Fatigue Analysis
For Extreme Environments
Design Against Fatigue
Outline

• Fatigue Crack Growth
• Design Considerations
• Design Criteria
• Analysis and Testing
• Non-Destructive Evaluation
• Summary
Fatigue Crack Growth
Fatigue Crack Growth

• There are different stages of fatigue crack growth (FCG). For most general situations, FCG can be broadly classified into the following stages:

• **Stage I – Nucleation of the microcrack**
  • Substructural and microstructural changes which cause nucleation of permanent damage.
  • The creation of microscopic cracks.
  • The growth and coalescence of microscopic flaws to form 'dominant' cracks, which may eventually lead to catastrophic failure. (From a practical standpoint, this stage of fatigue generally constitutes the demarkation between crack initiation and propagation.)

• **Stage II - Stable propagation of the dominant macrocrack.**

• **Fracture - Structural instability or complete fracture.**

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Fatigue Crack Growth

- FCG is a multiscale process where generally, nucleation is on or below microscale while propagation is on the macroscale.

Fig. 2. Diagram from Forsyth's 1961 (Cranfield) paper showing various stages of fatigue [11].
Fatigue Crack Growth

• Nucleation and propagation are strongly influenced by a wide range of mechanical, microstructural, and environmental factors.

• The principal differences among fatigue design criteria often rest on how the crack initiation and the crack propagation stages of fatigue are quantitatively treated.

• The major obstacle to the development of life prediction models for fatigue is the choice of definition for crack initiation where crack initiation is the point at which the microcrack is achieved a minimum detectable size on the macroscale (i.e. the ending flaw size of stage I).
Fatigue Crack Growth

• Materials scientists are concerned with the microscope mechanisms of fatigue are likely to regard the nucleation of micrometer-size flaws along slip bands and grain boundaries.

• A practicing engineer, on the other hand, tends to relate the limit of resolution of the (non-destructive) crack detection equipment (typically a fraction of a millimeter) with the nucleation of fatigue crack and with the initial crack size used for design.

https://www.flickr.com/photos/pnnl/31208559990
V8R Turbines
Fatigue Crack Growth

• There are a variety of definitions for crack nucleation which are specific to certain classes of fatigue-critical engineering applications.

• Overall, the total fatigue life is defined as the sum of the number of cycles to initiate a fatigue crack and the number of cycles to propagate it to some critical crack size.
Design Criteria
Fatigue Design Flow Chart

Geometry → Load History → Environment → Design Criteria → Material Properties → Processing Effects

Select Configuration, Material and Processes

Stress Analysis → Fatigue Life Model → Cumulative Damage Model → Life Prediction → Accept and Manufacture → Service

Testing Cycle

Component or Vehicle Test → modify

verify → modify
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
   - Uses nominal stresses and relates them to the local fatigue strengths in members.
   - 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
   - Uses local strains and relates them to the local fatigue strengths in members.
   - Several idealizations are compounded, leading to uncertainties in results
Fatigue Life Models

3. The **Fatigue Crack Growth** ($da/dN-\Delta K$) model, first formulated in the 1960s. Also called the Linear Elastic Fracture Mechanics approach;
   - Assumes an initial crack exists
   - Predicts crack growth with respect to stress intensity factor range, $\Delta K$
   - This model can be considered a total fatigue life model when used in conjunctions with existing initial crack size following manufacture.

4. The **two-stage model**, which consists of combining models 2 and 3 to incorporate both nucleation (initiation of the macroscopic fatigue crack) and fatigue crack growth.
Fatigue Life Models

- **Two-stage approach**
- The strain-life approach is applied to smooth specimen where a fixed strain amplitude, $\varepsilon_a$, is applied until microcracks have grown to a measure initial crack size, $a_i$, at a given cycles to initiation, $N_i$.
- Next, the FCG approach is applied where the crack growth rate, $da/dN$ as a function of stress intensity factor range, $\Delta K$ is measured to failure, resulting in cycles of propagation, $N_p$.

$$Total\ Fatigue\ Life\ \ N_f = N_i + N_p$$
Recent Advances

- In recent years, materials scientists have done amazing work in measuring Stage I FCG data.
- Recent Advancements include the in-situ fatigue testing of subcritical crack growth within TEM and SEM microscopes.

Nanomechanical Fatigue Test in-situ TEM of Silicon

Performed in Tel Aviv University, Department of Materials Engineering, Israel.
Recent Advances

- The in-situ SEM observations of processes of fatigue crack initiation and propagation are selectively shown in the Figure for [001] orientated specimen, loaded up to failure.

- Overall, crack initiation and growth were closely associated with slip bands developed during fatigue loading.

In-situ SEM observation of fatigue-crack initiation and growth for [001]-oriented single crystal specimen loaded at room temperature (loading direction is vertical).

Fatigue Design Criteria

• Fatigue Design Criteria have evolved from so-called “Infinite Life” to “Damage Tolerant” design.

• Each of the successively developed criteria still has its place, depending on the application.

• The criteria for fatigue design include usage of the four fatigue life models (S-N, ε-N, da/dN-ΔK, two-stage method).

• The Fatigue Design Criteria are
  • Infinite Life Design
  • Safe-Life Design
  • Fail-Safe Design
  • Damage Tolerant Design
Infinite Life Design

- **Def:** *Infinite Life Design* part is designed to never fail.
  - Unlimited safety is the oldest criterion.
  - It requires local stresses or strains to be essentially elastic and safely below the fatigue limit.
  - For parts subjected to many millions of cycles, like engine valve springs, this is still a good design criterion.
  - This criterion may not be economical (i.e. global competitiveness) or practical (i.e. excessive weight of aircraft) in many design situations.
Safe-Life Design

**Def:** Safe-Life Design part is designed for a finite life.

- Used on very critical parts or on those which cannot be inspected. At the end of the expected safe operation life, the component is retired from service. It is used in many industries, for instance automotive industry, in pressure vessel design, and in jet engine design.
- The safe life must include a margin for the scatter of fatigue results and for other unknown factors.
- The margin for safety in safe-life design may be taken in terms of life, in terms of load, or by specifying that both margins must be satisfied, as in the ASME Boiler and Pressure Vessel Code.
Fail-Safe Design

- **Def**: Fail-Safe Design parts fail as long as the system does not.
  - Used on components in which inspection is possible
  - Less conservative than the Safe-Life Design Approach
  - Fail-safe design recognizes that fatigue cracks may occur and structures are arranged so that cracks will not lead to failure of the structure before they are detected and repaired.
  - Multiple load paths, load transfer between members, crack stoppers built at intervals into the structure, and inspection are some of the means used to achieve fail-safe design.

Aircraft wing structure diagram
Modern aircraft wings are subject to both Statics and Fatigue Resilience Testing to ensure Fail-Safe Design.
Damage Tolerant Design

**Def:** *Damage Tolerant Design* involves designing a component to resist failure due to the presence of flaws, cracks, or other damage for a specified period of unrepaired usage.

- A refinement of the fail-safe philosophy.
- It assumes that cracks will exist, caused either by processing or by fatigue, and uses fracture mechanics analyses and tests to check whether such cracks will grow large enough to produce failures before they are detected by periodic inspection.
- Components also designed for inspectability
- Crack stoppers and tear strips also incorporated into design
- Three key items are needed for successful damage-tolerant design:
  - residual strength,
  - fatigue crack growth behavior, and
  - crack detection involving nondestructive inspection.

Examples: Pressure Vessel Leak, Turbine Blade Cracks
Damage Tolerant Design

• **Residual strength** is the strength at any instant in the presence of a crack.
  • With no cracks, this could be the ultimate tensile strength or yield strength depending upon failure criteria chosen.
  • As a crack forms and grows under cyclic loading, the residual strength decreases.

• Residual strength can be increased by adding compressive residual stress to the surface of components. This improves the resistance to crack initiation.
  • Shot peening
  • Laser shock peening
  • Rolling
How Laser Peening Works

https://www.youtube.com/watch?v=___hCW_EPPg
Damage Tolerant Design

• **Crack detection methods** using different non-destructive inspection techniques have been developed.
  • Inspection periods must be laid out such that as the crack grows, the applied stresses remain below the residual strength.
  • This philosophy looks for materials with slow crack growth and high fracture toughness. Damage-tolerant design has been required by the U.S. Air Force.

• In pressure vessel design **“leak before burst”** is an expression of damage-tolerant philosophy.

• **Retirement for cause** (extended service life) is a special situation requiring damage-tolerant usage.
Analysis and Testing

• Analysis and testing are both key aspects of fatigue design.

• A more complete and correct analysis involving iteration and optimization can provide prototypes that are closer to the final product and thus require less testing.

• Insufficient or incorrect analysis may result in too much dependence upon testing and re-testing creating both time and cost inefficiencies.
Analysis and Testing

• Complete computer programs are available for taking a product from an input such as a road profile, or a strain or load spectrum, to a final calculated fatigue life.

• However, even the best analysis should not necessarily be the final product design, particularly with safety critical products.

• A design based on analysis alone, without fatigue testing, either requires large margins for uncertainty or must permit for some probability of failure.
Analysis and Testing

- **Fatigue testing** has involved enormous differences in complexity and expense.
  - It can range from the simple constant amplitude rotating beam test of a small specimen to the simulated full-scale complex variable amplitude thermo-mechanical cycling of the Concord supersonic aircraft structure in the 1970s, or the Boeing 777 aircraft structure in the 1990s.
  - Durability testing requires a representative product to test and therefore occurs late in the design/development process.
  - Parts manufactured for fatigue testing should be processed just like production parts because differences in processing may have a major effect on fatigue resistance.
Analysis and Testing

• Since the introduction of closed-loop servo-hydraulic test systems in the late 1950s, significant emphasis has occurred in bringing the test track or proving ground into the laboratory.
  • Current simulation test systems are capable of variable amplitude load, strain, or deflection with one channel, or multiple channels of input.
  • Road simulators can provide principally one-dimensional input through the tires, or three-dimensional input through each axle shaft/spindle.
  • Test systems are, or can be, available for almost every engineering situation, discipline, or complexity.
Standards

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

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

• Ex: **ISO 1099:2006** - Metallic materials -- Fatigue testing – Axial force-controlled method
Standards

- There exist many test standards for collecting experimental data
  - ASTM 1820
  - BS 7448
  - E1290 – CTOD
  - E561 – R Curve Testing
  - To name a few.

- With progress in material science, Standards are revised, reapproved, replaced, or discontinued.
Standard Testing

Figure 1.1 © John Wiley & Sons, Inc. All rights reserved. (c) Photo courtesy of Brett Leister, Lehigh University.
Service Condition Testing

• Experiments can be performed to replicate/determine the service conditions.

• Three scales used to gage the fatigue strength
  • *Specimen sized* experiments with highly idealized component conditions (e.g. temperature and environment)
  • *Intermediate scale*
  • *Full size* components and system experiments at service conditions (e.g. accelerated testing)
Full-scale simulated fatigue test where an automobile is subjected to 3-D variable amplitude load inputs at each wheel spindle
Service Condition Testing

• Loading and environment similar to those encountered in service are prime requirements for simulated fatigue testing.
• Determining the service loads may be a major task. Multi-channel data acquisition systems are available to obtain load, torque, moment, strain, deflection, or acceleration versus time for many diverse components, structures, or vehicles subjected to service usage.

• Measurement transducers
  • Thermocouples
  • Strain gages, extensometers, LVDTs
  • Load cells
  • Accelerometers
• Data often needs to be reduced before evaluation
• Evaluation made via cycle counting techniques
• Cycle counting algorithms typically implemented as code
Analysis and Testing

• Acceleration of field testing is often required in order to bring products to market before the competition or to find a fix for improving marginal products and to control test costs.

• Three common methods to accelerate testing are by:
  • increasing test frequency,
  • using higher test loads and/or temperatures,
  • and/or eliminating small load cycles from the load spectrum.

• All three methods have significant advantages in that less test time and cost is required, but each has disadvantages.
Analysis and Testing

• **Increased frequency** may have an effect on life and may not provide enough time for environmental aspects to fully operate.

• **Increasing loads** beyond service loads may produce misleading results; residual stresses that might have remained in service may be changed by excessive test loads. Fretting and corrosion may not have enough time to produce their full effects.

• **Eliminating many small load cycles** from the test load spectrum is common. Elimination of low-damaging cycles may hide both fretting and corrosion influence.
Analysis and Testing

• **Proof testing** is a single loading of a component or structure to a level usually slightly higher than the maximum service load.

• It can provide information on maximum crack size that could exist at the time of proof testing which can be helpful in damage-tolerant design situations and in formulating inspection periods.

• Proof testing may alter fatigue resistance by creating desirable and/or undesirable residual stresses.
Non-Destructive Evaluation
Non-Destructive Evaluation (NDE)

• Assumption: Flaws exist even in new structures and they may go undetected

• Assumed initial flaw sizes vary based on industry and component:
  • Due to fabrication (~0.005”)
  • Slow crack growth structures (~0.050”)
  • Fail-Safe Structures (~0.020”)

• In-service inspection allows us to manage pre-existing defects in structures.
Non-Destructive Evaluation (NDE)

- **Inspection** schedule determined based on crack growth information and measurement sensitivity.

- Initial flaws are often assumed, and critical lengths are calculated.

- **Inspection intervals** should be established based on codes and standards.

- When not available at a minimum permit inspection twice before crack is of critical size.

- Subsequent inspection intervals determined based on prior findings.
Non-Destructive Evaluation (NDE)

• Obtaining records of loads through **continuous in-service monitoring** of customer usage, field testing, and from proving grounds, and deciding which loads are frequent, which are occasional, and which are exceptional is important. Past experience aids in this determination.

• **In-service inspection** is also a way to avoid surprises. Many companies put an early production model into severe service with a friendly user and inspect it very carefully at frequent intervals to find any weaknesses before others find them.

• Determining suitable **inspection intervals** and procedures of in-service inspection is often a key part of fatigue design. In damage-tolerant design, inspection for cracks is mandatory. This inspection must be nondestructive in order to be meaningful.
Oil pipes are inspected by defect-detecting devices called "smart pigs," named for the ultrasonic or magnetic sensors they carry.
Circumferential cracking defects can be addressed with robots utilizing ultrasonic shear wave technology.

**NDT Global's Evo Series Smart Pig**

Circumferential cracking defects can be addressed with robots utilizing ultrasonic shear wave technology.
Non-Destructive Evaluation (NDE)

• **Def:** Non-destructive evaluation (NDE) is testing that does not destroy the test object; synonymous with ND inspection (NDI) and ND testing (NDT)

• The American Society for Testing and Materials (ASTM), ASM International, and the American Society for Nondestructive Testing (ASNT), have published significant information for nondestructive inspection, NDI, and nondestructive testing, NDT.
  • ASTM committee E-07 on Nondestructive Testing is responsible for Vol. 03.03 that includes over 100 standards.
Non-Destructive Evaluation (NDE)

• Numerous texts on the nondestructive evaluation have been written.
Non-Destructive Evaluation (NDE)

- Many techniques are applicable to crack detection including:

  - Computed Tomography (CT)
  - Radiographic Testing
  - Impulse Excitation Technique (IET)
  - Infrared and Thermal Testing
  - Acoustic Emission (AE)
  - Electromagnetic Testing (ET)
  - Leak Testing or Leak Detection
  - Ultrasonic Testing (UT)
  - Hardness Testing (HT)
  - Liquid Penetrant Testing (PT)
  - Visual Inspection (VT)
  - Tap Testing
Non-Destructive Evaluation (NDE)

• **Some methods provide only qualitative information** on crack existence while others provide quantitative size measurements.

• **Excessive inspection is wasteful** and expensive and inspection delayed too long may be fatal.

• A simple nondestructive procedure involves railway inspectors hitting each axle of express trains with long handled hammers to detect fatigue cracks by sound before the cracks become large enough to produce fractures.
Non-Destructive Evaluation (NDE)

- Liquid Penetrant Test
  - Pre-clean article to be inspected
  - Apply penetrant to test part
  - Allow correct dwell time to elapse
  - Remove excess penetrant from part surface
  - Dry, if applicable
  - Apply developer and allow to dwell
  - Inspect component
  - Post-clean part

Cracks near turbine blade root
The Magnetic Particle Inspection (MPI) method of non-destructive testing is a method for locating surface and subsurface discontinuities in ferromagnetic materials.
Non-Destructive Evaluation (NDE)

• Applications of NDE
  • Automotive (e.g. engine parts, frame)
  • Aviation (e.g. frame, propellers)
  • Civil (e.g. structures, bridges)
  • Power Generation (e.g. pressure vessels, welds, piping, storage tanks)
  • Railways (e.g. rails, wheels)
  • Amusement Parks (e.g. rails, vehicles, structures)
Summary

➢ Do recognize that fatigue design is an iterative process involving synthesis, analysis, and testing.

➢ Do recognize that different fatigue design criteria and different analytical fatigue life models exist and that no one criterion or analytical model is best for all situations.

➢ Don’t forget that damage-tolerant design may be necessary due to the existence or development and growth of cracks in safety critical structures.

➢ Don’t consider computational/analytical fatigue life predictions/estimations as the end of the fatigue design process.
Summary

➢ Do emphasize digital prototyping and rely on fatigue testing primarily for product durability determination rather than product development.

➢ Do place more emphasis on bringing the test track or proving ground into the laboratory, but keep in mind that the more closely testing simulates the real in-service conditions, the greater the confidence in the results.

➢ Don’t neglect the advantages and limitations of accelerated fatigue testing.

➢ Do pursue inspection of in-service components, structures, and vehicles and continue to monitor customer usage.

➢ Don’t neglect the importance of environmental conditions in both analytical and testing aspects of fatigue design.
Homework 3

• Problem 1 – What safety critical parts on your automobile are (a) fail-safe and (b) safe-life? How could the critical safe-life parts be made fail-safe? Is this needed?

• Problem 2 – Why is damage-tolerant design used less in the automotive industry than in the aerospace industry?

• Problem 3 – Write a one-page review paper on a modern NDE technique used to measure crack size or to determine if cracks exist. Times New Roman, 12-point font, single spaced. Not including references, figures, equations, and tables.
References


CONTACT INFORMATION

Calvin M. Stewart
Associate Professor
Department of Mechanical Engineering
The University of Texas at El Paso
500 W. University Ave, Suite A126, El Paso, TX 79968-0521
Ph: 915-747-6179

cmstewart@utep.edu
me.utep.edu/cmstewart/