Using a common Test and Simulation environment to optimize the Durability Process and verify the results

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Abstract Manufacturers are under continuous and increasing pressure to reduce the "Time to Market" of new products while assuring a high reliability level of these products. Durability design and analysis is an essential element in achieving these objectives and involves a multi-disciplinary approach. In order to obtain rapid and realistic life predictions, Simulation and Testing should be used in synergy, each field bringing to the other the necessary information, making the durability process an integrated one. This paper reviews some modern durability management philosophies and the computer based tools available to meet the needs of design, test and development engineers. It also illustrates how the several steps involved by the whole durability process such as data acquisition, data processing, simulation & test validation can benefit from being integrated in a shared user environment.

1 INTRODUCTION

Durability refers in general to the resistance of a component or structure under several different damage mechanisms such as fatigue, wear, corrosion, creep, etc. It defines the ability of that component to survive its operating environment for a target duration.
However of all these failure mechanisms, fatigue accounts for the majority of in-service failures and the term durability will be used to describe mainly fatigue performance. It was traditionally evaluated late in the design cycle when a prototype was available for measurement & test, but nowadays simulation techniques allow investigating durability assessment and design options very soon before physical testing (Virtual Prototyping). This approach reduces development time and costs, by concentrating on only prevalidated designs.

Analytical techniques are available for load generation, stress state calculation, and fatigue analysis. These methods often rely on very complex models and need realistic measured test data as inputs and also for correlation purposes at each stage of the analysis process.

The diagram in figure 1 shows how analytical and physical approaches work in synergy in order to successfully analyse product performance. In this process, it is essential that numerical simulation techniques are employed at the earliest possible stage, so that the design can be developed, optimized and above all understood through analysis. Key elements in making reliable durability calculations, apart from the use of adequate models, is the accuracy of inputs such as: loads – measured, virtually derived or based on previous design - stresses induced by these loads on the structure and material behaviour laws – including manufacturing effects. Simulation allows sensitivity analyses to be conducted until an acceptable durability is obtained. These analysis loops give an insight to the predominant influencing factors and the distribution of fatigue lives.

In parallel to virtual analysis, physical tests are conducted in the field or laboratory. These tests provide the necessary information such as loads or materials data and allow correlation with simulation which is critical to ensure high confidence in the results. Due to the inherent scatter of the fatigue phenomenon and all possible sources of inaccuracy & variability, the physical test represents final validation of the design and is often time consuming. At this stage several test acceleration techniques may be applied in order to further optimize the process.

This paper reviews the main components of the durability process and the way they interact between each other. It also discusses how this process can benefit from an integrated approach in a common analysis interface.

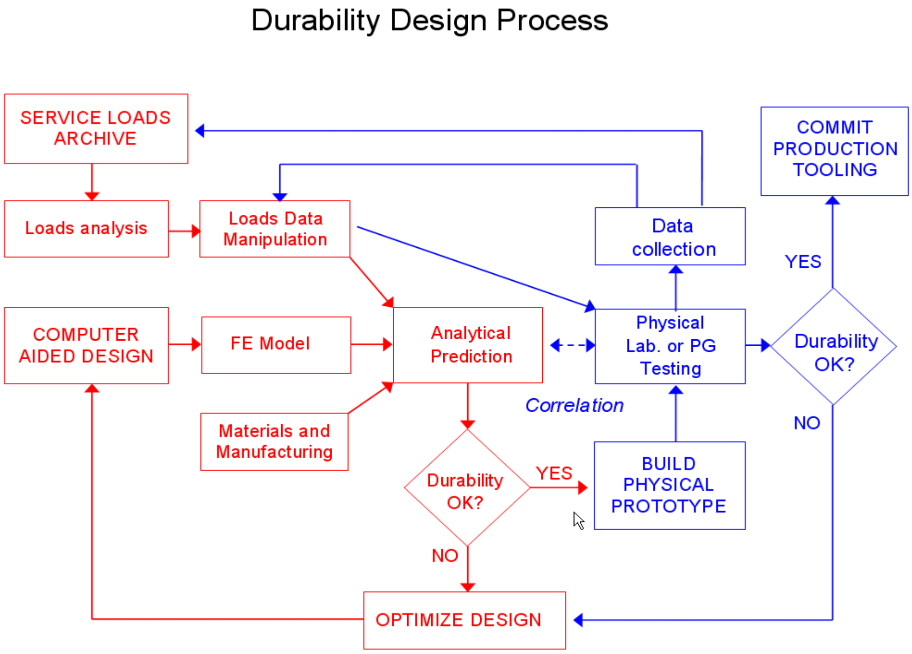


Figure 1. The Durability Design Process

2 OVERVIEW OF THE DURABILITY PROCESS

2.1 Load Data

Knowing the loads that a structure is experiencing in real conditions is not a trivial task and care should be taken when evaluating or measuring these loads so that they are representative of the in-service usage.

Physical loads can be obtained from in-service measurements using devices such as wheel force transducers, load cells, strain gauges, etc. from instrumented prototypes. It is the best source of data possible, but it requires long term records and many statistically representative samples.
The process can be accelerated by doing field (proving ground) or test rig measurements, taken over known events, with well established correlation to the real world.
To prevent any errors, it is essential that these measured loads are processed and validated before use in analytical models. This task could be very time-consuming and tedious as usually hundreds or thousands of measurement channels can be generated from a complete test campaign.

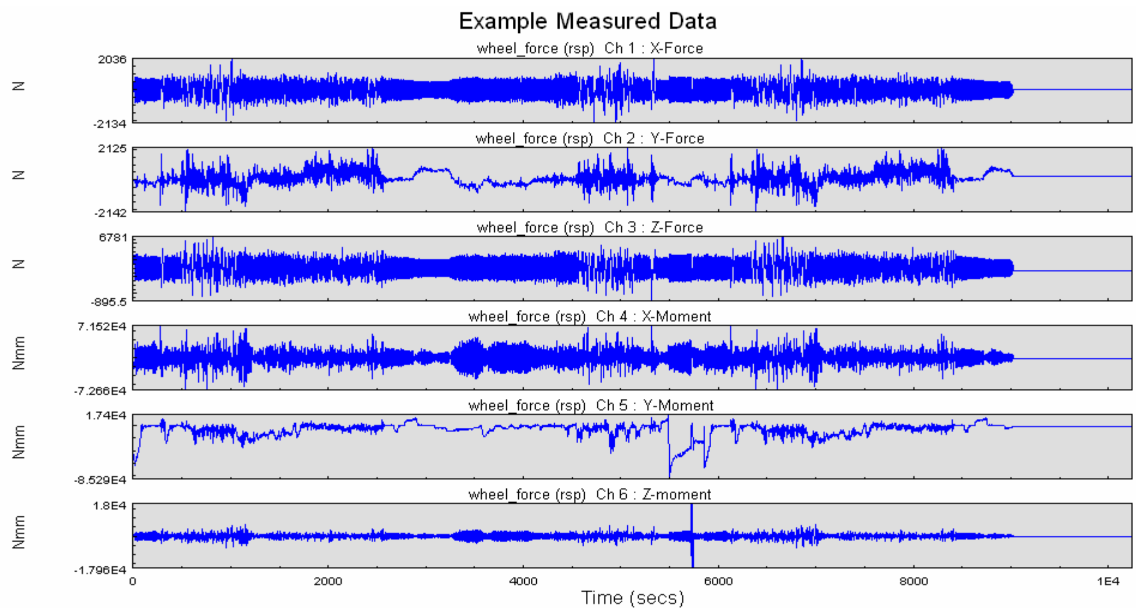
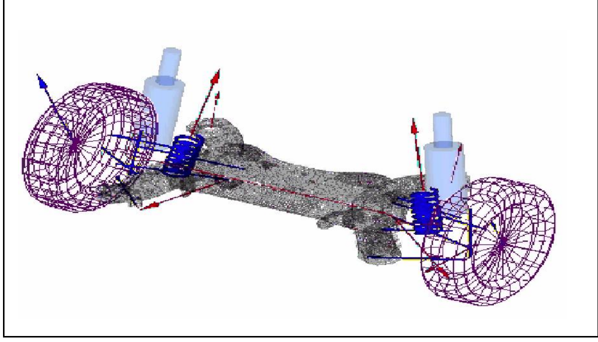


Figure 2. Example of real measured data

Virtual loads can be derived using Multibody Dynamics Simulation. MBS simulates mechanical systems to describe motion and interaction of kinematic assemblies of several parts, especially in a dynamic environment. It is used to determine the loading applied to a component given a system model and inputs. It acts as a transfer function, where external or system loads are the inputs and internal or component loads are the outputs. In order to eliminate prototype measurements, system inputs need to be derived from inputs that are independent of the design (example in the automotive industry could be road profile and driving conditions). System loads can also be actual loads, displacements, accelerations, etc (Ref.1).



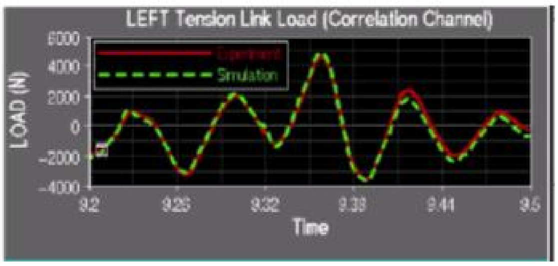


Figure 3. Virtual prototype of rear suspension

This approach is ideal for new breed product where no legacy data is available. However variable quality of data depends a lot on experience and model accuracy.

2.2 Stress - Strain Analysis

CAE based durability starts with the concept of a CAE model of the component or structure, which is then used to calculate the stress state due to the loading and boundary conditions.

Most common methods consist of applying each load case independently (often as a unit load) and using the principle of linear superposition, combining the loading histories and the Finite Elements analysis results, to obtain the local stress-strain time histories at each node or element.
This approach assumes a linear elastic behaviour of the component and material, and may be extended to include modest dynamic behaviour by Modal Superposition Method.
If significant dynamic effects are important, transient or random vibration analysis methods must be used. Transient analysis is performed in the time domain and proves to be computationally intensive, which generally restricts it to short discrete events. Random vibration analysis concerns the frequency domain, with loads being specified in terms of power spectral density functions. This form of analysis is relatively quick as it is based on a simple transfer function calculation.

All these methods can be used in conjunction of the fatigue analysis module.

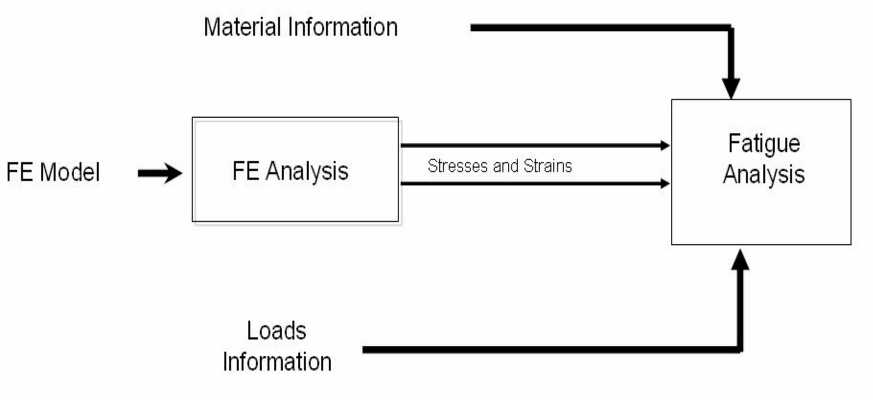


Figure 4. FE Analysis

2.3 Material Information

Another major input to any fatigue life estimation is a description of the material from which the component or structure has been manufactured.

Cyclic material properties are used to calculate stress-strain response and damage accumulation rate. The damage curves usually relate stress or stain amplitudes to life, or crack growth rate to stress intensity factor. The material parameters required depend on the fatigue modelling technique being used. They are usually obtained by specimen testing and may also be available in handbooks or specific literature.

It is worth nothing that due to the statistical nature of the fatigue phenomenon and the associated scatter, each damage curve requires an adequate number of specimens in order to capture the mean values and also their deviations. This information allows the damage curves to be defined in terms of certainty and bases the fatigue design on a minimized probability of failure.

Most of the important influencing factors on the fatigue life of a component, such as surface condition effects, mean stress, manufacturing processes and some geometric features are often modelled through modifications of the damage material curves.

Some empirical models such as those proposed by CETIM (Ref.2), Baumel Seeger (Ref.3), etc. allow deriving cyclic material properties from static ones. These models are approximations and helpful when no real data is available for A to B comparisons, but cannot be used in the scope of an absolute life prediction.

2.4 Virtual and Physical Life

2.4.1 Virtual Life

Depending on the stress-strain state complexity and operational environment of a component or structure, several fatigue analysis methods are available. Classical ones are: stress-life, strain-life, or linear elastic fracture mechanics. The appropriate analysis type depends on the material type and the proportion of the total fatigue life that is consumed in initiation and growth of a fatigue crack up to final failure.
For complex situations, involving phenomena such as non-proportional multiaxiality, thermo mechanical conditions, assemblies, more advanced models can be used.
It is mandatory to include in the analysis a variety of influencing factors such as mean stresses, notch effects, residual stresses, surface roughness and treatment, etc.
Details of the methods are beyond the scope of this paper; however more information is available in numerous publications including references 3 and 4.

The final result of an analysis is a fatigue life, number of repeats of the applied load time history until failure or a safety factor. The failure criterion is somewhat arbitrary and usually means formation of small, easily detectable crack.

Sensitivity analysis can then be carried out on load variability (result of variability in real usage), structure geometry (manufacturing issues) and material properties. These two last inputs are usually more precisely defined than the applied loads.

Figure 5 describes the necessary inputs to the fatigue analysis module and how these inputs are generated.

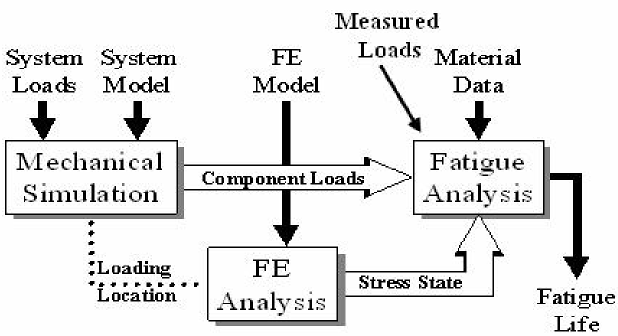


Figure 5. Fatigue simulation process

2.4.2 *Durability Test*

Test based durability starts with the development of a prototype from which physical loads can be measured. After data acquisition, signal processing and validation of the measurements is required in order to correct for any anomalies.

Durability tests consist of field or laboratory tests which should reproduce, in an accelerated way, the in-service or customer use of the product. They simulate life of systems, sub-systems or components and single point fatigue life calculations can be carried out (usually with a strain gauge or rosette) at a potential critical location.

Figure 6. Example durability tests

This part of the process is one of the most time-consuming and acceleration can be achieved by using fatigue editing techniques that reduce the loading time histories by removing the non damaging events.

Any data editing method must reduce the testing time in a technically valid, justifiable and repeatable manner. For the laboratory test to represent the in-service behaviour, it must reproduce the loading environment and the fatigue damage content of the original load data. This should ensure the duplication of the same failure modes and locations in the laboratory. Fatigue analysis can be used to mimic the fatigue life of the test before it is undertaken, to check that the edited drive signals still give a comparable fatigue life (in equivalent repeats of sequence) and to estimate the test duration reduction (Ref.5).

Some of the common test acceleration techniques available can be summarized as follows:

- Load amplification: consists of linearly scaling up the inputs and producing a failure at the same location in the component. This approach has to be used with caution as this is no longer the same test and previously non-damaging events in a random sequence become damaging. Peak loads can also cause static failure.
- Peak-Valley extraction: turning point extraction will typically reduce the number of points to reproduce in the test command by a factor of five to ten and is used when frequency is unimportant. It cannot be used in situations where resonance fatigue occurs or for materials sensitive to frequency (e.g., elastomers). Component durability tests can then be accelerated by replaying the reduced signals at a single cyclic frequency optimised to the test rig's capacity.
- Block load sequence: Rainflow cycle counting, whether by analysis of time series data or as an on-line data acquisition process results in a matrix of load blocs and during the classification process range gating can be used to remove small cycles. A histogram can be directly used as input to a fatigue analysis and inspection of cycles and corresponding damage histograms can reveal where to remove non-damaging cycles. Since typically only a small percentage of the cycles do all the damage, regeneration of a peak-valley drive file from an edited histogram can give very substantial speed increase factors to the point where impractical tests become practical. A major limitation is that these techniques only apply to single channel drive systems. The same comments apply here as for the peak-valley domain.
- Constant amplitude loading: constant amplitude equivalent loadings can be derived based on fatigue damage equivalence. The equivalent load is defined in terms of amplitude, mean and number of cycles. Also same comments apply here as for the peak-valley domain.

- Time correlated fatigue analysis: more rational techniques have been developed that can identify and remove time sections, from single or multi-channel rig drives, based on time-correlated damage. Each channel is divided into a number of damage time windows, which are marked for retention or deletion according to the editing criterion (e.g., the material test cut-off life). A logical OR operation across all the channels gives the list of windows to be retained. The corresponding windows from the original time series are then assembled, with joining functions added where necessary to ensure a smooth join from the end of one section of data to the start of the next section. This prevents the generation of artificial spikes or steps on any channel. The joining function must match the dynamics of the signal and the response capability of the test machine. This can address multiple inputs as well as multiple critical locations, and retains frequency effects.
- Mission profile and test synthesis: this technique is widely used when dealing with stochastic events that need to be reproduced on a shaker table or rig. It takes a mission profile consisting of time series with given repetitions and power spectral densities of given durations and constructs a single PSD or swept sine equivalent in terms of fatigue damage and shock response spectra to the duty mission. Test acceleration is made through setting of the synthesized PSD duration. This approach is described in details in the French military standard GAM EG-13 (Ref.6) and NATO AECTP 200 (Ref.7).

For all methods, the criterion for acceptance is that fatigue analysis before and after editing, shows the simulated test damage to be the same in each critical location. This is another example of where CAE can work with Test to compare the different loading systems (Full-Accelerated).

The physical life is considered to be the "real" answer and still constitutes the final validation of the design, even if it is often based on a single result!

2.4.3 Correlation

Correlations for both Test and CAE are critical to ensure high confidence in the results.

Field tests are correlated with the end customer or real usage of the structure. This needs some statistical or probabilistic measure of customer variations and patterns of usage, established through a combination of "fleet" measurements and extensive user surveys. Laboratory tests are often correlated with the field. This ensures that the target is realistic.

Any virtual simulation is dependent on the assumptions used to create the analytical model, and its environment. An important and mandatory step in the process is the correlation between the virtual model and the final validation tests. This aims to check the accuracy. It should be noted that correlation is not something that is just done at the end of the process, but rather at different stages of this process:

- Correlate virtual and measured loads
- Correlate calculated and measured responses (comparing for example strain gage measurements with virtual strains)
- Correlate virtual and physical life

3 ASSOCIATION OF CAE AND TEST BASED FATIGUE IN A COMMON USER ENVIRONMENT

Test helps numerical simulation in bringing realistic information in terms of loadings and materials. It helps to improve the analytical models, giving confirmation of local behaviour (displacement, strains, failure location…) and brings a reference physical life to correlate to.

CAE helps test by identifying locations to concentrate on for strain gauge positioning, for example, or simply by identifying hot spots on the component or structure. It can optimize the test schedule by eliminating unnecessary ones and can prove if the specified test is realistic and how long it should last.

Many software tools that deal specifically with either CAE fatigue or test fatigue are available. However greater benefits are achieved when using those that integrate both CAE and test in the same user environment. This integration is not trivial due to some barriers, a major one being the data files and formats. Effectively, several FE files from different packages have to be used, loading information may come from many hardware systems, and test rigs may need or generate different file formats. Moreover the amount of data to process quickly becomes very important and efficient processing and analysis algorithms are needed. While viewing the

information is always the first thing we are interested in, understanding this information and manipulating it in order to rapidly make decisions is the goal.
When achieved, this integration allows signal processing, test based fatigue and FE based fatigue analysis with the same tools in the same interface, which makes easier collaborative work and communication between test and simulation departments.

Figure 7 shows an example of a Test and CAE fatigue process in ICE-Flow GlyphWorks from nCode.

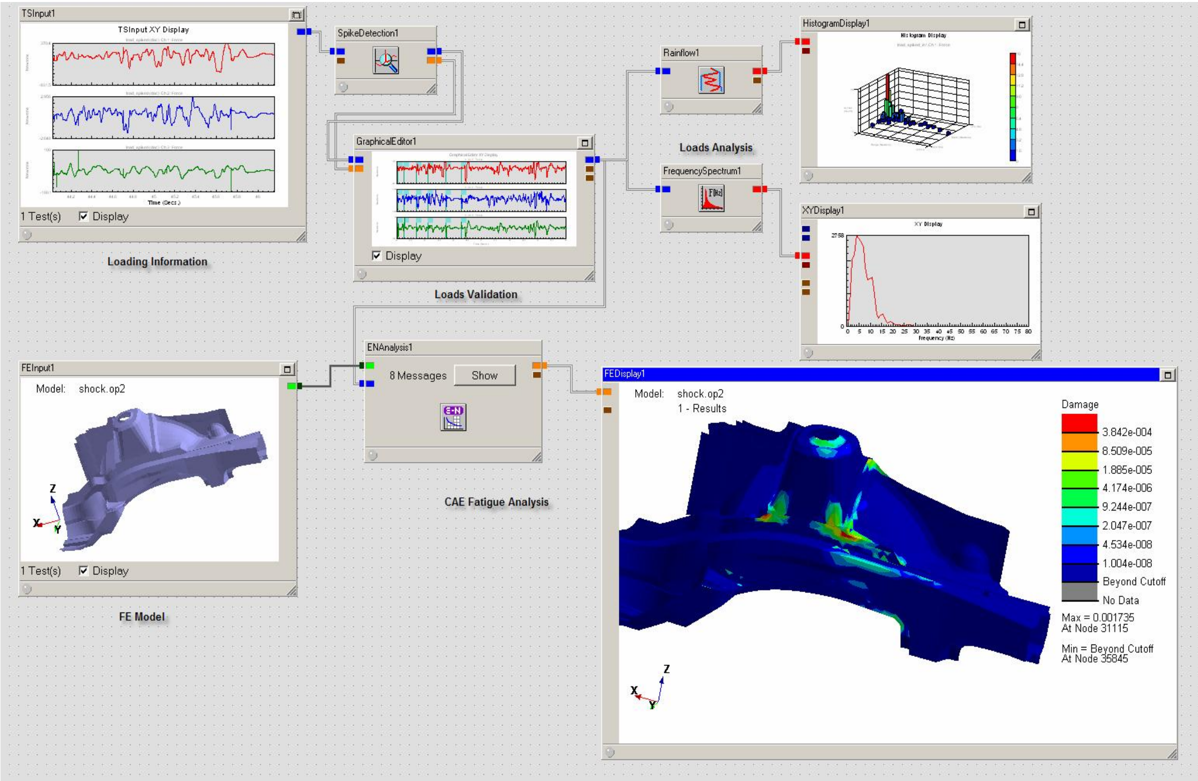


Figure 7. Test & CAE fatigue example analysis flow

4 CONCLUSIONS

CAE fatigue has advantages as it covers the whole component or structure and directly maps the results on the model. It can be used earlier in a project to assess several design options, in a controlled environment (no variations due to tolerances in manufacturing or material for example).

Test based fatigue has advantages too, as it validates the design and is often required for customer acceptance. Results implicitly include all complex factors that may not be possible to correctly account for in simulation (like non linear behaviour, residual stresses, micro-structure changes…).

Modern Durability Management techniques and software make a major contribution to both development time and costs. The ability to derive loads and stresses from Multi Body Dynamic and FE simulations for use in FE-based damage calculations greatly enhances the efficiency of early design investigations.

An integrated approach does not eliminate the need for prototype production and testing but, rather, allows efforts to be concentrated on analytically proven design options. Testing still remains important and brings necessary inputs at several steps of the simulation process. It allows verification, correlation and final product validation.

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