Failure Analysis

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Overview

Analyzing failures is a critical process in determining the physical root causes of problems. The process is complex, draws upon many different technical disciplines, and uses a variety of observation, inspection, and laboratory techniques. One of the key factors in properly performing a failure analysis is keeping an open mind while examining and analyzing the evidence to foster a clear, unbiased perspective of the failure.

Just as failure analysis is a proven discipline for identifying the physical roots of failures, root-cause analysis (RCA) techniques are effective in exploring some of the other contributors to failures, such as the human and latent root causes. Properly performed, failure analysis and RCA are critical steps in the overall problem-solving process and are key ingredients for correcting and preventing failures, achieving higher levels of quality and reliability, and ultimately enhancing customer satisfaction.

The importance and value of failure analysis to safety, reliability, performance, and economy are well documented. For example, the importance of investigating failures is vividly illustrated in the pioneering efforts of the Wright Brothers in developing self-propelled flight. In fact, while Wilbur was traveling in France in 1908, Orville was conducting flight tests for the U.S. Army Signal Corps and was injured when his Wright Flyer crashed (Fig. 1). His passenger sustained fatal injuries. Upon receiving word of the mishap, Wilbur immediately ordered the delivery of the failed flyer to France so that he could conduct a thorough investigation. This was decades before the formal discipline called failure analysis was introduced.

Fig. 1 Crash of the Wright Flyer, 1908. Courtesy of the National Air and Space Museum, Smithsonian Institution, Photo A-42555-A. Source: Ref 1

What Is a Failure?

A good definition of a failure is "the inability of a component, machine, or process to function properly." Failures come in all shapes and sizes; they can be individual parts, entire machines, or a process. Specific levels of failure causes can be physical, human, latent, or root. Failures are also specific to an industry and the specific requirements of that industry. It is necessary to be knowledgeable about defining the requirements of the failure at hand.

Failure can be defined on several different levels. The simplest form of a failure is a system or component that operates but does not perform its intended function. This is considered a loss of function. A jet engine that runs but can only produce partial thrust (insufficient for takeoff) is an example of a loss of function. The next level of failure involves a system or component that performs its function but is unreliable or unsafe. This is known as loss of service life. In the next level of severity of failure, a system or component is inoperable.

The physical failure of materials can be placed in one of many categories, depending on the classification system. For example, they may be divided into distortion or undesired deformation, fracture, corrosion, and wear.

Categories of Material Stressors

To determine the cause of material failure, one must consider the active stressors. A stressor is an external influence that can be a direct or indirect cause of failure. The influence of stressors is heavily dependent on the susceptibility of the component, performance criteria, the magnitude of the stressor, exposure, and the material susceptibility. The six stressors are:

- *Mechanical:* Applied static, dynamic, or cyclic loads, pressure, impact, fabrication-induced residual stresses, applied end movements
- *Chemical:* Inadvertent acute or chronic exposure to an aggressive chemical environment; material compatibility issues
- *Electrochemical:* A susceptible metal in a corrosive aqueous environment
- *Thermal:* Exposure to elevated temperatures resulting in material degradation
- *Radiation:* Ultraviolet lighting, sunlight, ionizing radiation from nuclear power plants, and so on
- *Electrical:* Applied electrical stress due to the presence of an electric field

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Why Do Failures Happen?

The most common reasons for failures include:

- Service or operation conditions (use and misuse)
- Improper maintenance (intentional or unintentional)
- Improper testing or inspection
- Assembly errors
- Fabrication/manufacturing errors
- Design errors (stress, materials selection, and assumed material condition or properties)

Clearly, through failure analysis and the implementation of preventive measures, significant improvements have been realized in the quality of products and systems. This requires not only an understanding of the role of failure analysis but also an appreciation of quality assurance and user expectations.

However, due to various business or cultural pressures, some organizations fall into the following pitfalls when problems arise:

- Do nothing and perhaps hope that the problem will go away
- Deny that the problem exists, minimize its importance, question the motives of those identifying the problem
- Troubleshoot in a haphazard fashion
- Chase false leads

Problem-solving is rooted in the scientific method:

1. Define the issue
2. Propose a hypothesis
3. Gather data
4. Test the hypothesis
5. Develop conclusions

Or, stated another way, the major steps in the model define the problem-solving process:

1. Identify the problem
2. Determine root cause
3. Develop corrective actions
4. Validate and verify corrective actions
5. Standardize

A logical failure analysis approach first requires a clear understanding of the failure definition and the distinction between an indicator (i.e., symptom), a cause, a failure mechanism, and a consequence. A clear understanding of each piece of the situation associated with a failure greatly enhances the ability to understand causes and mitigating options and to specify appropriate corrective action.

Recognizing the indicators, causes, mechanisms, and consequences helps to focus investigative actions:

- *Indicators(s):* Monitor these as precursors and symptoms of failures.
- *Cause(s):* Focus mitigating actions on these.
- *Failure mechanism(s):* These describe how the material failed according to the engineering textbook definitions. If the analysis is correct, the mechanism will be consistent with the cause(s).
- *Consequence(s):* This is what we are trying to avoid.

There are many other tools that must be considered in performing a failure analysis. Additional tools available to the analyst include:

- Review of all sources of input and information
- Interviews
- Laboratory investigations
- Stress analysis
- Fracture mechanics analysis

Just as an effective failure analysis requires a multidisciplinary approach, so does an effective failure-resistant design. Designers, materials scientists, engineers, fabricators, and quality-control specialists contribute to failure modes and effects analysis.

The Failure Mode and Effect Analysis (FMEA) Process

The FMEA methodology is based on a hierarchical, inductive approach to analysis; the analyst must determine how every possible failure mode of every system component affects the system operation. The procedure consists of:

1. Identify all item failure modes
2. Determine the effect of the failure for each failure mode, both locally and on the overall system being analyzed
3. Classify the failure by its effects on the system operation and mission
4. Determine the failure probability of occurrence
5. Identify how the failure mode can be detected
6. Identify any compensating provisions or design changes to mitigate the failure effects

The necessity to ensure interchangeability and compatibility of parts and safety factors in design led to the initial development of codes, standards, and regulations. Standards may be categorized as:

- Government regulations (i.e., requirement mandated by the government, such as Occupational Safety and Health Administration, or OSHA, regulations)

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- Government standards (federal specifications such as Military Specifications)
- Consensus standards (e.g., ASTM International and American National Standards Institute standards)
- Technical society, trade association, and industry standards
- Company standards (Both the supplier and the purchaser company may have their own standards.)
- Standards of good practice
- Standards of consumer expectation

The most controversial standards are often those concerned with safety, because they strongly influence the design, operation, and maintenance of technical systems and products. FMEA has evolved into a powerful tool that can be used by design engineers during all product-development phases to enhance product safety and reliability.

Why Is a Failure Investigation Performed?

In most instances, the purpose of a failure investigation is to determine the root cause(s). Determination of root cause is good engineering practice that crosses functional boundaries within a company and is an integral part of the quality-assurance and continuous-improvement programs. In addition, the most public reason to discover the root cause of a failure is to determine the fault or innocence of a company or person during litigation. For industrial purposes, however, it is more common that once the root cause is discovered, the corrective action to prevent future occurrences is implemented, thus saving the company time and money.

Nine Steps of a Failure Investigation

The steps in a failure investigation include:

1. Understand and negotiate goals of the investigation
2. Obtain clear understanding of the failure
3. Objectively and clearly identify all possible root causes
4. Objectively evaluate likelihood of each root cause
5. Converge on the most likely root cause(s)
6. Objectively and clearly identify all possible corrective actions
7. Objectively evaluate each corrective action
8. Select optimal corrective action(s)
9. Evaluate effectiveness of selected corrective action(s)

Failure Analysis Procedures

The principal task of a failure analyst during a physical-cause investigation is to identify the sequence of events involved in the failure. Like the basic process of the scientific method, failure analysis is an iterative process of narrowing down the possible explanations for failure by eliminating those explanations that do not fit the observations. The basic steps are:

1. Collect data
2. Identify damage modes present
3. Identify possible damage mechanisms
4. Test to identify actual mechanisms that occurred
5. Identify which mechanism is primary and which is/are secondary
6. Identify possible root causes
7. Test to determine actual root cause
8. Evaluate and implement corrective actions

Generally, a failure analyst will start with a broad range of possible explanations but, over time, will narrow and refine the existing possibilities. The failure analyst must repeatedly ask the following questions as an investigation develops possible explanation(s) for actual events:

- What characteristics are present in the failed/damaged component?
- What characteristics are present or expected in an undamaged component?
- What are the possible explanations that would account for the differences between damaged and undamaged components?
- What test(s) can be performed to confirm or eliminate possible explanations and refine knowledge about the observed damage?

The investigator must understand the potential ways a component could be damaged, the clues that would differentiate between these various scenarios, and the physical meaning each of these clues would have. Comparison of observations with characteristics of expected damage and mechanisms will enable the analyst to narrow down the possible failure explanations and understand the meaning of the observations made.

Limiting conditions that refine the scope of explanations for observed damage can be defined by using the following two rules of thumb:

- *The Sherlock Holmes Rule:* When you have eliminated the impossible, whatever remains, however improbable, must be the truth.
- *Occam's Razor:* When two or more explanations exist for a sequence of events, the simple explanation will more likely be the correct one.

Accident Reconstruction

The term *accident reconstruction* has traditionally been used to describe the investigation and analysis of motor vehicle and air-

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craft accidents. However, the term is also being used more often to describe the investigation and analysis of any unexpected event that causes loss or injury. Accident reconstruction is rarely a simple endeavor, and accident reconstruction requires personnel with proper training and experience in performing investigations/reconstruction. Reconstruction also often requires the assistance of other personnel with specialized expertise to address certain aspects of the investigation. The investigation and analysis of accidents and failures must be thorough to ensure that all information pertaining to the incident has been scrutinized and that accurate conclusions have been drawn. A complete failure analysis of the collapsed pedestrian walkway shown in Fig. 2 may require an accident reconstruction.

Fig. 2 Collapse of pedestrian bridge over a highway. Source: Ref 1

Types of Accident Reconstruction

The following are some of the more common types of accident reconstruction:

- Motor vehicle
- Aircraft
- Structural
- Electrical
- Industrial
- Mechanical
- Construction
- Fire investigations

Failure Prevention

Failure prevention begins with a state of mind in the specification, design, manufacture/fabrication, installation, operation, and maintenance of any component. However, before failure-prevention measures are taken, the degree of reliability required in a specific situation must be determined.

There is a cost associated with failure prevention, and, of course, there is a cost associated with accepting failures. For example, the consequence of an aircraft structural failure is very high, thus demanding a high assurance of reliability. In contrast, the failure of a screwdriver may be low-cost, although certainly a nuisance.

REFERENCE

1. *Failure Analysis and Prevention,* Vol 11, *ASM Handbook,* ASM International, 2002