Combining Durability with Multibody Dynamics

Mark Pompetzki, Ph.D.
nCode International
26877 Northwestern Hwy, Suite 220
Southfield, MI 48034

Abstract

A primary application of multibody dynamics is the prediction of loads. These loads can be used to define the service environment for a component; a critical input for durability analysis. This paper describes a number of durability analysis techniques that can be used to enhance the usefulness of the results provided by multibody dynamics analysis.

Introduction

Durability analysis can be used to determine how long a component can survive in a given service environment. In the general case, durability refers to failure according to a number of different mechanisms such as fatigue, corrosion, wear, creep, etc. In practice, however, the predominant failure mode is fatigue and so, in this paper, the term durability analysis will be used to describe the analysis of fatigue performance.

Fatigue is defined as the cracking and subsequent failure of components under cyclic loading. Traditionally, loading information could only be derived by direct measurement and so fatigue analyses and testing have traditionally been applied only towards the end of a design cycle. However, the prediction of fatigue loading through the use of multibody dynamics now allows the design engineer to undertake durability assessments at a much earlier stage.

Durability Analysis

When external forces are applied to a multibody system, these forces are transferred through that system from one component to the next, where a component is defined as an element within that system. The fatigue life of a component is governed by the loading environment to which it is subject, the distribution of stresses and strains arising from that environment, and the response of the material from which it is manufactured. As a result, the major inputs to any fatigue analysis are loading, component geometry, and cyclic material properties. These data are combined in the fatigue analysis process to estimate life as shown in Figure 1. Subsequent sections of this paper describe each of these inputs in more detail and also provide a description of some common fatigue analysis methods together with insight into interpretation of fatigue results.

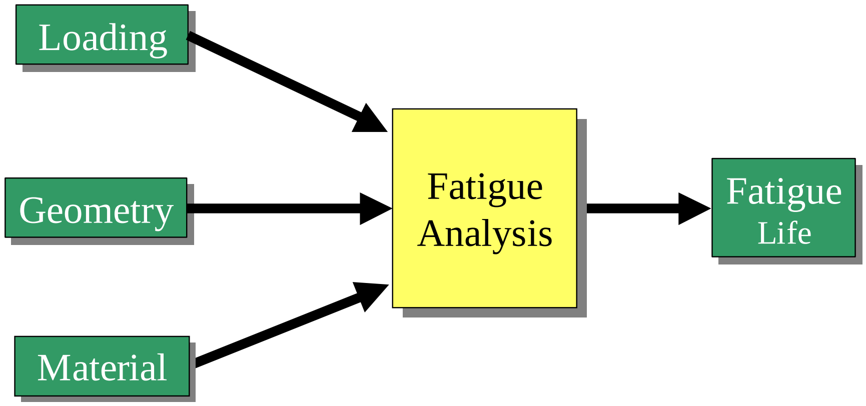

Figure 1 – Fatigue analysis process “the 5 box trick”

Loading

Loading information can be obtained using a number of different methods. Local or nominal strains can be measured by means of strain gages. Nominal loads can be measured through the use of load cells or, more recently, they can be derived externally by means of analysis. Since early methodologies relied on measurement from physical components, the application of fatigue analysis methods has been confined to the analysis of service failures or, at best, to the latter stages of the design cycle where components and systems first become available.

The ability to predict component loads analytically means that physical components are no longer a prerequisite for durability analysis and so analysis can proceed much earlier in the design cycle. It is important to note that, in this context, loading environment is defined as the set of phase-related loading sequences (time histories) that uniquely map the cyclic loads to each external input location on the component.

Geometry

In the context of fatigue analysis the term geometry is often used to describe how loads are transformed into stresses and strains at a particular point in a component. For local stress, the geometry defines the following function:

$$\boldsymbol{\sigma} = f\,(L_i)$$

where $\boldsymbol{\sigma}$ is the local elastic stress and L_i is the externally applied load at location i. The effect of geometry may be determined in either one of two ways. Firstly, by means of an elastic stress concentration factor, K_t and secondly, by means of finite element analysis.

Stress concentration factors are used to calculate local stresses and strains at specific locations from their nominal counterparts or from the applied loading. Stress concentration factors for specific geometries are usually obtained from handbooks (1), experimental stress analyses, or finite element methods. Since the process needs to be repeated for every potential critical location within the component this approach becomes very cumbersome, particularly in situations where a large number of external loads are applied and multiple critical locations need to be considered.

Finite element analysis can be used to calculate the stress distribution for an entire component or structure and so provides an ideal precursor to durability analysis. By combining the linear elastic finite element methodology with fatigue analysis, the life at each node or element can be calculated. Complex multi-axial loading scenarios can be easily taken into account by linear elastic superposition. The process can be illustrated through a consideration of the formulation of the stress tensor time history at any given location:

$$\sigma^{l}_{ij}(t) = \sum \left((\sigma^{l}_{ij})_{k} * L_{k}(t) \right)$$

where σ^{l}_{ij} is the stress tensor at location l in the component model due to the application of unit load for load-case k, and $L_k(t)$ the loading history corresponding to that load case.

Material

Another major input to fatigue analysis is a definition of how a material behaves under cyclic loading conditions. Cyclic material properties are used to calculate elastic-plastic stress-strain response and the rate at which fatigue damage accrues due to each fatigue cycle. The material parameters required depend on the analysis methodology being used. Normally, these parameters are measured experimentally and may also be available in various handbooks and other publications. In situations where specific data are not readily available, approximate values may be deduced from static tensile properties such as ultimate tensile strength and ductility.

Fatigue analysis methods

Fatigue analyses can be undertaken by using of one of three basic methodologies, i.e. the stress-life method, the strain-life method, and linear elastic fracture mechanics. The stress-life approach was first applied over hundred years ago and considers nominal elastic stresses and how they are related to life particularly in situations where large numbers of cycles (greater than 10^5) are involved. Life is usually associated with catastrophic failure. The strain-life methodology, which evolved fifty years ago, considers elastic-plastic local stresses and strains. It represents a more fundamental approach and is used to determine the number of cycles required to initiate an engineering crack. Linear elastic fracture mechanics is used to predict how quickly pre-existing cracks grow and also to estimate how many cycles are required for them to reach a critical size. Details of these methods are beyond the scope of this paper, however, more information is available in numerous publications including references (2) and (3).

Fatigue results

Fatigue results are usually expressed in terms of the numbers of cycles, or repeats of particular loading sequences, required to reach a specified failure criterion at a location. Sometimes these values are associated with physical quantities such as hours, miles or fractions of a durability route. These results are, of course, sensitive to each of the major inputs; loading, geometry and material.

Sensitivity to variation in loading magnitude is particularly acute due to the logarithmic relationship between load and life. A 10% change in load, for example, can alter predicted life by up to a factor of two. From the designer's point of view, variations in loading conditions are largely the result of variability in customer usage. To a large extent this variability is beyond the control of the designer, other than through the provision of adequate safety factors. Material behavior and the impact of geometry, on the other hand, can usually be defined more precisely and variability is usually much less than that associated with applied load.

Durability Analysis Techniques with Multibody Dynamics

In situations where the component loading environment has been defined by means of analytically derived loads, three different strategies for durability assessment can be considered. These are, a load based relative analysis, a location based durability analysis, and a finite element (FE) based durability analysis. Each technique requires slightly different inputs and is applicable under different conditions. The inputs are given in Figure 2 and described in detail in the following sub-sections along with a description of analytical loads.

Inputs	Load based relative analysis	Location based durability analysis	FE based durability analysis
Loading	Component loads	Component loads	Component loads
Geometry	Range of Geometry	Scale factor and K_t	FE
Material	Generic or Cyclic	Cyclic material	Cyclic material

Figure 2 – Inputs for each durability analysis technique

Analytical Loads

For all of the techniques defined above, multibody dynamics is used to predict the loads applied to a component (i.e. component loads) given external system inputs. Three basic types of multibody dynamic models are applicable for this loads derivation:

- A full system model using real-life inputs.
- A partial system model using measured forces, motions, or displacements.
- A complete system model of the test specimen and the test rig, where the inputs are through the test rig actuators.

Load based relative analysis

A load based relative analysis, also known as "load intensity" analysis, involves predicting fatigue life for two sets of conditions (i.e. different design iterations) and comparing the results in a relative sense. The technique can be used for components with multiple load inputs and calculates the damage for various load combinations. Load combinations must be considered, because critical locations are sensitive to such loading scenarios. Load intensity is based on the concept of linear superposition in which all possible load combinations are derived for a set of given inputs. A fatigue analysis is subsequently performed for each of these load combinations. By comparing the relative damage that accrues for each load combination, it is possible to determine the durability characteristics of the input load histories. If a design change improves the durability characteristics of the loading, the relative damage for all the load combinations is reduced. This process is shown in Figure 3.

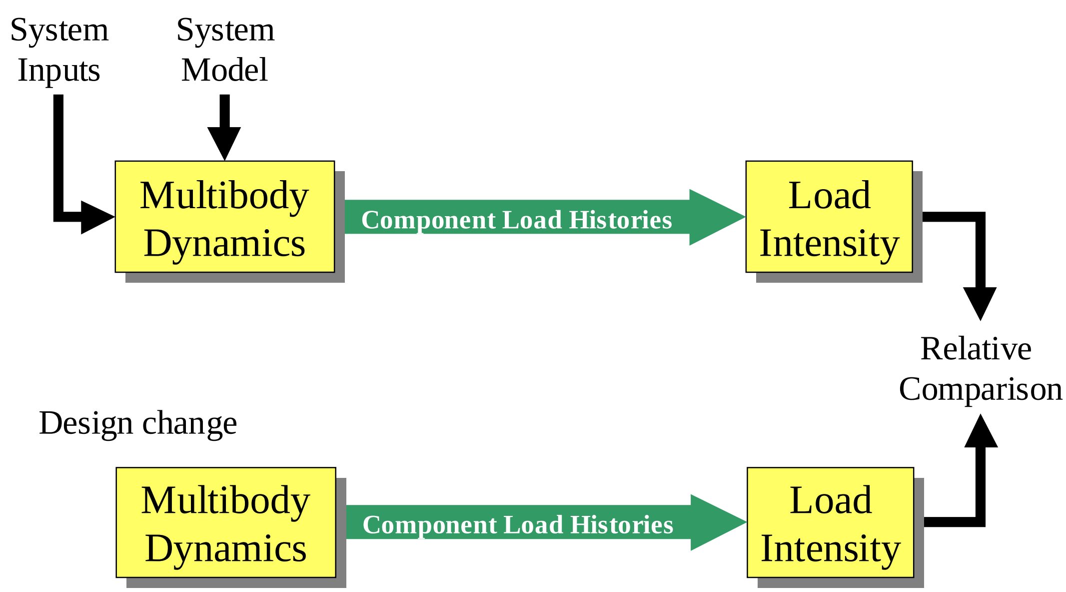

Figure 3 – Load based relative analysis

Figure 3, implies that inputs for material and geometry are not required in this approach. These factors are not being ignored; they are being included through the use of generic material properties and a range of load combination to describe the geometry. It is important to note, however, that whilst generic material properties can be usefully used for relative fatigue calculations, they are inappropriate for absolute estimation of fatigue life.

Since the load intensity approach is based solely on load inputs the procedure can be executed very rapidly, as opposed to an FE approach which can take considerably longer. The trade-off for this faster analysis, however, is that the level of accuracy is reduced. The technique is particularly suited to the study of design changes early in the design cycle and, when appropriate, for pointing the way towards more detailed analyses using one of the other techniques.

Location based durability analysis

Location based durability analysis utilizes a traditional approach in which each analysis is confined to a single location. The nominal stress is calculated from the external loading information through the use of a scale factor. A stress concentration, K_t, is then used to calculate the local elastic stresses at the critical location. These local stresses are used together with appropriate material properties to calculate fatigue life at that location. This procedure is illustrated in Figure 4.

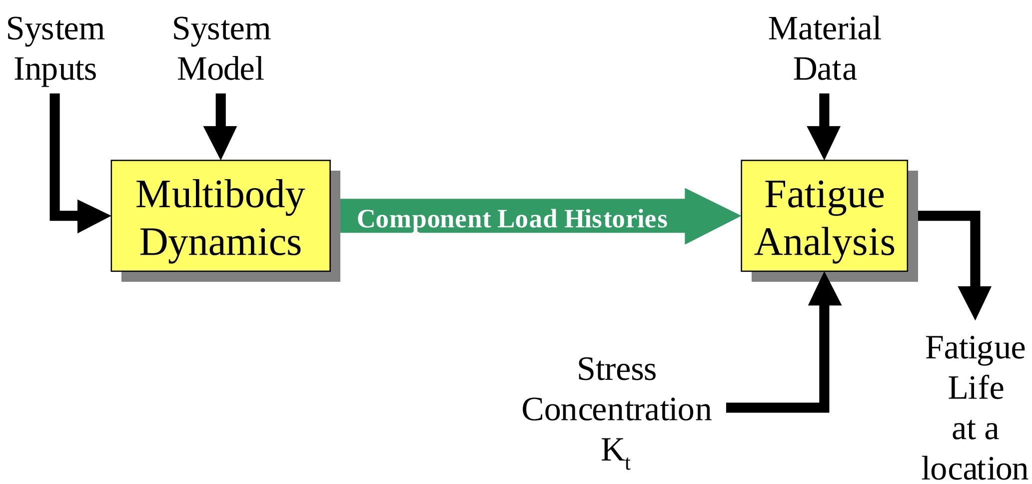

Figure 4 – Location based durability analysis

Again, the advantage of the technique is that a finite element model is not required and so analysis time is kept to a minimum. It is also more accurate than the load intensity approach described above. However, it should be noted that it is not a trivial task to determine the appropriate scale factor and stress concentration for a particular location, especially when the component is subjected to a large number of external load input locations. Another disadvantage is that the method only provides results for a single location which may lead to other critical locations being overlooked.

FE based durability analysis

An FE based durability analysis is considered to be a complete analysis of an entire component. Fatigue life can be estimated for every element in the finite element model, and contour plots of life or damage plotted in a similar way to stresses. As with the other techniques, component loading is provided through multibody dynamic analysis.

Geometry information is provided by FE results for each load case applied independently, i.e. the FE results define how an applied load is transformed into a stress or strain at a particular location in the component. Appropriate material data are also provided for the desired fatigue analysis method. This process is detailed in Figure 5 below.

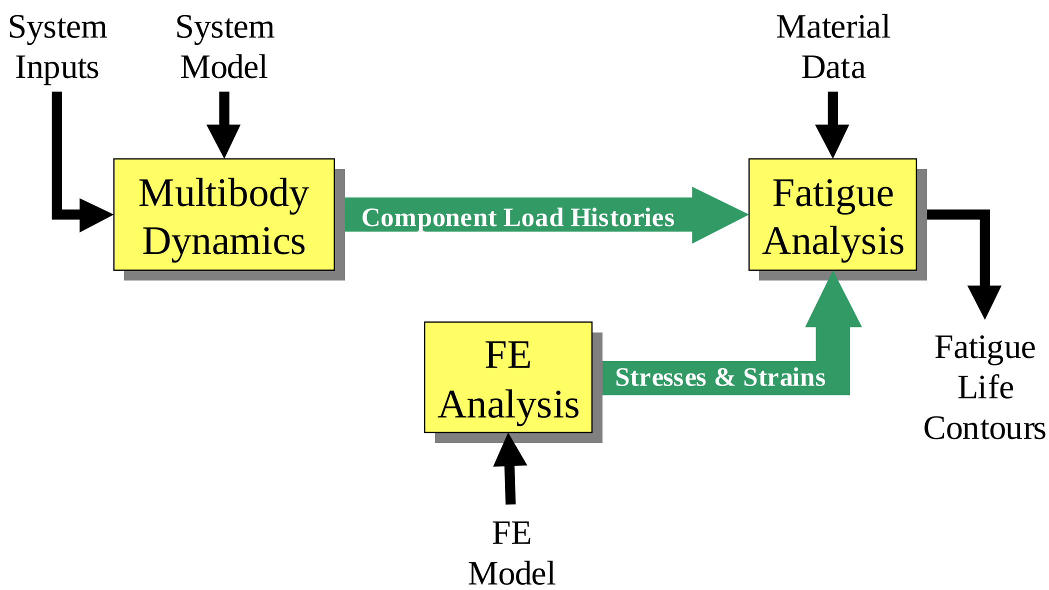

Figure 5 – FE based durability analysis

The advantage of this technique is that fatigue life can be calculated for the entire component and so all critical locations can be identified, along with the order in which they occur. In addition, the technique can highlight regions which are non-critical in terms of durability and so offer potential for cost or weight reduction. The disadvantage is that setup and analysis times can become significant. Furthermore, a prodigious amount of data can be generated which can lead to potential errors and problems if not managed appropriately. Additional difficulties can also arise from file conversions, consistency of units, polarity, and the mapping of loading locations between multibody dynamics, FE and fatigue analyses.

Integrated analysis

An integrated approach to durability analysis would combine multibody dynamics analysis, finite element analysis and fatigue analysis into a consistent entity for the prediction of the durability of a component. Since all of these analyses can be undertaken from within the CAE environment, this integration lends itself to application early in the design cycle. The process involves large amounts of data and different areas of engineering expertise. Special techniques are required to execute the complete analyses in a reasonable time. An integrated approach requires pulling together at least five primary areas, i.e., multibody dynamics, finite elements, fatigue, data management, and data flow as shown in Figure 6.

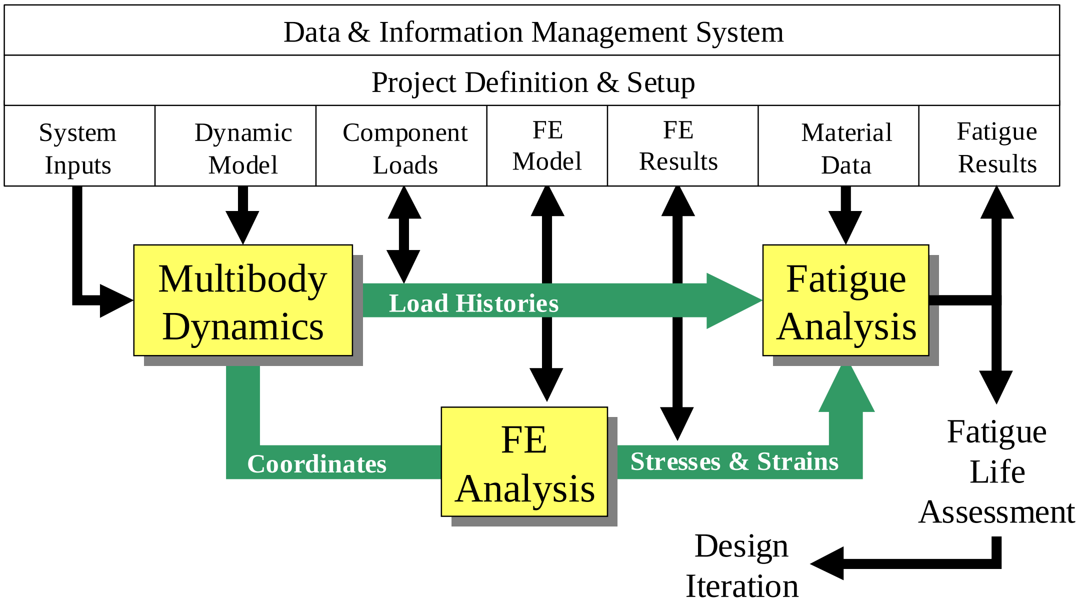

Figure 6 – Integrated durability analysis

Although this level of integration is not currently available in commercial software, it is nevertheless a desired goal within the durability analysis community. An integrated approach could provide better flow of data, which would result in fewer errors (hence greater accuracy) and faster analyses through the automation of various sections of the process.

Comparison of the Techniques

The three durability analysis methodologies together with the integrated approach are compared in Figure 7. This figure shows a relative comparison for the level of accuracy and analysis time of each technique.

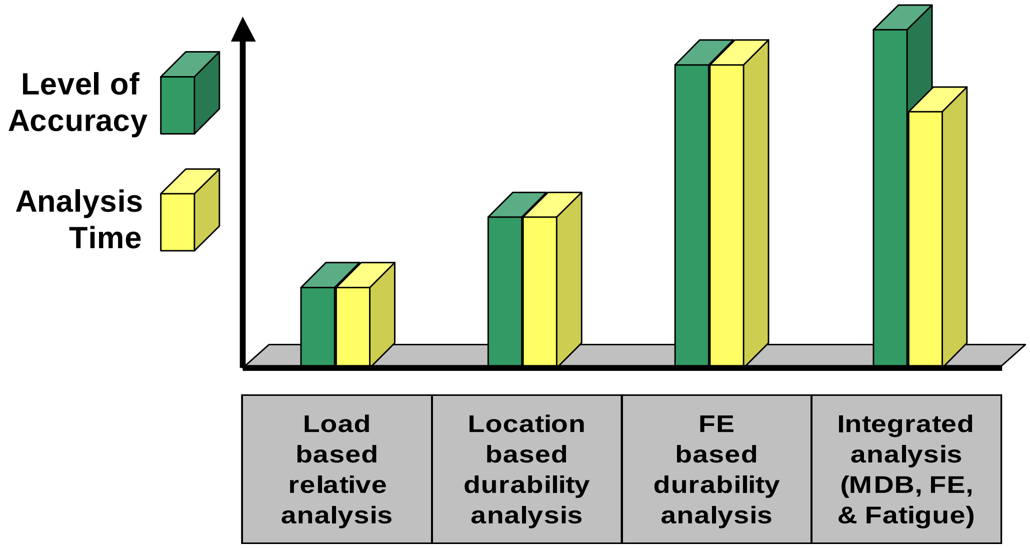

Figure 7 – Comparison of durability analysis techniques

Summary

The ability to derive loads by means of multibody dynamics provides an opportunity to greatly enhance the efficiency of durability assessment of early designs. Three techniques have been described for performing durability analyses based on analytically derived loads. Each technique has been shown to have both advantages and drawbacks with applicability in different situations. In addition to the three techniques, an integrated approach has also been described which improves efficiency and accuracy through the use of data structures for the management and exchange of information.

References

[1] “Stress Concentration Factors”, R.E. Peterson, John Wiley & Sons 1974, ISBN 0-471-68329-9

[2] “Fundamentals of Metal Fatigue Analysis”, J. A. Bannantine, J. J. Comer, & J. L. Handrock, Prentice-Hall Inc. 1990 ISBN 0-13-340191-X

[3] “Metal Fatigue In Engineering”, H. O. Fuchs & R.I Stephens, John Wiley & Sons, 1980, ISBN 0-471-05264-7

Acknowledgements

The author would like to thank Chris Musiol and Tony Yardley for their assistance and numerous suggestions.