IT IS OFTEN STATED that history repeats itself. Yet, when it comes to the failure of structural components and equipment, structural designers, manufacturers, and users do not want a repeat of history. The consequences and costs of fractured, cracked, corroded, and malfunctioned equipment are unwanted, dangerous, and expensive. Through the years, history has demonstrated that failures occur. History has also shown that the engineering communities have responded to prevent failure from occurring again. Some of the historic structural failures that have occurred in the 20th century are summarized in Table 1. These historic failures, as well as other failures, have revolutionized design philosophies, inspection techniques and practices, material development, and material processing and controls and have redefined the criteria for failure. Furthermore, the pursuit of understanding how and why these failures occurred has resulted in the development of structural integrity programs, enhanced analytical modeling and prediction techniques, accurate life-assessment methods, and a fortified commitment to avoid the recurrence of these failures through improved designs. The examples cited in Table 1 were serious and often tragic failures that had a great impact on structural designs and life-assessment developments. However, not all failures or malfunctions of equipment are as pivotal in history as those mentioned in Table 1. Yet, any failure, no matter how seemingly insignificant, should be investigated and the findings used to improve the design and increase the life and reliability of that component or equipment.

**Industrial Significance of Fatigue**

*Fatigue is the process of progressive localized permanent structural change occurring in a material subjected to condi-*
tions that produce fluctuating stresses and strains at some point (or points) and that may culminate in cracks or complete fracture after a sufficient number of fluctuations.

A simplistic view of the fatigue process is shown in Fig. 1. In this example (Fig. 1a), the component is first loaded from a zero load (stress) to some maximum positive value, and then the load starts reversing, falling back through zero to a maximum negative value and finally back to zero to complete one cycle. After a number of such cycles, a small crack will initiate, usually on or near the surface at a discontinuity such as a scratch or gouge. As more cycles accumulate, the crack grows until finally the remaining uncracked portion can no longer carry the load, and the component fractures. The fatigue lives of typical steel and aluminum alloys are shown in Fig. 1(b). If the stress is low enough for this steel alloy, it can be

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Historic failures and their impact on life-assessment concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure</td>
<td>Year</td>
</tr>
<tr>
<td>Titanic</td>
<td>1912</td>
</tr>
<tr>
<td>Molasses tank failures</td>
<td>1919, 1973</td>
</tr>
<tr>
<td>Tacoma bridge failure</td>
<td>1940</td>
</tr>
<tr>
<td>World War II Liberty ships</td>
<td>1942–1952</td>
</tr>
<tr>
<td>Liquefied natural gas (LNG) storage tank</td>
<td>1944</td>
</tr>
<tr>
<td>Comet aircraft failures</td>
<td>1950s</td>
</tr>
<tr>
<td>F-111 aircraft No. 94 wing pivot fitting</td>
<td>1969</td>
</tr>
<tr>
<td>Seam-welded high-energy piping failures Aloha incident, Boeing 737</td>
<td>1986–2000</td>
</tr>
<tr>
<td>Sioux City incident</td>
<td>1989</td>
</tr>
<tr>
<td>Earthquake in Kobe City, Japan, and Northridge, California</td>
<td>1994, 1995</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Ref 1
theoretically cycled forever; that is, it has a definite endurance limit. On the other hand, aluminum alloys do not have an endurance limit; if enough cycles are applied at even very low loads, they will eventually fail in fatigue.

The discovery of fatigue occurred in the 1800s when several investigators in Europe observed that bridge and railroad components were cracking when subjected to repeated loading. As the century progressed and the use of metals expanded with the increasing use of machines, more and more failures of components subjected to repeated loads were recorded. By the mid-1800s, A. Wohler proposed a method by which the failure of components from repeated loads could be mitigated and, in some cases, eliminated.

Undoubtedly, earlier failures from repeated loads had resulted in failures of components such as clay pipes, concrete structures, and wood structures, but the requirement for more machines made from metallic components in the late 1800s stimulated the need to develop design procedures that would prevent failures from repeated loads of all types of equipment. This activity was intensive from the mid-1800s and is still underway today. Even though much progress has been made, developing design procedures to prevent failure from the application of repeated loads is still a daunting task. It involves the interplay of several fields of technology, namely, materials engineering, manufacturing engineering, structural analysis (including loads, stress, strain, and fracture mechanics analysis), non-

![Image](https://via.placeholder.com/150)

**Fig. 1** The process of fatigue. (a) Cyclic loading. (b) Fatigue life of steel with an endurance limit and aluminum with no endurance limit. Source: Ref 2
destructive inspection and evaluation, reliability engineering, testing technology, field repair and maintenance, and holistic design procedures. All of these must be used in a consistent design activity that may be referred to as a fatigue design policy. Obviously, if other time-related failure modes occur concomitantly with repeated loads and interact synergistically, then the task becomes even more challenging. Inasmuch as humans always desire to use more goods and place more demands on the things we can design and produce, the challenge of fatigue is always going to be with us.

Until the early part of the 1900s, not a great deal was known about the physical basis of fatigue. However, with the advent of an increased understanding of materials, which accelerated in the early 1900s, a great deal of knowledge has been developed about repeated load effects on engineering materials. The fatigue process has proved to be very difficult to study. Nonetheless, extensive progress on understanding the phases of fatigue has been made in the last 100 years or so. It now is generally agreed that four distinct phases of fatigue may occur:

- Crack nucleation
- Structurally dependent crack propagation (often called the short crack or small crack phase)
- Crack propagation that is characterized by either linear elastic fracture mechanics, elastic-plastic fracture mechanics, or fully plastic fracture mechanics
- Final instability and failure

Each of these phases is an extremely complex process (or may involve several processes) in and of itself. For example, the nucleation of fatigue cracks is extremely difficult to study, and even pure fatigue mechanisms can be very dependent on the intrinsic makeup of the material. When extraneous influences are involved in nucleation, such as temperature effects (e.g., creep), corrosion of all types, or fretting, the problem of modeling the damage is formidable.

The Brittle Fracture Problem

Fracture is the separation of a solid body into two or more pieces under the action of stress.

Fracture can be classified into two broad categories: ductile fracture and brittle fracture. As shown in the Fig. 2 comparison, ductile fractures are characterized by extensive plastic deformation prior to and during crack propagation. On the other hand, brittle fracture takes place at stresses below the net section yield strength, with very little observable plastic deformation and a minimal absorption of energy. Such fracture occurs very abruptly with little or no warning and can take place in all classes of materials. It is a major goal of structural engineering to develop methodolo-
gies to avoid such fractures, because they are associated with massive economic impacts and frequently involve loss of life.

It is difficult to identify exactly when the problems of failure of structural and mechanical equipment became of critical importance; however, it is clear that failures that cause loss of life have occurred for over 100 years. Throughout the 1800s, bridges fell and pressure vessels blew up, and in the late 1800s, railroad accidents in the United Kingdom were continually reported as “the most serious railroad accident of the week.”

Those in the United States also have heard the hair-raising stories of the Liberty ships built during World War II. Of the 4694 ships considered in the final investigation, 24 sustained complete fracture of the strength deck, and 12 ships were either lost or broke in two. A spectacular example of this problem was the SS Schenectady, whose hull completely fractured while it was docked at its fitting-out pier. The fractured ship is shown in Fig. 3. In this case, the need for tougher structural steel was even more critical because welded construction was used in shipbuilding instead of riveted plate. In riveted plate construction, a running crack must reinitiate every time it runs out of a plate. In contrast, a continuous path is available for brittle cracking in a welded structure, which is why low notch toughness is a more critical factor for long brittle cracks in welded ships.

Similar long brittle cracks are less likely or rare in riveted ships, which were predominant prior to welded construction. Nonetheless, even riveted ships have provided historical examples of long brittle fracture due, in part, from low toughness. In early 1995, for example, the material world

![Image](image_url)

**Fig. 2** Appearance of (a) ductile and (b) brittle tensile fractures in unnotched cylindrical specimens. Courtesy of G. Vander Voort. Source: Ref 3
was given the answer to an old question, “What was the ultimate cause of the sinking of the Titanic?” True, the ship hit an iceberg, but it now seems clear that because of brittle steel, “high in sulfur content even for its time,” an impact that would clearly have caused damage perhaps would not have resulted in the ultimate separation of the Titanic into two pieces, where it was found in 1985. During the undersea survey of the sunken vessel with Soviet Mir submersibles, a small piece of plate was retrieved from 12,612 ft below the ocean surface. Examination by spectroscopy revealed a high sulfur content, and a Charpy impact test revealed the very brittle nature of the steel. However, there was some concern that the high sulfur content was, in some way, the result of 80 years on the ocean floor at 6000 psi pressures. Subsequently, the son of a 1911 shipyard worker remembered a rivet hole plug that his father had saved as a memento of his work on the Titanic. Analysis of the plug revealed the same level of sulfur exhibited by the plate from the ocean floor. In the years following the loss of the Titanic, metallurgists have become well aware of the detrimental effect of high sulfur content on the fracture of steel.

There are numerous other historical examples where material toughness was inadequate for design. The failure of cast iron rail steel for engine loads in the 1800s is one example. A large body of scientific folklore has arisen to explain structural material failures, almost certainly caused

![SS Schenectady](image)

**Fig. 3** Brittle fracture of the SS Schenectady. Source: Ref 4
by a lack of tools to investigate the failures. An article on the building of the Saint Lawrence Seaway described the effect of temperature on equipment: “The crawler pads of shovels and bulldozers subject to stress cracked and crumbled. Drive chains flew apart, cables snapped and fuel lines iced up . . . And anything made of metal, especially cast metal, was liable to crystallize and break into pieces.” It is difficult to realize that there still exists a concept of metal crystallization as a result of deformation that in turn leads to failure. Clearly, the development of fluorescence and diffraction x-ray analysis, transmission and scanning electron microscopes, high-quality optical microscopy, and numerous other analytical instruments in the last 75 years has allowed further development of dislocation theory and clarification of the mechanisms of deformation and fracture at the atomic level.

Brittle fracture has also plagued the aviation industry. In the 1950s, several Comets, the first commercial jet aircraft, produced in Britain, mysteriously exploded while in level flight. The cause was eventually traced to a design defect in which high stresses around the sharp corners on the windows caused small fatigue cracks to initiate, from which the fractures initiated. In the late 1960s and early 1970s, the U.S. fighter F-111 aircraft experienced catastrophic failure of the wing throughbox (the structure at which the wings join to the fuselage). Failures of the F-111 were related to the choice of a very brittle material (D6AC, a high-strength tool steel) and a heat treating procedure that produced nonuniform microstructures. In 1988, the upper fuselage of a Boeing 737 operated by Aloha Air fractured without warning during level flight over the Pacific Ocean. The reasons for this were related to corrosion of the aluminum alloy skin material and the frequent fuselage pressurization cycles resulting from many takeoffs and landings during short flights among the Hawaiian Islands.

In addition to the aforementioned, there are also numerous fracture examples of bridges, train wheels, and heavy equipment. In virtually every case, the reasons for brittle fracture can be found in inappropriate choice of materials, manufacturing defects, faulty design, and a lack of understanding of the effects of loading and environmental conditions. In all of the cases cited, there was severe economic loss and/or loss of life. For these reasons, it is an important engineering and ethical undertaking to reduce to an absolute minimum such accidents caused by brittle fracture.

In the previously mentioned examples, there are some common factors. Brittle fracture generally occurs in high-strength alloys (D6AC steel for the F-111 wing box; high-strength aluminum alloys for the Comets and 737), welded structures (Liberty ships, bridges), or cast structures (train wheels). It is significant that all failures started at small flaws which had escaped detection during prior inspections (in some cases, e.g., the F-111, many previous inspections). Subsequent analysis showed that in most instances, small flaws slowly grew as a result of repeated loads or a cor-
rosive environment (or both) until they reached a critical size. After reaching critical size, rapid, catastrophic failure took place. The following sequence of events is usually associated with brittle fracture:

1. A small flaw forms either during fabrication (e.g., welding, riveting) or during operation (fatigue, corrosion).
2. The flaw then propagates in a stable mode due to repeated loads, corrosive environments, or both. The initial growth rate is slow and undetectable by all but the most sophisticated techniques. The crack growth rate accelerates with time, but the crack remains stable.
3. Sudden fracture occurs when the crack reaches a critical size for the prevailing load conditions. Final fracture is rapid, proceeding at almost the velocity of sound.

During the postwar period, predictive models for fracture control were pursued based on earlier work by Griffith, Orowan, and Irwin. Since the paper of Griffith in 1920 and the extensions of his basic theory by Irwin and others, we have come to realize that the design of structures and machines can no longer under all conditions be based on the elastic limit or yield strength. Griffith’s basic theory is applicable to all fractures in which the energy required to make the new surfaces can be supplied from the store of energy available as potential energy, in the form of elastic strain energy. The elastic strain energy per unit of volume varies with the square of the stress and hence increases rapidly with increases in the stress level. One does not need to go to very high stress levels to store enough energy to drive a crack, even though this crack can be accompanied by considerable plastic deformation and hence consume considerable energy. Thus, self-sustaining cracks can propagate at fairly low stress levels.

**Changes in Design Philosophy**

Because of failures similar to those in Table 1, predicting performance and assessing the remaining life with greater confidence becomes increasingly important as costs for manufacturers and operators need to be reduced. Furthermore, the cost of failure is progressively greater as systems become more complex, downtime costs increase, and liability for failure increases. A brief discussion follows on the design process because it is important for failure investigators and life-assessment engineers to understand some of the design issues. Each structure has unique design requirements, but all structures are designed using some basic design principles. The relationship among the design phase, testing, systematic failure analysis, and life assessment of components is shown in Fig. 4.

One alternative for avoiding failures used in the past was to overdesign and to operate at very conservative loads. The economic penalties for both are increasingly significant; however, the economic penalties for failures
are significant as well. It is necessary, then, to pay more attention to predicting and ensuring performance. Predicting and ensuring performance is fundamentally a part of the design process for buildings, power plants, aircraft, refineries, and ships. For any given design, the mission and the intended use are established. Predicting the performance and design life of a component depends on defining what life or performance is required in

Fig. 4 Flow diagram showing the relationship between the design phase and the investigative tasks for in-service failure, structural aging, and fitness-for-service of structural components. Source: Ref 1
the anticipated combinations of mechanical and chemical environments. Defining performance may involve defining end points such as acceptable length of propagating cracks, maximum depth of propagating pits, acceptable remaining thickness of corroding pipes, maximum number of fatigue cycles or extent of cumulative damage, maximum number of plugged tubes, maximum number of failed circuits, maximum leakage, or appearance of a maximum area or number of rust spots. Defining such end points is a critical part of predicting life, because prediction defines when these end points will be reached and therefore when failure occurs.

Defining failure is also related to what is meant by the design life. For example, for the aerospace industry, a fighter aircraft may be designed for 8000 flight hours and analyzed for two lifetimes, or 16,000 flight hours. For the power industry, the design life of components is sometimes taken as 40 years. This means that the equipment is expected to perform satisfactorily at its rated output for 40 years. This is not to say that some maintenance is not necessary. However, to assert to a customer that a component has a 40 year design life, it is necessary to develop bases for such a claim. Such bases are usually provided by analyses, accelerated testing in the laboratory, and with prototype and model testing. As part of the life-assessment process, it is important to understand how a structural component—whether a pressure vessel, shaft, or structural member—is designed in order to understand how it may fail and to perform meaningful life assessment. For example, the first step in the design of any pressure vessel is to select the proper design code based on its intended use. A pressure vessel may be a power or heating boiler, a nuclear reactor chamber, a chemical process chamber, a hydrostatic test chamber used to test underwater equipment, or a pressure vessel for human occupancy. Once the intended use is identified, the appropriate design code can be selected. For example, pressure vessels use codes provided by many organizations and certifying agencies, such as the American Society of Mechanical Engineers (ASME), the American Bureau of Shipping, and European agencies that have similar pressure vessel design codes. Strict adherence to these codes for the design, fabrication, testing, and quality control and assurance allows the finished pressure vessel to be certified by the appropriate authorizing agency.

One of the first incentives to develop a pressure vessel code occurred after the Boston molasses tank incident in 1919, when the tank failed by overstress and consequently released more than 2 million gallons of molasses, resulting in the loss of life and property. Even after that catastrophic failure and understanding the nature of the failure, another molasses tank failure occurred in New Jersey in 1973. The destruction caused by this molasses tank incident is shown in Fig. 5. These molasses tank incidents demonstrate how important it is to prevent failures, and they underscore that good designs consider the operating conditions and limitations of materials of construction.