A ROBUST DURABILITY PROCESS FOR MILITARY GROUND VEHICLES

Nammalwar Purushothaman, PhD
Paramsothy Jayakumar, PhD
James Critchley, PhD
U.S. Combat Systems
BAE Systems
Troy, MI

Sandip Datta, PhD
Venkat Pisipati
TAC Worldwide for
BAE Systems
Troy, MI

ABSTRACT

BAE Systems has departed from traditional design rules of thumb and implemented a full-vehicle durability fatigue life analysis process at the design concept level to support lighter weight component designs. The durability process includes derivation of test duty cycles, generation of virtual loads from vehicle dynamic simulations, cascading of hundreds of channels of suspension attachment loads, and prediction of accumulated damage/fatigue life for both quasi-static and transient responses using a finite element vehicle structural model. The fatigue analysis process is typically deterministic, however the stochastic nature of the loads, material properties, and build variations should also be considered to ensure a robust durability process. The process is demonstrated on a heavy wheeled-vehicle platform using a generic duty cycle with examples shown at each stage of the process. This study additionally demonstrates the effects of variability of loads, materials, and geometry on the overall durability performance of the structure.

INTRODUCTION

Vehicle durability refers to the long term performance of a vehicle under the repetitive loading due to driving and other operating conditions. In normal operating conditions, tires and suspensions experience road loads and cascade throughout the vehicle body. The transfer and distribution of loads varies with the structural, inertial, and material attributes of the vehicle body and manifest as repetitive loads on the system and components. These repetitive loads cause fatigue damage and the accumulation of damage ultimately results in the initiation of cracks, crack propagation, and system or part failure. A design for durability process is a method of managing the accumulation of fatigue damage to prevent cracks from initiating in advance of the complete design life of the vehicle.

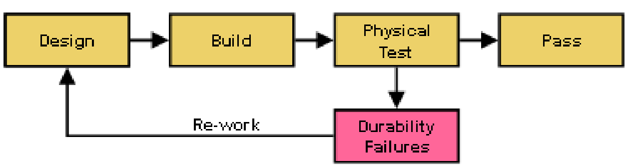

Figure 1: Historical build and test durability process.

The most basic durability process is shown in figure 1. The process involves testing a production ready vehicle for durability performance and reworking the design in the event of any failures. Depending on the variability of the end to end processes involved in the manufacturing and test of a vehicle, this method of verification requires tens of vehicles to establish reasonable confidence in the result. The process also introduces significant durability risk as any major structural durability issues are not identified until a design is mature enough for a build.

The common commercial automotive durability process is shown in figure 2. In this process prototype vehicles are instrumented to provide loads for structural durability simulations. These analytical simulations typically provide results concurrent with the preparation of a build ready design. Should analysis identify any issues then the design must be changed, prototyped, and measured as appropriate. In practice this process works quite well in the design of commercial automobiles because most vehicles have similarities in weight, geometry, suspension characteristics and operational capability with existing models and the risk of a significant durability issue is effectively mitigated by related design experience and large volumes of relevant test data. In this case the process effectively identifies all issues

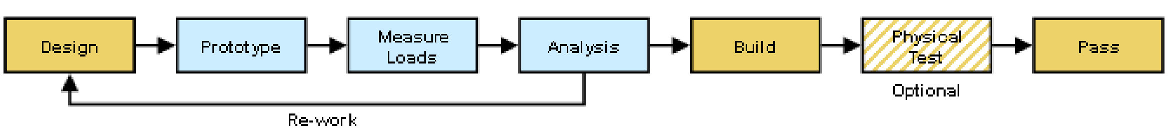

Figure 2: Prototype measurement and analysis based durability process.

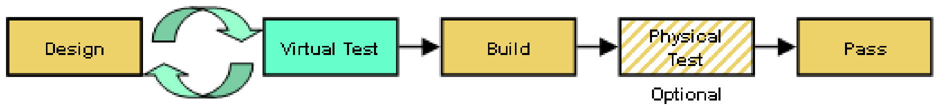

Figure 3: A virtual test durability process.

as minor fixes which are readily applied to production designs.

In contrast, it is common for each military ground vehicle program to define a new weight, geometry, suspension, and operational capability. When applying the process of figure 2 to these designs, the durability risk of the initial design is significant and following the process can result in the construction of many costly vehicle prototypes before a design is ready for build. To eliminate the need for multiple prototypes, the BAE Systems team has implemented a completely virtual test durability process as shown in figure 3 [1].

The virtual test environment is a one to one replacement of physical prototype measurements with completely virtual load evaluations and is enabled by the high confidence off-road mobility load predictions which have been performed by the BAE Systems U.S. Combat Systems organization for three decades. The virtual durability environment is constructed and maintained concurrent with the design to provide upfront durability assessments. Such analyses also enable structural and weight optimizations of design while ensuring a durable finished product which passes customer testing on the first attempt.

Some commercial automotive teams are also able to support up front durability considerations without a prototype measurement phase. The LMS Hybrid Road approach [2] is one such example which uses available test data to calculate an “effective road profile” from the measured motions and forces and defines a process for reapplying them to similar vehicles and generating loads. This method effectively supports the process of figure 3 for the design of most commercial passenger vehicles. However the approach to military ground vehicles must be different due to the absence of test data for neighboring vehicle solutions. LMS is currently promoting the virtual road loads method in an integrated package similar to that of [1] on their web site [3] for coupled multibody vehicle dynamics and durability evaluation.

The virtual durability process consists of five activities, duty cycle development, computation of vehicle dynamic behaviors and extraction of loads, pseudo damage evaluation, structural modeling, and fatigue life evaluation. It is important to note that the simulation of strength events, those events which are expected to cause immediate and perceptible damage to the vehicle, is also an important aspect of durability. Simulations of such discrete events are commonplace in today’s analysis environment and will not be discussed further. From this point on the terms fatigue and durability will be used interchangeably.

The following sections detail the activities which constitute a virtual evaluation of fatigue life for military ground vehicles and provides generic examples as appropriate. The variability of the entire fatigue process is then assessed including variations of testing conditions/loads, materials, and geometry.

DUTY CYCLE DEVELOPMENT

Commonly a vehicle Purchase Description (PD), Test Operating Procedures (TOP), and other explicit requirement documents can be used to determine the physical testing duty cycle which has been deemed equivalent to operational use and expected life. Duplicating the complete physical test duty cycle in a virtual environment allows physical test reports to be used as correlation for the virtual durability process and ultimately enables vehicle designs to pass life cycle testing on the first attempt. Establishing a high confidence in the virtual process also enables additional operational characteristics of low volume variant platforms to be verified virtually with high confidence.

The duty cycle of a military ground vehicle is usually characterized in an accelerated automotive duty cycle combined with other discrete operational events which are specific to a vehicle’s capability. The automotive duty cycle can be made up of any combination of smooth roads, secondary roads, rough roads such as washboards, potholes, bumps, trails, dry river beds, cross country terrain, and so forth. Test courses can be characterized as shown in figure 4 where roughness can be measured in terms of RMS.

A selection of common off road courses and events can be

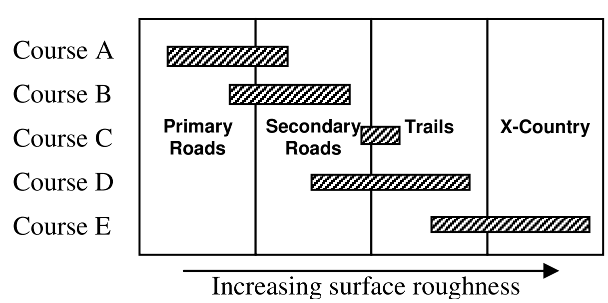

Figure 4: Characterization of terrains.

Test Procedure				Virtual Test	
course	length (miles)	cycles	total length	segment length	cycles
A	5	80	400	0.5	800
B	0.2	40	8	0.2	40
C	1	80	80	0.5	160
D	0.5	100	50	0.5	100
E	0.75	20	15	0.25	60

Table 1: A virtual duty cycle.

found at Nevada Automotive Test Center [4]. Most test courses and obstacles are maintained to specifications which are also available. Many courses are routinely measured by profilometer in which case a detailed digitized representation can be obtained.

Requirement documents further identify the operational specifications of the mission equipment which is usually adequate to construct additional duty cycle events. These events include turreted weapon operations, towing, plowing, recovery operations, and so forth which are expected to occur over the course of the product life.

The repetitive nature of durability testing enables a collection of relatively short virtual loads evaluations to be used to construct a complete virtual representation. Table 1 illustrates one such mapping where long segments of rough but regular roads are replaced with shorter representative segments and length multiplication factors. Additionally, for wheeled vehicle structures, it is also common practice to ignore the smooth road operation and focus on the off-road portions which are known to cause the majority of damage. Resonances which may occur and cause damage on mildly-rough road surfaces should be identified through modal analyses and eliminated from designs prior to complete duty cycle virtual testing. In the case of tracked vehicles, high speed operation of the track on hard surfaces can be a significant contributor to fatigue damage through the sprocket and idler attachments loads. Simulation of these surfaces should not be automatically removed from the duty cycle.

VEHICLE DYNAMIC AND EVENT LOADS

Road loads to be applied to the vehicle structure are obtained by driving a virtual multibody dynamic representation of a vehicle over digitized terrains and extracting the loads at the suspension attachment points (figure 5). Analogous to the prototype measurement procedure, over one hundred channels of dynamic and load data are required.

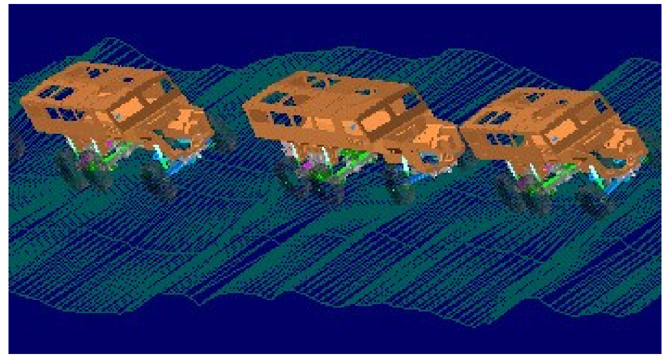

Figure 5: Off-road simulation.

Obtaining road load data which correlates to test data requires that virtual evaluations closely mimic the physical test which relies on a human driver. Some test areas have fixed speeds that drivers are required to maintain. However in other areas the test drivers are instructed to slow down when vehicle motions are overly jarring or when there is perceived instability. A driver is also required to control a vehicle's path through steering wheel input.

Six watts of absorbed power is the standard human fatigue limit for sustained operation of vehicles and machinery. The absorbed power can be computed directly from the hull motions (motions at driver and passenger seats) in the same way for both test and simulation. The suggested speed for each course is used and the absorbed power evaluated. The speed is then iteratively increased or decreased to obtain the driver threshold speed. The same iteration is performed for a specific G-load (acceleration) which most humans will slow down to avoid.

Stability can be assessed by increasing speed on terrain until vehicle rollover or inability to follow the path (washing out on turns, etc.) is obtained. A fixed fraction of the rollover speed is used to approximate a driver stability limit. The lower of the two driver speeds (ride comfort and stability) is used for durability evaluation and also serves as virtual evaluation of these requirements.

Many of the extreme off-road events are straight line courses. Differential left-right obstacle impacts which occur on terrain will cause uncontrolled vehicles to wander from the desired path. A proportional-integral-derivative (PID) type control is popular but typically requires custom tuning for each terrain segment and narrow speed range. These difficulties with PID control have led many to use constraints which are at best akin to trailer-ing or the direct application of explicit vehicle body forces to maintain the path. Such methods add fictitious forces to the body which invalidate the road loads. BAE Systems has implemented a simple control scheme which utilizes driver steering input to maintain accurate and robust path following [5].

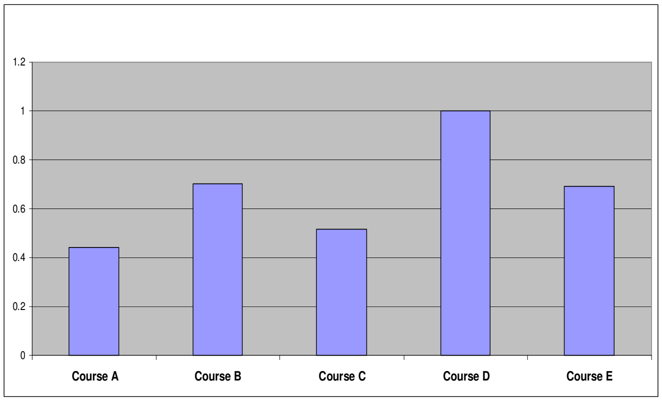

Figure 6: Pseudo damage example.

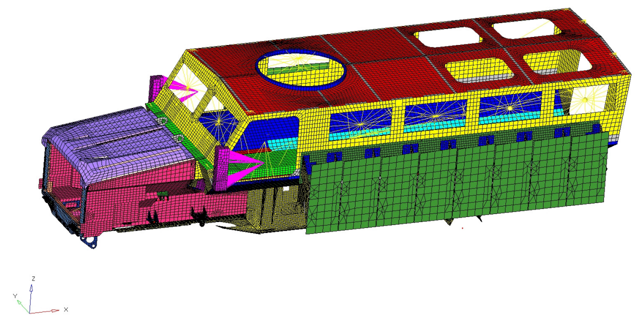

Figure 7: A vehicle system structural model.

Other transient event loads which may be applied to vehicle structure relate to machinery vibration, crew usage, transport, and the operation of mission equipment. Loads from vibrating machinery include the engine, transmission, and auxiliaries such as pumps and compressors. Crew usage includes standing, stepping, or jumping on all available interior and exterior features (hood, doors, fenders, steps, shelves, floor boards, etc.), the slamming of all doors, armored hatches, and compartments, and dropping heavy objects. Transportation loads relate to aircraft, ship, and rail operations. Part or all of a vehicle may be designed to be dropped from an aircraft, lifted by a crane, or, tied to a rail car, all of which have potential to experience large impulsive loads many times over the life of the vehicle.

The mission equipment induces loads which are specific to a vehicle's operational role. Any weapon events such as the firing large munitions, the rapid release medium caliber weapons, and quick slew to stop capabilities of large turret and gun inertias should all be considered for potential damage. Panic braking of tracked vehicles, ramming objects, personnel carrier ramp, winch, mine plow or roller system, and towing operations are common features in combat vehicles. Other utility vehicles also feature flat beds, booms, cranes, stabilizers, and additional capacity for equipment, fuel, or water. Each operational capability has specific design requirements which translate to physical events that should be evaluated to ensure reliability of the vehicle.

PSEUDO DAMAGE

The term pseudo damage refers to a relative measure of fatigue damage based only on the load data. The calculation uses a suitable strain life (ε-N) curve, rain-flow counting, and Miner's Rule. The result is a set of damage estimates for each portion of the duty cycle under consideration (as shown in figure 6). These metrics are used to screen out non-damaging portions of test data so that the set of fatigue input loads is smaller and more manageable.

In an analysis-driven design for durability process, a pseudo damage evaluation adds confidence and saves time. For example, it is common for suspension components to be tuned for both ride/handling dynamics and loads. In the case of ride/handling tuning the road loads change as a result of improvements for driver feel. These updated road loads can actually be of little consequence to the complete vehicle damage analysis. A pseudo damage calculation rather than a peak load comparison provides a reliable basis for fatigue estimates and improves work flow by eliminating a re-run of all structural damage analyses. On the other hand, the explicit objective of durability tuning is to decrease the current damage valuation and pseudo damage provides a rapid evaluation of relative damages for iterative tuning before submitting loads to the complete structural fatigue life model.

In a similar fashion the pseudo damage can be used in real-time to immediately evaluate the impact of a change in a vehicle program's mobility requirements.

STRUCTURAL MODELING

Fundamentally the modeling requirements for fatigue models are the same as for any other structural analysis model and any validated approach may be used. Added considerations for fatigue models focus on consistency and model run time.

Figure 7 shows a full vehicle structural model which is ready for durability analysis. Such a model is intended to capture the structural portions (the hull, passenger compartment, engine compartment, front and rear suspensions, etc.) using detailed structural elements and the non-structural components trim items (the hood, fenders, grill, bumper, doors, boxes, etc.) using concentrated mass elements with appropriate connections. This approach is required for early design verification of the support structure and serves as a baseline model to further predict the performance of any specific component or group of components by substituting detailed local component models into the full vehicle environment. In this way the system shown in figure 7 is actually configured to test a hood design in detail.

Shell elements are used throughout the hull where such assumptions are valid and solid models are used for the cast and forged components as found in the suspension and other areas. For computational efficiency all elements are modeled with linear shape functions. If loads are found to challenge the linear approximation of the stiff vehicle structure then either the load case is properly considered a strength event or redesign is required as high cycle nonlinear deformations will result in failure.

Special attention is given to the element quality at welded and bolted connection areas where crack initiation is expected to occur. An industry standard 5-7 mm mesh size is used for the critical areas of the structure and a progressively higher size is used away from the critical areas to manage model size and computation time. Solid parts are also given a coat of thin shells (of negligible stiffness) to obtain accurate surface stresses for the linear elements.

FATIGUE LIFE

There are two types of fatigue analyses in use for structural durability. The first is stress based or σ-N analysis which is applicable for low stress and high cycle fatigue. In vehicle systems this corresponds to loads from high speed rotating equipment such as the engine, transmissions, and auxiliaries. The second is strain based or ε-N analysis which is applicable for high stress, low cycle fatigue as from road loads and other transient loads. A process of integrating the strain based method is described here.

Typical operating loads can be broadly classified as quasi-static or dynamic, with quasi-static accounting for over 90% of all structural fatigue analysis. It is the dynamic/modal response of the vehicle or component under the given loading which determines whether the loading is to be treated as quasi-static or dynamic.

When the flexible modes of the structure are much greater than the dominant excitation frequency of the loads (3 to 4 times), it suffices to apply a quasi-static fatigue analysis. At the other extreme transient simulations must be used.

A dynamic load analysis may be required if the validity of the quasi-static assumption is in question. Typically modal fatigue analysis entails a significant cost penalty over quasi-static fatigue analysis and should be used only if the following conditions are satisfied:

i. The dominant mode of the structure is approximately equal to the dominant mode of the loading excitation.
ii. The damage of the structure under quasi-static fatigue analysis is significant.

The three frequency ranges («, ≈, ») and conditions for the modal/dynamic case can then be used to evaluate the proper structural models and generate the basis stress on the structure. The quasi-static method generates the six components of the stress tensor for each element under unit loading in each excitation degree of freedom. These stresses are scaled by the road loads to generate the stress tensor time history for each element.

For modal fatigue analysis, the modal stresses are generated from unit excitations for all modes up to a pre-determined maximum frequency of interest. This maximum frequency is typically 1.75 to 2.5 times the maximum excitation frequency of the loading.

For transient fatigue analysis a modal transient dynamic method is used to generate the basis stress tensors. Typically the transient loading is in short duration ranging from 80 msec to 2 seconds. The transient excitation is applied to the structure and the transient stress response is obtained for all elements of interest. An example of a transient excitation and dynamic stress response are shown in figures 8 and 9 respectively. These transient stress cycles are used for cycle counting and subsequent fatigue damage calculation.

Once the stress tensor is obtained for all elements under study, the fatigue process performas a linear superposition of

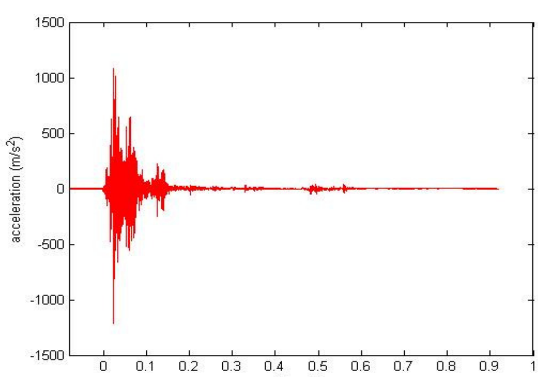

Figure 8: An example transient load.

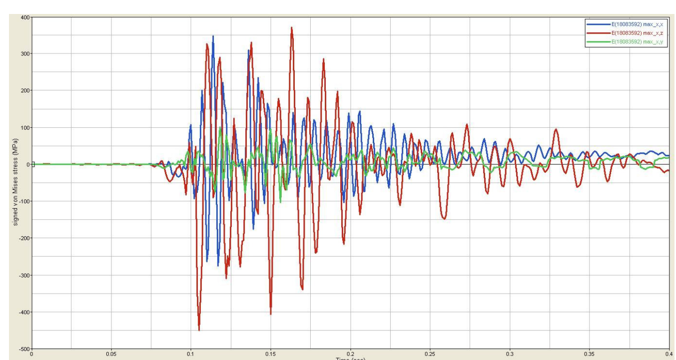

Figure 9: An example of transient stress response.

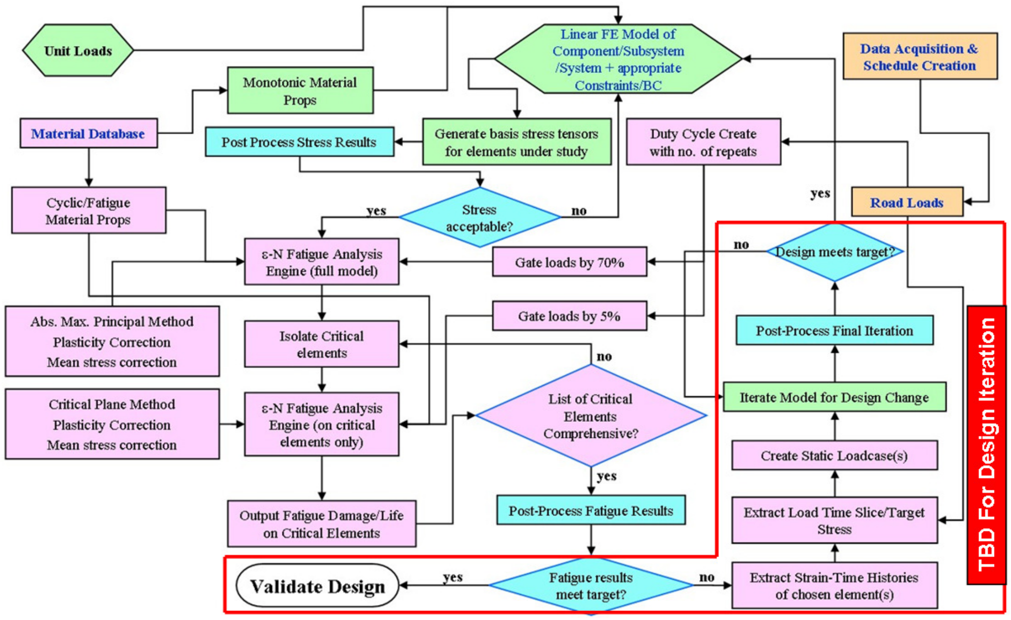

Figure 10: Fatigue life process.

all stress tensors for all excitation loading and obtains an overall stress time history for each element. Subsequently,

- The 3D stresses are projected on a 2D plane in a way that the stress on this plane is the maximum 2D stress (Critical Plane). The principal stress on this 2D plane is used for fatigue analysis. The critical plane is calculated for each element stress.
- Rainflow cycle counting is done on the cyclic stress to estimate the stress-range-mean-frequency histogram for fatigue analysis.
- Mean stress correction is used to eliminate any static bias in the cyclic stress.
- If the linear stress is beyond the yield stress of the material, a plasticity correction is used to calculate the actual (plastic) strain. The cyclic stress-stain curve for the material is used to estimate the actual cyclic strain on the elements. This strain is used to estimate the damage of the element for each strain-range and frequency of the cycle counted histograms.
- Miner's Rule is used for damage summation for all cycles.

The overall detail of the fatigue life process using quasi-static fatigue analysis is shown in the flowchart of figure 10.

THE DURABILITY PROCESS AND RELIABILITY

With each activity identified in the previous sections, the complete durability process can be assembled and summarized as shown in figure 11. Apart from the material test data, all aspects of the durability process are deterministic, meaning that the same output values will be obtained for each run of the same input. In reality the durability of a part or system is statistical in nature due to variations in loading, material properties, and component and system construction. Variations and the associated impact on fatigue life have been studied by many [6-8]. Agrawal et al. [6] and Wang et al. [8] have used Design of Experiments (DOE) methods to create a Response Surface Model (RSM) for fatigue life and applied Monte Carlo simulations to study the input variability effect. The nCode team [7] used Monte Carlo simulations automated through Isight software [9] to study separately the effect of load variations and material variations on fatigue life. The selected studies are all applications to automotive components in which measured road loads are assigned an assumed distribution without individually considering the

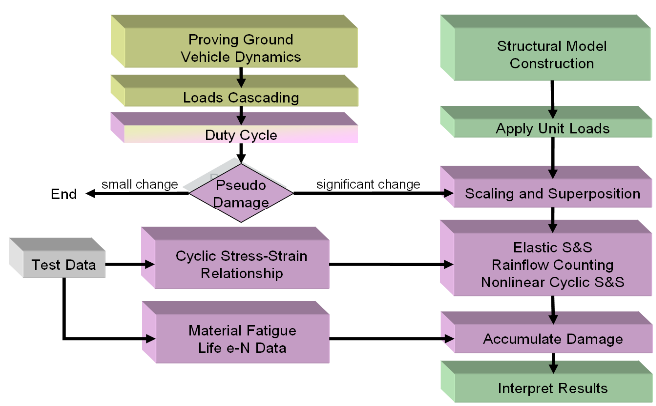

Figure 11: Durability process summary.

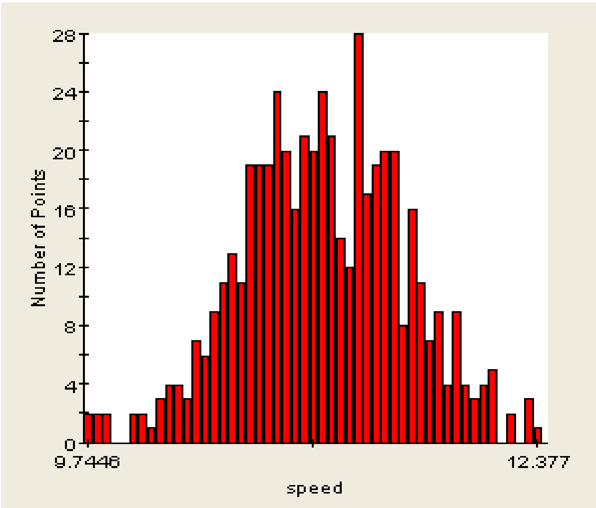

Figure 12: Wheel speed distribution (radians/sec).

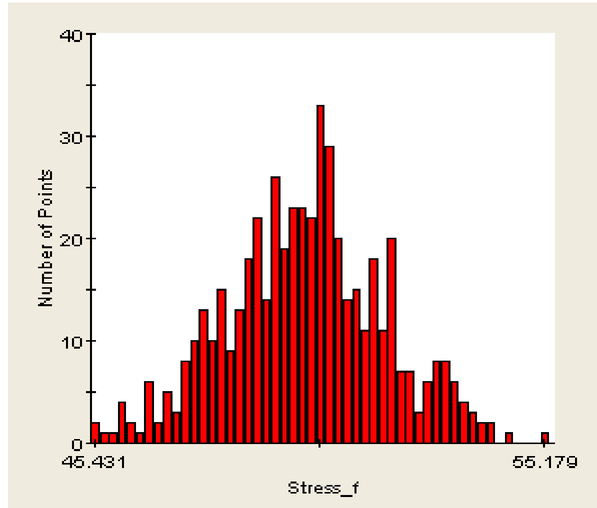

Figure 13: Material variation (%CoS).

variations in parameters such as the prototype and driving conditions effect on the load-time history distribution.

The study conducted by BAE Systems has taken a similar but refined approach to the statistical nature of the fatigue life of military ground vehicles. Instead of applying an assumed coefficient of variation to the load-time history, virtual load time histories for varying driving conditions are simulated and used for statistical fatigue life calculations. The objective is to extend the durability process outlined in the previous sections to the durability life certification of components with a known confidence. Such confidence is assessed by predicting fatigue scatter taking in to account the allowable design tolerance, material properties scatter, and the load time history variations due to driving conditions.

The process is demonstrated through an example of a stowage box attached to the side of a wheeled ground vehicle and the results are provided that identify the requirement for a 95% confidence target.

Load Variations

For this study, virtual load time histories are generated using DADS [10] for a single abbreviated proving ground course. The loads are cascaded as acceleration-time histories from the tire patch of the full vehicle model to the box attachments on the hull. Loads are sensitive to many factors with the dominant contributions coming from variability in the human driver for which a speed variability of ±2 mph is considered for this example. It should be noted that such speed variations will further result in path tracking (steering correction) variations and will effectively sample broader testing variations. The normal distribution of the speed as randomly generated by Monte Carlo simulation is shown in figure 12.

Material Variations

The material used was an Aluminum alloy selected from the nCode material library. Normally nCode strain or stress-life curves are set at 50% certainty of survival (%CoS) where 50% of tested specimens are predicted to fail. The Certainty of survival (%) allows statistical variations in material behavior to be taken into account [8]. The certainty of survival values are converted into a number of standard errors using a lookup table [11] and is used to adjust the cyclic stress-strain and strain-life curves. For this example, ±5%COS was considered. The normal distribution of the material variation generated by Monte Carlo simulation is shown in figure 13.

Geometry Variations

All vehicle component designs contain geometric tolerances to which manufacturers must adhere. In this case the thickness of the stowage box has been given as 3.175 ±0.125 mm. The normal distribution of the thickness generated by Monte Carlo is shown in figure 14.

Automated Reliability Process

Simulia Isight is used to automate and integrate the entire process and is shown in figure 15. Monte Carlo simulations are driven by Isight to generate various random variables for vehicle operating speed, %COS, and thickness.

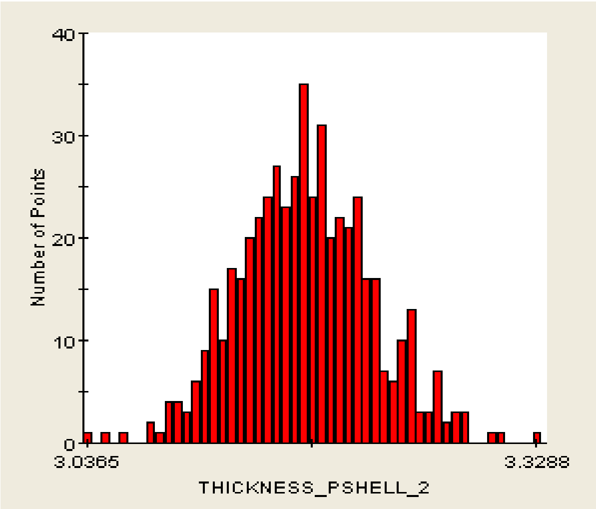

Figure 14: Thickness variation (mm).

After each set of random values are provided by the Monte Carlo engine, Isight automatically submits in order the DADS, NASTRAN, and nCode evaluations to provide a single fatigue life value. Isight has a standard NASTRAN component which takes the thickness variable and runs NASTRAN to provide an output file containing elemental stresses for unit loading. DADS and nCode have batch interfaces which are run by custom scripts. These scripts are executed by Isight through a component called Simcode.

For each operating speed value, DADS computes the load time history for the whole vehicle over terrain and provides cascaded stowage box attachment acceleration time histories. nCode takes these accelerations and time histories and the elemental stresses from NASTRAN and the %COS to compute the damage for all elements and writes out logarithmic life (log life) of the element with the lowest value.

RESULTS AND DISCUSSION

Five hundred Monte Carlo simulations were run on a single desktop computer overnight. The log life response probability distribution and cumulative distribution are shown in figures 16 and 17. The probability distribution of a log life is a normal distribution as expected. The mean life is 3.76 repeats of the given duty cycle with a standard deviation of 0.074. Values of life at three standard deviations above and below the mean are 6.27 and 2.25 respectively.

From the cumulative distribution, it can be interpreted that at 50% confidence the life is 3.76 repeats and at 95% confidence the life is 2.87. The ratio of 50% confidence value to 95% confidence value is 1.3 for this particular study. A factor of safety of 2 to 4 is the current automotive industry value being applied to the analytically predicted fatigue life to account for all variability.

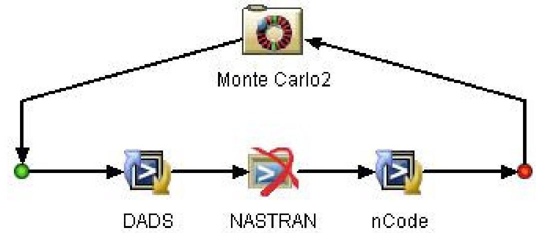

Figure 15: Isight process.

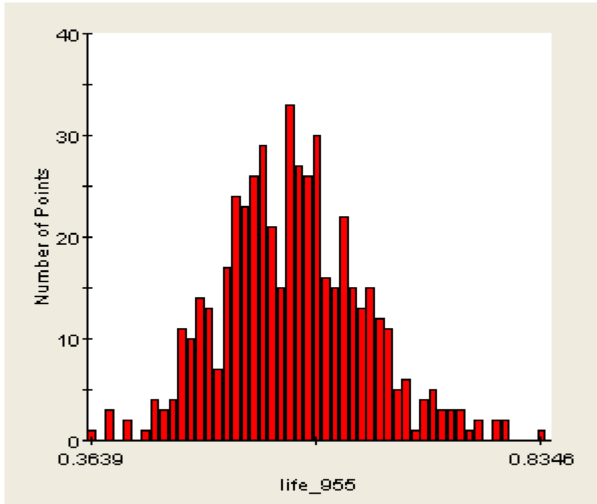

Figure 16: Log life probability distribution.

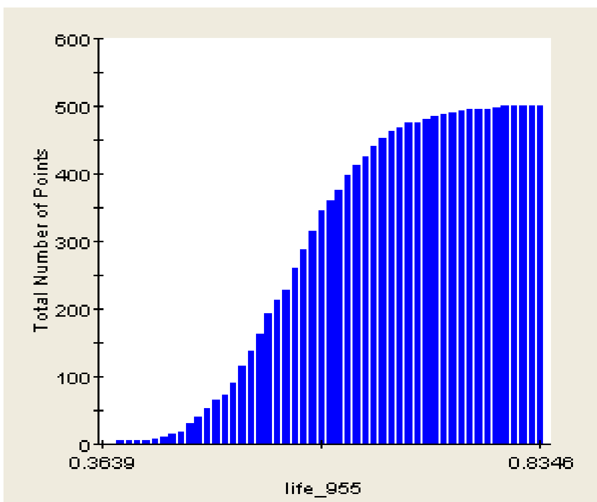

Figure 17: Log life cumulative distribution.

The effect of various factors has been shown in the Pareto chart of figure 18. The box thickness design tolerance, even though very small, has the most influence on fatigue life followed by the material properties. To influence the variations of fatigue life, larger speed variations or the

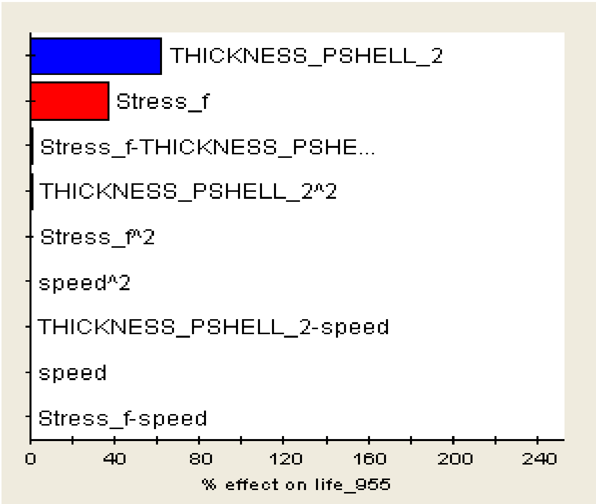

Figure 18: Pareto chart of influence on life.

complete suite of test courses may be required to affect a significant change in the magnitude of the loads seen on the hull structure. A more detailed study varying distributions of material, driving conditions, suspension parameters, and other effects will be pursued in the future.

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