microscope reveals structural abnormalities, crack origin, and crack path. Fracture surface examination using optical microscope and scanning electron microscope reveals telltale marks characteristic of such failure modes as tensile overload, shear overload, rapid brittle fracture, fatigue, stress corrosion, and so forth. These are described with illustrations in Chapter 4.

Chapter 5 deals with certain advanced techniques of failure analysis. These techniques evolved in recent times, necessitated by the needs of failure analysis in sophisticated industrial systems. In thermal plants that have been in service for a long time, study of samples taken for biopsy without affecting the integrity of the plant has helped in condition monitoring of the plant and estimating its residual life. Fracture Surface Topography Analysis (FRASTA) is another advanced technique by which the evolution of the fracture process could be studied. The practical applications of this technique are described briefly. Other techniques described in this chapter are fault tree analysis (FTA), failure modes and effects analysis (FMEA), failure experience matrix (FEM), expert systems for failure analysis, study of fractals, and quantitative fractography.

Failures in machines and structures are sometimes deliberately caused by antisocial elements, using explosive devices. When metallic objects deform and fracture under explosive conditions where the strain rates are of the order of $10^6\ s^{-1}$, certain distinct features can be found in the fragments produced by explosions. These features are permanent and they survive subsequent crash impact forces. These features are different from the telltale marks produced under normal static loading conditions. In Chapter 6, the signatures of explosion are catalogued under surface features, edge features, microstructural features, and fragment shapes, with illustrations. These have been extremely helpful in the investigation of aircraft accidents caused by explosive sabotage. Two such accidents are described in detail.

Major catastrophes are invariably followed by serious, prolonged, and expensive litigations in courts. Many of the failures and accidents involve a combination of component malfunction and mismanagement. While routine failure investigations aim at finding the cause of the mishap, investigations in courts attempt also to fix responsibilities and recommend punitive action. These can be extended for several years after the accident. Exact evidence with supporting data of high standard has to be presented in the courts to justify penal action. Some of the major accidents described in Chapter 2 were followed by judicial inquiries in which experts provided the required testimony. A few cases of forensic investigations are presented in Chapter 7.

The follow-up actions after failure analysis have indeed resulted in numerous advantages to industries. These advantages are described in Chapter 8. Process modification after failure analysis in a chemical industry significantly reduced the hazards encountered earlier. Choice of better and cleaner materials resulted in increased reliability and safety. Codes and standards have been modified to ensure greater safety in hazardous industries. Certain specific actions also ensured greater security in industries, especially aviation. The numerous advantages accrued after taking remedial measures, following an understanding of failures, more than justified the statement, "Many should benefit from the misfortunes of a few."

Part 2 of the book deals with detailed description of various failure cases investigated by the Failure Analysis and Accident Investigation Group at NAL. The majority of cases deal with aviation machines, while a few cases of industrial failures are also included.

The Failure Analysis activity at NAL was nurtured by senior scientists and Directors of the Laboratory, namely, Dr. S. Rameshan, Dr. V.S. Arunachalam, Dr. A.K. Singh, Dr. S.R. Valluri, Dr. R. Narasimha, Dr. K.N. Raju, Dr. T.S. Prahlad, and Dr. B.R. Pai. The members of the Failure Analysis Group, Dr. T.A. Bhaskaran, Mr. C.R. Kannan, Mr. M.A. Parameswara, Mr. S. Radhakrishnan, Mr. R. Rangaraju, Mr. Dwarakanath Rao, and Mr. M.A. Venkataswamy, contributed in no small measure in the investigation of numerous cases described in Part 2.

Because failure analysis is a multidisciplinary activity, expertise from other divisions and sections of the Laboratory was drawn frequently as needed. Significant help was received from Graphic Arts, Chemical Analysis Group, X-ray Laboratory, Fatigue Laboratory, and Engineering Services. The authors are thankful to Mr. K. Venkata Ramaiah for his help in computer graphics. In compiling this book, the authors had very useful discussions with Dr. M.K. Asundi of Bhabha Atomic Research Centre, Bombay; Dr. R. Krishnan of Gas Turbine Research Establishment, Bangalore; and Dr. R. Viswanathan of Electric Power Research Institute, Palo Alto.

Designers, manufacturers, maintenance personnel, and users of machines are the beneficiaries of the results of failure analysis. It is hoped that this book would be of use to students of engineering and practicing engineers.

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CHAPTER 1

Failure Analysis: Why and for Whom?

SERVICE FAILURES of components and structures have been increasingly experienced in several industries, quite often without any warning. Some failures may be trivial, while others may have serious consequences. Service failures may result in:

- Fatalities
- Injuries to personnel
- Damage to property
- Shutdown of an entire plant
- Loss of production
- Ecological problems such as release of hazardous materials
- Expensive and prolonged litigations affecting the credibility of the manufacturers and the reliability of their products

Thus, failures have a great impact on the society and its economy. Failures of structures can occur at various locations, for instance, at home, on the road, in a machine, in an aircraft, or in a big plant. Failure of an aluminum ladder in a home, which led to personal injuries to a woman and the following litigation between her and the manufacturer of the ladder, is an example where the effect of failure is limited to an individual. In contrast, the failure of a pipe in a chemical plant, carrying an inflammable chemical resulted in the total devastation of the entire factory with extensive damage to the community. As the complexity of our technological systems increases, so do the possible catastrophic consequences of the failure. For understanding failures and their prevention, there is a need for the application of many disciplines of science and technology.

The last century witnessed several catastrophic failures. Some of these failures are described in later sections. One of the most tragic brittle failures was that of a molasses tank that failed in Boston on Jan. 15, 1919 and flooded the city with 2.3 million gallons of molasses, drowning people and horses and knocking over the Boston elevated railway structure. Several rapid brittle failures have occurred in structures such as tanks, pressure vessels, ships, and bridges in the United States, Canada, and Europe. The problem was fully appreciated in the 1940s when out of 5000 merchant ships built during World War II, over 1000 had developed cracks of considerable size. At least nine T-2 tankers and seven Liberty ships had broken completely into two as a result of brittle fractures originating from sharp corners and square cutouts.

There have been some more catastrophes in recent times. The tragedy at Bhopal, India on Dec. 3, 1984, which claimed the lives of over 2000 people and maimed many due to the release of the poisonous methyl isocyanate gas is still fresh in memory. The Boeing 747 aircraft Kanishka of Air India plunged into the Atlantic Ocean on June 23, 1985 without any warning, killing all 329 occupants. On Jan. 2, 1988, a 4 million gallon oil storage tank at Ashland, near Pittsburgh, collapsed while filling. Five hundred thousand gallons of diesel fuel flowed into the Monongahela and Ohio rivers, causing a serious environmental problem. Water supply to the city of Pittsburgh was stopped for two weeks. On April 28, 1988, a Boeing 737 aircraft of Aloha Airlines, while flying over the Hawaiian Islands, suddenly experienced explosive decompression, and a major portion of the upper crown skin and structure in the front portion of the main cabin separated in flight, opening the cabin to the sky and causing a serious accident. On Dec. 24, in the same year, an oil pipeline in Missouri collapsed, spilling 800,000 gallons of crude oil into the Missouri River.

Studies following several mishaps have resulted in an awareness that it is not the yield strength or the ultimate tensile strength of a material that would determine the life of a component but rather the formation of a crack and its rate of growth. Crack initiation and propagation can be influenced by a variety of factors that must be understood and appreciated for failure prevention.

Failure of a component or structure can be defined as an unacceptable gap between its expected and actual performance. It is a condition that makes the structure unable to perform its intended function safely, reliably, and economically. Such an unacceptable difference can be due to many reasons. A later chapter explains that the causes of failures rest in defects of one type or another introduced mostly inadvertently during the various stages of the manufacture of a component and its usage.

These defects could get introduced during the design of a component, its manufacture, assembly, inspection, and maintenance. Manufacture of a component involves materials selection, materials certification, processing operations such as casting, forming, joining, machining, heat treatment, surface treatment, and so forth. Service abnormalities and abuses also play a major role in addition to environmental factors. The personnel responsible for the quality assurance at these various stages would get very useful feedback from a detailed failure analysis so that at each stage appropriate precautions could be taken to avoid introduction of deleterious defects. Hence, when there is a failure in a component or structure, the beneficiaries of failure analysis are many in the system.

The failure rate of a system, be it a component, a machine, or a large structure, can be compared with the mortality rate of human beings. This is depicted in the so-called "bath tub" curve (Fig. 1.1), having three distinct zones. During the early life or the infant stage, the failure rate is high. This is generally due to poor design, defective manufacture, and assembly faults of the system. In the next zone, representing the useful service life, the failures have a constant rate and are random. As the system ages beyond a certain service life, the failure rate increases again. This is the geriatric stage, after the system has suffered wear and other degradation processes. At this stage, the system can no longer function reliably,

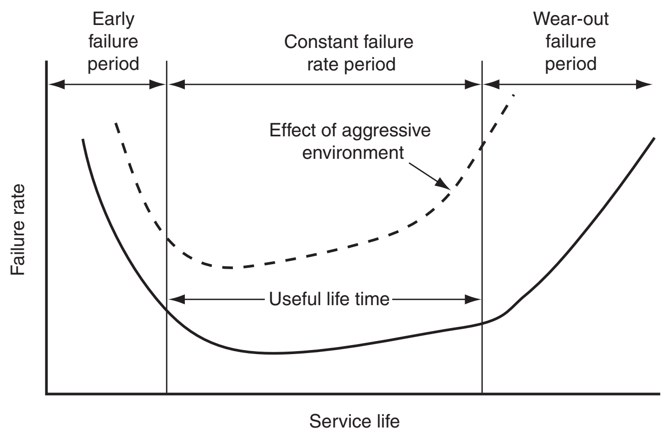

Fig. 1.1 Failure rate during the service life of a system. Source: Ref 1

safely, and economically. All quality control efforts aim at reducing the failure rate in the first zone and extending the life in the second zone.

Failure can be considered a real time test for the integrity of a structure. When a major disaster such as an aircraft accident occurs, it is the manufacturer who is most concerned about investigating the mishap to find out what went wrong and at what stage. Failure is a fact of life. It cannot be totally avoided, as a failure-free system is unattainable or prohibitively expensive. However, when a failure does occur, and if a systematic analysis is carried out, very useful input can be provided to management, engineers, and/or regulatory authorities for taking appropriate corrective actions. Thus, many can benefit from the misfortunes of a few.

Chapter 1: Failure Analysis: Why and for Whom?

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