

Durable Design and Maintenance of Military Vehicles -Crack Initiation and Crack Growth Applications

2011-01-1047

Published
04/12/2011Nammalwar Purushothaman, James Critchley, William Deporter and Michael McCullough
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doi:10.4271/2011-01-1047

ABSTRACT

The service life of a military ground vehicle is measured in decades and throughout its life it is expected to see several theaters with severe terrain and complex evolving operating conditions. The core of the vehicle, like the chassis and the hull, are often in continuous use, undergoing routine repair, reset, and re-fielding. Other components attached to the hull and chassis have more limited life spans and by design become damaged, worn-out, or outdated and are repaired, replaced, and/or upgraded. New components like armor, weapons, and sensor packages are frequently added to the existing structure for improved mission performance (survivability, lethality, etc.) as threats and strategies change. Designing military vehicles for durability is therefore very challenging and should not end when the product is designed, validated with hardware tests, manufactured, and sold. Changes in operational use, upgrade kits, and the overall growth of such vehicles mandates that the life of any such platform be continuously assessed by virtual methods to anticipate and mitigate failures. Surface and sub-surface defects induced during manufacture (and re-manufacture) in welds, forgings, and castings also pose significant challenges as these defects may grow rapidly under repeated operations resulting in ultimate failure of parts well before reaching the design life. To address the design and maintenance of military ground vehicles from cradle to grave, a comprehensive virtual durability process is presented which uses in-house tools and commercial software applications to predict crack initiation and crack growth. Application of this process to predict and extend the residual life of a fielded vehicle for different operating conditions, duty cycles, and vehicle configurations (additional weight) is demonstrated.

INTRODUCTION

Over the past decade completely virtual predictions of durability for ground vehicles have matured significantly. Durability analysis begins with loading and the commercial automotive companies have successfully developed the high fidelity vehicle dynamics models which provide simulated durability proving ground loads of sufficient quality to support predictive analysis [1]. The fatigue life durability process is then achieved by applying the loads (virtual or measured) to Finite Element Analysis (FEA) based fatigue methods and has been demonstrated to mitigate major risks during validation testing of hardware and minimize rework cost and time [2]. More precisely, durability prediction replaces the design-build-test-fix process with scientifically supported methods resulting in reliable designs that save millions of dollars in prototyping and warranty claims [3].

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 virtual durability process consists of several activities including, duty cycle development, computation of vehicle dynamic behaviors and extraction of loads, pseudo damage evaluation, structural modeling, fatigue life evaluation, crack initiation and propagation. 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.

More recently several defense contractors have applied similar virtual methods to enable rapid development of optimized ground combat vehicles [4][5]. While these advanced methods are often applied to evaluate failure modes of designs or to fix field failures, it is important to develop a comprehensive durability process specifically addressing the military customer's expectations. In other words, the durability process must address the unique aspects of the military vehicle product life cycle including design and development, production, test and validation, fielding, sustainment, and upgrades.

In what follows, the Department of Defense (DoD) acquisition model is briefly reviewed and aligned to a comprehensive durability support process assembled from several existing technologies. Each phase of the DoD process is then reviewed in the context of appropriate durability activities and supported by examples as appropriate. The benefits of the systematic deployment of durability throughout the life cycle are then summarized and next steps provided.

A COMPREHENSIVE DURABILITY PROCESS

The development and deployment of all military vehicles is subject to the Defense Acquisition Management System published by DoD in Instruction 5000.02 [5]. This process is summarized succinctly in [Figure 1](#). The management system contains five phases: Material Solution Analysis (MSA), Technology Development (TD), Engineering and Manufacturing Development (EMD), Production and Deployment (PD), and Operations and Support (OS). Further detail with respect to purpose, activities, milestones and deliverables for each phase can be found in the DoD Instruction. Defense contractors therefore align their internal life cycle management processes to the management system phases.

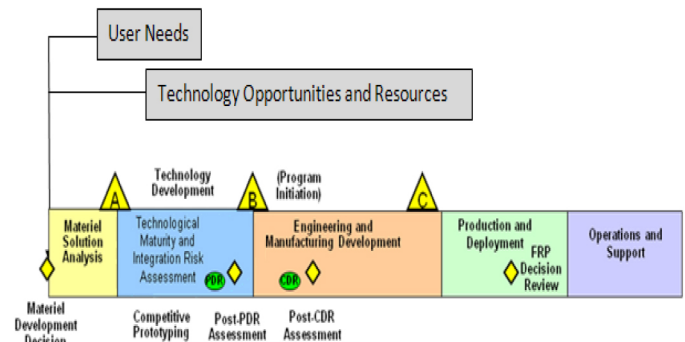


Figure 1. Defense Acquisition Management System

A comprehensive durability process should define the support of engineering teams throughout the program life cycle as shown in [Figure 2](#). The majority of the durability analysis is performed in the MSA, TD, and EMD phases to obtain optimized material solutions and mitigate risk of failure attributed to design and manufacturing. A design failure of a component or a structure is caused by its inadequate stiffness and material strength to withstand repeated loading for its expected service life. A manufacturing failure is caused by the residual stresses or surface cracks imparted to the part or weld joints by the manufacturing process that will reduce the component's ability to resist repeated loading. During PD phase, production issues such as lack of weld fusion, missed welds and surface cracks at the cast parts can be supported by the durability analyses and all the lessons learned and models should be archived for future use. In OS phase durability analysis responds to evolving operational environment conditions such as change of duty cycle, mission packages, structural upgrades and weight growth.

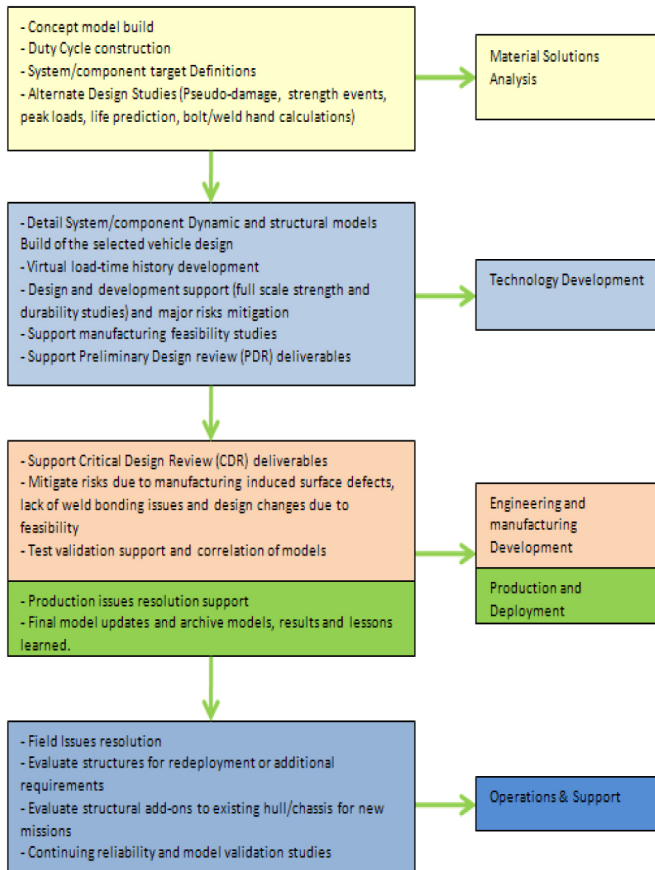


Figure 2. A Comprehensive Durability Process Mapping to DOD Life Cycle Management

MATERIAL SOLUTION ANALYSIS (MSA) PHASE

Several concept level tasks can be performed to support the MSA deliverables and prepare analysis support for subsequent life cycle phases. However, detailed durability analysis of the system or component is not generally possible due to the unavailability of detailed design information and measured load-time histories for early concepts. The durability process in the MSA phase consists of five activities, duty cycle development, defining durability targets, concept or surrogate model development, computation of vehicle dynamic behaviors and extraction of loads, and Analysis of Alternatives (AOA).

DUTY CYCLE DEVELOPMENT

The operational use of a military ground vehicle is usually characterized for validation purposes in an accelerated automotive duty cycle combined with other discrete 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 (washboards, potholes, and bumps), trails, dry river beds, cross country terrain, and

so forth. A selection of these and other common off-road and events can be found at Nevada Automotive Test Center [6]. The discrete events test a vehicle's operational features such as turreted weapon motions and firing, towing, plowing, recovery operations, and so forth which are also expected to occur over the life of the product. The durability duty cycle then specifies a number of repetitions for each event and miles and speed on each type of terrain.

The repetitive nature of durability testing enables the approximation of the complete virtual duty cycle using relatively short duration virtual loads evaluations. [Table 1](#) illustrates one such mapping where long segments of rough but regular roads are replaced with shorter representative segments and length multiplication factors.

Table 1. Virtual Duty Cycle

Test procedure				Virtual test	
Course	Length (miles)	Cycles	Total length	Segment length	Cycles
Primary Road	10	140	1400	0.5	2800
Secondary Road	5	100	500	0.4	1250
Cross Country Level	2	40	80	0.2	400
Cross Country Hill	1	40	40	0.2	200

It is also common practice for wheeled vehicle structural durability evaluations to ignore the smooth road operation and focus on the off-road portions which must 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.

DURABILITY TARGETS

Commonly a vehicle Purchase Description, Test Operating Procedures, and other explicit requirement documents supplied by the government customer can be used to determine the physical testing duty cycles which are deemed equivalent to operational use and expected life. The life target for a full system will usually be set to the total number of virtual duty cycles the vehicle has to undergo multiplied by a factor of safety. For example, given the duty cycles shown in [Table 1](#), the life target will be 4650 cycles or 2020 miles with a safety margin. This safety factor is included to account for the variability in loading, material properties, design tolerances and manufacturing. The factor of safety is usually obtained either by validating analyses results to a number of

hardware tests or from analysis based statistical studies. The first method of validating analytical results to hardware tests is very expensive, time consuming, and requires a well controlled test environment. Alternatively, statistical studies such as that shown in [Figure 3](#) are relatively quick, inexpensive, and are being used with increasing frequency [7] [8]. In the absence of either method, a factor of 1.5 to 4 may be applied to full level system quasi static analyses [1][7].

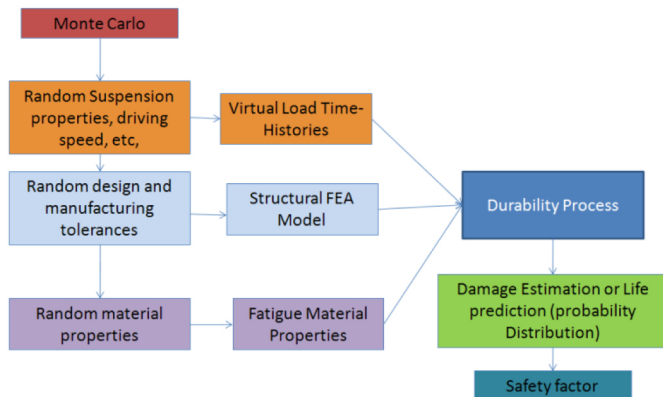


Figure 3. Analytical Variability Study

CONCEPT MODEL DEVELOPMENT

The concept model is usually derived from one or more existing platforms. This is possible whether the design is an update to an existing vehicle or entirely a new vehicle. One begins with existing nearest neighbor designs and morphs them to fit the concept vehicle dimensions. The model is then further refined by adding or deleting design elements and contents to match the new vehicle definition. First order suspension system properties are defined (spring, shock, and bushing responses) consistent with the desired mobility performance and a dynamics model can then be driven virtually over the duty cycle to obtain initial load targets. The variance of these loads should also be approximated by comparison with the quality of all prior conceptual estimates to fielded designs, paying particular attention to any nearest neighbor vehicles. These loads will be used for initial sizing of structural elements as well as to examine the trade space of design alternatives.

VIRTUAL LOADS GENERATION

Road loads to be applied to the vehicle structure are obtained by driving a virtual multibody dynamic representation of a concept vehicle over digitized terrains of representative lengths ([Figure 4](#)). Analogous to physical prototype measurement procedures, over one hundred channels of acceleration and load data are collected at the spindles and suspension attachments. Obtaining road load data which correlates to test data requires that virtual evaluations closely mimic the physical test which relies on a human driver. To obtain appropriate loads path following steering control must

be implemented through steering wheel input and for which any number of controllers are possible [10]. For speed control, some test areas have fixed speeds that drivers are required to maintain, while in other areas the test drivers are instructed to slow down when vehicle motions are overly jarring or when there is perceived instability.

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 of 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 of 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.

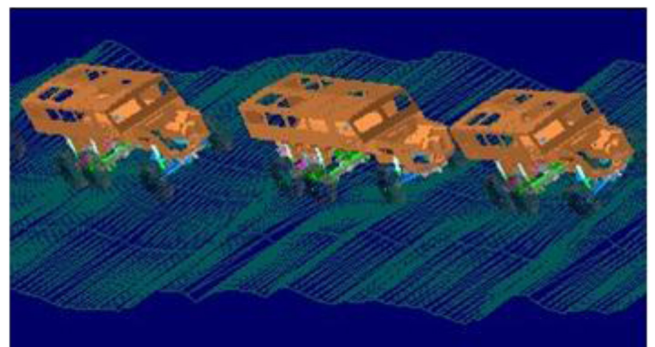


Figure 4. Off-road Simulation

ANALYSIS OF ALTERNATIVES

In the concept phase, several design ideas can be compared in terms of performance, cost, and weight. Designs may be entirely new, taken from company catalog/archives, or from supplier databases. Each must consider durability