CHAPTER 1 - INTRODUCTION

- MECHANICAL FAILURE MODES
- IMPORTANCE OF FATIGUE CONSIDERATIONS IN DESIGN
- HISTORICAL OVERVIEW OF FATIGUE

MECHANICAL FAILURE MODES

- Mechanical failures involve a complex interaction of ***load***, ***time***, and ***environment*** (i.e. temperature and corrosion).
  - ***Loads*** may be monotonic, steady, variable, uniaxial or multiaxial.
  - The loading ***duration*** may range from centuries to years, as in steel bridges, or to seconds or milliseconds, as in firing a handgun.
  - ***Temperatures*** can vary from cryogenic with rocket motor fuels, to over a thousand degrees Celsius, with gas turbine engines. Temperatures may be isothermal or variable.

MECHANICAL FAILURE MODES (CONTINUED)

- ***Corrosive environments*** can range from severe attack with automobile engine exhaust and salt water exposure, to essentially no attack, in vacuum or inert gas.

- The interaction of load, time and environment along with material selection, geometry, processing, and residual stresses create a wide range of possible failure modes ***in all fields of engineering***.

- Table 1.1 provides a list of possible mechanical failure modes in metals.

TABLE 1.1: MECHANICAL FAILURE MODES OF METALS

- **Excess deformation** – elastic, or yielding (i.e. onset of plasticity)
  - Excess deformation by yielding is probably the most commonly studied failure mode. It is based upon the maximum shear stress criterion or the octahedral shear stress criterion.
  - Failure by excess deformation may also be elastic such as in rotating machinery where seizure can occur.

- **Ductile fracture**
  - Ductile fracture involves significant plasticity.
  - It is associated with high-energy absorption with fracture.

MECHANICAL FAILURE MODES OF METALS (CONT’D)

- Brittle fracture
  - Brittle fracture contains little plasticity.
  - It involves low energy absorption.
- Impact or dynamic loading
  - Can cause excess deformation or fracture.
  - Impact or dynamic loading conditions that create high strain rates in metals tend to cause lower toughness and ductility.
- Creep
  - can cause excess deformation or fracture.
  - In metals it is most predominant at elevated temperatures.
  - Example: gas turbine engine blades due to centrifugal forces.

MECHANICAL FAILURE MODES OF METALS (CONT'D)

- Relaxation
  - Relaxation is primarily responsible for loss of residual stress and loss of external load that can occur in bolted fasteners at elevated or ambient temperature.
- Thermal shock
  - Thermal shock tends to promote cracking and/or brittle fracture.
  - Example: quenching operation during heat treatment of metals.

MECHANICAL FAILURE MODES OF METALS (CONT'D)

- Wear
  - Can occur at any temperature and include many possible failure mechanisms.
  - Dominant in roller or taper bearings and in gear teeth surfaces.

- Buckling
  - Buckling failure can be induced by external loading or by thermal conditions.
  - Can involve elastic or plastic instabilities.
  - Most dominant in columns and thin sheets subjected to compressive loads.

MECHANICAL FAILURE MODES OF METALS (CONT'D)

- Corrosion, hydrogen embrittlement, neutron irradiation (Not mechanical failure modes , but usually interact with mechanical aspects)
    - Corrosion by itself involves pitting and crack nucleation.
    - Hydrogen embrittlement is most susceptible in high strength steels and can lead to brittle fracture.

- Stress corrosion cracking (environmental assisted cracking)
    - Crack growth can occur due to interaction with applied and/or residual stresses and the corrosive environment.
    - This interaction is called stress corrosion cracking, SCC, or environmental assisted cracking, EAC.

MECHANICAL FAILURE MODES OF METALS (CONT'D)

- Fatigue
  - Fatigue failure is due to repeated loading.
  - At least half of all mechanical failures are due to fatigue. Many books and articles have suggested between 50 and 90 percent of all mechanical failures are fatigue failures.
  - Most of these are unexpected failures.
  - They include simple items such as door springs and electric light bulbs to complex components and structures involving ground vehicles, ships, aircraft and human body implants.
  - Examples are automobile steering linkage, engine connecting rods, ship propeller shafts, pressurized airplane fuselage, landing gears and hip replacement prostheses.

The different aspects of fatigue include:

- Fatigue crack nucleation
- Fatigue crack growth
- Constant or variable amplitude loading
- Uniaxial/Multiaxial loading
- Corrosion fatigue
- Fretting fatigue
- Creep-fatigue
    - Isothermal
    - Thermo-mechanical
- Combinations of the above

Interaction and/or synergistic effects of these aspects are often present.

IMPORTANCE OF **FATIGUE** CONSIDERATIONS IN DESIGN

- A comprehensive study of the cost of fracture in the United States indicated a $119 billion (in 1982 dollars) cost occurred in 1978 [National Bureau of Standards].
- This is about 4% of the gross national product.
- The investigation emphasized this cost could be significantly reduced by using proper and current fatigue design technology.

IMPORTANCE OF FATIGUE CONSIDERATIONS IN DESIGN

Major Sector Contributions to the Annual Costs of Fracture (1982 Dollars in Billions)

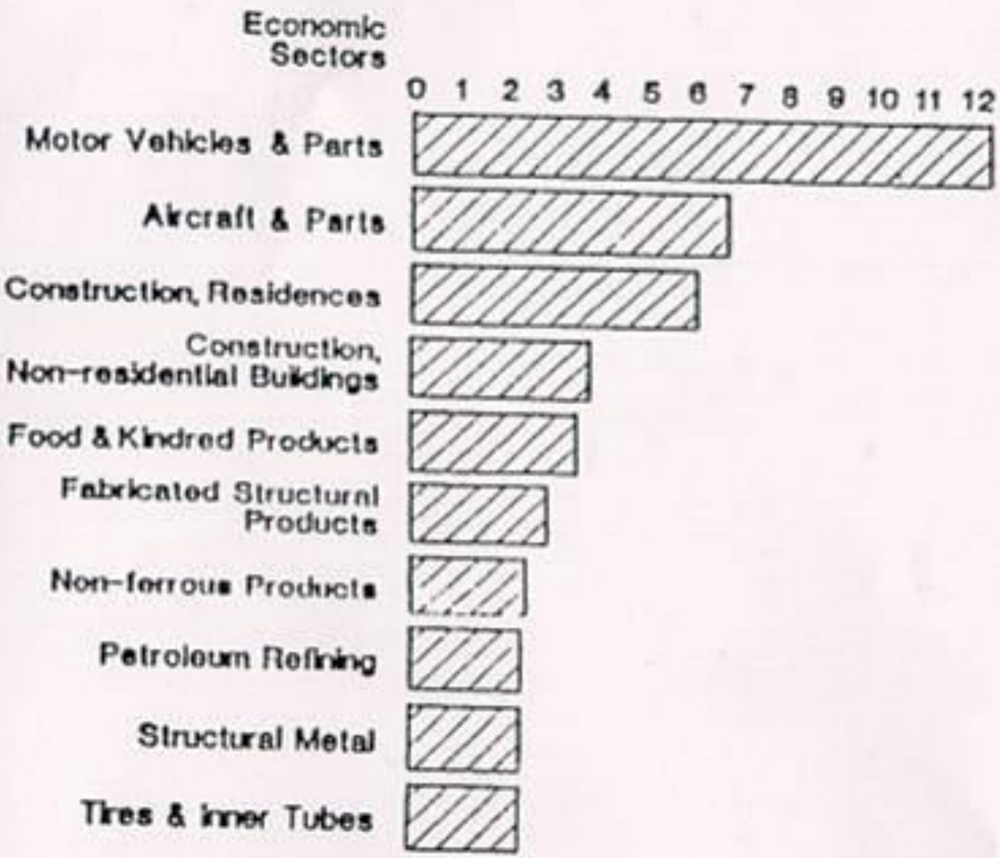

Figure 1.15 Annual costs
to the U.S. economy for var
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IMPORTANCE OF FATIGUE CONSIDERATIONS IN DESIGN

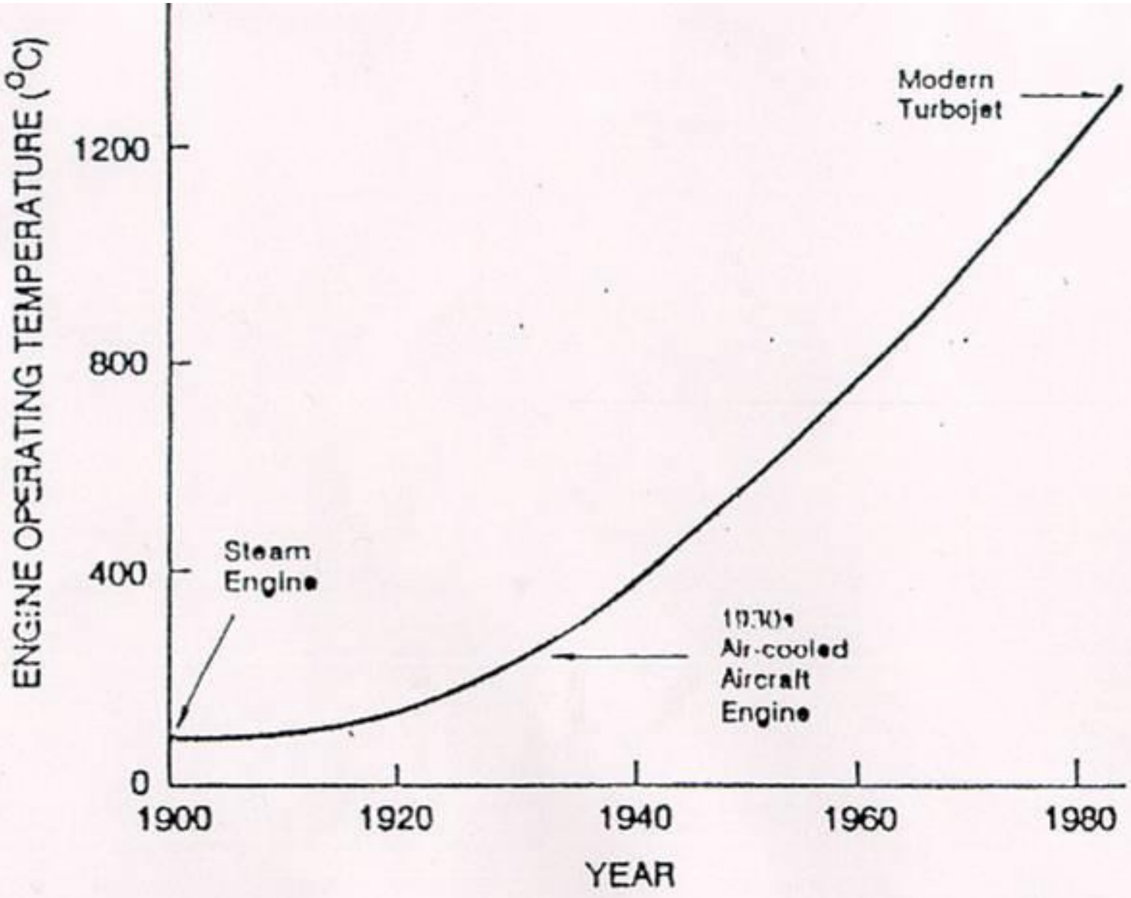

Figure 1.14 The steep climb in operating temperatures of engines during

IMPORTANCE OF FATIGUE CONSIDERATIONS IN DESIGN (CONT'D)

- Proper fatigue design involves synthesis, analysis and testing.
- Fatigue testing alone is not a proper fatigue design procedure, since it should be used for product durability determination, and not for product development.
- Analysis alone is also insufficient, since current fatigue life models, including software programs, are not adequate for safety critical parts.
- Both analysis and testing are required components of good fatigue design.
- The greater the analysis and testing simulates the real situation the greater the confidence in the results.

IMPORTANCE OF FATIGUE CONSIDERATIONS IN DESIGN (CONT'D)

- Many approaches to fatigue design exist.
- They can be simple, inexpensive approaches or they may be extremely complex and expensive.
- A more complete fatigue design procedure may initially be more expensive, but in the long run it may be the least expensive.
- Current product liability laws have placed special emphasis on explicitly documented design decisions.

IMPORTANCE OF FATIGUE CONSIDERATIONS IN DESIGN (CONT’D)

- Safety factors are often used in conjunction with or without proper fatigue design.
- Values too high may lead to non-competitive products in the global market, while values too low can contribute to unwanted failures.
- Safety factors are not replacements for proper fatigue design procedures, nor should they be an excuse to offset poor fatigue design procedures.

IMPORTANCE OF FATIGUE CONSIDERATIONS IN DESIGN (CONT'D)

- Fatigue failures occur in every field of engineering.

- For example, they can involve:
  - thermal/mechanical fatigue failure in electrical circuit boards involving electrical engineers,
  - bridges involving civil engineers,
  - automobiles involving mechanical engineers,
  - farm tractors involving agricultural engineers,
  - aircraft involving aeronautical engineers,
  - heart valve implants involving biomedical engineers,
  - pressure vessels involving chemical engineers, and
  - nuclear piping involving nuclear engineers.


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HISTORICAL OVERVIEW OF FATIGUE

- Fatigue of materials is still only partly understood and what we do know has been developed step by step.

- The first major impact of failures due to repeated stresses involved the **railway industry in the *1840s***, where railroad axles failed regularly at shoulders.

- The word "**fatigue**" was introduced in the *1840s* and *1850s* to describe failures occurring from repeated stresses.

HISTORICAL OVERVIEW OF FATIGUE (CONT'D)

- In Germany during the ***1850s*** **and** ***1860s*** **August Wöhler** performed many fatigue tests on railway axles. These are considered to be the first systematic investigation of fatigue.

- He showed from stress versus life (*S-N*) diagrams how fatigue life decreased with higher stress amplitudes and that below a certain stress amplitude, the test specimens did not fracture. Thus, he introduced the concept of the ***S-N*** **diagram & the fatigue limit**.

- He pointed out that for fatigue the **range of stress** is more important than the maximum stress.

HISTORICAL OVERVIEW OF FATIGUE (CONT'D)

- **Gerber** along with **Goodman** investigated the influence of **mean stress** and proposed simplified theories concerning mean stresses.

- **Bauschinger** in *1886* showed the yield strength in tension or compression was reduced after applying a load of the opposite sign that caused inelastic deformation. This was the first indication that one single reversal of inelastic strain could change the stress-strain behavior of metals.

- In the early *1900s* **Ewing** and **Humfrey** used the optical microscope to pursue the study of **fatigue mechanisms**. Localized slip lines and slip bands leading to the formation of microcracks were observed.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- **Basquin** in *1910* showed that alternating stress amplitude versus number of cycles to failure **(*S-N*)** in the finite life region could be represented as a **log-log linear relationship**.

- In the *1920s* **Gough** and associates contributed heavily to the understanding of **fatigue mechanisms.** They also showed the combined effects of bending and torsion (**multiaxial** fatigue).

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- In *1920* **Griffith** published the results of his theoretical calculations and experiments on **brittle fracture** using glass.
- He found the strength of glass depended on the **size of microscopic cracks**.
- If S is the nominal stress at fracture and a is the crack size at fracture the relation is $\boldsymbol{S\sqrt{a} = \text{constant}}$.
- By this classical pioneering work on the importance of cracks Griffith developed the **basis for fracture mechanics**.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- In *1924* **Palmgren** suggested a **linear cumulative damage model** for variable amplitude loading.

- **McAdam** in the *1920s* completed extensive **corrosion fatigue** studies where he showed significant degradation of fatigue resistance in various water solutions.

- In *1929/30* **Haigh** presented his rational explanation of fatigue when **notches** are present. He used concepts of notch strain analysis and residual stresses that were later more fully developed by others.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- During the *1930s* an important practical advance was achieved by the introduction of **shot peening** in the automobile industry.

- Where fatigue failures of springs and axles had been common, they then became rare.

- **Almen** correctly explained the spectacular improvements by **compressive residual stresses** produced in the surface layers of peened parts and promoted the use of peening and other processes that produce beneficial residual stresses.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- In *1937* **Neuber** introduced **stress gradient effects at notches**.
- During World War II many brittle fractures in welded tankers and **Liberty ships** motivated substantial efforts concerning **preexisting defects and cracks** and the influence of stress concentrations.
- In *1945* **Miner** formulated a **linear cumulative fatigue damage criterion** suggested by Palmgren in 1924. This linear fatigue damage criterion is now recognized as the Palmgren-Miner rule.
- The formation of **ASTM committee E-09 on fatigue** in *1946* provided a forum for fatigue testing standards and research.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- The **Comet**, the first jet propelled passenger airplane, started service in May *1952* after more than 300 hours of flight tests. Several Comet aircrafts **crashed** catastrophically.

- After exhaustive investigations it was concluded that the accidents were caused by **fatigue failure** of the pressurized cabin.

- All Comet aircraft of this type were taken out of service and additional attention was focused on **airframe fatigue design**.

- Shortly after this, the first emphasis on **fail-safe design** in aircraft rather than safe-life gathered momentum in the USA. This would place much more attention on maintenance and inspection.

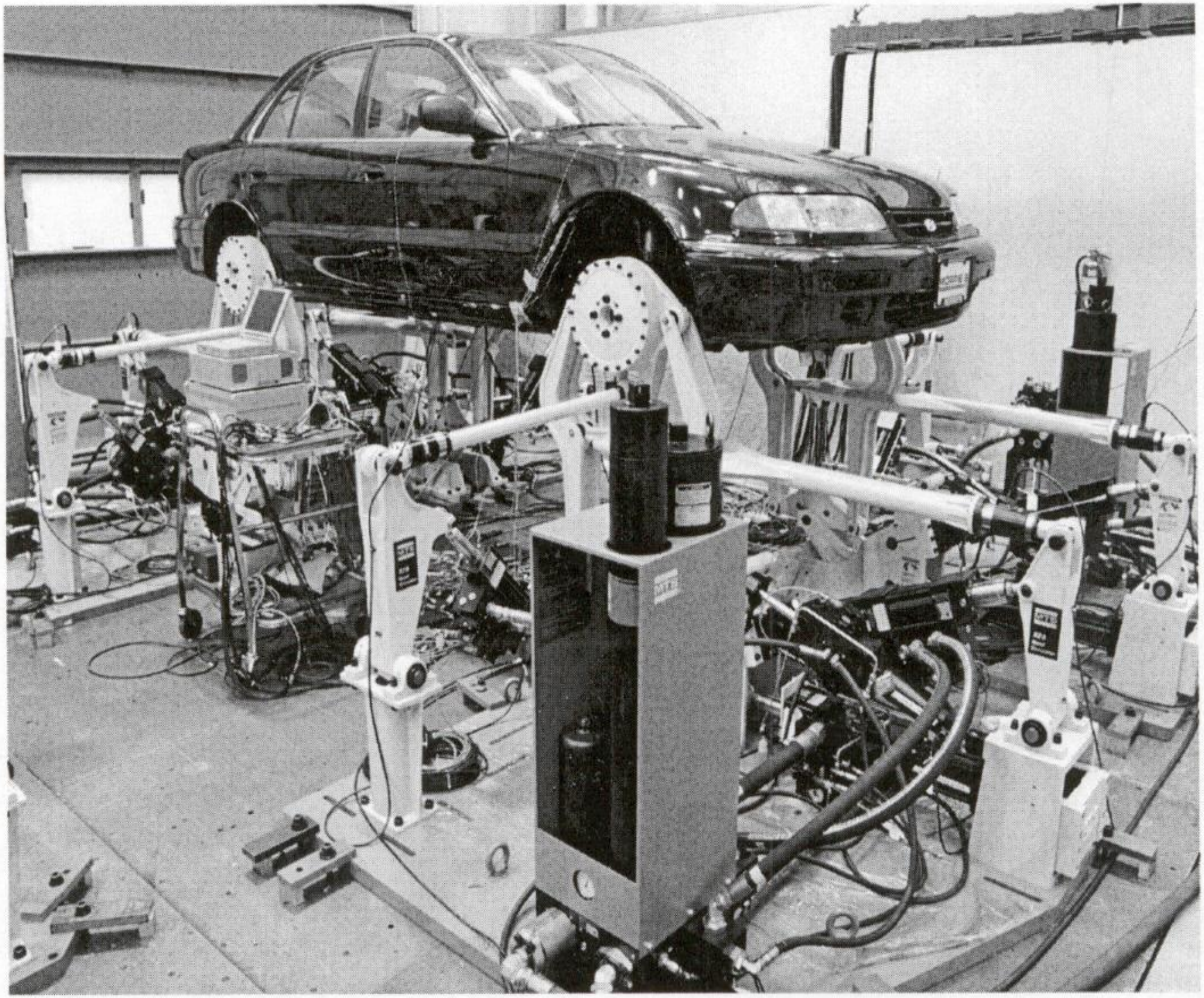
HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- Major contributions to the subject of fatigue in the *1950s* included the introduction of **closed-loop servohydraulic test systems**. This allowed better **simulation of load histories** on specimens, components, and total mechanical systems.

- **Electron microscopy** opened new horizons to better understanding of basic **fatigue mechanisms**.

- **Irwin** introduced the **stress intensity factor**, which has been accepted as the basis of linear elastic fracture mechanics (**LEFM**) and of fatigue crack growth life predictions.

- The **Weibull distribution** provided statistical distributions for **probabilistic fatigue** life testing and analysis.



HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- In the early *1960s* low cycle **strain-controlled fatigue** behavior became prominent with the **Manson-Coffin** relationship between plastic strain amplitude and fatigue life.

- **ASTM committee E-24 on fracture** testing was formed in *1964*. This committee has contributed significantly to the field of fracture mechanics and fatigue crack growth and was joined with ASTM committee E-09 in *1993* to form the **committee E-08 on fatigue and fracture**.

- **Paris** in the early *1960s* showed that **fatigue crack growth rate** could best be described using the stress intensity factor range.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- In the late *1960s* the catastrophic **crashes of F-111 aircraft** were attributed to brittle fracture of members containing **pre-existing flaws**.
- These failures, along with fatigue problems in other U.S. Air Force planes, laid the groundwork for the use of **fracture mechanics concepts** in the **B-1 Bomber development** program of the *1970s*.
- This program included **fatigue crack growth life considerations** based on a pre-established detectable initial crack size.
- **Schijve** in the early *1960s* emphasized **variable amplitude fatigue crack growth** testing in aircraft along with the importance of tensile overloads in the presence of cracks that can cause significant fatigue **crack growth retardation**.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HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- In *1967* the **Point Pleasant Bridge** at Point Pleasant, West Virginia collapsed without warning.

- An extensive investigation of the collapse showed that a **cleavage fracture** in an eyebar caused by the **growth of a flaw to critical size** was responsible for the collapse.

- The initial flaw was due to fatigue, **stress corrosion cracking**, and/or corrosion fatigue.

- This failure has had a profound influence on subsequent **design requirements established by AASHTO** (American Association of State and Highway and Transportation Officials).

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HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- In 1970 **Elber** brought out the importance of **crack closure** on fatigue crack growth. The crack closure model is commonly used in current fatigue crack growth calculations.

- In *1970*, **Paris** demonstrated that a **threshold stress intensity factor** could be obtained for which fatigue crack growth would not occur.

- In *1974* the **U.S. Air Force** issued Mil A-83444, which defines **damage tolerance requirements** for the design of new military aircraft. This brought out an increased need for improved quantitative **non-destructive inspection capability** as an integral part of the damage tolerance requirements.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- During the *1980s* and *1990s* many researchers were investigating the complex problem of **multiaxial fatigue**.
- The **small crack problem** was noted during this time period and many workers attempted to understand the behavior. The small crack problem is important, since these crack conditions grew faster than longer cracks based upon the same driving force.
- Interest in **fatigue of electronic materials** increased along with significant research in **thermo-mechanical fatigue**.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- **Composite materials** based on polymer, metal, and ceramic matrices were being developed for many different industries.
  - The largest accomplishments and usage involved polymer and metal matrix composites.
  - These were heavily motivated by the aerospace industry, but also involved other industries.

- During this time period many complex expensive aircraft components designed using safe-life design concepts were routinely being retired with potential additional safe usage (**Fatigue of Aging Structures**).
  - This created a need to determine a retirement for cause policy.
  - From a fatigue standpoint this meant significant investigation and application of non-destructive inspection and fracture mechanics.

HISTORICAL OVERVIEW OF FATIGUE (CONTINUED)

- Also during the *1980s* and *1990s* significant changes in many aspects of fatigue design were attributed to advances in **computer technology**.
    - This included software for different fatigue life (durability) models *and* in the ability to simulate real loadings under variable amplitude conditions with specimens, components, or full-scale structures.
    - This significantly brought more field testing into the laboratory.
    - Integrated computer aided engineering, CAE, involving dynamic simulation, finite element analysis and life prediction models motivated the idea of restricting testing to component durability rather than for development.
    - Increased **digital prototyping** with less testing has become a goal for the 21st century fatigue design.

SUMMARY AND DOS AND DON'TS IN DESIGN

- Many **different mechanical failure modes** exist in all fields of engineering.
- These failures can occur in simple, complex, inexpensive or expensive components or structures.
- Failure due to **fatigue**, i.e., repeated loading, is the **most common** cause of mechanical failure.
- Proper fatigue design includes synthesis, analysis and testing.
- The closer the simulated analysis and testing are to the real product and its usage, the greater confidence with the engineering results.

SUMMARY AND DOS AND DON’TS IN DESIGN (CONT’D)

- Don’t rely on safety factors to attempt to overcome poor design procedures.
- Do consider that fatigue durability testing should be used as a design verification tool, rather than as a design development tool.
- Don't overlook the additive or synergistic effects of load, environment, geometry, residual stress, time, and material microstructure.

ENGINEERS AND SCIENTISTS WITH SIGNIFICANT HISTORICAL CONTRIBUTUONS TO THE FIELD OF FATIGUE

- August Wöhler (1819-1914).
- John Goodman (1862-1935).
- Johann Bauschinger (1833-1893).
- Herbert J. Gough (1890-1965).
- Herbert F. Moore (1875-1960).
- Jesse B. Kommers (1884-1966).
- Alan A. Griffith (1893-1963).
- Bernard P. Haigh (1884-1941).
- John Otto Almen (1886-1973).
- Heinz Neuber (1906-1989).
- Rudolph E. Peterson (1901-1982).
- George R. Irwin (1907-1998).
- Waloddi Weibull (1887-1979).

- *S. S. Manson (1919).*
- *Louis F. Coffin Jr. (1917).*
- *Timothy H. Topper (1936).*
- *JoDean Morrow (1929).*
- *Paul C. Paris (1930).*
- *Jacobus (Jaap) Schijve (1927).*
- *Wolf Elber (1941).*
- *Keith J. Miller (1932).*

Biographical sketches are provided at the end of Chapter 1.