



CHAPTER 2

FATIGUE DESIGN METHODS



FATIGUE DESIGN METHODS

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- PROBABILISTIC DESIGN AND RELIABILITY
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STRATEGIES IN FATIGUE DESIGN

Four fatigue life models exist:

1. **Nominal** stress-life (**S-N**) method

- First formulated in the 1850s to 1870s.
- Uses nominal stresses and relates these to local fatigue strengths for notched and unnotched members.

2. **Local** strain-life (**ϵ -N**) method

- First formulated in the 1960s.
- Local strain at a notch is related to smooth specimen strain-controlled fatigue behavior.
- Analytical models can be used to determine local strains from global or nominal stresses or strains.



STRATEGIES IN FATIGUE DESIGN (CONT'D)

3. Fatigue crack growth ($da/dN-\Delta K$) method

- First formulated in the 1960s.
- Requires the use of **fracture mechanics** to obtain the number of cycles to grow a crack from a given length to another length and/or to fracture.
- This model can be considered a total fatigue life model when used in conjunction with existing initial crack size following manufacture.



STRATEGIES IN FATIGUE DESIGN (CONT'D)

4. **Two-stage method** by combining 2 and 3 to incorporate both fatigue crack nucleation and growth.
- Incorporates the local ε -N model to obtain the life to the formation of a small macrocrack and then integration of the fatigue crack growth rate equation for the remaining life.
 - The two lives are added together to obtain the total fatigue life.

All four of these fatigue life models are covered in this course/book and each have areas of best applicability.



FATIGUE DESIGN CRITERIA

- Criteria for fatigue design have evolved from infinite life to damage tolerance.
- 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).
- These criteria are:
 - **Infinite-Life** Design
 - **Safe-Life** Design
 - **Fail-Safe** Design
 - **Damage-Tolerant** Design



FATIGUE DESIGN CRITERIA (CONT'D)

■ Infinite-Life Design

- 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.



FATIGUE DESIGN CRITERIA (CONT'D)

■ Safe-Life Design

- The practice of designing for a finite life is known as "safe-life" design.
- It is used in many industries, for instance automotive industry, in pressure vessel design, and in jet engine design.
- The calculations may be based on stress-life, strain-life, or crack growth relations.
- Ball bearings and roller bearings are examples of safe-life 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.



FATIGUE DESIGN CRITERIA (CONT'D)

■ Fail-Safe Design

- Fail-safe design requires that if one part fails, the system does not fail.
- 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.



FATIGUE DESIGN CRITERIA (CONT'D)

■ Damage-Tolerant Design

- This philosophy is 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.
- Three key items are needed for successful damage-tolerant design:
 - residual strength,
 - fatigue crack growth behavior, and
 - crack detection involving nondestructive inspection.



FATIGUE DESIGN CRITERIA (CONT'D)

- **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.
- **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.



FATIGUE DESIGN CRITERIA (CONT'D)

- 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 (CONTINUED)

- 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 (CONTINUED)

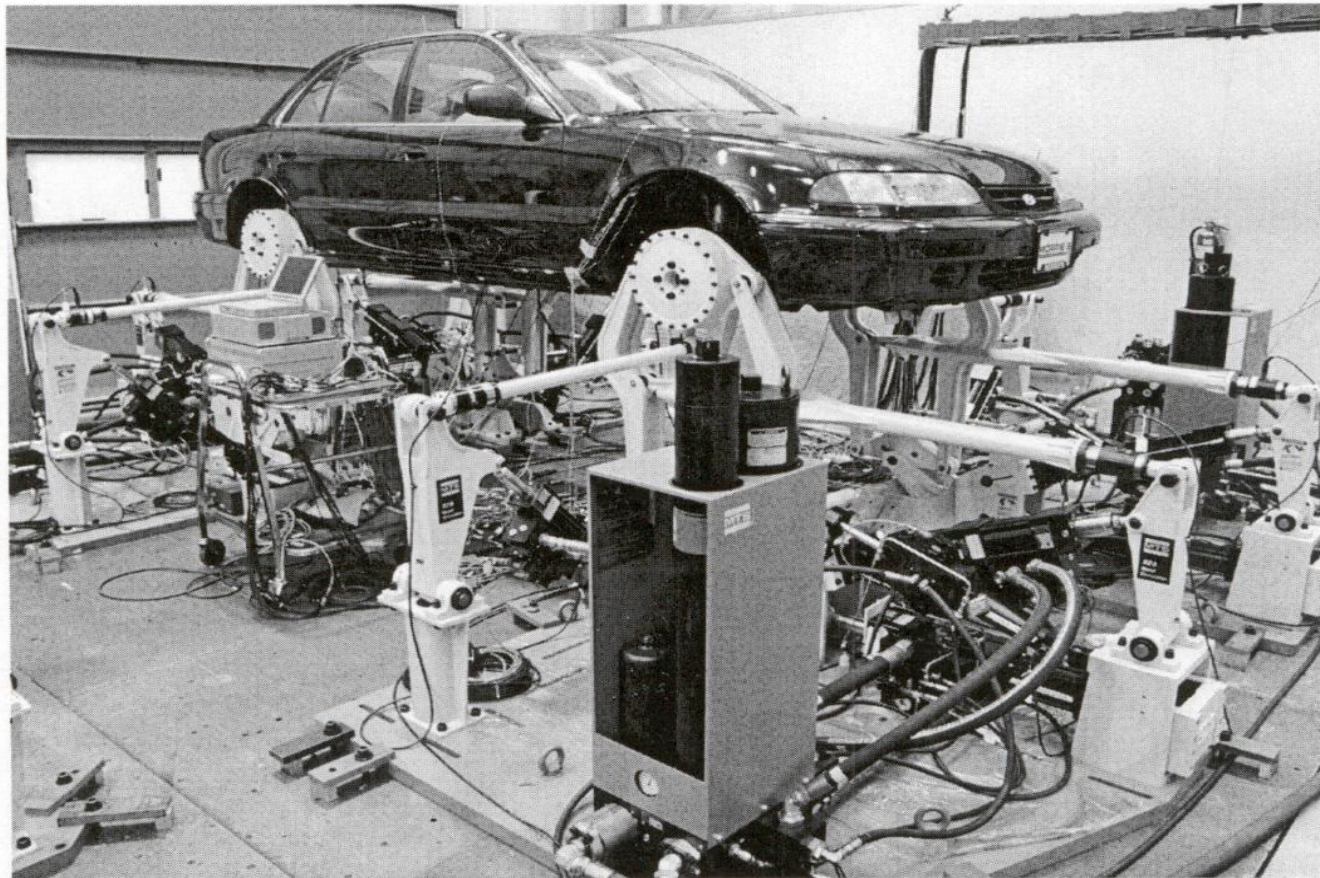
- **Fatigue testing** has involved enormous differences in complexity and expense.
 - It can range from the simple constant amplitude rotating beam test of a small specimen to the simulated full-scale complex variable amplitude thermo-mechanical cycling of the Concord supersonic aircraft structure in 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 (CONTINUED)

- 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.

Full-scale simulated fatigue test where an automobile is subjected to 3-D variable amplitude load inputs at each wheel spindle





ANALYSIS AND TESTING (CONTINUED)

- 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.



ANALYSIS AND TESTING (CONTINUED)

- **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 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 (CONTINUED)

- 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 (CONTINUED)

- ***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.



PROBABILISTIC DESIGN & RELIABILITY

- **Variability** in fatigue life has ranged from almost a factor of one, to over several orders of magnitude for a given test or service condition.
- Fatigue data available at present permit probabilistic design for a few situations down to a probability of failure of about 10 percent. For lower probabilities we hardly ever have the necessary data.
- Extrapolation of known probability data to lower probabilities of failure requires large margins for uncertainty or safety factors.
- Fatigue reliability can be determined from service experience.



CAE AND DIGITAL PROTOTYPING

- Digital prototyping refers to a computer generated realistic prototype model near or at the final state of the product.
- Its goal is to reduce product development time and cost, and to provide close to an optimal product.
- Computational schemes can provide fatigue life prediction analysis, reliability analysis, design sensitivity analysis, and design optimization.
- This can require component/structure/vehicle modeling, rigid or flexible multi-body kinematics and dynamics for velocity, acceleration, or load-time history determination, material properties, processing effects, and fatigue life prediction methodology.
- The use of CAE and digital prototyping is a very important and rapidly growing key segment of fatigue design.

IN-SERVICE INSPECTION AND ACQUISITION OF RELEVANT EXPERIENCE

- 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.

IN-SERVICE INSPECTION AND ACQUISITION OF RELEVANT EXPERIENCE (CONTINUED)

- 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.

IN-SERVICE INSPECTION AND ACQUISITION OF RELEVANT EXPERIENCE (CONTINUED)

- *ASM Handbook, Nondestructive Testing and Quality Control, Vol. 17, ASM International, Materials Park, OH, 1989.*
- *Nondestructive Testing Handbook, Second Edition, Vol. 1-10, ASNT, Columbus, OH, 1982-1993.*
- D.E. Bray and R.K. Stanley, *Nondestructive Evaluation: A Tool in Design, Manufacturing, and Service, Revised Edition, CRC Press, Boca Raton, FL, 1997.*
- D.E. Bray and D. McBride, Editors, *Nondestructive Testing Techniques, Wiley Interscience, New York, NY, 1992.*
- H. Berger and L. Mordfin, Editors, *Nondestructive Testing Standards-Present and Future, ASTM STP 1151, 1992.*

IN-SERVICE INSPECTION AND ACQUISITION OF RELEVANT EXPERIENCE (CONTINUED)

- **Nondestructive testing/inspection techniques** applicable to crack detection include:
 - acoustic emission
 - electromagnetic (eddy current)
 - gamma and x-radiology
 - leak
 - liquid penetrant and magnetic particles
 - neutron radiology,
 - ultrasonic
 - emerging NDT methods

IN-SERVICE INSPECTION AND ACQUISITION OF RELEVANT EXPERIENCE (CONTINUED)

- 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.

SUMMARY AND DOS AND DON'TS IN DESIGN

- The fatigue design process is an iterative process involving synthesis, analysis, and testing.
- Four different analytical or computational fatigue life models, $S-N$, $\epsilon-N$, $da/dN-\Delta K$, and a two-stage method are available.
- Four different fatigue design criteria exist involving infinite life, safe-life, fail-safe, or damage-tolerant design. Each of these criteria has specific goals and significant differences.

SUMMARY AND DOS AND DON'TS IN DESIGN (CONTINUED)

- Don't forget that damage-tolerant design may be a necessity due to the existence or development and growth of cracks in safety critical structures.
- Optimum analysis and testing is a major decision in fatigue design from the standpoint of time, cost, and product reliability.
- Analytical or computational fatigue life predictions should not be considered sufficient, particularly for safety critical situations. They can, however, provide excellent prototype design.

SUMMARY AND DOS AND DON'TS IN DESIGN (CONTINUED)



- The total cost of design, testing, and manufacture must be balanced against the cost (in money, reputation, or even lives) of fatigue failures.
- Don't neglect the advantages and limitations of accelerated fatigue testing.



PROBLEMS FOR CHAPTER 2

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?
2. Why is damage-tolerant design used less in the automotive industry compared to the aerospace industry?
3. What fatigue design considerations must be made when converting (a) a regular commercial jet aircraft to the “stretch” version? and (b) a regular automobile to a “stretch” limousine?



PROBLEMS FOR CHAPTER 2 (CONTINUED)

4. What type of loading modes exist, e.g. axial, torsion, bending, combined torsion/bending, pressure, etc., for the following components:
 - a. Hip replacement prosthesis
 - b. Jet engine turbine blade
 - c. A rear leg of a chair you frequently use
 - d. Motorcycle front axle
 - e. Alaska Pipeline

5. Sketch a reasonable load spectrum for the components of problem 4. How would you determine the actual service load spectrum for each component?



PROBLEMS FOR CHAPTER 2 (CONTINUED)

6. For components of problem 4, how would you integrate analysis and testing for each component? What testing would you recommend?
7. For components of problem 4, what design criteria would be best suited for each component and why?
8. For the following four components, what fatigue life model (i.e. S-N, ε -N, da/dN - ΔK , or two stage method) would you recommend for (a) an automobile axle without stress concentrations, (b) a gear subjected to periodic cyclic overloads, (c) a plate component with an edge crack, and (d) a riveted plate such as an airplane wing? Explain why you chose a particular fatigue life model for each of the four cases.