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DEVELOPING A DURABLE PRODUCT

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ABSTRACT. *Traditionally, the assessment of durability and reliability in the ground vehicle industry has been relatively ad hoc with end-users often being the first to discover durability problems and so, inadvertently, becoming an integral part of the development process. Over time the industry has developed both field and laboratory based procedures that aim to simulate typical or severe customer usage. These procedures have been used to develop products by means of prototypes that are used to demonstrate the durability of the final product prior to its release. Varying durability objectives have often led to similar but different testing methods and procedures.*

Today, increasing commercial pressures to develop and deliver reliable products in a timely manner necessitate more intelligent testing to be coupled with CAE procedures such as multi-body dynamics (MBD), finite element analysis (FEA), and fatigue life analysis, (FLA) into a coherent durability engineering process. In the future, as engineering processes come to rely even more heavily on CAE methods, engineering requirements will drive the development of predictive methods and systems that are more efficient and robust and can address a wider variety of applications than are currently possible.

This paper presents the methods for obtaining improved customer usage information and how that can be included within a durability process to refine and accelerate vehicle development through both physical and virtual methods.

Keywords. *Fatigue, Durability, Data Acquisition, Multi Body Dynamics, Finite Element Analysis, Rig Testing, Fatigue Life Analysis, Correlation.*

INTRODUCTION

The scale of the challenge facing the durability engineer is put into perspective when considering the following statement,

"Weather prediction has a target of 65% accuracy for the next 3 to 5 day period. Fatigue prediction is expected to be 95% accurate for the next 10 years of product life." [H.P.H. Tabarelli, Head of Testing Department, Transporters, DaimlerChrysler.]

This statement provides useful insight into the perception of the accuracy of fatigue prediction by people outside the fatigue community. The challenge facing the durability engineer is not confined just to the accurate assessment of life. It also includes requirements to establish where, when and for what reason fatigue failures will and in fact do occur. This paper describes why answers to these challenges are more likely to come from recent advances in telecommunications and the Internet, within the context of a durability process, rather than from improvements in fatigue modeling techniques where advances might be expected to improve accuracy rather than usability and applicability. The need for durability assessment will be discussed and an outline of basic fatigue methodologies presented. The application of these technologies to differing industries and processes will also be discussed.

THE NEED FOR FATIGUE ANALYSIS

Fatigue analysis is primarily used to help obviate undesirable mechanical failures and thereby to ensure public and consumer safety. The penalties for getting it wrong are severe. In addition, repeated catastrophic failures can severely impact the perception of product reliability and so influence business performance through costly product recalls.

Safety Issues

A good example of failure to meet stringent safety requirements can be found, some 150 years ago, in the fledgling railroad industry where some of the first mass-produced products, axles and rails, were prone to failures with accompanying loss of life. In many cases this led to litigation and bankruptcy. More recently a multi-billion dollar Company called Railtrack with responsibility for the entire rail infrastructure within the United Kingdom was declared bankrupt as a direct result of unwarranted fatigue failures of railroad track.

A more contemporary example from a different industry relates to the De Haviland Comet; one of the first passenger jet airliners (1949 to 1980) to enter production. In 1954 these aircraft suffered a number of tragic accidents during service as a result of mid-air structural failures of the airframe arising from the initiation of fatigue cracks at the corners of rectangular windows. As a result of the loss of life, series production was held up for a number of years allowing competing products, such as the Boeing 707, to be brought to market first and so to establish unassailable market share. Mechanical fatigue testing repeated the same failure mode in the same location after a mere 1830 simulated flights.

Economic Considerations

Fatigue failure of non-safety-critical components can also affect financial performance adversely through costly warranty related recalls. According to independent studies carried out by the Batelle group in 1982, between 80-90% of all structural failures occur through a fatigue mechanism and the estimated annual cost of such failures to the United States was estimated to be 4.4% of GDP. The Batelle study further concluded that this cost could be reduced by up to 29% through the application of current fatigue analysis technologies.

A common methodology used to avoid fatigue failures is conservative over design or design for infinite life. However, present day demands for optimized products that need to meet stringent weight and fuel efficiency requirements preclude the luxury of this approach. On the other hand, real costs are associated with up-front durability assessment. Test tracks, simulation laboratories and CAE technologies can only be acquired at a price. These costs, however, are considerably lower than those likely to be incurred as a result of recalls and in-service fixes. Further, while it is also true that overall costs decrease as assessments migrate from the physical to the virtual, the scope for errors can increase. One way of mitigating these errors is through adherence to a framework for analysis and assessment – the durability process.

The components that constitute a durability process, their connectivity and utilization will be dealt with in much more detail later on. For the moment, it is sufficient to note that a durability process is the compendium of required inputs, analytical procedures and correlation tools required to conduct a durability assessment at an appropriate time within the design cycle.

AN INTRODUCTION TO FATIGUE

THE PHYSICS OF FATIGUE

Fatigue is defined as 'failure under a repeated or otherwise varying load, which never reaches a level sufficient to cause failure in a single application.' Fatigue cracks always develop as a result of cyclic plastic deformation in a localized area. This plastic deformation often arises, not due to theoretical stresses in a perfect part, but rather due to the presence of a small crack or pre-existing defect or notch on the surface of a component.

August Wöhler was one of the first engineers to study the fatigue phenomenon as it related to railway axles. He realized that knowledge of cyclic loading conditions was crucial and so he measured them on actual vehicles and subsequently constructed a test rig that subjected two axles to the measured loads simultaneously. This test procedure later became known as the rotating bending test. He varied the maximum load and found that as it decreased so the life increased until finally a lower limit load was reached at which point no further failures were observed. It took about thirty years for other workers to present his tabular results in the form of the now familiar stress-life plot (fig. 1).

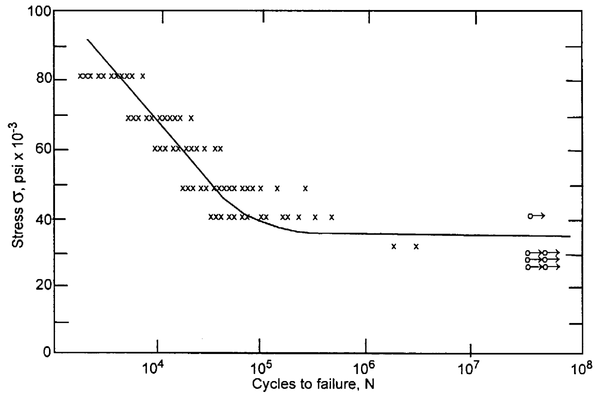

Figure 1. Wöhler's Stress Life Data.

During his experiments, Wöhler also observed that when geometric discontinuities such as a groove or notch were introduced into the test samples the stress required for a given life was significantly reduced. These early observations laid the groundwork for our understanding of the fatigue damage process.

Typically a fatigue crack initiates at a free surface and grows in two stages. During the first stage it propagates at approximately 45º to the direction of applied load following the line of maximum shear stress. After traversing a number of grains it changes direction to propagate at approximately 90º to the direction of the applied load. Cracks growing through these stages are often referred to as Stage I and Stage II cracks respectively (fig. 2).

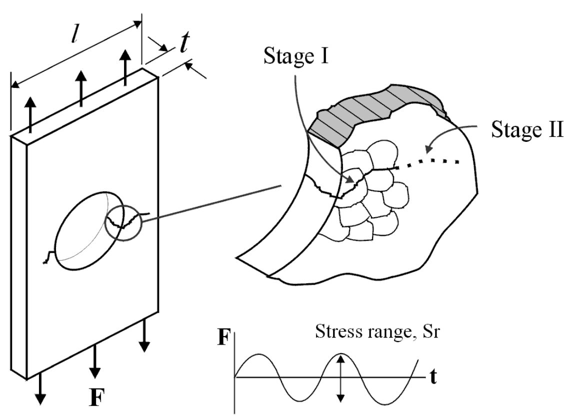

Figure 2. Illustration of Stage I and Stage II Crack Growth.

A Stage I crack undergoing alternating stress leads to persistent slip bands forming along the planes of maximum shear. These bands slip back and forth, much like a deck of cards, and give rise to surface extrusions and intrusions. The surface intrusions form an ‘embryonic’ crack (fig. 3). The Stage I crack propagates in this mode until it encounters a grain boundary, at which point it briefly stops until sufficient energy has been applied to the adjacent grain and the process continues.

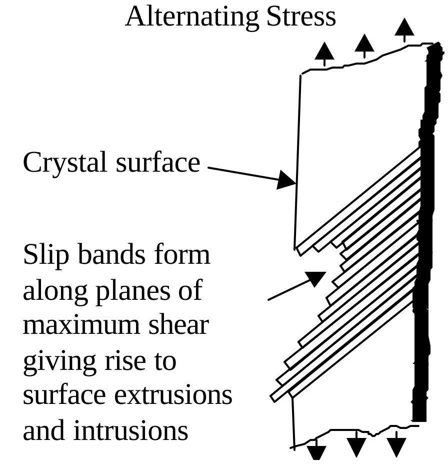

Figure 3. Illustration of persistant slip bands.

After traversing two or three grain boundaries the direction of crack propagation now changes into a Stage II mode. In this stage the physical nature of the crack growth changes. The crack itself now forms a macroscopic obstruction to the flow of stress that gives rise to a high plastic stress concentration at the crack tip. It should be noted that not all Stage I cracks evolve to Stage II.

The Stage II crack grows by a ratcheting mechanism. As the tensile stress increases the crack tip opens giving rise to local plastic shear deformation. As the tensile stress now decreases the crack tip closes and the permanent plastic deformation gives rise to a distinctive saw tooth profile known as a striation. On completion of the cycle the micro crack has advanced a small distance and has formed an additional striation. The extent of crack growth is proportional to the range of elastic-plastic crack tip strain applied. Many repetitions of these cycles will result in fatigue failure, and the distinctive 'beach marks' on the fracture surface.

This understanding of the Stage II crack growth ratcheting mechanism forms the basis of the linear elastic fracture mechanics crack propagation fatigue methodology.

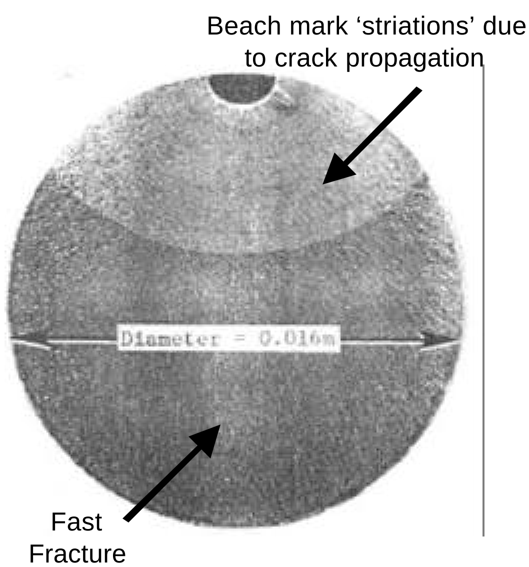

Figure 4. Beach marks (striations) on a fatigue fracture surface.

FACTORS AFFECTING FATIGUE DURABILITY

Fatigue durability is influenced by a number of factors some of which are detailed below.

- Stress or Strain Range
- Mean Stress
- Surface Finish and Quality
- Surface Treatments
- Sequence effects

Stress or Strain Range

In both Stage I and Stage II growth, crack development arises through plastic shear strain on a microscopic scale. Consider, the plastic shear strain forming along the Stage I slip planes or at the tip of a Stage II crack as a result of the nominal stress time history shown in figure 5.

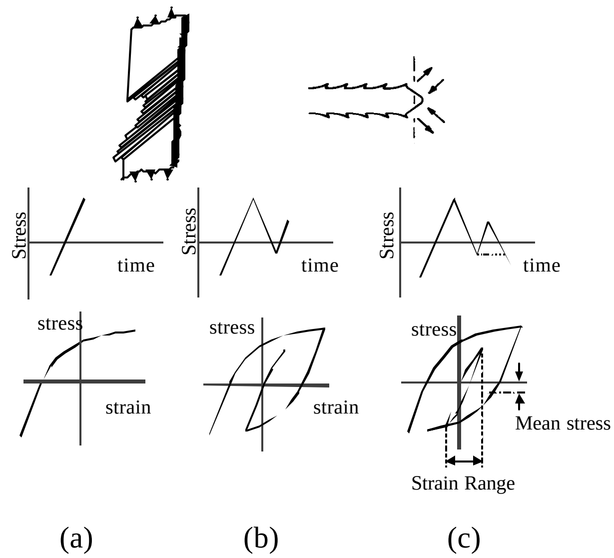

Figure 5. Elastic-plastic stress and strain along a slip plane and at the root of a crack.

Figure 5a shows the nominal stress rise with time. On a microscopic level, in the presence of a crack or pre-existing defect, the stress and strain become plastic and can be plotted in the stress vs. strain diagram shown.

Figure 5b shows what happens when the nominal stress is reduced and then raised again by a smaller amount. Again the local stress vs. strain can be plotted showing the effect of local yielding.

Figure 5c shows another reduction in the nominal stress. The stress vs. strain plot shows the formation of a hysteresis loop. A loop in the stress vs. strain plot indicates release of strain energy where the total energy released is equal to the area of the loop. This has released a quantity of shear strain energy and this has been expended in sliding the slip planes or advancing the Stage II crack.

This illustrates that a ‘quantum’ of shear strain energy is released when the nominal stress is cycled into tension and then back again. Also, the larger the stress cycle, the greater the energy released. From the stress life curve shown in figure 1, we see that fatigue life drops exponentially as the stress cycle range increases.

This understanding of the elastic-plastic stress and strain behavior at the root of a crack is the basis of the strain-life or local strain fatigue methodology.

Mean Stress

A non-zero mean stress influences the rate at which fatigue damage accrues. A *tensile* stress applied to a Stage II crack forces it to open and any stress cycles applied will have a more damaging affect. Conversely, compressive mean stress forces the crack to close thereby reducing the effectiveness of any applied stress cycle.

Surface finish

Since fatigue cracks usually initiate from a pre-existing defect at the surface of a component, the quality of the surface will greatly influence the chance of a crack initiating. Most material test specimens have a mirror finish and therefore achieve the best fatigue lives. In practice most components are seldom as good and so it is necessary to modify the fatigue properties accordingly. Surface finish has a more significant effect on the fatigue of components subjected to low amplitude stress cycles. The effect of surface finish can be modeled by multiplying the stress life curve by the surface correction parameter at the endurance limit.

Surface Treatments

Surface treatments can be applied to improve the fatigue resistance of a component. These usually work by inducing a residual compressive stress at the surface. Under low amplitude cycles the stresses at the surface are significantly lower or even remain compressive. Therefore the fatigue life is greatly improved. This effect is only true for components subjected to low amplitude stress cycles. If large amplitude cycles are applied then these start to overcome the pre-compression and the benefit is lost.

The effect of surface treatments can be modeled in the same way as surface quality.

Sequence effects

The sequence in which cycles are ordered can influence the fatigue life. Consider the two time histories shown in figure 6. Both appear to consist of two cycles having the same range and mean stresses. A plot of their elastic-plastic strain response shows that the smaller cycle has a tensile mean in the first example and a compressive mean in the second. Therefore the first example will create more damage than the second.

For most practical analyses, sequence effects are insignificant because the probability of one sequence occurring is equal to that of the other. However, it is worth noting when planning some simplified and idealized loading sequences.

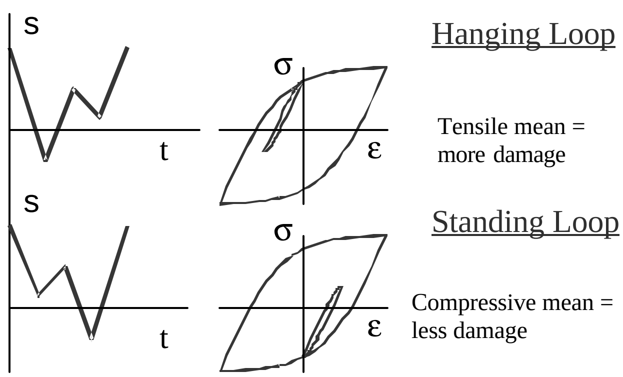

Figure 6. Illustration showing the effect of cycle sequence.

THE COMPONENTS OF A FATIGUE ANALYSIS

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 component geometry, service loading, and cyclic material properties. These data are combined in the fatigue analysis process to estimate life as shown in figure 7. Subsequent sections of this paper describe each of these inputs in more detail and provide a description of some common fatigue analysis methods.

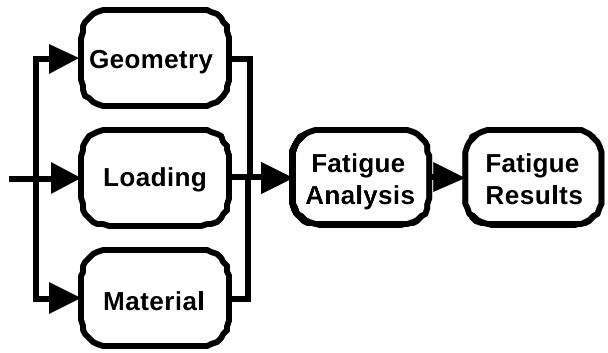

Figure 7. Components of a fatigue analysis.

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. The geometry is the function between the externally applied load(s) and the local stress. 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, 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. Subsequent sections of this paper describe how this is overcome with the use of multi body dynamics and finite element analysis within a durability process.

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 multi body dynamic 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.

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

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 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 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 the first and second reference in the reference listing.

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 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.

THE COMPONENTS OF A DURABILITY PROCESS

A structural durability process will make use of one or more of the functions shown in figure 8. Subsequent sections will illustrate how different industries exploit specific sub-processes depending on their durability requirements and constraints.

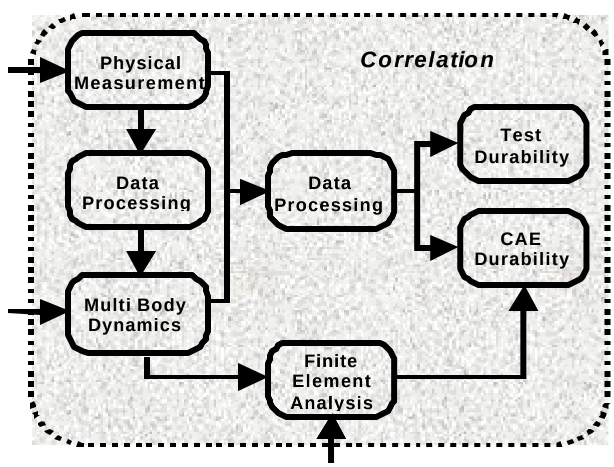

Figure 8. A Durability Process.

Physical Measurement

Figure 9. Physical Measurement.

Data acquired by physical measurement is a major source of information in the ground vehicle and aerospace industries. Figure 9 illustrates a vehicle under test at a proving ground designed to simulate various aspects of customer usage. Using prototype or similar vehicles, non-intrusive transducers such as accelerometers and strain gages are used to measure vehicle behavior. Loads are measured using either off-the-shelf or custom-built load cells. More recently, to provide the inputs required by multi-body dynamic simulation, wheel force transducers are being used to measure the six load components at the wheel spindle

Physical measurements are generally divided into two groups. Those that acquire synchronous time history data and those that acquire reduced data over much longer periods of time.

Synchronous time history data are acquired and stored on some local mass storage device inside the vehicle for the duration of the test. After completion of the test(s) the gathered information is viewed and validated to ensure transducer integrity and consistent results. This type of acquisition can generate large quantities of information very quickly. For example, a 100 channels sampled at 512 Hz will generate 12 MBytes of data per minute or 720 MBytes per hour of recording. Automotive data acquisition can easily exceed 100 channels per vehicle, while aerospace and marine shipping can exceed 500 simultaneous channels.

Reduced data are generally collected for fewer channels but usually over much longer times; weeks, months or even years. These data are generally collected in some form of histogram or matrix in order to classify the incoming information, typically time at level, level crossing, rainflow, or frequency spectra. Storage requirements, in this case are much lower, for example rainflow matrices are usually characterized by 128 x 128 histograms, and for 20 channels this represents about ½MByte of storage requirement.

Major disadvantages of on-line data reduction include the fact that synchronicity between channels is lost and also that “wild-points” or spikes appear as individual values within extreme matrix elements making them difficult to distinguish from valid entries. However, modern acquisition systems can at least address the second issue by acquiring short bursts of time series information pre and post suspicious events thus allowing them to be put into context and eliminated as appropriate.

The trend in physical measurement is increasingly towards the use of longer-term reduced data acquisition as a means of characterizing real customer usage. Furthermore, recent advances in on-board storage capacity, global positioning technology and Internet access make these devices increasingly useful for long term monitoring of product performance and usage.

The characterization of the loading environment to which a component or subsystem is subjected by means of physical measurement provides the durability engineer with access to an essential element of the durability process. However, physical measurement requires physical components from which the measurements are to be made and this precludes the adoption of analytical durability methodologies early in the development cycle when parts are not yet available.

Multi Body Dynamics

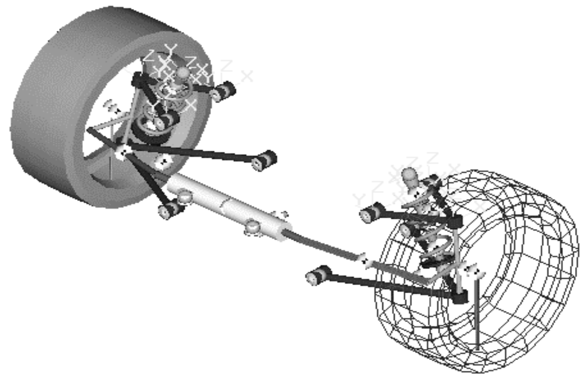

Figure 10. Multi Body Dynamics.

A multi body dynamic model can be used to simulate vehicle behavior; an automotive front suspension system is illustrated in figure 10 above. Such models are commonly used very early in a development program for initial package work of the major masses to deliver some key aspects of the vehicle dynamic behavior. Within the automotive industry these models are most often used to predict ride and handling characteristics.

Most recently, dynamic modeling has been used in conjunction with a finite element analysis (FEA) as part of a CAE durability process for either semi-analytical or fully analytical modeling of load histories for combination by either liner or modal superposition with FEA results as part of a fatigue analysis.

Semi-analytical methods include physical measurement of a limited data set in order to support analytical determination of all the remaining required loads. The six component loads provided by wheel force transducers are particularly suitable for this method. Fully analytically derived loads require full vehicle models that require a digital representation of the surface profile to be simulated and an adequate durability tire model. Current durability tire models are not ideal, further development is required before this approach receives general use.

The loads derived using fully analytical methods are mostly used for relative durability calculations to select design alternatives or investigate component change effects. Many companies are striving to develop these methods to replace the semi-analytic ones and thus eliminate the need for any measured data and hence any physical vehicles or parts. However, the need for physically measured information will remain for the foreseeable future. The use to which it is put is, however, is evolving towards calibration and validation of analytical methodologies.

Data Processing

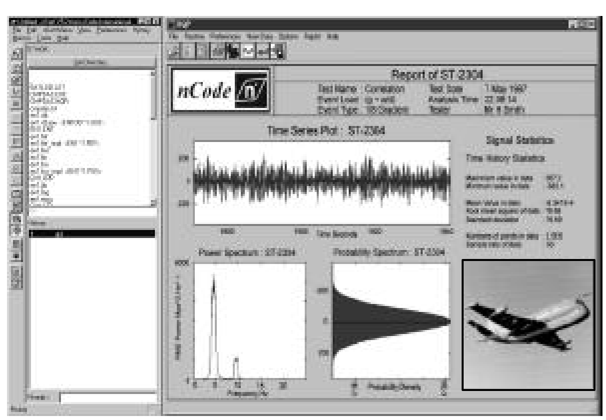

Figure 11. Data Processing.

The one common thread, integral to all components of a durability process is 'time histories,' an example report is shown in figure 11. They are what are acquired by physical measurement. They are the input to and the output from multi body dynamics. They are the input to test rig based test durability and to CAE durability, and are an output from both. 'Time histories' are viewed, manipulated and processed in many different forms throughout the whole durability process.

Because 'time histories' are so integral to the process, speed and flexibility of data processing are essential. Speed is realized in two ways, by the speed of individual operations and the ability to create macros of sequential analyses for batch processing. A macro facility also addresses the flexibility requirements.

It is used for visual validation of data from physical measurements. The trend is towards automated anomaly detection techniques of which some of these are suitable for automatic correction.

Measured time histories need to be modified before use as inputs to a multi body dynamic model. They may require polarity and/or units conversion from the measurement co-ordinate system and units to those required by the model, filtering to remove high frequencies and offset removal to remove a static mean.

Finite Element Analysis

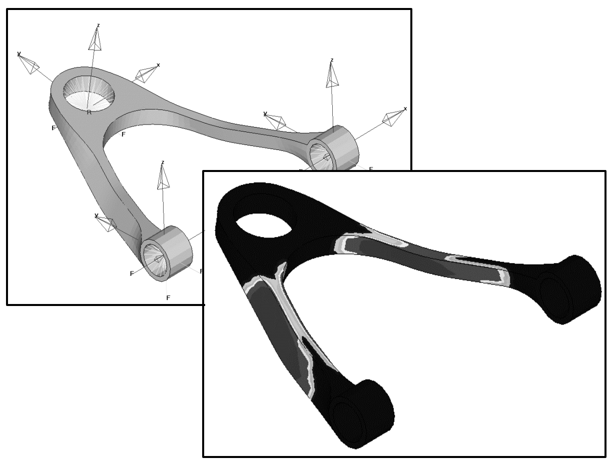

Figure 12. Finite Element Analysis.

Finite element analysis is a long established CAE analysis tool, and is widely used in all engineering industries. An example finite element model showing the boundary conditions and resulting stress distribution is shown in figure 12.

Finite element analysis is used to calculate the stress distribution for an entire component or structure and so provides an ideal precursor to fatigue 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 taken into account easily by linear elastic or modal superposition.

Transient time step FEA calculation is required when the structure exhibits a non-linear stress and strain response. Loading histories are not required here, they are calculated explicitly within each time step. This methodology, while useful for handling non-linearities, is very time consuming because a complete finite element analysis is required for each step.

The increasing number of model variants built on each platform calls for a large number of FE models to be built. In addition, the reduction in the number of possible physical prototype stages necessitates an increasing number of 'virtual test' loops for each variant. In these conditions, it is important to minimize the number of models that are developed. In the case of the modeling and analysis of car bodies for instance, it is common to develop several models of the car body in order to meet the differing analysis requirements for crash, NVH, and durability. Critical requirements for NVH include accurate prediction of global stiffness and modal characteristics, whereas for durability the main requirement is for accurate local stresses in critical areas.

Test Durability

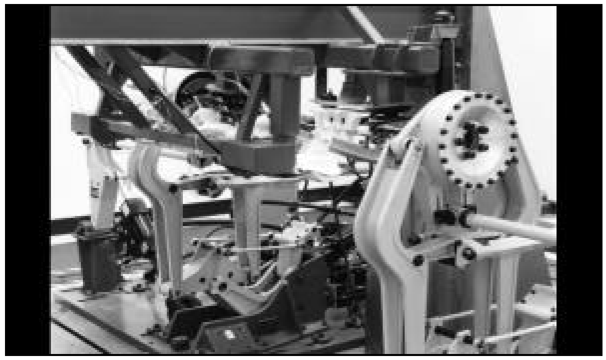

Figure 13. Test Durability.

Test durability refers to any physical testing, either at a proving ground or on a test rig in a simulation laboratory; a typical test rig fixture is illustrated in figure 13.

Test based durability assessment includes predictive fatigue life analysis from measured strain gage data acquired during proving ground or rig testing. It is common to apply large numbers of strain gages, typically more than fifty, to chassis structures and measure the strain due to simple single axis frame tests or during field operation of full vehicles. Highly integrated data acquisition and fatigue analysis software systems are required to automate analysis of many strain gages in combination with multiple vehicle operations and events that together represent typical customer usage.

A proving ground based durability test is often used as part of final vehicle sign off. These tests are intended to simulate a lifetime of product usage in a relatively short time. An automotive vehicle sign off procedure, for example, may reduce a 150,000 mile customer target to 20,000 miles on the proving ground, and may take 2 months to complete.

Laboratory based durability testing is intended to reproduce failure modes and locations similar to those observed on the proving ground, but in a shorter and more controlled and reproducible environment. The complexity and configuration of the testing fixtures required for valid simulation depends on the complexity of the components under investigation and can range from single up to as many as sixteen channels of synchronous actuation. The most complex tests require a considerable amount of computational time to develop the signals required to drive the multi-channel test rigs in a realistic manner.

It is usual for laboratory testing to take less time to complete than equivalent proving ground tests. This acceleration stems primarily from the twenty-four hour uninterrupted operation possible on a test rig. Further acceleration of laboratory tests can be achieved through the use of analytical fatigue editing techniques in which non-damaging events are excluded from drive signals while at the same time maintaining synchronicity between channels. Typically, ninety five percent of damage can be retained during a test that might require only ten percent of real time to execute. In spite of this acceleration, and the need for final sign-off, testing remains a relatively inefficient and costly method for optimizing designs.

CAE Durability

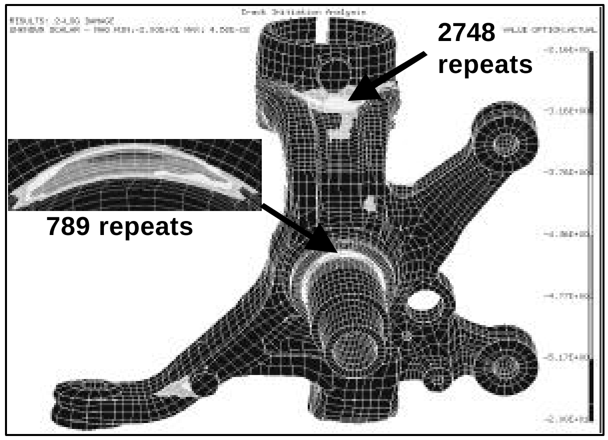

Figure 14. CAE Durability, Fatigue Life Analysis.

CAE durability refers to multiple fatigue life analyses for nodes or elements within a finite element model. Figure 14 illustrates the results from a strain life analysis of an automotive steering knuckle.

Three CAE durability methodologies are currently available. The first relies on linear static superposition of elastic finite element stress or strain results scaled according to appropriate loading histories, the second on modal superposition combining multi body dynamic modal stress and modal response time histories and the third on a transient time step analysis with all inputs coming directly from the finite element results.

The fatigue analysis methodologies available to the CAE durability analyst are the same as those available to the test engineer the only difference being that the former processes loads from which stresses and strains are computed by means of finite element analysis and the latter measured strain histories. The fully analytical approach can, however, export local strain histories from which magnitudes and stress states can be compared with those obtained by measurement.

Large models, in excess of 100,000 elements, can be easily processed, however, when taken together with large numbers of load cases, greater than 50, long time histories, in excess of 100,000 values, and the requirement to process multiple events, analysis times can become inordinately long. For example, a linear static analysis of a light truck frame can take in excess of 24 hours to complete. However, fatigue-editing techniques similar to those used in test durability and nodal elimination methods that automatically exclude non or slightly damaged nodes from detailed analysis can be used to accelerate the computational process. Using auto-elimination techniques for the analysis of the above truck frame so as to process only the top 1% of the structure with the highest stressed nodes reduced computation time down to 15 minutes while analyzing the top 10% took 2 hours. Note that it is unlikely that a structure could sustain significant fatigue damage at more than 10% of nodes without being subject to gross yielding.

The challenge for CAE durability remains how to accelerate the analysis process. The minimum acceptable analysis period for a 'full' analysis is about twelve hours, equivalent to running the analysis overnight.

Distributed computing together with parallel processing are ideally suited to meet these computational challenges because fatigue life calculations are usually similar at each node or element. Selecting which nodes are to be analyzed more intelligently and optimizing time history reduction methods will go a long way towards meeting the challenge.

Adaptive fatigue methods will add intelligence to the fatigue life analysis, taking expert knowledge and implementing it within a software application. The software will choose the most appropriate fatigue method for each location with regard to its service environment, and keep a record explaining why it made those choices.

The change to a virtual development process has been driven by a number of factors, particularly reduced development times, increased model diversity, increased complexity and the need to optimize performance and cost.

This is driving the introduction of new methods that address the actual durability problems encountered during development; for example spot welds, thin sheet seam welds.

There is now also increased focus on fatigue of other types of structural joints, high temperature fatigue and thermo-mechanical fatigue, and fatigue of elastomers, plastics and composites.

The application of CAE durability within a durability process enables components and systems to be designed to meet their desired durability criteria. However there are many variables that analytical durability analyses cannot adequately consider; such as wear, manufacturing processes, assembly, material non-homogeneity and residual stresses. Therefore, laboratory durability tests and vehicle proving grounds will continue to be necessary for design verification and system or full vehicle sign-off.

Correlation

Correlation takes many forms at different stages of a durability process.

Some examples are:

- Correlation of time histories; where one time history should overlay another
- Correlation of data characteristics; where frequency spectra, Rainflow cycles, level crossing, fatigue damage should be the same as another
- Correlation of failure; where the predicted location and failure mode should compare with physical observation
- Correlation of customer usage with proving ground; what combination of proving ground surfaces are equivalent to a customer usage profile
- Correlation between proving grounds; what combination of proving ground ‘A’ surfaces are equivalent to proving ground ‘B’ surfaces
- Correlation of proving ground to physical testing; is an accelerated test schedule equivalent to the proving ground

All analytical components of a durability process require correlation with something physical to validate the analytical model. The actual correlation method used is dependent on the particular process.

A multi body dynamics model is correlated with physical measurements by comparing representative response time histories with those measured on the vehicle.

Within a durability process a finite element analysis can calculate unit load case stress for linear static superposition, modal stress contributions for modal superposition or transient time step stress. Detailed stresses are difficult to correlate independently. However, it is possible to correlate the mode shapes from a modal analysis with modal response testing.

Several results from CAE durability analysis can be correlated. A fatigue life contour plot is correlated with physical components in three ways: to identify the failure locations, to rank them in order of severity and to predict the fatigue life. Extracting corresponding strain time histories from the CAE durability model can correlate strain gage rosette measurements from physical testing.

HOW DIFFERENT DESIGN PHILOSOPHIES INFLUENCE THE DURABILITY PROCESS

The following design philosophies are not an either or option. There is usually a bit of both in every product development process, however the emphasis does shift depending on both the industry or particular products within that industry.

Typical philosophies that influence the durability process are:

- Regulated and Unregulated
- Corporate Owners and Consumers
- Product Development and Product Monitoring

- Durability Performance and Other Performance Targets
- Production Numbers
- Manufacturing Methods
- Test Durability and CAE Durability

Regulated and Unregulated

There are regulations of some form in all industries. The differences are really down to how prescriptive those regulations are for durability.

A very prescriptive regulated industry is civil aerospace. The appropriate governing bodies define regulations covering all aspects of the aircraft and their durability requirements, even prescribing the fatigue methods that are approved for use. Full documentation of all durability calculations must be maintained during the whole life of the aircraft that can easily exceed 30 years. In the aerospace industry the certifying authorities require the durability and damage tolerance of vehicles to be demonstrated analytically or experimentally

Durability calculations in the commercial aircraft industry are driven by the need to meet legal safety requirements and to satisfy the requirements of the certifying authority. This has led to some inertia in adopting new methods; once a method has proved acceptable to the certifying authorities, there is little motivation to adopt new and possibly less conservative methods.

In comparison durability analysis within the automotive industry is unregulated. The legal requirements for durability in the automotive industry are alarmingly vague, even for safety critical parts. Currently there are no effective standards regarding fatigue durability that apply to the automotive industry, either in respect of methods or of targets. Each manufacturer sets their own durability targets and defines the methods that are to be used to attain those targets.

This situation has certain advantages – it permits a flexibility of approach and promotes innovation, because the main factor motivating an improved approach to durability is commercial advantage. The final verification of product durability within the automotive industry is normally a fairly severe sign-off test.

An interesting reflection on the issue of regulation is that consumer driven industries tend to be unregulated while corporate owner industries tend to be regulated. Consumer driven industries tend to become self-regulating due to consumer pressure.

Corporate Owners and Consumers

The end customer of the product influences the durability process during development.

For example military aircraft are not required to adhere to the same regulations as civil aircraft. This is because the durability drivers for safety and legal requirements for a commercial airliner with several hundred fare-paying passengers are very different to those for a military pilot involved in a conflict.

The commercial airliner must have very high confidence in aircraft safety. The service environment for the aircraft will be relatively stable and well known. Conversely a military fighter jet needs every ounce of performance, and when used in anger will be pushed to the extremes and even beyond its service envelope.

Within an automotive environment there can be differences that will impact the durability process. If the end customer is a vehicle leasing company with a large fleet of vehicles they may agree to have on-board data acquisition in the vehicle during the service life of the vehicle. For the leasing company it enables them to exert some control over their leasing customers who abuse the vehicle, and for the manufacturers it is a source of valuable information about real customer usage.

However, a member of the general public who purchases their own vehicle is unlikely to agree to data acquisition from their vehicle, as it could be an infringement on their civil liberties. They may agree to it if, for example, this was a means to reduce their insurance premiums.

Product Development and Product Monitoring

A safe design product development philosophy aims to produce a product where no fatigue failures occur within its service life. In reality the service environment of the product forms part of a distribution of different customers. For example durability targets for non-safety critical components could be set to the 90th percentile customer. The durability target for safety critical components is then set to the 90th percentile of the non-safety critical distribution. This is illustrated in figure 15.This safe design philosophy is typically employed within the automotive, truck and agricultural industries.

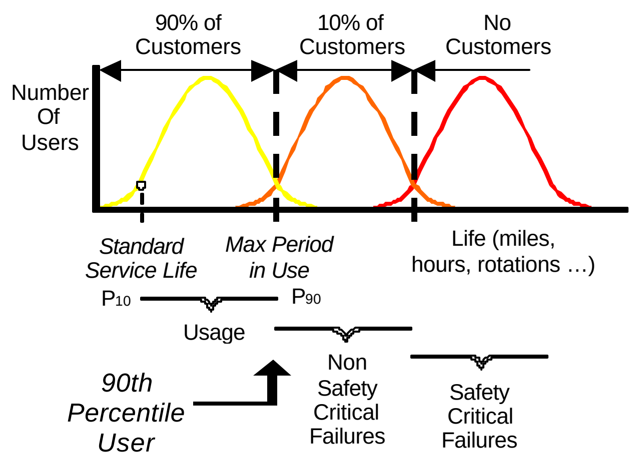

Figure 15. Durability Targets for 90th Percentile Customer.

Product monitoring aims to continually monitor the performance of the product and its service environment. From the results of this continuous feedback maintenance schedules are planned to exchange components that are nearing the end of their durability life. If the product experiences excessive conditions then immediate preventative maintenance action can be taken.

This philosophy is typically employed within rail and aerospace vehicle industries, and for large civil structures such as power stations and railway infrastructure.

Durability Targets and Other Performance Targets

This considers the importance of durability targets within the overall targets for the vehicle.

A good example of this can be seen when comparing the agricultural and automotive industries. The agricultural industry, especially tractors, is a good example where durability and reliability is the most important vehicle performance target. Within the automotive industry durability requirements are ranked below those of crash and NVH.

The effect of these different performance targets can be seen by how the durability process is different within these different industries. Within the automotive industry durability targets are mainly to reduce weight, which improves overall vehicle performance. They are not usually a customer driver; who will expect vehicles to last over 150,000 miles (a common sign off target). Leasing companies and new purchasers will have replaced with a newer vehicle long before then.

For automotive vehicles the primary performance criteria are (in priority order).

- Crash – must meet government regulations
- Noise Vibration Harshness (NVH) – to minimize noise within the vehicle
- Ride & Handling – driving feel and performance
- Durability – safety critical / non-critical components – reduce weight.

These performance criteria, and others, are also applicable to other vehicles, light trucks, heavy trucks, agricultural, etc. but their priority order is different corresponding to their different customer types and customer expectations.

Production Numbers

The number of vehicle or structures to be produced has a big effect on the durability process options available.

Off structures, for example, power generation plants, offshore platforms, space vehicles, etc. it is impractical to build full-scale prototype structures for development purposes.

Ground vehicle industries in general have high production numbers. The automotive industry is mass production, but relatively low value per unit. To achieve efficient manufacturing the industry employs highly automated production lines. Making changes to this production line are very expensive. To prevent this they invest considerable effort in product development to eliminate durability problems.

The railway and off-highway industries have much lower production runs but higher unit values. The production lines tend to be less automated, and tend to have more flexibility for late changes to be introduced. If an issue is identified in a current production model, their lower volumes also mean it is possible to stockpile vehicles and release them after retrofitting the solution.

Aircraft production falls some where between these two extremes. All aircraft fleets have at least one aircraft constantly in a test rig throughout the service life of the aircraft that always has more ‘flight time’ than any serving aircraft.

Manufacturing Methods

This shows the effect different manufacturing methods can have on the durability process.

A good example of this can be seen when comparing the agricultural and automotive industries.

During a consultancy project for an agricultural OEM, CAE durability techniques were used in parallel with the OEM using a test durability approach. There were two components being studied; a pivoting rear axle and the chassis frame. The rear axle was a rectangular tube fabricated from thick plate with pivot attachment and drops for the wheel spindles. For a single design iteration the OEM was able to build a prototype, apply strain gages, measure data and analyze this data faster than CAE techniques could be applied.

Even with the vehicle frame, a much larger fabricated structure, with a more complicated geometry. The CAE approach was only just as fast as their ability to build and test a new frame. However, the CAE approach did justify itself by identifying a small number of critical locations that were not found from testing.

The point of this example is that because these components were relatively simple fabrications it was possible to follow a test durability strategy quicker than a CAE durability strategy.

Within the automotive industry, when dealing with complex stamped and spot welded vehicle body structures, or cast/forged suspension components it is not possible to make something very quickly and test it.

It is the influence of manufacturing methods which goes part of the way to explaining why the automotive industry tends to follow a predominantly CAE durability strategy while the agricultural industry tends to follow a test durability strategy.

Test Durability and CAE Durability

Their definition and their place within a durability process have been discussed in some detail earlier.

A test durability philosophy is based on physical measurements and physical testing of components/products. Some form of test based durability, whether on the test rig or the proving ground, will always remain for final vehicle sign off.

This philosophy is typically dominant within Tier 2 and Tier 3 suppliers, who may have very little CAE durability capability. As OEM’s push more design responsibility to their suppliers then these lower level suppliers are having to increase both their test and CAE durability capabilities to meet the OEM’s requirements.

To implement a solely CAE durability strategy is very difficult. At some stage physical measurements are needed to input into a CAE durability process. This is the primary means of enabling multiple design options to be assessed and for progressive iteration of a design.

For ground vehicle industries this is seen as the means by which they can reduce development costs and timescales. For aerospace industries CAE durability may be the only option.

HOW DIFFERENT INDUSTRIES IMPLEMENT FATIGUE ANALYSIS WITHIN A DURABILITY PROCESS

The following assumes a very simplistic breakdown of industry sectors, and discusses how they consider durability. Out of necessity it has to make generalizations, and examples are used for illustration where possible.

It is noted that the appropriate tools used within a durability process are mostly driven by the engineering sector and what drives that sector. However at the component level it is the fatigue mechanism that drives the actual fatigue analysis methods used.

The following paragraphs illustrate this by means of a simple breakdown of industry sectors.

Static Structures

Predominantly use a product monitoring approach to ensure fatigue failure is not an issue during the service life of the structure.

Mobile Structures

Predominantly use a product development approach to ensure fatigue failure is not an issue during the service life of the structure.

Within mobile structures the main durability drivers will be considered for aircraft, ground vehicles, marine vessels and space vehicles.

Mobile Structures / Aircraft

Predominantly CAE durability during development. After product release make significant use of test durability with an aircraft constantly in a test rig throughout the service life of the aircraft which always has more “flight time” than any serving aircraft.

This sector is very heavily regulated, especially for civil aircraft.

Military aircraft are often fitted with a rudimentary ‘fatigue meter’ based on cumulative ‘g’ levels to record severity of maneuvers. The next generation of military aircraft are aiming to have a much more advanced form of “fatigue meter,” with many loads and strains being constantly measured and using on-board fatigue analysis software to calculate accumulated fatigue damage.

From a fatigue methods perspective aircraft can be divided into

- Fuselage (crack growth, rivets)
- Gas Turbine Engines (local strain crack initiation, high temperature, isothermal, creep, very specialized materials)
- Undercarriage (stress life, multiple mean stress)

Mobile Structures / Ground Vehicles

Off-highway vehicles (agricultural, construction and industrial) are predominantly test durability during development. This is mainly because of their manufacturing methods, where workshop fabrication of plate material enables a very quick ‘build it, test it, fix it’ iteration loop. CAE durability methods are being increasingly used to reduce development times for complex structures. The most important performance parameter for these vehicles is durability.

On-highway vehicles (automotive, light truck, heavy truck and buses) are evenly split between test durability and CAE durability. Prototypes are much more expensive to build, so far greater emphasis is placed on CAE durability. Final vehicle sign-off is still test based. The automotive industry is the most eager to take up a fully CAE durability approach and it is seen as the means to provide competitive advantage where weight reduction reduces cost and improves performance.

On-rails vehicles (locomotives, passenger and freight rolling stock) employ a combination of both CAE and test durability strategies during product development. However, during service they use a product monitoring approach to prevent fatigue failure during the life of the vehicle.

The service environments for these three vehicle types are significant and are very different. The on-rails vehicles have the most defined service environment; the major variables here are the vehicle speed and the surface condition of the rails themselves. The off-highway service environment is the most undefined, and any fatigue analysis must consider the many different abuse operations that can and will occur.

The on-highway service environment is somewhere between the other two. Luckily those vehicles traveling the most miles are those doing so under non-damaging smooth road conditions on a highway. However, high-speed smooth roads that are non-damaging for the vehicle suspension system can be very damaging for the engine and powertrain components.

Interestingly the recent advances in telecommunications for mobile data acquisition are likely to be first seen in off-highway and on-rails vehicles, though for different reasons.

To start with, much agricultural equipment, for example combine harvesters, already have equipment build into them to identify their location and map the yield within a field. Large and specialized off-highway vehicles are relatively expensive; the additional cost of an in-build data acquisition unit is small in comparison. The added value to the manufacturer and the end customer to be able to schedule preventative maintenance from a durability perspective when it is needed means reduced down time and greater equipment availability.

For on-rails vehicles the reasons include those for public safety for accident prevention, together with the ability to schedule preventative maintenance.

From a fatigue methods perspective ground based vehicles can be divided into

- Body (stress life based thin sheet spot welds and seam welds, residual stresses and thinning introduced during forming)
- Suspension (local strain crack initiation, uniaxial and multiaxial, elastomers)
- Chassis (local strain crack initiation, uniaxial and multiaxial, thick sheet seam welds)
- Reciprocating Engines (stress life, factor of safety, uniaxial and multiaxial, high temperature, isothermal)
- Exhaust (local strain crack initiation, uniaxial and multiaxial, high temperature, isothermal, corrosion, elastomers)
- Powertrain (local strain crack initiation, stress life, factor of safety, uniaxial and multiaxial)

Mobile Structures / Marine Vessels

These structures can be divided into marine shipping (merchant and Naval) and offshore platforms. In general fatigue and durability is not a major design criterion. They generally employ a product monitoring approach to prevent fatigue failure of critical systems. They have more in common with static structures such as power generation and chemical processing plants than they do with mobile structures.

The most important ships system is the prime mover (power pack), usually either a diesel electric or direct drive. These can be one third of the cost of the vessel, and the vessel is build around the power pack.

No one builds multi body dynamics models of ship structures. Finite element analysis is used for the overall structural integrity of a ships hull. Using static stress analysis and transient analysis of extreme wave conditions.

Merchant vessels have no commercial incentive to change. Weight is not an issue. For an 8,000 ton ship, the additional weight incurred to prevent fatigue by ‘making it bigger’ is negligible.

Naval vessels will consider durability if there is any prospect of fatigue failure reducing the combat effectiveness of the vessel. The primary design criteria for these vessels are redundancy of systems to retain combat ability.

The cruise liner industry follows the Naval strategy of redundant systems but for commercial reasons of a service industry.

Durability is becoming very important for offshore platforms. Many were originally built, in the 1970s, for a 25 year service life, and at the time fatigue was not the most important criterion. These platforms are nearing the end of their service life and are now seeking ‘life extension’ to 35 years. These require a detailed risk assessment, ultrasonic crack detection and fatigue based safety cases on all the welds.

From a fatigue methods perspective marine vessels can be divided into

- Large welded structures (crack growth)
- Engines (stress life, factor of safety, high temperature, isothermal)
- Processing Plant: Compressors, Purifiers (stress life)

Mobile Structures / Space Vehicles

Space vehicles (launchers, satellites, probes) are almost wholly CAE durability during development. After deployment there is very little opportunity to repair or maintain these structures. Everything must be designed to the target life of the whole vehicle. These structures make considerable use of multi body dynamics because there is no opportunity to perform physical measurements in service conditions.

CONCLUSIONS

This paper has described the need for durability assessment and presented an outline of basic fatigue analysis and durability process methodologies. It has discussed the application of these technologies to differing industries.

A clear distinction has been made between a fatigue analysis and a durability process.

The appropriate implementation of a durability process is necessary to develop a durable product.

Improvements in telecommunications and Internet access will help durability engineers predict when and where fatigue failures will occur. This will be through increased access to a larger quantity of long-term reduced data acquisition, to better characterize real customer usage.

Improvements in fatigue modeling techniques will improve the accuracy of a fatigue life prediction.

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REFERENCES

Bannantine, J.A., Comer, J.J. and Handrock, J.L. 1990. *Fundamentals of Metal Fatigue Analysis.* Prentice Hall Inc.

Fuchs, H.O. and Stephens, R.I. 1980. *Metal Fatigue in Engineering*. John Wiley & Sons.

Peterson, R.E. 1974. *Stress Concentration Factors.* John Wiley & Sons.