MECH 5390 – Fatigue Analysis for Extreme Environments

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Objective

• To provide a brief overview of Fatigue Analysis and introduce students to the concepts that will be covered in this course.
Introduction to Fatigue Analysis

• Mechanical Failure
• Solid Mechanics Concepts
• Fatigue
• Fatigue Design Considerations
• Types of Fatigue
• Mesostructural Aspects
• Microstructural Aspects
• Designing Against Fatigue Failure
• Fatigue and Fracture
• Standards, Journals, and More
• Questions
Mechanical Failure

- **Mechanical Failures** have caused many injuries and much financial loss; however, relative to the large number of successfully designed mechanical components and structures, mechanical failures are minimal.

- **Mechanical failures** involve an extremely complex interaction of load, time and environment.

Schematic of the X-51 WaveRider Hypersonic Cruise Vehicle.
Mechanical Failure

- **Loads** may be monotonic, steady, variable, uniaxial, or multiaxial.
- **Load durations** may range from centuries to years, as in steel bridges, or to seconds or milliseconds, as in firing a handgun.

Tacoma Narrows Bridge collapse, 1940.
Mechanical Failure

- **Temperatures** can vary from cryogenic with rocket motor fuels, to ambient with household kitchen chairs, to over 1000°C in a gas turbine engine.
Mechanical Failure

- **Environments** can range from severe corrosion attack with automobile engine exhaust and salt water exposure to essentially no attack in vacuum or inert gas, to radiation damage in nuclear reactors.
Mechanical Failure

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

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**TABLE 1.1 Mechanical Failure Modes of Metals**

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<thead>
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<tbody>
<tr>
<td>1.</td>
<td>Excess deformation—elastic, yielding, or onset of plasticity</td>
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<td>2.</td>
<td>Ductile fracture—substantial plasticity and high-energy absorption</td>
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<td>3.</td>
<td>Brittle fracture—little plasticity and low-energy absorption</td>
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<td>4.</td>
<td>Impact or dynamic loading—excess deformation or fracture</td>
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<td>5.</td>
<td>Creep—excess deformation or fracture</td>
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<td>6.</td>
<td>Relaxation—loss of residual stress or external loading</td>
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<td>7.</td>
<td>Thermal shock—cracking and/or fracture</td>
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<td>8.</td>
<td>Wear—many possible failure mechanisms</td>
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<td>9.</td>
<td>Buckling—elastic or plastic</td>
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<td>10.</td>
<td>Corrosion, hydrogen embrittlement, neutron irradiation*</td>
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<td>11.</td>
<td>Stress corrosion cracking (environmental assisted cracking)</td>
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<td>12.</td>
<td>Esthetic aspects*</td>
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<td>13.</td>
<td>Fatigue—repeated loading</td>
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<td></td>
<td>a. Fatigue crack nucleation</td>
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<td>b. Fatigue crack growth</td>
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<td>c. Constant or variable amplitude loading</td>
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<td>d. Uniaxial/multiaxial loading</td>
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<td>e. Corrosion fatigue</td>
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<td>f. Fretting fatigue</td>
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<td>g. Creep-fatigue</td>
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<td>1. Isothermal</td>
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<td>2. Thermomechanical</td>
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<td>h. Combinations of a to g</td>
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* These are not mechanical failure modes, but they usually interact with mechanical aspects.
Mechanical Failure

• 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

• 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

• 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.

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

• 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.

• 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.
Mechanical Failure

• 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.

• Fatigue
  • Fatigue failure is due to repeated loading.
  • Most of these are unexpected failures.
Solid Mechanics Concepts

• Solid Mechanics concepts used in the Design against Mechanical Failure

- Stress
- Strain
- Strain Energy
- Stress Intensity Factor
Solid Mechanics Concepts

- **Engineering Stress and Strain**
  \[ \sigma = \frac{P}{A_0} \quad \varepsilon = \frac{l_f - l_0}{l_0} \]

- **Young’s Modulus**
  \[ \sigma = E\varepsilon \]

- **Strain Energy**
  \[ U = \int \sigma d\varepsilon \]

Yield strength, \( S_y \), point where significant plastic deformation begins, or where permanent set reaches a fixed amount, usually 0.2% of the original gauge length.

Ultimate strength, \( S_u \), defined as the maximum stress on the diagram.
Solid Mechanics

• **Stress intensity factor** $K_I$ is a function of geometry, size, and shape of the crack, and type of loading.

• For various load and geometric configurations, a stress intensity modification factor $\beta$ can be incorporated.

$$K_I = \beta \sigma \sqrt{\pi a}$$
Definition of Fatigue

• **Def:** Fatigue - microstructural degradation of a material that occurs when subjected to repeated application of stresses or strains.

• **Notes:**
  • 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.
  • Materials have distinct damage mechanisms and fatigue properties.
Fatigue Considerations in Design

• **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.
Fatigue Considerations in Design

- 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.
Fatigue Considerations in Design

- 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.
Fatigue Considerations in Design

• 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.
Types of Fatigue

- Mechanical Fatigue
- Multiaxial Fatigue
- Thermal Fatigue
- Creep-Fatigue
- Thermomechanical Fatigue
- Corrosion Fatigue
- Contact/Fretting Fatigue
- And so on

- Includes combinations of above

“Son…old soldiers don’t die. They just get medal fatigue”
Examples of Mechanical Fatigue

• Material or component is subjected to isothermal mechanical cycling at room or elevated temperature conditions

• Mechanical strain rate is designed to avoid time-dependent deformation (e.g. creep)

• Examples: Automotive shafts, welded structures

Helical compression spring
Examples of Multiaxial Fatigue

- Loads are simultaneously applied in several directions, producing stresses with no bias to a particular direction.
- Can we apply or extend fatigue analysis techniques derived from uniaxial situations to these cases?

Steering knuckle
Examples of Thermal Fatigue

• Material is subjected to thermal cycling and nominally fixed boundary conditions
• Thermal stresses cause buckling and/or fracture
• Examples: Hot spots on turbine components, cold spots
Examples of Contact Fatigue

• Sliding or roller contact elements under elastic and cyclic conditions
• Maximum principal stresses occur beneath the surface
• Examples: Roller and ball bearings
Mesostructural Aspects

• *Stage I* – Initiation of micro-crack due to cyclic plastic deformation

• *Stage II* – Progresses to macro-crack that repeatedly opens and closes, creating bands called *beach marks*

• *Stage III* – Crack has propagated far enough that remaining material is insufficient to carry the load, and fails by simple ultimate failure

Fig. 6–1


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Microstructural Aspects

**Stages of Surface-Initiated Fatigue Cracking:**

1. Microstructural changes cause nucleation of permanent damage
2. Creation of microscopic cracks
3. Growth and coalescence of microscopic flaws to form dominant cracks
4. Stable propagation of dominant macrocrack
5. Structural instability or complete fracture
Microstructural Aspects

4. Stage I (shear) fatigue crack

3. Intrusions, extrusions

2. Persistent slip bands

5. Stage II fatigue crack

1. Cyclic slip
Fatigue Design Flow Chart
Fatigue Life Models

Choosing the fatigue life model is a significant decision. Four Classic Models:

1. The nominal **Stress-life (S-N)** model, first formulated between the 1850s and 1870s;
   - Least accurate, particularly for low cycle applications
   - Most traditional, easiest to implement

2. The local **Strain-life (ε-N)** mode, first formulated in the 1960s;
   - Detailed analysis of plastic deformation at localized regions
   - Several idealizations are compounded, leading to uncertainties in results

3. The **Fatigue crack growth (da/dN-ΔK)** mode, first formulated in the 1960s. Also called the Linear Elastic Fracture Mechanics approach;
   - Assumes crack exists
   - Predicts crack growth with respect to stress intensity

4. The two-stage mode, which consists of combining models 2 and 3 to incorporate both macroscopic fatigue crack formation (nucleation) and fatigue crack growth.
Approaches to Fatigue Design

- Criteria for fatigue design have evolved from so-called infinite life to damage tolerance. The criteria for fatigue design include usage of the four fatigue life models on the previous slide.
  - Infinite-Life Design
  - Safe-Life Design
  - Fail-Safe Design
  - Damage Tolerant Design

Fatigued Helical Gear Teeth
Scales of Fatigue
Standards

- **Def:** *Standard* – an accepted guide that governs concepts, procedure, definitions, etc.

- Ex: **ASTM E606** - Standard Practice for Strain-Controlled Fatigue Testing

Fatigue Testing

Fatigue tests should be designed to simulate the service conditions of a component as much as possible.
Fatigue Journals

• International Journal of Fatigue
• Fatigue and Fracture of Engineering Materials & Structures
• Engineering Failure Analysis
• Materials Science and Engineering
• Journal of Mechanical Sciences
Fatigue Texts
Fatigue Analysis

Fatigue Analysis can be used to determine each of the following:
• Number of cycles to failure
• Effect of altering the component (e.g., material, processing, geometry)
• Effect of environment and temperature
• Effect of presence of stress concentrations and cracks on fatigue life
• And more
Dos and Don’ts in Design

• Do recognize that fatigue failures are the most common cause of mechanical failure in components, vehicles, and structures and that these failure occur in all fields of engineering.

• Do recognize that proper fatigue design methods exist and must be incorporated into the overall design process when cyclic loadings are involved.

• Don’t rely on safety factors in attempting to overcome poor design procedures.

• Do consider that good fatigue design, with or without computer-aided design, incorporates synthesis, analysis, and testing.

• 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 effect of load, environment, geometry, residual stress, time, and material microstructure.
Assignment

• Problem 1.3 from the text.
• Problem 1.8 from the text. (Times New Roman, 12 point, double spaced)
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