11 FATIGUE DESIGN METHODS

11.1 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, 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. The flow chart clearly brings out the many aspects of fatigue design applicable to any of the above different product situations. Figure 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. 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.

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 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.

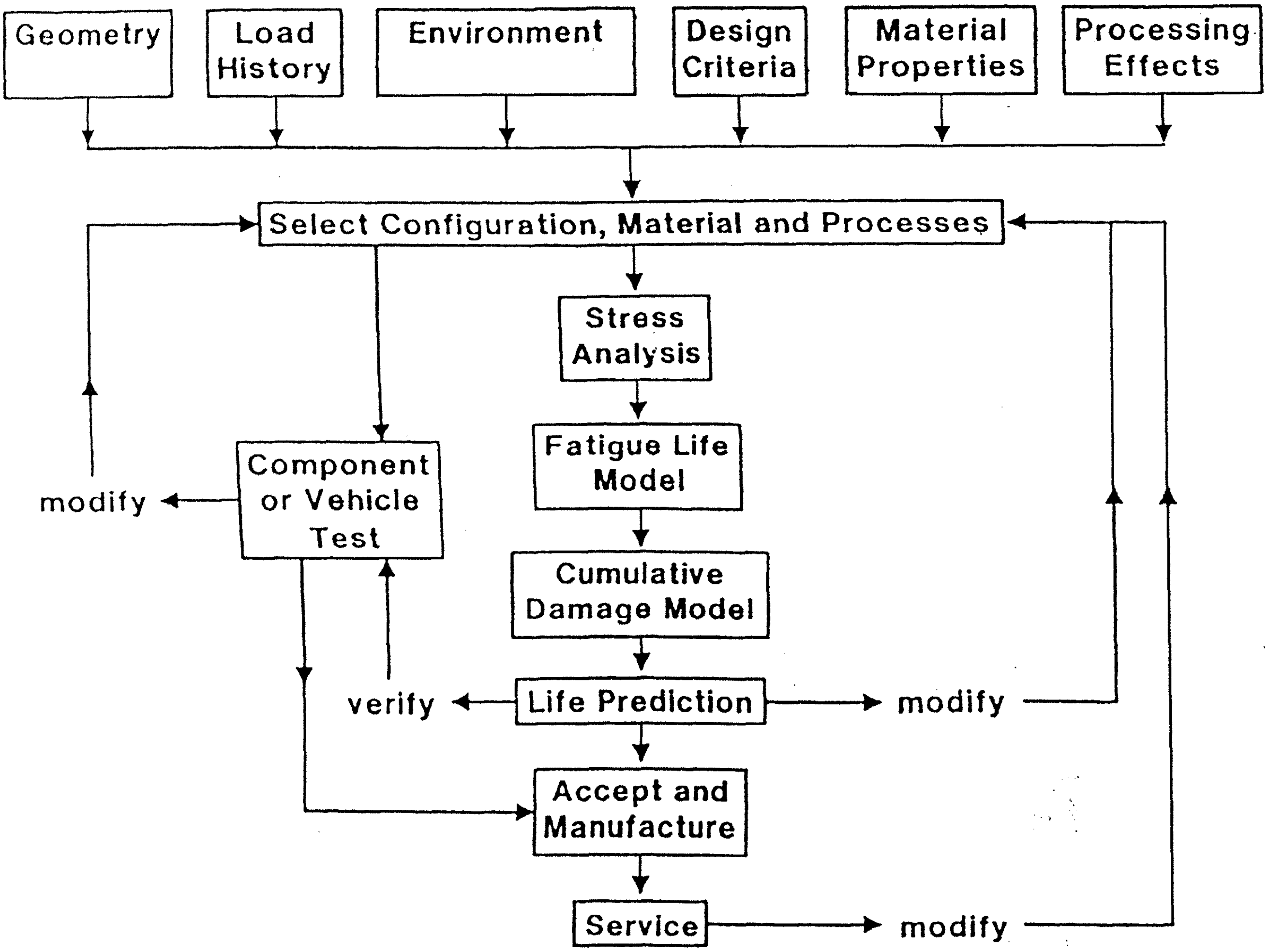


Figure. Fatigue design flow chart originated

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 s-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 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 s-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.

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

1. Designing a device or tool, to be used in the plant where it was designed. “in-house tool.”
2. Changing an existing product by making it larger or smaller than previously, using a different material or different shapes. “new model.”
3. Setting up a major project that is quite different from past practice. 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 code authority. “design to code.”

11.1.1 The In-House Tool

If part of a tool is subjected to repeated loads 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 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.

11.1.2 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 4.1.1, 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. 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.

11.1.3 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 of 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.

11.1.4 Design to Code

Many industries provide data on permissible stresses, for instance, curves that show recommended stresses as a function of the desired life for various types of materials and notches. This codes have 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.

11.2 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 discussed in Section 4.1.

11.2.1 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.

11.2.2 Safe-Life Design

Infinite-life design was appropriate for the railroad axles that Wohler investigated, but 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 may occur only occasionally during the life of a vehicle; 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 industries – 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 X desired life), in terms of load (e.g., assumed load = 2 X expected load), or by specifying that both margins must be satisfied.

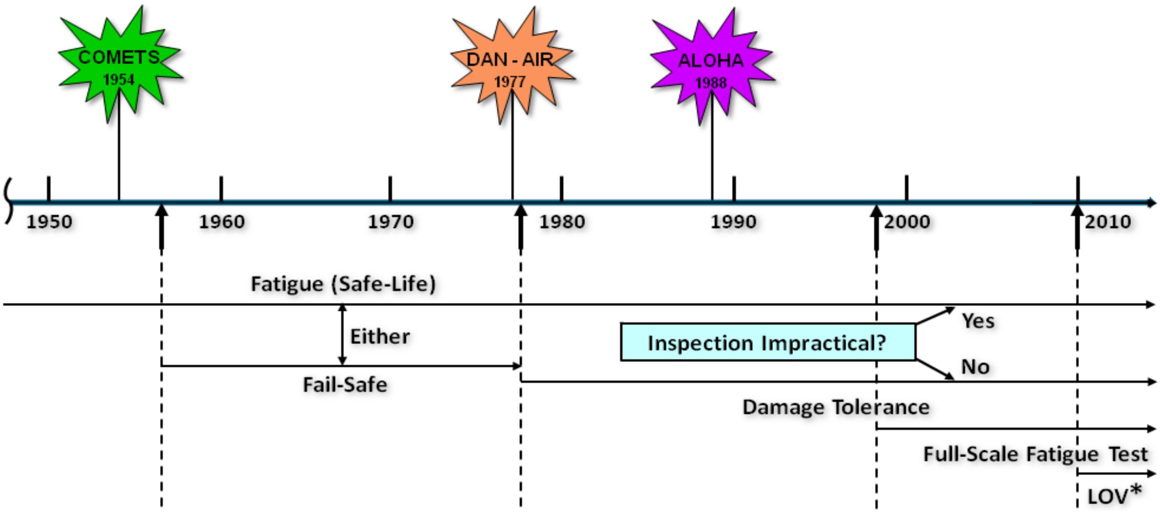
11.2.3 Fail-Safe Design

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.

11.2.4 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.

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.



Milestone civil aircraft accidents and evolution of civil aircraft fatigue requirements:

*LOV = Limit of Validity