BENEFITS OF HIGH PERFORMANCE COMPUTING IN THE DESIGN OF LIGHTWEIGHT ARMY VEHICLE COMPONENTS

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ABSTRACT

The insertion of lightweight composite materials in the applications of military vehicle chassis components has the potential of significantly reducing vehicle weight and improves its durability, life, and reliability. The use of hybrid material (composites wrapped over metal) in a double A-Arm suspension of a HMMWV resulted in a weight reduction of 33% as compared to that made from all steel construction. The shapes of the hybrid composite control arms were tailored to produce stiffness that is at least equivalent to the one obtained from a unit made from all steel construction. The double A-Arm unit was evaluated for reliability and durability under static and fatigue loading. With optimization and use of hybrid material, the static ultimate load and fatigue life were improved by 1.2 and 1.75 times, respectively, as compared to all steel design. The redesign required repeated progressive failure analysis (PFA) evaluations to determine load limits coupled with optimization. In addition to performing robust design of the suspension unit with advanced hybrid composites materials, benefits from high performance computing (HPC) with respect to run time reduction were evaluated. It was concluded that HPC can reduce the run time for PFA by more than 50% only for structures requiring the use of large finite element (FE) models (larger than 100,000 elements).

1. INTRODUCTION

Composite materials have found many applications as advanced engineering materials due to their lightweight, relative low cost, and the evolution of automated composite material/structure fabrication processes. Composite materials are being effectively employed in the manufacture of aircraft, automobiles, transportation systems, infrastructures, and power plants. This trend is intensifying with the development of new constituent materials and fiber reinforcement configurations. In particular, fiber reinforced composites are becoming increasingly more cost effective for applications in aerospace and automotive components. The safety and reliability of composite systems are dependent on the composite constituents, their configuration and application in a system design.

Weight reduction of military vehicles is a key focus for the US Army. The addition of armor tended to make the vehicles heavier. This resulted in more frequent breakdowns, increased fuel consumption, and a shorter vehicle life span. The use of advanced composites will remedy some of these problems specifically with respect to weight reduction and improved survivability in harsh environments. The Defense Advanced Research Projects Agency (DARPA) provided funding for High Performance Computing (HPC) pilot project to explore chassis weight reduction for military vehicles (HMMWV). With the advent of super computing, the automotive industry can exploit accurately these advanced materials to their maximum potential. The work presented here leveraged HPC to provide robust design capability of complex automotive structures by applying coupled durability-reliability-optimization solution to use light weight materials in components of military vehicles.

The authors assessed using HPC weight, durability, and fatigue life benefits as a result of using lightweight glass and carbon based polymer composites in suspension unit of a HMMWV. Multi-scale finite element based PFA (Abdi, 2005) is integrated with probabilistic and optimization methods to assess durability and damage tolerance (D&DT), life, and reliability of vehicle components in an HPC environment. The methodology, integrated in the engineering analysis software, characterizes any fiber reinforced laminates configuration (e.g. tape, 2/3D braided and woven laminates) to identify root cause for damage and failure in the composite. PFA is a Virtual Testing (VT) process that uses an iterative finite element analysis approach to predict and track the critical damage events: initiation, progression and the final residual strength. The stresses and strains on micro level are calculated through a mechanics-of-material-approach from the finite element (FE) results of the macro-mechanical analysis. Degradation due to damage on micro level is reverse engineered to obtain their effect on the macro level. This analysis is performed progressively to track all damage events.

Under this effort, the suspension unit was first evaluated under static and fatigue spectrum loading for current state of the art all metallic steel construction. Then it was re-evaluated under the same loading conditions for hybrid composite construction (80%

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composite and 20% steel), and all polymer composites construction. The shape of the upper and lower control arms had to be tailored to meet stiffness and frequency requirements. Finite element analysis (FEA) engine within the PFA environment used MPI (Message Passing Interface) parallel computing. It was designed for high performance on both massively parallel machines and on workstation clusters. PFA thru the FEA solver is capable of distributing the job on several CPUs.

This paper is divided into two parts. The first is a structural durability evaluation of metallic and hybrid composite double A-Arm suspension unit (Figure 1). It is preceded by a description of progressive failure analysis principles. The second part describes the benefits of HPC in the durability and design of structural components made from lightweight materials requiring intense computational operations. The ultimate objective of the work presented here is take advantage of high power computing to deliver a design that is effective, robust, and light in weight. It must be reliable for operation in all topographical terrains such as rocks, sand, paved roads, and even shallow waters and different weather conditions such as cold, warm and humid conditions. PFA is described next followed by results from design optimization coupled with progressive failure analysis.

Fig. 1. Schematic of the double A-Arm suspension of HMMWV

2. DESCRIPTION OF PROGRESSIVE FAILURE ANALYSIS (PFA)

PFA takes a full-scale finite element model and accounts for the average material failure at the microscopic level. Material properties are updated for all iterations, reflecting any changes resulting from damage or crack propagation. PFA's hierarchical approach (Figure 2) allows integration of a wide range of specialized programs, from micro to macro, into an existing verified progressive failure (Abdi, 2005) and probabilistic analysis tool (Shiao, 1993 and Abumeri, 2007). This makes it possible to accomplish synthesis of a variety of composite materials and structures based on progressive failure analysis and virtual testing to predict structure/component safety based on the physics and micro/macro mechanics of materials, manufacturing processes, available data, and service environments. This approach takes progressive damage and fracture processes into account and accurately assesses reliability and durability by predicting failure initiation and progression based on constituent material properties.

The life prediction code integrates: (a) finite element structural analysis, (b) micro-mechanics, and fracture mechanics options, (c) damage progression tracking, (d) probabilistic risk assessment, (e) minimum damage design optimization, and (f) material characterization codes to scale up the effects of local damage mechanisms to the structure level to evaluate overall structural performance and integrity.

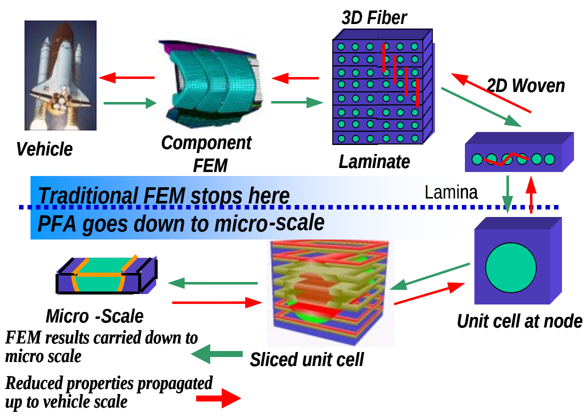


Fig. 2. Hierarchical distribution of damage, stress, and strain from the macro to micro mechanical level

A significant advantage of using a life prediction tool in the durability and damage tolerance is that the number of experimental tests at the component and substructure levels can be substantially reduced and experimental testing that is done can be made more efficient and effective. The damage progression module relies on a metals/composite mechanics code for metals/composite micro-mechanics (Chamis,1983), macro-mechanics, laminate analysis, as well as cyclic loading durability analysis. The same module calls a finite element analysis using anisotropic thick shell elements to model metals or laminated composites. This capability predicts the loads where damage initiates and propagates, all the way to structural fracture. These failure criteria are given in Table 1. The first 9 criteria are stress limits computed by the micromechanical equations based on a material's constituent stiffness and strength values. In addition to the 9 failure criteria based on stress limits, interply delamination due to relative rotation of plies and modified distortion energy (MDE) failure criterion that takes into account combined stresses, are considered.

If a failure criterion indicates failure of a lamina, then the mathematically modeled properties of the lamina are changed according to a mathematical sub-model of degradation of the affected material properties. When this happens, the initial nonlinear solution no longer corresponds to an equilibrium state. It becomes necessary to re-establish equilibrium, using the modified lamina properties for the failed lamina while maintaining the current load level. This iterative process of obtaining nonlinear equilibrium solutions each time a local material sub-model is modified is continued until no additional lamina failures are detected. However, because in this progressive failure methodology, small load step sizes are used the need for a second iterative process over the small step could be eliminated in obtaining equilibrium solutions. The load is incremented and the foregoing analysis repeated until catastrophic failure of the structure is detected.

Table 1. Failure modes considered in PFA

Mode	Description
Longitudinal Tensile	Fiber tensile strength and the fiber volume ratio.
Longitudinal Compressive	1. Rule of mixtures based on fiber compressive strength and fiber volume ratio 2. Fiber microbuckling based on matrix shear modulus and fiber volume ratio, and 3. Compressive shear failure or kink band formation that is mainly based on ply intralaminar shear strength and matrix tensile strength.
Transverse Tensile	Matrix modulus, matrix tensile strength, and fiber volume ratio.
Transverse Compressive	Matrix compressive strength, matrix modulus, and fiber volume ratio.
Normal Tensile	Plies are separating due to normal tension
Normal Compressive	Due to very high surface pressure
In Plane Shear	Failure due to in plane shear with reference to laminate coordinates
Transverse Normal Shear	Shear Failure due to shear stress acting on transverse cross section oriented in normal direction of the ply
Longitudinal Normal Shear	Shear Failure due to shear stress acting on longitudinal cross section oriented in a normal direction of the ply
Modified Distortion Energy Criterion	Modified from Distortion Energy combined stress failure criteria used for anisotropic materials
Relative Rotation Criterion	Considers failure if the adjacent plies rotate excessively with respect to one another

3. DESIGN OF HYBRID COMPOSITES DOUBLE A-ARM SUSPENSION UNIT

The finite element model considered in progressive failure analysis of the double A-Arm suspension unit is presented in Figure 3. Arrows in the figure indicates the location of applied loading while the triangle indicates location of constraints applied. The bushings are assumed to be attached to the frames of the vehicle while the spindle, spring seat and tie rod are loaded. The model size consisted of 92214 elements and 67293 nodes. Sell elements are used in the upper and lower control arms while solid elements are used in the spindle. Typical loads applied are presented in Figure 4.

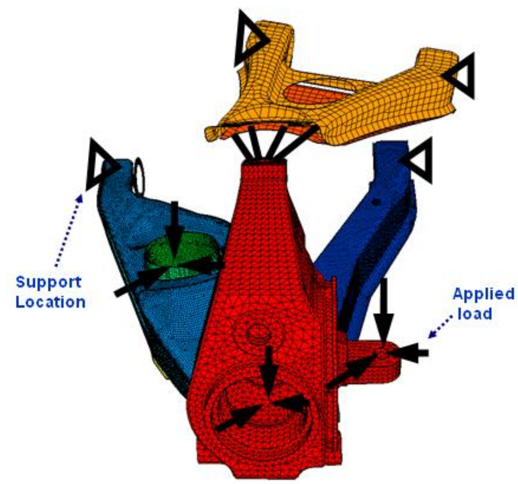


Fig. 3. Finite element model used in progressive failure analysis of the Double A-Arm suspension unit

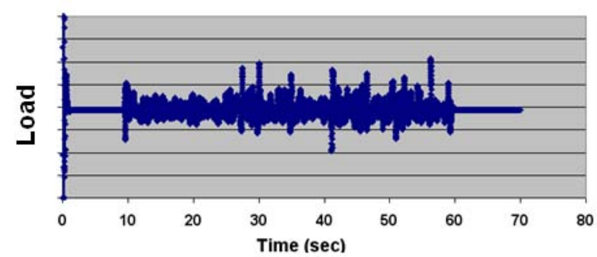


Fig. 4. Typical loads applied to the suspension unit

Existing design of the suspension unit uses all metallic steel construction (SAE 950X Steel). The suspension unit was evaluated for durability and damage tolerance under increased static loading and fatigue cycles. The objective was to determine failure modes, failure locations, and ultimate loads and cycles to failure. The analysis was repeated twice: (1) with all hybrid composite construction consisting of 20% steel and 80% carbon fiber reinforced polymer composites and (2) 100% all carbon fiber composites.

For the considered loading and boundary conditions, the steel suspension unit fractured when the static load applied reached 4.05 times the initial load for a given terrain condition. As shown in Figure 5, the suspension unit was damaged in the joint areas in the lower and upper control arms. The fracture modes were caused tensile and shear strains. As for the fatigue life analysis, the suspension unit experienced similar damage pattern at about 40,000 blocks of loading cycles.

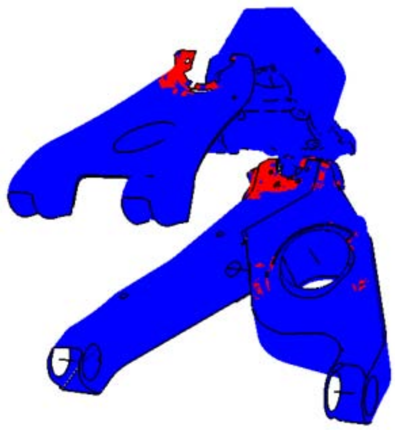


Fig. 5. Structural damage in the suspension unit for all steel construction (red color indicates damaged elements)

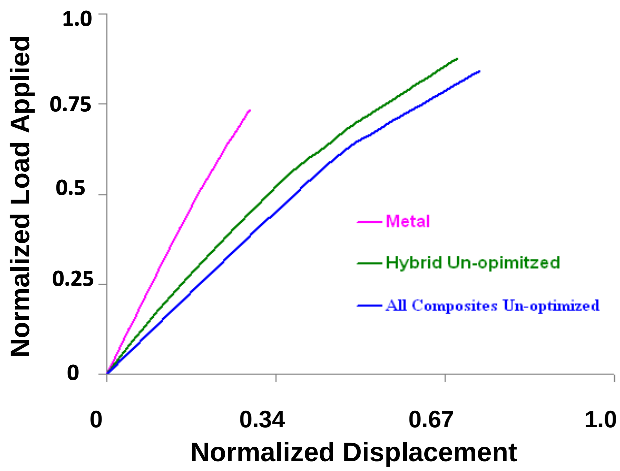


Fig. 6. Load displacement relationship for all metallic, hybrid, and all composites construction

The durability analysis was repeated with PFA for hybrid construction and all composites construction as well. The normalized load displacements are presented in Figure 6. The introduction of composites leads to a reduction in stiffness as compared to that of original design.

Figures 7-a and 7-b show, respectively, the structural damage in the upper control arm and in the suspension unit at the ultimate load. The composite material contributing failure modes are: fiber tensile and compressive failure, matrix damage in tension, compression, and shear, and out of plane delamination. As for the steel layers, the dominant failure modes were caused by tensile and shear strains.

Shape optimization was used to tailor the steel and composite thickness as needed and redistribute the mass where the loads are applied to increase the stiffness. Optimization was done on the hybrid composite and all composites suspension unit.

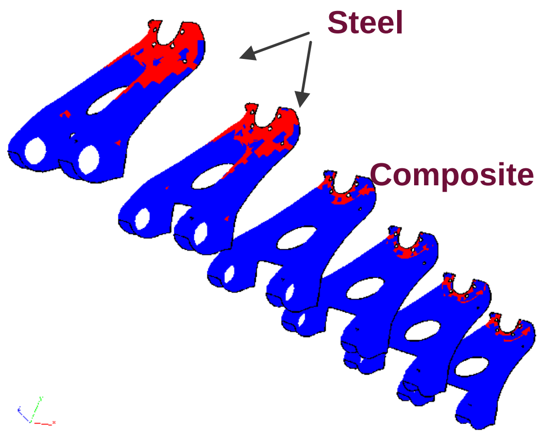


Fig. 7-a Structural damage (marked in red) at ultimate load in steel and composite layers of the hybrid upper control arm

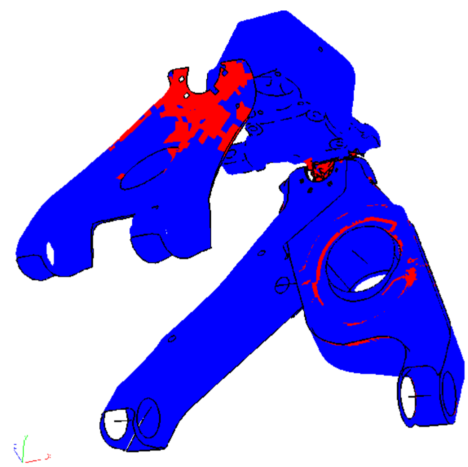


Fig. 7-b Overall structural damage (marked in red) at ultimate load in the hybrid suspension unit

The use of composites was only considered in the upper and lower control arms of the suspension unit where remaining components were considered to retain the original material (steel). The flow chart for the optimization process is shown in Figure 8. The optimization design objective function was set to minimize the weight of the structure. The set of optimization design variables included the layer or ply thickness and fiber orientation. The design constraints included maximum and minimum deflection (stiffness) and strength/failure index. Optimization changes both the amount of steel and composite (via thickness) to produce at optimum maximum displacement that is equal or lower than that of the original construction. Another important constraint during the weight minimization process was to make sure the composite failure index is less than 1.0 (greater than one would produce first ply failure). As indicated in Table 2, after optimization, the stiffness obtained with hybrid composites is 25% higher than the one from all steel construction. Also, the composite failure index is reduced from 2.0 to 0.9 at optimum. The overall weight was reduced with optimization from one unit to 0.67.

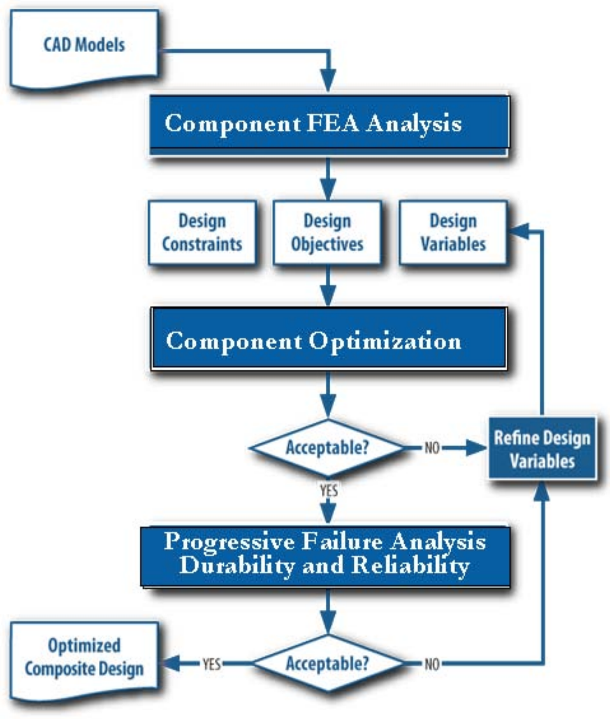


Fig. 8. Flow chart for optimizing the shape of the suspension unit

Table 2. List of design constraints before and after optimization

	Steel	Initial Hybrid	Optimized Hybrid
Normalized Maximum Deflection	**1. 0**	**1.15**	**0.75**
Composite Failure Index	**NA**	**2.0**	**.9**

The analysis was repeated for fatigue loading to determine a base line for the number of block loading that it will take for the suspension unit to fatigue. Table 3 lists the weight benefits obtained from the use of hybrid composites in the construction of the suspension unit. After optimization, the weight of the suspension unit made with hybrid material was 33% lighter than that of the steel. Similarly, the fatigue life of the hybrid unit was improved by 1.75 times as compared to existing design. The optimized hybrid design met the stiffness requirements for the design because of the ability to shift the mass around where needed the most to reduce the deflection and increase the stiffness.

4. Application of HPC in the Durability and Damage Tolerance (D&DT) of Composite structures

With the ability to assess the performance of composite chassis components using progressive failure analysis, the focus turns to evaluating the benefits from HPC for similar application.

Progressive failure analysis functionality follows a well structured approach as outlined here: (1) composite mechanics calculate thermo mechanical properties from fiber-matrix to lamina and laminate; (2) stress, strain and displacement calculation in all elements for a given loading condition using finite element analysis; (3) decomposition of stress to laminate, lamina and fiber – matrix to track damage and fracture; (4) update of finite element using degraded properties due to damage accumulation (if any); and (5) increase load to the next level (all the way to failure). Parallel processing can be applied in two areas here: (1) finite element analysis for a given load iteration; and (2) composite mechanics and damage tracking for all elements/plies in the model; Finite element stress solvers that are commercially available offer parallel processing through MPI.

Table 3. Weight benefits, static load limit, and fatigue life for optimized hybrid and all composites suspension unit

Material	*Normalized Weight*	*Normalized Ultimate Load (static)*	*Normalized Fatigue Life*
SAE950X Steel	*1*	*1*	*1*
Optimized Hybrid (20% steel and 80% polymer composites)	*0.667*	*1.2*	*1.75*

During the course of D&DT evaluation, MPI was exercised to assess benefits from HPC. PFA was run using FEA program as a stress solver. The D&DT evaluation was run using 1, 2, 4, and 8 CPU cores. It was evident from the results that the return in terms of run time reduction would be significant for structures requiring the use of large finite element models (in excess of 100,000 elements). For the suspension unit, very little reduction in run time was observed (about 5%) with HPC. For model sizes exceeding 100,000 elements D&DT with PFA indicated significant run time reduction as shown in Figure 9. Using the finite element models shown in Table 4, the PFA run time for the boxed beam modeled with more than 270,000 elements was reduced by 38% as compared to 1 CPU. That is extensive as PFA requires iterative finite element analysis to determine load limits for a givens structure. The authors do not assert that analysts use large finite element models when not warranted. For HPC to be effective, it would be ideal to apply it on whole vehicle design where single parts are not modeled and analyzed in isolation.

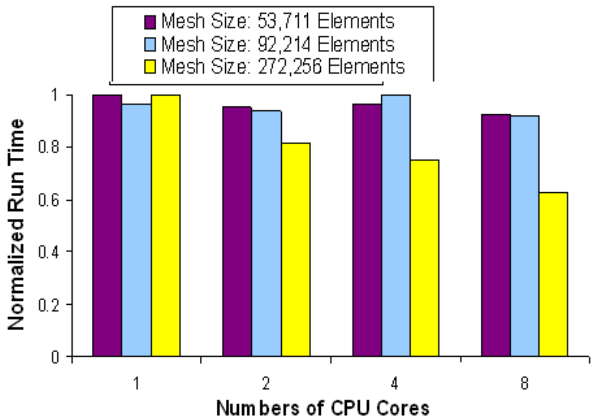
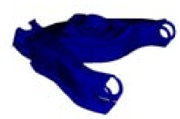
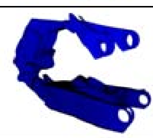
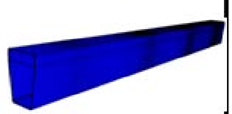


Fig. 9. HPC benefits with PFA for models with different mesh sizes

Table 4. Finite element models used in the HPC study

FEA Model Mesh Size (Number of Elements)	Model Description	Case Study
53,711	Lower Control Arm	
92,214	Double A-Arm Suspension	
272,256	Boxed Beam	

PFA reduction potential with HPC was also evaluated using a frame structure of a large truck made from composite material. The finite element model consisted of nearly 400,000 elements with millions of composite plies in the model (Figure 10). For static and fatigue PFA type analysis, a reduction of 55 an 52%, respectively, were observed from PFA (Figures 11-a and 11-b). Advancement in computing technology opens the door to exploit advanced materials to their maximum potential. Furthermore, it allows for detailed iterative design in a virtual manner without resorting to iterative testing if the design does not meet the mission requirements. Testing would be essential for certification when satisfactory performance is obtained virtually. Another benefit is the ability to test virtually the structure under conditions not possible in a test setting (i.e. combined loading/multiple environments, etc.). Figure 12 shows the relationship between finite element model size and percent reduction in run time for 8 CPUs. As the number of finite elements increases, the relationship to the percent reduction in run time with 8CPUs as compared to 1 CPU becomes non-linear. This indicates that for very large FEA models parallelization of finite element analysis in PFA can bring about significant reduction in run time allowing for elaborate design optimization to improve durability and reliability of military vehicle structures.

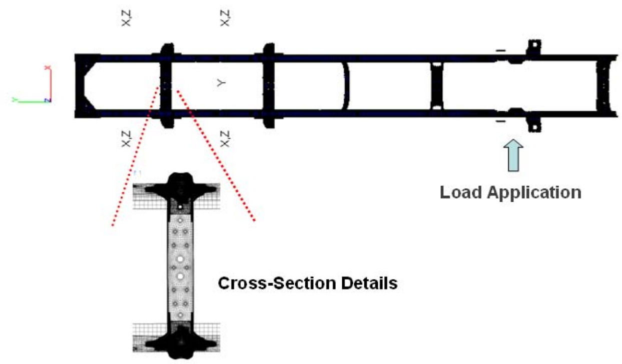


Fig. 10. Frame structure of large truck is modeled with nearly 400,000 finite elements

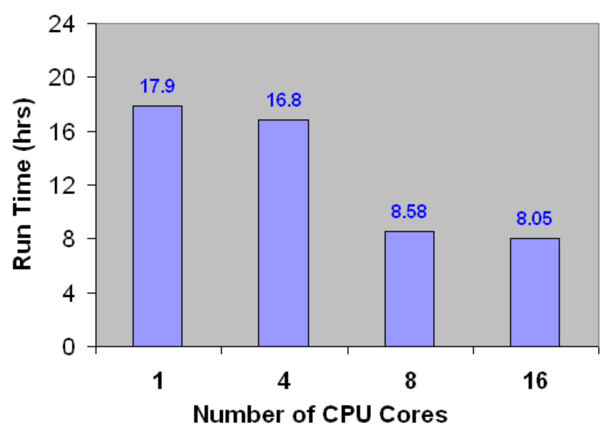


Fig. 11-a. Reduction of PFA run time with HPC under static loading for the frame structure

As mentioned earlier in the paper, in addition to using MPI in finite element analysis to assess potential HPC benefits with PFA, the authors examined the effect of parallelizing composite mechanics computation prior to finite element iteration in PFA. Although most computational efforts in a typical PFA run are exhausted with finite elements, parallelizing the composite mechanics segment can speed up the solution time as well. For example, for a finite element model consisting of 22774 elements with 4 plies per element, the run time is reduced by a factor of 2.1 when the composite mechanics calculation is parallelized (using 8 CPUs). When the number of plies are increased by a factor of 40 (that is 160 plies), the run time is reduced by a factor of 10.25 times with composite mechanics parallelization as compared to conventional computing. That is very significant reduction in run time with promising high returns for optimization and reliability calculations.

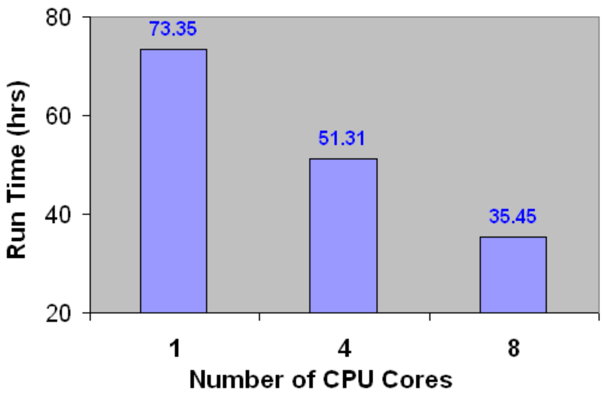


Fig. 11-b Reduction of PFA run time with HPC under fatigue loading for the frame structure

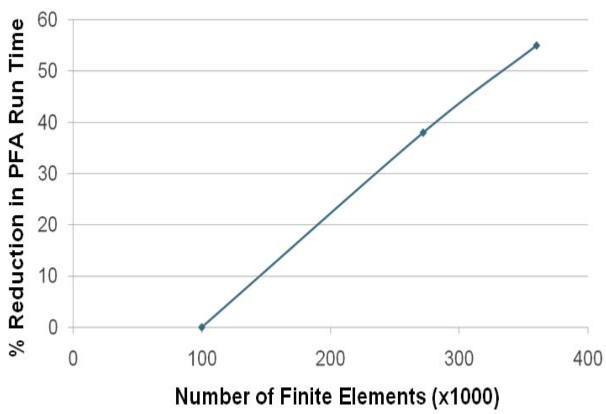


Fig. 12. CPU reduction as a function of model mesh size

CONCLUSIONS

An advanced methodology was used in high performance computing environment to reduce weight and improve durability of military vehicle components made from lightweight hybrid (composite and steel) materials. The method judiciously combines composite micro and macro mechanics, finite element, durability and damage tolerance, with optimization methods. The following can be concluded from the present study:

1) The use of MPI in finite element analysis based progressive failure analysis can significantly reduce the run time when large finite element models are employed (larger than 100,000 elements).

2) Parallelization of composite mechanics computation in progressive failure environment yields significant run time reduction as well.

3) Use of hybrid composite material consisting of composites and steel coupled with shape optimization can produce equivalent stiffness as compared to all metallic construction with a minimum weight savings of 30%.

4) The methodology is robust and applicable to all vehicle structures, especially where data is difficult to obtain.

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