CHAPTER 2

FATIGUE DESIGN METHODS

2.1 STRATEGIES IN FATIGUE DESIGN

Fatigue design methods have many similarities but also differences. The differences exist because a component, structure, or vehicle may be safety critical or nonsafety critical, simple or complex, expensive or inexpensive, and failures may be a nuisance or catastrophic. Only a single end product may be desired or perhaps thousands or millions of the end product are to be produced. The product may be a modification of a current model or a new product. Significant computer-aided engineering (CAE) and computer-aided manufacturing (CAM) capabilities may or may not be available to the design engineer. In all of the above situations, the commonality of fatigue design can be represented by the fatigue design flow chart shown in Fig. 2.1. The flow chart clearly brings out the many aspects of fatigue design applicable to any of the above different product situations. Figure 2.1 indicates the iterative nature of fatigue design and the need for significant input items (top row) such as geometry, load history, environment, design criteria, material properties, and processing effects. With these inputs, fatigue design is performed through synthesis, analysis, and testing. This requires selecting the configuration, material, and processes, performing stress analysis, choosing a fatigue life and a cumulative damage model, and making a computational life prediction/estimation. (We will use the words "prediction" or "estimation" interchangeably throughout the book; both terms are common in fatigue literature.) This is followed by durability testing, which can suggest modification or the decision to accept and manufacture the product and put it into service. Evaluation of service usage and success is part of the fatigue design method.

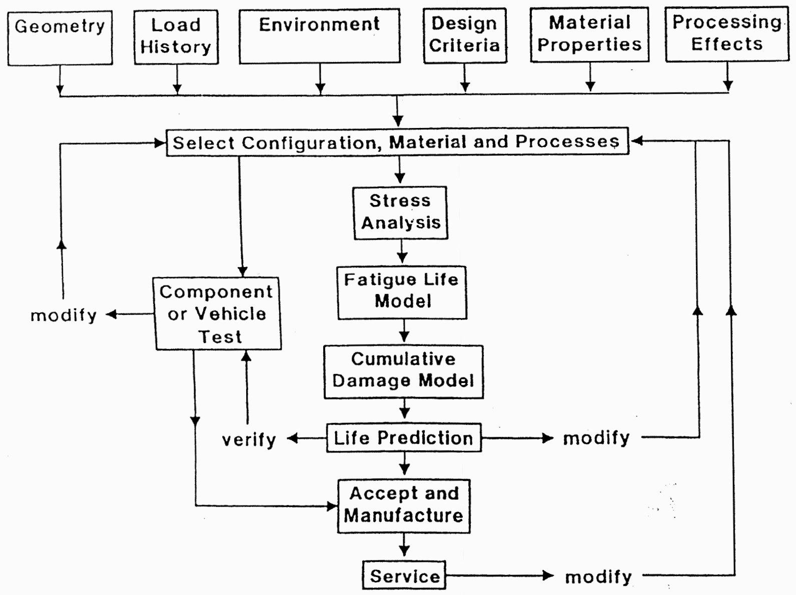

Figure 2.1 Fatigue design flow chart originated by H. S. Reemsnyder from Bethlehem Steel Corp. and slightly modified by H. O. Fuchs. It was created for use by the Society of Automotive Engineers Fatigue Design and Evaluation (SAEFDE) Committee–University of Iowa's annual short course on Fatigue Concepts in Design.

Choosing the fatigue life model is a significant decision. Currently four such models exist for design engineers. These are:

1. The nominal stress–life (S–N) model, first formulated between the 1850s and 1870s.
2. The local strain–life (ε–N) model, first formulated in the 1960s.
3. The fatigue crack growth (da/dN–ΔK) model, first formulated in the 1960s.
4. The two-stage model, which consists of combining models 2 and 3 to incorporate both macroscopic fatigue crack formation (nucleation) and fatigue crack growth.

As noted, the S–N model has been available for about 150 years, while the other models have been available only since the 1960s. The nominal S–N model uses nominal stresses and relates these to local fatigue strengths for notched and unnotched members. The local ε–N model deals directly with local strain at a notch, and this is related to smooth specimen strain-controlled fatigue behavior. Several analytical models can be used to determine local strains from global or nominal stresses or strains. The fatigue crack growth da/dN–ΔK model requires the use of fracture mechanics and integration of the fatigue crack growth rate equation to obtain the number of cycles required 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 it is used in conjunction with information on the existing initial crack size following manufacture. The two-stage method incorporates the local ε–N model to obtain the life to the formation of a small macrocrack, followed by 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 book, and each has areas of best applicability.

Depending on the purpose of the design and the different conditions discussed above, the design engineer will proceed through Fig. 2.1 in different ways. For the purpose of illustration, we look at four of the many different possible situations:

1. Designing a device, perhaps a special bending tool or a test rig, to be used in the plant where it was designed. We call it an "in-house tool."
2. Changing an existing product by making it larger or smaller than previously, using a different material or different shapes, perhaps a linkage and coil spring in place of a leaf spring. We call it a "new model."
3. Setting up a major project that is quite different from past practice. A spacecraft or an ocean drilling rig or a new type of tree harvester are examples. We call it a "new product."
4. Designing a highway bridge or a steam boiler. The expected loads, acceptable methods of analysis, and permissible stresses are specified by the customer or by a code authority. We call it "design to code."

2.1.1 The In-House Tool

If part of a tool is subjected to repeated loads, as, for instance, a ratchet mechanism or a rotating shaft carrying a pulley, it must be designed to avoid fatigue failure. For the in-house tool, provided that the designer knows the expected load-time history to which the part will be subjected in service, he or she will start with a shape that avoids stress concentrations as much as possible, will determine the stresses, and will select a material and treatments, depending on the requirements for weight, space, and cost. The design may have a suitable margin between the stress that corresponds to a 50 percent probability of failure at the desired life and the permitted stresses. A second and a third iteration may be required to balance the conflicting factors of weight or space, expected life, and cost. If the expected loadings are not uniformly repeated, the designer will consider cumulative damage.

The differences between design for fatigue resistance and design for a few loadings are greater attention to the details of shape and treatments and the need to decide on a required lifetime of the part. The designer may prevent serious consequences of failure by making the part accessible for inspection and replacement, by providing a fail-safe design or by using larger safety factors, and by performing appropriate fatigue tests.

2.1.2 The New Model

For a new model, more certainty may be required and more data should be available from service records or previous models. In addition to the steps outlined in Section 2.1.1, tests are needed to confirm the assumptions and calculations. Broken parts from previous models provide the most useful data. They can be used to adjust the test procedures so that testing produces failures similar in location and appearance to service failures. Tests that produce other types of failure probably have a wrong type of loading or wrong load amplitude. From experience with previous models, one sometimes also knows what type of accelerated uniform cycle test is an index of satisfactory performance. In testing passenger car suspension springs, for instance, it has been found that 200 000 cycles of strokes from full rebound to maximum possible deflection is an acceptable test that is much quicker and less expensive than a spectrum test with different amplitudes. Data on loads encountered by the parts may be available directly from previous models or by analogy with previous models. Instead of doing a complete stress analysis, it may be possible to determine the relation of significant stresses to loads from measurements on previous satisfactory models and to reproduce the same relation in the new model.

2.1.3 The New Product

This requires the greatest effort in fatigue design. Predicting future loads is the most important factor. No amount of stress analysis can overcome an erroneous load prediction. After the loads or load spectra have been obtained, one can analyze the fatigue worthiness of all parts. Many computer software programs are available to do this. The results are verified by component fatigue tests, which may lead to design modifications. Whenever possible, prototypes or pilot models are used to confirm functional performance and the predicted loads.

2.1.4 Design to Code

Many industries provide data on permissible stresses. The American Welding Society and the British Standards Institution, for instance, have published curves that show recommended stresses as a function of the desired life for various types of weldments. The ASME Boiler and Pressure Vessel Code has recommended fatigue design criteria based upon current fatigue models and many fatigue test data. Such codes permit the designer to use data based on the experience of many others. As a rule, a design according to code is a conservative, safe design. However, in case of a product liability lawsuit, U.S. courts do not accept compliance with a code as sufficient to exonerate the manufacturer or seller of a product that eventually failed.

2.2 FATIGUE DESIGN CRITERIA

Criteria for fatigue design have evolved from so-called 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, and the two-stage method) discussed in Section 2.1.

2.2.1 Infinite-Life Design

Unlimited safety is the oldest criterion. It requires local stresses or strains to be essentially elastic and safely below the pertinent fatigue limit. For parts subjected to millions of cycles, like engine valve springs, this is still a good design criterion. However, most parts experience significant variable amplitude loading, and the pertinent fatigue limit is difficult to define or obtain. In addition, this criterion may not be economical or practical in many design situations. Examples include excessive weight of aircraft for impracticality and global competitiveness for cost effectiveness.

2.2.2 Safe-Life Design

Infinite-life design was appropriate for the railroad axles that Wöhler investigated, but automobile designers learned to use parts that, if tested at the maximum expected stress or load, would last only hundreds of thousands of cycles instead of many millions. The maximum load or stress in a suspension spring or a reverse gear may occur only occasionally during the life of a car; designing for a finite life under such loads is quite satisfactory. The practice of designing for a finite life is known as "safe-life" design. It is used in many other industries too—for instance, in pressure vessel design and in jet engine design.

The safe life must, of course, include a margin for the scatter of fatigue results and for other unknown factors. The calculations may be based on stress–life, strain–life, or crack growth relations. Safe-life design may be based solely or partially on field and/or simulated testing. Examples of products in which field and simulated testing play a key role in safe-life determination are jet engines, gun tubes, and bearings. Here appropriate, regular inspections may not be practical or possible; hence, the allowable service life must be less than the test life or calculated life. For example, the U.S. Air Force historically has required that the full-scale fatigue test life of production aircraft/parts be four times longer than the expected or allowable service life. With gun tubes, the U.S. Army has required both actual firing tests and simulated laboratory pressure fatigue tests of six or more tubes to establish the allowable service life as a fraction of the mean test life. Ball bearings and roller bearings are noteworthy examples of safe-life design. The ratings for such bearings are often given in terms of a reference load that 90 percent of all bearings are expected to withstand for a given lifetime—for instance, 3000 hours at 500 RPM or 90 million revolutions. For different loads or lives or for different probabilities of failure, the bearing manufacturers list conversion formulas. They do not list any load for infinite life or for zero probability of failure at any life.

The margin for safety in safe-life design may be taken in terms of life (e.g., calculated life = 20 × desired life), in terms of load (e.g., assumed load = 2 × expected load), or by specifying that both margins must be satisfied, as in the ASME Boiler and Pressure Vessel Code.

2.2.3 Fail-Safe Design

When a component, structure, or vehicle reaches its allowable safe life, it must be retired from service. This can be inadequate since all the fleet must be retired before the average calculated life or test life is attained. This practice is very costly and wasteful. Also, testing and analysis cannot predict all service failures. Thus fail-safe fatigue design criteria were developed by aircraft engineers. They could not tolerate the added weight required by large safety factors, or the danger to life created by small safety factors, or the high cost of safe-life 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. This philosophy originally applied mainly to airframes (wings, fuselages, control surfaces). It is now used in many other applications as well. Engines are fail-safe only in multiengine planes. A landing gear is not fail-safe, but it is designed for a safe life.

2.2.4 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 determine 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. Of course, environmental conditions, load history, statistical aspects, and safety factors must be incorporated in this methodology.

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 the failure criteria chosen. As a crack forms and grows under cyclic loading, the residual strength decreases. This decrease as a function of crack size is dependent upon material, environment, component and crack configuration, location, and mode of crack growth. Residual strength is usually obtained using fracture mechanics concepts. Fatigue crack growth behavior is also a function of the previous parameters and involves fracture mechanics concepts. Crack detection methods, using several different nondestructive inspection techniques and standard procedures, have been developed. Inspection periods must be laid out such that as the crack grows, the applied stresses remain below the residual strength. Cracks need to be repaired or components replaced before fracture occurs under the service loads. 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 this philosophy.

Retirement for cause is a special situation requiring damage-tolerant usage. Imagine the number of jet engine turbine blades that have been retired from service because they have reached their designed safe-life service life based upon analytical and test results. This cost is enormous since most of these blades could have significant additional service life. To allow for possible extended service life, damage-tolerant methodology based upon both analytical considerations and additional blade testing is required. In the case of jet engine turbine blades, this is not an easy task because of the safety-critical situation and the many complex parameters involved. Retirement for cause, using damage-tolerant procedures, can be applicable to many engineering situations involving products already designed by safe-life methods or with new designs.

2.3 ANALYSIS AND TESTING

Analysis and testing are both key aspects of fatigue design, as indicated in the flow chart of Fig. 2.1. How much time and money should be put into each is an important engineering decision. 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 retesting, creating both time and cost inefficiencies. Analysis capabilities are largely dependent upon the computer capabilities available to the engineer. 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, the engineer must realize that these calculations are for the models; the key to confidence in these results is how closely the models represent the real product and its usage. For example, environmental influence and nonproportional multiaxial loading conditions are not usually properly integrated into the calculations, along with the fact that the results have varied from excellent to fair to poor. Thus, even the best analysis should not necessarily be the final product design, particularly with safety critical products. However, analysis is a must in proper fatigue design and should lead to a very reasonable prototype design. A design based on analysis alone, without fatigue testing, requires either a large margin for uncertainty or an allowance for some probability of failure. A probability of failure of a few percent can be permitted if failures do not endanger lives and if replacement is considered a routine matter, as in automobile fan belts. In most other situations, analysis needs to be confirmed by tests.

Fatigue testing has involved enormous differences in complexity and expense and has ranged from the simple constant amplitude rotating beam test of a small specimen to the simulated full-scale, complex, variable amplitude thermomechanical cycling of the Concord supersonic aircraft structure in the 1970s or the Boeing 777 aircraft structure in the 1990s. The objective of fatigue testing may be to obtain the fatigue properties of materials, aid in product development, determine alterations or repairs, evaluate failed parts, establish inspection periods, or determine the fatigue durability of components, subassemblies, or the full-scale product. 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 (for instance, cut threads instead of rolled threads or forged parts instead of cast parts) may have a major effect on fatigue resistance. Test specimens may be considered one-dimensional, as with small cylindrical specimens used for baseline material characterization under well-controlled environmental conditions. They may be considered two-dimensional in simple component testing that may include geometrical discontinuities and surface finish such as an engine connecting rod. Three-dimensional specimens would include subassembly structures such as a truck suspension system including joints and multiple parts to full-scale structures such as the Concorde and the Boeing 777 aircraft.

Since the introduction of closed-loop servohydraulic test systems in the late 1950s, significant emphasis and success have 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 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. One such full-scale simulated fatigue test is shown in Fig. 2.2, where an automobile is subjected to three-dimensional variable amplitude load inputs at each wheel spindle. Simulated laboratory testing and test track or proving ground testing can be performed at the same time. They both provide significant input to final product decisions.

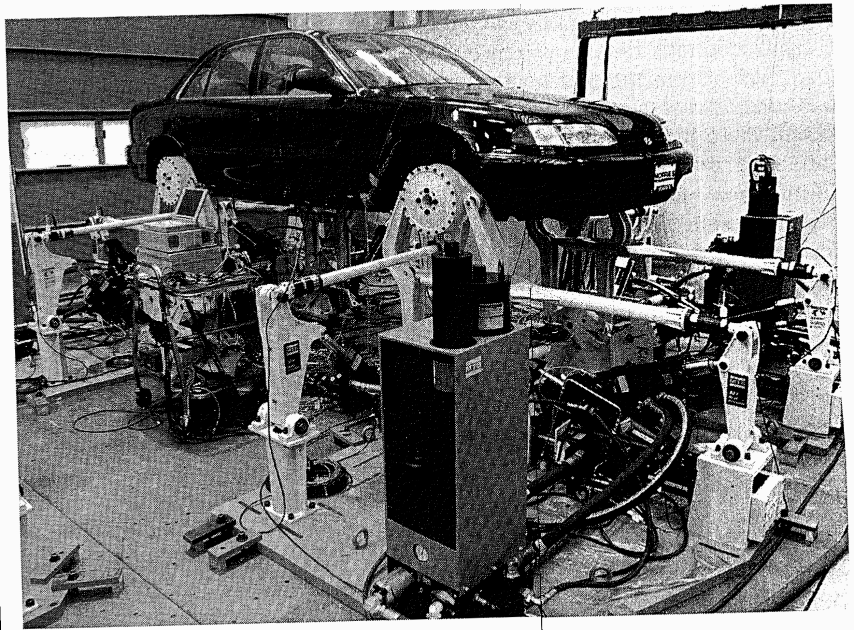

Figure 2.2 Full-scale simulated road fatigue test of an automobile (courtesy of MTS Corporation).

Fatigue or durability testing for design verification, or development testing, is an art. It is far more demanding than the art of fatigue testing for research because it requires the engineer to make the test represent conditions of use, but it is far less demanding than fatigue testing for research in its requirements for precision. Loading and environment conditions similar to those encountered in service are prime requirements for simulated fatigue testing. Determining the service loads may be a major task. Multichannel data acquisition systems are available to obtain the load, torque, moment, strain, deflection, or acceleration versus time for many diverse components, structures, and vehicles subjected to service usage.

Acceleration of simulation or field testing poses problems. It is often required in order to bring products to market before the competition or to find a method for improving marginal products and controlling test costs. Three common methods to accelerate testing involve increasing test frequency, using higher test loads, and/or eliminating many small load cycles from the load spectrum. All three methods have the significant advantages of less test time and lower costs, but each has disadvantages. Increased frequency may have an effect on life and may not provide enough time for environmental aspects to operate fully. Increasing loads beyond service loads accelerate tests but 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, and several analytical methods exist to aid in eliminating so-called nondamaging cycles. We prefer to call these "low-damaging" rather than "nondamaging" cycles because we cannot be sure if these small cycles will or will not influence fatigue life. Elimination of low-damaging cycles may hide the influence of both fretting and corrosion. In fatigue testing, the more closely the simulation or field test represents the service conditions, the more confidence one can have in the results.

Proof testing involves 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 determining inspection periods. Proof testing may alter fatigue resistance by creating desirable and/or undesirable residual stresses. Periodic proof testing at low temperature has been used on F-111 airplane wings as part of the routine in-service inspection procedure to ensure continuous damage-tolerant fleet readiness.

2.4 PROBABILISTIC DESIGN AND RELIABILITY

Fatigue behavior of simple or complex specimens, components, structures, or vehicles involves variability. The variability in life has ranged from almost a factor of 1 to several orders of magnitude for a given test or service condition. These two extremes, however, are not the norm. 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. However, design without data from service experience cannot, with our present knowledge, provide quantitative reliability figures in the ranges that are required or desired for service. Chapter 13 on statistical aspects of fatigue covers these topics.

2.5 CAE AND DIGITAL PROTOTYPING

CAE involves computer usage to perform much of the iteration of synthesis and analysis in the design procedure. "Digital prototyping" refers to a computer-generated realistic prototype model near or at the final state of the product. Thus, this means that a computer prototype is formed by analysis and synthesis only. This procedure could also be called "digital testing." Its goals are to reduce product development time and cost and to provide a nearly optimal product. The computational scheme could begin at several entry levels. These include known or assumed road or terrain profiles for ground vehicles, load–time histories, and stress– or strain–time histories. The computational procedures and information needed depend upon the entry level. The most extensive computational requirements occur for the road input entry level, and the least extensive ones occur for the stress– or strain–time history entry level. Computational schemes can provide fatigue life prediction analysis, reliability analysis, design sensitivity analysis, and design optimization. This can require three-dimensional graphics for shape determination, component/structure/vehicle modeling, rigid or flexible multibody kinematics and dynamics for velocity, acceleration, or load-time history determination, material properties, processing effects, and fatigue life prediction methodology. Design sensitivity analysis and optimization can be accomplished based upon stress, strain, stiffness, and so on, or fatigue life. The use of CAE and digital prototyping is a very important and rapidly growing key segment of fatigue design.

2.6 IN-SERVICE INSPECTION AND ACQUISITION OF RELEVANT EXPERIENCE

Imperfections of design will eventually become known. Either the part is too weak and fails too often or it is too strong and a competitor can produce it more economically. Part of engineering responsibility involves efforts to find and correct weaknesses before customers and competitors find them. 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, which are exceptional, and how much greater loads than those measured can occur are 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. The ASTM, ASM International, and the American Society for Nondestructive Testing (ASNT) have published significant information on nondestructive inspection (NDI) and nondestructive testing (NDT) [1–3]. Additional books on these subjects and on nondestructive evaluation (NDE) are also available [4–6]. ASTM Committee E-07 on Nondestructive Testing is responsible for Vol. 03.03 [1], which includes over 100 standards on the following nondestructive testing/inspection techniques applicable to crack detection: acoustic emission, electromagnetic (eddy current), gamma and x-radiology, leakage, liquid penetrant and magnetic particles, neutron radiology, ultrasonic, and emerging NDT methods. Both ASM and

ASNT handbooks [2,3] also have significant information on these same methods that range from simple to very sophisticated in terms of required user capability. 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, yet tough inspection decisions need to be made. 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.

2.7 SUMMARY

The fatigue design process is determined by design objectives and by the extent of the available knowledge. It is an iterative process involving synthesis, analysis, and testing. The extent to which these three processes are used depends upon the situation and the computational and testing capabilities available. Four different analytical or computational fatigue life models—S–N, ε–N, da/dN–ΔK, and a two-stage model—are available to the engineer, and each has been used successfully (and unsuccessfully). Four different fatigue design criteria exist involving infinite-life, safe-life, fail-safe, and damage-tolerant design. Each of these criteria has specific goals and significant differences. In-service inspection and continuous monitoring of customer usage are part of fatigue design.

Optimum analysis and testing is a major decision in fatigue design from the standpoint of time, cost, and product reliability. Current digital prototyping can produce computer prototypes formed at different levels of input, such as road profile, load, stress, or strain histories. These computer prototypes can be optimized using fatigue life predictions. However, analytical or computational fatigue life predictions should not be considered sufficient, particularly for safety critical situations. They can, however, provide excellent prototype designs. Testing for final product durability but not for development then becomes an important aspect of fatigue design. The total cost of design, testing, and manufacturing must be balanced against the cost (in money, goodwill, reputation, or even lives) of fatigue failures.

2.8 DOS AND DON'TS IN DESIGN

1. Do recognize that fatigue design is an iterative process involving synthesis, analysis, and testing.
2. 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.

3. Don't forget that damage-tolerant design may be necessary due to the existence or development and growth of cracks in safety critical structures.
4. Don't consider computational/analytical fatigue life predictions/estimations as the end of the fatigue design process.
5. Do emphasize digital prototyping and rely on fatigue testing primarily for product durability determination rather than product development.
6. 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.
7. Don't neglect the advantages and limitations of accelerated fatigue testing.
8. Do pursue inspection of in-service components, structures, and vehicles and continue to monitor customer usage.
9. Don't neglect the importance of environmental conditions in both analytical and testing aspects of fatigue design.

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PROBLEMS

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 than in the aerospace industry?

3. What fatigue design considerations must be kept in mind when converting (*a*) a regular commercial jet aircraft to the "stretch" version and (*b*) a regular automobile to a "stretch" limousine?

4. What types of loading modes (e.g., axial, torsion, bending, combined torsion/bending, pressure) exist 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 Problems 4*a* through 4*e*. How would you determine the actual service load spectrum for each component?

6. For the components of Problems 4*a* through 4*e*, how would you integrate analysis and testing for each component? What testing would you recommend?

7. For the components of Problems 4*a* through 4*e*, what design criteria from Section 2.2 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 the 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.

9. Write a one- to two-page review paper on one of the different NDI techniques used to measure crack sizes or to determine if cracks exist.