FAILURE ANALYSIS: A PERFORMANCE THEME FOR ENGINEERING DESIGN

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Abstract

Failure Analysis is a course in the Metallurgical and Materials Engineering curriculum that deals with the practical and theoretical aspects of material failure and performance analysis. Fractures and failed components, when constructively exploited can be uniquely revealing in the engineering design sense. The fracture face of a broken part, for example, often contains a remarkably detailed record of the conditions and events leading to the failure. In the case of fatigue failures, the service history of the component can sometimes be read from the fracture face in a manner similar to the way that a forester interprets the growth rings of trees. Fracture patterns in glass and in various brittle materials, can also be very revealing as to the origin and progression of the fracture, and thus the likely cause.

Fundamental to an understanding of design for failure avoidance is an equally thorough understanding of how and why materials, in their fabricated forms, fail. The latter understanding is not generally obtainable from studying laboratory fractures of standard test specimens. These fractures are usually quite different in appearance from the fractures typically found in manufactured components subject to real service environments and to real load spectra.

The instructional opportunities in failed parts are manifold – stress concentration, welds, heat treatment, fatigue, wear phenomena, corrosion, etc. Handling, studying, and analyzing a service failure can give the student a learning experience not readily equaled by any textbook or laboratory exercise. Since failure normally represents a severe deviation from the expected performance of the component, the lesson may have profound and long-lasting implications that transcend its purely technical content.

While engineering failures can result in positive outcomes, such as improved designs and new innovations, many people may only think of engineering failures in negative terms.

Can engineering students learn from mistakes, failures, disasters, and flawed designs, if properly exploited? Our experience in our Failure Analysis course has demonstrated that getting engineering students to think about the consequences of design failures is an essential part of a quality engineering education.

Introduction

Petroski [1] writes that those who forget the mistakes of the past are doomed to repeat them in the future. He urges engineers and engineering students to examine what's gone wrong in previous engineering designs as a way to anticipate what can happen again if they don't take proper design precautions. "Failure is a unifying theme in engineering," Petroski says, yet engineering curricula often focus on successful designs and neglect unsuccessful ones. Ironically, this reliance upon past successes can lead to future failure [1]. Perhaps Petroski's notion could be slightly altered to incorporate the concept: "Failure Analysis should be the performance theme in engineering design!" One of the paradoxes of engineering is that success doesn't necessarily teach you very much. A successful bridge teaches you that that particular bridge works, but that same bridge at another location with a different set of service environment parameters may not be successful [2].

A case in point is the Tacoma Narrows Bridge, which shook apart in wind conditions just a few months after its opening in 1940. The chief design engineer had ignored the wind-related problems that had damaged other bridges dating back to as early as 1818 [1,3].

A Course of Study

The topical outline for our Failure Analysis course is listed in Table I. The course content attempts to provide a broad coverage of the various failure modes and failure mechanisms. At the same time, materials design concepts are emphasized with coverage of topics that include fracture toughness design and assessment.

Table I. Topical Course Outline – Failure Analysis

I. Historical Overview of Engineering Failure
II. Structural Failure Modes and Fracture Toughness
III. Nondestructive Testing
IV. Fracture Mechanics
V. Sub-Critical Cracking Mechanisms
VI. Wear
VII. Embrittlement
VIII. Elevated Temperature Failures
IX. Failures of Welded and Cast Components

Historical Overview

Our coverage of an historical perspective of structural failure attempts to correlate the parameters of mechanical strength, critical defect size, and the increasing metallurgical/materials design complexity of everyday material systems as a function of time. Fracture mechanics infers that a structural component is only as strong as its largest defect. However, with the advancements of materials and manufacturing technologies, achievable mechanical strengths are higher and defect conditions are smaller. High-strength maraging steels that approach about 25% of the theoretical strength of a crystalline solid have critical flaw sizes under reasonable service loads of the order of four microns. Flaw sizes of this magnitude are below the detection resolution limits of conventional NDE. This situation represents a difficult dilemma!

Also, materials engineers need to prioritize fracture toughness in the design of materials systems. Strength at the expense of toughness is going to promote more service failures via brittle fracture or sub-critical cracking mechanisms. Clearly the control of fracture is of prime concern where safety is involved; service failures can be tragic as well as catastrophic and may involve prolonged and expensive litigation. The Tacoma Narrows Bridge incident, the Titanic’s sinking, and the Space Shuttle Challenger disaster all reference landmarks engineering failure tragedies.

Nondestructive Testing (NDT)

The fundamentals of nondestructive testing are covered that include dye penetrant, magnetic particle, radiography, ultrasonics, acoustic emission, and eddy current. The former five topics are demonstrated in the lab and made available for the students to attempt their hand on various test pieces.

Fracture Mechanics

The application of linear elastic, elastic-plastic, and sub-critical fracture mechanics to failure analysis is also presented. These topics greatly complement the discussions of fracture toughness assessment and nondestructive defect characterization. Although there are a great number of fracture mechanics (FM) software packages available that could be used in the course, we present a package of applicable FM relations that cover a wide array of engineering components, devises, and mechanisms. However, we also offer an Advanced Failure Analysis course in which the software packages are used.

Sub-Critical Cracking Mechanisms

The topics included under this heading include fatigue, hydrogen-assisted cracking, and stress-corrosion cracking. Other forms of hydrogen damage are covered in the section on Embrittlement. Since fatigue predominates machine component failure, an extensive amount of time is dedicated to this topic. Interpretation of fatigue fracture evidence includes recognizing crack initiation site(s), crack growth directions, the presence of stress concentrators and nominal stress magnitude, the form of the service load, e.g., rotational bending fatigue, reversed bending, etc., and the recognition of stages II and III. Students are initially introduced to "classic" failure evidence, although non-classic failures are presented to challenge their skills. The recognition and interpretation of this evidence is important, but we also attempt to go beyond this level to identify how such a failure could be prevented in the same service environment. Fatigue as well as the other form of sub-critical cracking is covered in a case study format, usually in 35-mm slide or in *POWERPOINT* format.

Wear

It has always been surprising how little engineers know about recognizing the forms of wear and designing to minimize wear damage. This may not be a universal problem, but it appears to be a deficiency at UTEP. The introductory lecture for this topic entails bringing to class about twenty wear-induced failures covering adhesive, abrasive, contact fatigue, and corrosive wear, and also fretting. We allow the physical forms of the damage, whether minute or catastrophically severe, to lend themselves to discussion of the various wear mechanisms and their design remediation schemes.

Embrittlement

This is a great topic and serves to explore particularly ferrous alloy design issues. We focus on hydrogen damage, blue brittleness, temper embrittlement, tempered martensite embrittlement, and Sigma-phase embrittlement. This is only a small proportion of the topics available under this category, but do to time constraints, this is all that is covered in the first course. Embrittlement presumes that the structural material was formerly ductile, and by processing and/or service conditions, the material is rendered less ductile and more susceptible to a brittle fracture mode. As an example, let's examine blue brittleness. Low-carbon, low-alloy steels are the most susceptible to this form of embrittlement. The widely used AISI-SAE 1020 or ASTM A-36 steels would be examples of materials with a propensity for blue brittleness. If these alloys are process annealed in the temperature range of approximately 230-370 ^{o}C, or experience service in this temperature span, they lose tensile ductility and fracture toughness, and are thus more susceptible to transgranular cleavage fracture.

Elevated-Temperature Failures

This topic area explores creep, creep rupture, thermal fatigue, oxidation, sulfidation, and decarburization. We have numerous case studies that explore elevated temperature service degradation representing power plant operations, thermal processing equipment, and turbines, both for aircraft and land-base applications. One of the more interesting aspects of this topic area involves the design and degradation aspects of super- alloys. Nickel-base superalloys for turbine buckets with thermal barrier coating systems represent materials technology marvels. Case studies that explore the complexity of alloy systems like IN738 with NiCrAlY coatings in service at 700 ^{o}C are very challenging to the students.

Failures of Welded and Cast Components

These product forms are appropriate to team-up, since they have the common potential of fusion defects that may greatly influence their service capacity. Obviously, welded structures must also be considered for additional defects stemming from joint design and peculiarities derived from a particular welding process, e.g., exogenous tungsten inclusions derived from the TIG welding process. Again, our abundance of case studies, serving to identify a wide array of fusion and weld defects; provide the means for a very hands-on approach to these topic areas. Most of the weld defects are visualized through macro-sections of weld joints showing inadequate fusion, inadequate penetration, inclusions, hot and cold cracks, concavity, etc.

The Team Project

Ultimately, the culmination of the course is the team project. Students “best” learn failure analysis by doing it themselves. To this end, the students are configured into multidisciplinary teams with as much diversity as possible. Since the mechanical and civil engineers out number the metallurgical and materials engineering majors, each team will have at least on member with materials expertise. Each team is given a failure project provided by industry with an appropriate background and a contact person within each company. After they receive their project, the team must devise a proposal or work scope for the failure analysis project. This is submitted and reviewed by the instructor. The student teams may now start their analysis usually by commencing with as-received photographic documentation. An interesting as aspect to the projects at UTEP – all of the teams work on their projects outside of class and receive no laboratory credit for this additional work assignment. As the sample team proposal illustrates, the students generally must perform at least one NDT inspection, along with metallography, a mechanical property assessment, fractography via scanning electron microscopy, chemical analysis via optical emission spectroscopy to name a few of the analytical instrumentation requirements. Many of the student teams facilitate their stress analysis utilizing finite element analysis software. Again, the multi-disciplinary teams serve to broaden the technical skills of the entire team.

The final project products consist of a poster display and a *POWERPOINT* presentation to the class, which includes representatives from each of the industries that furnished student projects. Fortunately, the poster displays are retained by the department and serve as future educational and case study displays for the course.

Conclusions

The control of failure continues to be an important problem for engineers and materials scientists. This is due to the increased use of novel and high strength materials, the widespread use of welded construction, the design of large structures, and operations under more extreme conditions in the interest of efficiency. In addition, as new areas of technology are developed, novel failure problems will inevitably appear. Should failure analysis become a required topic in metallurgical and materials engineering curricula? In all engineering curricula? Since failure analysis encompasses robust design situations, ethics, quality control and manufacturing liability issues, and the pitfalls of engineering design failures, the answer should logically be "yes."

Bibliography

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2. Henry Petroski, *To Engineer is Human: The Role of Failure in Successful Design*, Vintage Book, 1992.
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