Lightweighting Automotive Materials for Increased Fuel Efficiency and Delivering Advanced Modeling & Simulation Capabilities to U.S. Manufacturers

Final Technical Report

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Acronyms and Abbreviations

AMS&A	Advanced Modeling, Simulation and Analysis
ATMP	Advanced Thermo-Mechanical Processing
BCC	Blue Collar Computing
BoM	Bill of Material
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CBN	Cubic Boron Nitride
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
CWRU	Case Western Reserve University
DCPD	Dicyclopentadiene
DCT	Deformation Control Technology, Inc.
DOE	Department of Energy
ECAE	Equal Channel Angular Extrusion
ECC	Electroceramic Coating
EDM	Electrical Discharge Machining
EPA	Environmental Protection Agency
EPM	Engineered Performance Materials
FEA	Finite Element Analysis
FEM	Finite Element Model
GE-GRC	General Electric Global Research Center
GFRP	Glass Fiber Reinforced Polymer
GPU	Graphics Processing Unit
GUI	Graphic User Interface
HPC	High Performance Computing
ISV	Internal State Variable
LAMP	Lightweight Automotive Materials Program
M&S	Modeling and Simulation
MAG-IAS	MAG Industrial Automated Systems
MDB	Moving Deformable Barrier
MRR	Material Removal Rate
NCF	Non-Crimp Fabric
NCMS	National Center for Manufacturing Sciences
NCSA	National Center for Supercomputing Applications
NETL	National Energy Technology Laboratory
OEM	Original Equipment Manufacturer
OSC	Ohio Supercomputer Center
PCD	Polycrystalline Diamond
PMC	Polymer Matrix Composite
R&D	Research and Development
ROI	Return on Investment
RTM	Resin Transfer Molding
SWR	Strength-to-Weight Ratio
Tg	Glass Transition Temperature

UML	University of Massachusetts – Lowell
U.S.	United States
USCAR	United States Council for Automotive Research
UTS	Ultimate Tensile Strength
VARTM	Vacuum-Assisted Resin Transfer Molding
WSU	Wayne State University
YS	Yield Strength

Abstract

The National Center for Manufacturing Sciences (NCMS) worked with the U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL), to bring together research and development (R&D) collaborations to develop and accelerate the knowledgebase and infrastructure for lightweighting materials and manufacturing processes for their use in structural and applications in the automotive sector.

The purpose/importance of this DOE program:

- 2016 CAFÉ standards.
- Automotive industry technology that shall adopt the insertion of lightweighting material concepts towards manufacturing of production vehicles.
- Development and manufacture of advanced research tools for modeling and simulation (M&S) applications to reduce manufacturing and material costs.
- U.S. competitiveness that will help drive the development and manufacture of the next generation of materials.

NCMS established a focused portfolio of applied R&D projects utilizing lightweighting materials for manufacture into automotive structures and components. Areas that were targeted in this program:

- Functionality of new lightweighting materials to meet present safety requirements.
- Manufacturability using new lightweighting materials.
- Cost reduction for the development and use of new lightweighting materials.

The automotive industry's future continuously evolves through innovation, and lightweight materials are key in achieving a new era of lighter, more efficient vehicles. Lightweight materials are among the technical advances needed to achieve fuel/energy efficiency and reduce carbon dioxide (CO_2) emissions:

- Establish design criteria methodology to identify the best materials for lightweighting.
- Employ state-of-the-art design tools for optimum material development for their specific applications.
- Match new manufacturing technology to production volume.
- Address new process variability with new production-ready processes.

1. Executive Summary

There were nine DOE projects that used Advanced Modeling, Simulation and Analysis (AMS&A) for optimization. This Lightweight Automotive Materials Program (LAMP) developed and validated cost-effective high-strength materials technologies that could significantly reduce vehicle weight without compromising cost, performance, safety, or recyclability. The designed components were fabricated, assembled, tested, and predictions from the analytical tools were compared to a tested response. The areas using AMS&A development were in aluminum and titanium manufacturing, and composite multi-material development.

The use of AMS&A at the supplier level is key to focusing the work in areas of highest importance and impact for widespread deployment of lightweighting materials. This requires affordable access to high-performance computing (HPC) hardware, software and people. These tools were used to optimally define how functionality, manufacturing cost, and sustainability are inter-related. The chosen research projects then focused on the key variables affecting the deployment of lightweighting materials.

The knowledge of new materials and the fabrication processes used to build them has historically been gained through testing validated experiential development models. This is a costly, time-consuming and risky process that can take years to decades before some consequences may be understood. Today many original equipment manufacturers (OEMs) in the automotive, aerospace and other industries use physics-based simulation to compliment prototype testing, improve design and accelerate time-to-market. Over the past decade, the design time for new car models has dropped from 60 months to less than 30 months.

However, most innovations related to lightweight materials are taking place at smaller companies where these tools have yet to be fully leveraged. So while overall vehicle design and development incorporates these powerful cost improving, time saving, risk reducing tools, the foundational material and process developments have not been afforded the same opportunity. They have not been effectively used because of lack of awareness of the value of AMS&A tools at these companies, the capital investment, the ongoing cost of maintenance and the access to a qualified workforce to fully implement and leverage these powerful tools.

NCMS worked with collaborating member companies to investigate at least one potential enabling mechanism in each project. These included required aspects related to remote access to hardware, novel software licensing models, leveraging talent at universities, or similar or remote data management infrastructure.

AMS&A was necessary to quickly develop entirely new materials. The lightweight, energy-efficient vehicles of the future will be manufactured out of materials that don’t even exist today; materials that will be lighter, stronger, safer, and more environmentally friendly than current materials. The application of new lightweight materials goes well beyond ground vehicles, as well. Aviation, commercial transport, shipping, and many other sectors can benefit from lightweight materials.

To begin the process and address the demands of automotive fuel efficiency requirements, NCMS assembled an innovative suite of software tools and cross-industry innovators to help OEMs, Tier One suppliers, and component manufacturers to create and realize the benefits of lightweight materials while lowering costs, minimizing risk, and speeding commercialization.

The nine projects under this program leveraged the use of AMS&A to support the selection and optimization of lightweight materials for their products during the product design phase.

1.1 Conclusion

Through the use of AMS&A, manufacturers selected optimal lightweight materials for their concept work during the design phase of development. The HPC and digital manufacturing tools developed during LAMP, allowed the project participants to use cutting edge capabilities which in the past were cost prohibitive and generally not available, particularly to our nation's small and medium-size automotive suppliers.

NCMS and its partners in the lightweight materials R&D projects are confident that the automotive industry will have the opportunity to adopt new materials and leverage them into vehicle designs:

- Developed and demonstrated a software tool to predict the response of age hardenable aluminum alloys for 7075 aluminum.
- Optimized digital M&S polymer matrix composite (PMC) manufacturing cycle time by 30%.
- Incorporated high strength-to-weight ratio (SWR) alloys as an economical and feasible option for the automotive market to reduce vehicle mass and emissions.
- Analyzed results from HPC simulations with advanced software tools and experience to generate a structural composite design saving 3kg (6.6 lbs.) of body structure mass while increasing crash performance by 12%. A web-based portal integrating the user with hardware and specialized software can be interconnected seamlessly and competitively utilized for large scale design iterations and optimizations.
- Redesigned an aluminum connecting rod suitable for passenger cars based on preliminary material properties and achieved a 46% mass reduction compared to baseline forged steel design.
- Identified glass fiber composite/balsa core sandwich composites and their processing methods for automotive applications in stiffness critical applications. Results confirm that material, process method, and design for performance can be successfully realized for this class of composites for weight reduction in automotive composite application.
- Developed computational procedures to predict the impact performance of the automotive structures with sandwich constructions.
- Forming simulations performed using the finite element model (FEM) were excellent examples of its potential to be used as design-aid to simulate the composite forming process.
- Developed an easy-to-use portal and inexpensive way to leverage HPC resources to allow trailer designers and parts suppliers to model the airflow and corresponding aerodynamic forces over a tractor/trailer through the application of OpenFOAM®.

Ultimately, this program's development work will contribute towards improved manufacturability, lower costs, and greatly increase sustainability and fuel efficiency.

2. LAMP Projects

Nine lightweighting efforts were completed under this Program:

- Automotive Component Manufacture in Titanium (130171)
- Lightweight Material Usage Optimization for Multi-Mode Safety, Noise, Vibration, Hardness and Durability Performance using High Performance Computing (HPC) (130172)
- Ultra-Fine Grained/Nano Aluminum Material for Connecting Rods (130173)
- Low-Cost Resin System for Lightweight Polymer Matrix Composite (PMC) Components (130174)
- Thermal Processing of Aluminum Alloys (130175)
- Ultra-Lightweight Sandwich Composite Constructions for Autobody Applications (130176)
- Lightweight Fiber Composite Structures with Embedded Communications (130177)
- Simplified Computational Fluid Dynamics (CFD) Analysis of Tow Vehicle & Trailer Bodies (130181)
- Ultra-Lightweight Sandwich Composite Constructions for Autobody Applications – A Predictive Simulation Approach (130182)

The sections below detail the projects.

2.1 Automotive Component Manufacture in Titanium (130171)

2.1.1 Phase I

A frequent method used in vehicle lightweight engineering is to adopt and implement light-weight materials such as aluminum, magnesium, titanium, high-strength steels, or composites. Considering these materials, titanium, which is highly used in the aerospace industry, still lags in usage for the automotive market. Although titanium has a superior SWR as compared to existing automotive metals and a great corrosion resistance, material and processing costs are still the major barriers to widespread adoption in the automotive industry. This work examined methods for cost-effective implementation of titanium into automotive architecture by considering the design and manufacturing of an existing vehicle component in titanium, where the justification of use of the material and associated process plan decisions were warranted through a lifecycle cost analysis. Hence, the purpose of this project was to demonstrate the feasibility of manufacturing an automotive component in titanium, with such components integrated to critical areas of vehicle design for reducing mass and improving fuel efficiency. The lifecycle cost analysis and design were based on the assumption that the parts would be manufactured using standard wrought Ti-6Al-4V products. The first titanium P1 was a geometric recreation of the current production component manufactured using rod and plate stock. The second P2 was a titanium leveraged design which exploited the high-strength properties of titanium and also used standard wrought products. The major result from the lifecycle analysis was that the total life-cycle costs of the two titanium prototypes were comparable to that of the original ductile iron component even with the higher raw-material costs. What this immediately suggests is that material replacement with a lightweight higher cost aerospace alloy, such as Ti-6Al-4V could be an economically feasible and viable option for the automotive market due to initial costs being offset by the energy savings over the operating life of the vehicle. The lifetime savings in gasoline for the titanium prototypes ranged from 83-114 liters (22-30 gallons) for this component. This case scenario was derived for a gasoline price of \$0.8/liter (\$2.91/gal); a higher unit gasoline price would yield higher savings. Thus, when extending the fuel, energy, emission and monetary advantages to the annual production volume of this vehicle, and further to the OEM production scale, the advantages are significant enough to substantiate material replacement and justification from an economic standpoint. With respect to processing of the components, standardized titanium plate/rod stock was transformed to the final product using processes such as electrical discharge machining (EDM), waterjet machining, milling, turning, and warm bending operations to produce the major pieces for assembly. The major parts of the component were joined using tungsten inert gas welding and then the assembly was stress-relieved to remove any stresses developed from the joining operation. Following the stress relief, final finish machining was carried out and then the part was surface treated to remove any coloration caused by the welding and heat treating processes. In summary, automotive titanium prototypes were produced and functionally validated by laboratory and in-vehicle testing. The cost justification for these components was warranted through a lifecycle cost analysis which showed the costs to be comparable to the original component in the vehicle. As a result of this work, it is suggested that titanium components can be cost effectively incorporated within consumer vehicles to re-place heavier vehicle components. Though a vehicle OEM is typically not a beneficiary for these lifecycle cost savings (profits incurred during operation), it would be a strategic move, to market this fact as their demonstrated commitment for: (1) energy consciousness through fossil fuel savings, (2) environmental responsibility through reduced emissions, and (3) a higher performing vehicle.

2.1.2 Phase II

The poor machinability of titanium components increases the processing cost through a trade-off between extended cycle time (labor cost) and increased tool wear (tooling cost). This has classified titanium as a “difficult-to machine” material, and the commercial automotive industry has therefore been reluctant to adopt titanium alloys in spite of their proven energy and lifecycle cost savings, except for a few feasibility studies of low volume prototypes. The poor machinability of titanium alloys is due to their unique combination of low thermal conductivity and low elastic modulus along with high chemical reactivity and high temperature strength. Even with the development of ultra-hard tool materials such polycrystalline diamond (PCD) and cubic boron nitride (CBN), from a net-cost standpoint, the most economical cutters for titanium machining still are “throwaway” straight carbide inserts. Though general guidelines exist for machining titanium alloys, operating within the recommended range of parameters still result in very frequent and catastrophic wear/failure. Thus, there is a critical need to explore the vast design space when machining titanium alloys with carbide tools. This is where the simulation of the titanium machining process using HPC comes in. Sweeping the vast multi-variable, multi-level design space through simulation expands the amount of information that could otherwise be obtained by experiment. The objective of this HPC project augmentation was to learn how to cost effectively realize the most profitable material removal rate (MRR) (optimized cost of processing and cost of tooling) in machining titanium alloys, through the simulation of cutting performance for identifying the key characteristics that result in tool wear. The procedure was to take all available variables into account by replacing the design variables in the FEM of the titanium machining process with their ranges and distributions. This was done by wrapping Third Wave Systems’ AdvantEdge FEM machining simulation software with Dassault Systèmes’ Isight for building experi-mental designs. Isight was used to create experimental designs for distribution over a large number of AdvantEdge FEM analyses to run in parallel on the Clemson University HPC cluster. Results were analyzed in SimaFore/ OntoSpace™ complexity analysis software to identify key characteristics and outliers. These simulation results were used to complement and augment the empirical information gained through the process experimentation from Phase I. In summary, this HPC project, through validated simulations enabled the detailed scrutiny of the multi-level, multi-variable design space of machining titanium alloys from a profitability standpoint, which was otherwise not feasible to explore through cutting experiments alone. Further, it was found that process optimization needs to be done with MRR as the control variable, as opposed to the traditional cutting-speed-only approach. This is especially pertinent when machining titanium alloys as catastrophic tool wear/failure is directly related to the interface cutting temperature which is an exponential function of surface speed.

2.1.3 Conclusions

Even with titanium's superior SWR to other engineering alloys and its greater corrosion resistance, present material and processing costs are the major barriers to widespread use in the automotive industry. Two titanium prototypes were produced using standard Ti 6Al- 4V wrought products. P1 was a geometric recreation of the original component and P2 was a titanium leveraged design with the goal of minimizing component mass. A lifecycle cost analysis showed that the cost of both titanium prototypes were closely comparable to that of the original ductile iron component. This then directly suggests that the incorporation of high SWR alloys is an economically and feasible option for the automotive market to reduce vehicle mass and emissions. The process of electrically-assisted manufacturing was examined for forming and machining operations to improve process efficiency. During this process, direct electrical current is applied through the work piece to alter the material flow characteristics. For forming, lower forming forces are now required and the material has improved ductility. In machining, initial tests showed lower machining forces and an improved workpiece surface finish as compared to traditional machining. Alternate alloys to Grade-5 titanium (Ti-6Al-4V) have been developed for markets other than the aerospace industry. Similarly, a grade suitable for the automotive market that is considerably cheaper than the "workhorse" Grade-5 has to be developed; this is critical for a widespread adoption of titanium. This project enabled a first-hand study of the multi-level, multi-variable design space in titanium machining, that is too vast to be explored by physical experiment alone – this resulted in a validated simulation set of the titanium turning process for multiple configurations, alloys, tool geometries, and cutting conditions. The main trends observed from the simulation results were: (1) an increase in temperature with increasing feed and cutting speed, (2) a reduction in forces (Fx/Fy) with increasing cutting speed, and, (3) an increase in cutting and feed forces with increasing feed. It was found that for titanium machining process optimization (for profitability), MRR needs to be the control variable as opposed to the traditional cutting speed. From bivariate analysis, it was found that the choice of titanium alloy was the most significant input variable, followed by surface speed, and cutting edge radius. From the bivariate analysis of derived variables, wear rate and MRR were found to be the significant productivity-controlling variables. Further, the rake angle was the other significant tool geometry based input variable. Multiple linear regression analyses confirmed the additional significance of cutting feed on temperature and cutting/feed forces as well. During validation experiments, the high feed, low speed corner of the feed-speed design space was found to consistently result in chatter and/or catastrophic tool wear/failure. On assessing comparative tool performance of different substrates through simulation, carbide tools were found to experience similar peak cutting/feed forces as with PCD and CBN tools, thus substantiating their selection. This project highlighted the challenges and importance of seamless integration between associated software, particularly from data-transfer and data-format standpoints – it took a substantial amount of initial effort and time for "semi-automating" the HPC loop. An elaborate design-space sweep using HPC clusters such as in this project typically entails a much larger input design of experiment as well as larger set of output results to compile and analyze – this aspect should be taken into consideration when running such projects. The higher temperature regime associated with titanium machining was mirrored in simulation by the higher than normal "aggressive" re-meshing as a result, a much finer mesh was needed for convergence, rewriting many rules-of-thumb for mesh sizing. The higher associated temperatures resulted in longer than normal times for simulation stabilization – lengths of cut were increased appropriately, increasing computation time. Twice the computing power does not mean half the computation time – benchmarking for the optimum processor-operating system-software bit combination is suggested. Though not the rule, HPC/HTC clusters are typically run on UNIX/Linux environments, and commercial engineering software on Windows platforms. A virtual machine was used in this case; this is an important aspect to consider when running such projects.

2.2 Lightweight Material Usage Optimization for Multi-Mode Safety, Noise, Vibration, Hard-ness and Durability Performance using High Performance Computing (HPC) (130172)

At the highest level, the project sought to utilize experience and technical skills provided by L&L, remote hardware supplied by R Systems, and Altair's simulation software for computer-aided engineering (CAE) and workload management, HyperWorks® and PBS Works™, to create and leverage remote HPC resources for access to large quantities of computing capacity. All computer simulations were submitted remotely by L&L with results transmitted back for analysis. The central issue for this project was the design exploration and optimization of a full vehicle, public domain computer model of a typical four-door automobile. This vehicle was analyzed for both traditional (steel) and composite hybrid solutions. Multiple safety modes, along with basic static and dynamic stiffness configurations were used to create a holistic set of performance targets. A comprehensive solution was developed and optimized virtually. Finally, various optimization routines were utilized for both structural performance and manufacturing cost optimization of the final solution proposal.

The project team conducted a multi-year study to determine the customer and manufacturer value of leveraging on-demand HPC to support automotive crashworthiness design. L&L is a custom chemical compounder located in southeast Michigan designing, testing, and manufacturing structural composites for automotive companies worldwide. By combining technical design and manufacturing expertise from L&L with software from Altair, large numbers of crash simulations typical to the automotive product design process were run on hardware hosted at R Systems facilities. Results from these simulations were analyzed with advanced software tools and experience to generate a structural composite design saving 3kg (6.6 lbs.) of body structure mass while increasing crash performance by 12%. A secondary project phase managed by Nimbis and Altair's framework proved that a web-based portal integrating the user with hardware and specialized software could be interconnected seamlessly and competitively utilized for large scale design iterations and optimizations.

This LAMP project has been of great importance to L&L in that it extended existing engineering design experience by providing new tools (software and hardware) previously not available. While L&L owned a HPC system, problems such as design with multi-mode simulation, material cost anticipation, and design optimization requiring increased capacity could not be addressed. This project allowed hardware and software to be leveraged. New software tools were developed that will provide higher quality results in the existing design process, better traceability in future design projects, and access to any required capacity that might be useful in the future. Finally the business case, that ultimately must be brought forward to management, can be built to examine the return on investment (ROI) representing the value that such HPC leveraging brings to the business stakeholders.

For the crash test scenarios examined (roof strength – FMVSS 216 and side impact – IIHS side impact), a sequence of optimizations were able to define part designs in two areas. The first solution was able to reduce body structure weight while maintaining constant performance. This design was built upon iteratively to generate the final, optimal solution which increased performance 12% while actually reducing the body structure's mass. The combination of better performance for less mass is the most desirable situation sought by automobile manufacturers.

In addition to the technical tools and skills gained, the relationships between the team members continue to grow and provide both advantages and new challenges. The members expect that the high value and exceptional opportunity being gained will continue through many years.

2.2.1 Detailed Task

A public domain FEM was located and investigated to gain knowledge of best choice for this study. A bill of material (BoM), graphical outlines and overviews, and generated input "deck" for the baseline model were generated. This led to using several available resources, conducting in-depth design reviews for baseline model structure and highlighted areas of substandard design. These areas were targeted for upgrades in material, gage or complete replacement/redesign. Initial simulations of baseline model for run-time error eliminations were conducted. These were run with default moving deformable barriers (MDBs), not correlated to any test conditions. Through L&L's engineering experience and detailed computer-aided design (CAD) interaction, new design geometry and all necessary engineering specs for a modern equivalent to the model.

The first large scale computational effort for this project was the creation and execution of an optimization for the steel structure of the model. Macro composites can be formed from nearly any material (nylon, aluminum, steel, etc.) and bonded into the steel body structure of passenger cars via L&L's proprietary crash toughed, epoxy-based expanding adhesive. These adhesives are moldable and heat activated to expand, filling manufacturing or variability gaps in the steel and securely bonding the composite reinforcement into the steel auto body for crash load endurance. Such parts are capable of multiplying the crash loads several times in scenarios such as roof crush, side, and frontal impacts.

A MDB is required for the so-called side impact simulation crash modes. This MDB represents the approximate stiffness, crush profile, and mass of another vehicle as it impacts the vehicle under consideration. Physical as well as virtual versions of this MDB exist and are routinely used in the product development and design process by automotive manufacturers.

A central necessity of this project was the procurement, revision, and verification of a vehicle model from a limited known supply of nonproprietary FEMs in existence. All current models freely available to the public lacked credibility with vehicle designers due to the dated nature of their structures. The chosen model (closest to what was needed for this project effort) lacked central structural support that is typical of today's vehicle architectures. Only by manually creating these strategic parts, developing CAD for each, creating finite element meshes for each, and attaching them at engineered locations within the vehicle model, has a virtual realization of modern design been achieved.

L&L conducted virtual design studies in the form of statistically guided design of experiments of almost 90 design variants of IIHS side impact and roof strength simulation. The design of the body structure can be improved substantially with small or negligible mass increases. The improvement is in the vehicle survival space under an IIHS-defined side impact load and increased weight reduction and design value. While these improved vehicle structure designs give side impact performance enhancements, they were additionally validated to not give adverse effect to other safety metrics.

The optimization necessary for this value gain is enabled by large scale CAE simulation was the collaborative work of Altair and R Systems (later extended by Nimbis).

This application was installed at R Systems and all necessary debugging done by Altair in conjunction with R Systems allowing multiple users at L&L access to the hardware resources. Users have input files stored locally to the hardware and can align them with two (linear and non-linear) solver applications depending on the simulations desired.

Collaboration between Altair, L&L, and Nimbis was undertaken as an addendum to this project. This addition incorporated learning from the project to this point to enable automation and "real world" utilization tasks that are practically necessary in real production development cycles to be accomplished in a much more efficient manner.

The value in time savings and completeness of the design process of just this development would be hard to overestimate.

2.2.2 Nimbis Integration and Approach

Nimbis, under contract with NCMS, developed, maintained, and supported a secure cloud portal for on-demand procurement and access to technical computing applications.

For registered users the Nimbis website encapsulates the LAMP portal services into a catalog product that users can purchase using a typical e-commerce storefront with shopping cart, checkout, and payment method options including credit card, PayPal, and purchase order. Nimbis implemented and demonstrated the required e-commerce capabilities required for a deployed LAMP product.

Users need an R Systems login node that hosts the LAMP portal software. Users use the login node to upload their input files, submit batch job runs, and view and download results. Ordering of a login node was implemented and demonstrated in this pilot.

At the end of this workflow is the remote desktop on the login node at R Systems. The Altair software installed at R Systems allows users to launch and use the software on their desktop machine through this remote desktop. Using the remote desktop and the file manager, an L&L user had access to the Altair software and associated software licenses installed at the R Systems HPC center.

2.2.3 Optimization

Through the two designed experiments that were utilized in the project, L&L was able to define the so-called design sensitivities that exist between the input variables and responses. The input variables will typically be material stiffness and thickness, two commonly altered geometric values in an automotive product development process. Such designed experiments make use of statistical theories to create a robust and systematic method for exploration of the unknown design space related to a product, process, and manufacturing environment. As many of these design parameters are systematically altered, a large “design matrix” is built.

Having extracted the essential information from the simulations, many methods may be used to extract meaning from the underlying design space. It is this design space that the design of experiment has meant to explore and has given the product developers insight into. The size of the “window” that the designers get to peer through is dependent on many factors such as time available to work on the design (thus the number of simulations and post-processing that can be done), the knowledge and experience of those designers, the clarity through which they can look (e.g. the design resolution of the design of experiment), and the available software tools used to explore that space. For this project, the design objectives were selected to be the survival space in side impact and the SWR in roof strength tests.

The final design space investigations tended to show a material thickness and geometry set which was imposed on the FEM. A critical point to the project for L&L is that this point would be the stopping one for traditional design efforts at L&L. It would not have previously been possible to further explore combinations of structural composites with material thickness considerations on multiple models within a reasonable customer time frame. The access provided by this LAMP effort to HPC and “on-demand” software allows the next level of composite part development.

As is often the case, some structural changes that improve one aspect of test modes will degrade the performance of another. Such competing objectives make analysts intuition driven optimization “tricky” and are more robustly accomplished by advanced computing tools.

2.2.4 Design Cost Modeling

Key to the ROI value proposition for leveraging is the understanding of raw material costs at the time of manufacture. Pushing the value to the customer by removing mass and increasing performance placed a new burden on L&L’s pricing understanding as seen in this project. As L&L obtains the raw materials, understanding their future price becomes imperative.

One of the key manufacturing parameters was found to be a global shipping index and was then predicted for four months into the future. Some of the key factors considered when creating the resulting Neural Network and ARIMA models are the manufacturing parameters with respect to the cost driver correlation such as underlying frequency, autocorrelation, and stationary. A model was developed that was able to extend F(x) relationship four months into the future with high forecast accuracy when back tested.

This LAMP project has been of great importance to L&L in that it coupled designer experience with new hardware and software tools (previously not available) to obtain an infinite number of design possibilities to explore and document. The business case that ultimately must be brought forward to management can be built which examines the ROI representing the value that such HPC leveraging brings to the business stakeholders. The typical part was seen to make the vehicle structure 3kg (6.6 lbs.) lighter while improving crash performance in multiple modes by 12%.

The partnership between L&L, Altair and R Systems was critical for paving the path for large scale job submission utilities, trials, debugging, and scaling studies. This partnership leveraged L&L’s simulation needs with Altair’s PBS Works job management applications, and R Systems hardware to obtain useful, on-demand, multi-core simulation capacity. Two prevalent crash modes of side impact (crash safety, FMVSS 214) and roof strength (crash safety, FMVSS 216) were explored. Altair and R Systems graciously invested large amounts of time structuring the hardware systems and installing the software as required. L&L continues to utilize the secure network accounts and disk space located on R Systems machines and has installed the required secure shell protocol software necessary for client confidentiality. This makes the effort expended in this project extensible to future (“real”) customer projects and will provide previously unobtainable resources for many years.

The team feels extremely fortunate that this project has allowed some of that post-processing automation to be implemented at L&L. Never in the past would processing and understanding of results for many hundred full-vehicle simulations been possible. Through extended work with Altair’s application engineering staff, several scripting tools have been developed. These have reduced the hours necessary for post-processing 200 simulations from about 100 days, to less than a week, even to a couple days if duplicate design of experiment designs is the intention. The long-term benefits of the knowledge gained during this effort will be hard to estimate. Through the project L&L has gained knowledge of the value of remote HPC usage, advanced design of experiment methods, simulation and result reporting development, full scale, multi-mode crash simulation experience, access to state-of-the-art hardware and built relationships with partners that will continue to grow for future years. The value of HPC has been addressed. Both weight and part cost savings have been captured and enumerated while improving performance that will ensure L&L to be the leader in structural composite for crashworthiness.

2.3 Ultra-Fine Grained/Nano Aluminum Material for Connecting Rods (130173)

This project sought to develop and validate an aluminum connecting rod suitable for passenger cars. As the connecting rod is translating the combustion pressure from the cylinder to the rotational motion of the crankshaft, high compression load and high temperature resistance from the part is required. The part must be capable of withstanding high inertia loading.

The most common materials for passenger car connecting rods are forged steel and forged iron-based powder metal. A now common material elsewhere in the automotive industry, aluminum has not been used in any volume production passenger car connecting rod application to date. This material has long been used in motorsports and small engine applications, but concerns about fatigue resistance and thermal stability have limited its use. This project investigated the potential application of an aluminum material modified for passenger car applications. Aluminum alloys offer a significant mass reduction compared to steel alloys. However, if used for a structural component such as a connecting rod, special requirements including fatigue resistance and thermal stability must be met. To meet this goal, MAHLE worked with partner Engineered Performance Materials (EPM) to develop a material which was suitable for the application.

Through NCMS, working in partnership with the DOE, MAHLE and its collaboration with EPM proposed to develop low-cost, high-strength aluminum materials and manufacture lightweight connecting rods. This R&D collaboration in the automotive sector was intended to develop and accelerate the knowledgebase and infrastructure for lightweight materials and manufacturing processes for their use in powertrain applications. Specifically the challenge was to provide tangible results through the state-of-the-art technology of equal channel angular extrusion (ECAE) and advanced thermo-mechanical processing (ATMP) to produce a unique ultra-fine/nano grain material structure to produce mass production automotive high performance connecting rods, providing high-strength fatigue and longevity.

As part of MAHLE's commitment to delivering innovative solutions to the marketplace, cylinder component mass reduction has become very important to enable engine manufacturers to meet future CO_2 and fuel economy requirements. One path to achieving weight reduction is the use of advanced materials. This project assessed the feasibility and impact of using an ultra-fine grained aluminum material for passenger car connecting rods. MAHLE is committed to a complete system integration approach that combines extremely reliable and innovative components that are both economical and environmentally friendly.

2.3.1 Material

The initial step was to analyze the microstructure of the various materials and compare the elasticity of the materials based on the modulus of elasticity (Young's Modulus), ductility of the materials via the yield strength (YS) and the fracture propagation method when the materials reached their ultimate tensile strength (UTS).

A connecting rod material must display excellent "high-cycle fatigue strength" – the ability to survive a loading condition for a sustained duration. The loading on a connecting rod is comprised of both tension and compression forces. The tension is a function of the inertia of the power cell assembly (conrod, piston, piston rings, piston pin and circlips), while the compression is a function of the cylinder pressure generated by combustion.

After an extensive period of benchmarking and material research, the material selected for the program was aluminum alloy 2618 (AA2618). AA2618 is a relatively low-cost forgeable and heat treatable aluminum alloy with phases of copper, magnesium, iron and nickel. It is widely used in the automotive and aircraft industries. Due to the additions of iron and nickel, it has improved microstructural thermal stability. Based on the material properties of AA2618, a new design was created which resulted in a nearly 50% mass reduction compared to the existing microalloy forged steel part. This mass reduction was achieved without sacrificing the structural integrity of the component as confirmed by advanced numerical simulation including finite element analysis (FEA).

Small scale industrial forging trials were conducted that confirmed the suitability of the material within the existing manufacturing lines. The forged parts were then finish machined with a special big end bore ovality. The conrods were designed to run in the engine without bearings and with special anti-wear and anti-friction coatings on the thrust faces and bores. As the final step in the project, an engine durability test was successfully completed to confirm the real-world component reliability.

The end result of ECAE/ATMP processing produced a unique ultra-fine/nano grain material-structure that would produce mass production automotive high performance connecting rods.

It is primarily accomplished through improved fatigue strength and increased temperature stability with regards to both fatigue strength and thermal expansion.

2.3.2 Component Design

With preliminary mechanical properties for the AA2618 ATMP material determined, the component design process started. The first step of this process was to select a platform in which to demonstrate the aluminum connecting rod; this resulted in the selection of a high performance V8. As only one engine test was planned, the eight available cylinders would allow for different bore coatings on the finish part and a higher degree of confidence should it survive engine testing.

Models were based on a parametric connecting rod model which already considers all tolerances and limitations of the manufacturing process. The first step in optimizing the part was iterating between the 3D models and the RodCalc program. The MAHLE software “RodCalc” was used to ensure that all aspects of the finish part had sufficient strength and integrity. RodCalc is an Excel-based tool which enables a designer to input the engine loading and proposed geometry of the connecting rod in order to ensure safety and perform a preliminary optimization.

2.3.3 Industrial Trials

Many production conditions such as processing speed, material flow and operation in real dies play significant role in thermo-mechanical processing. The temperature control during billet heating and forging is a key factor. Because of adiabatic localization, forging with high-speed hammer forges is not a viable option for aluminum conrods. Shear cracks may be eliminated by utilizing mechanical forging presses with lower speed.

Experiments were performed with a mechanical forging press using careful control of heating temperatures and other processing conditions. Billets were pre-heated in an electric furnace to attain the correct forging temperature and fully solutionized condition. Immediately after upsetting, billets were immersed in a cold water bath for quenching. All samples were sectioned to prepare small pieces for following aging and material characterization as well as samples for fatigue and mechanical testing.

In preparation for next phase of this trial, AA2618 material was ordered and passed through ECAE processing at EPM. A press forging die manufactured per the connecting rod forging model was completed, and a special furnace for pre-heating the billets.

2.3.4 Mass Reduction

The finished parts had a 46% less mass than the standard. A similar mass reduction may be achievable on other engine platforms, although the exact magnitude will be determined only after completing the design and development process as outlined in prior sections. Due to the substantial mass reduction achieved in the connecting rods, it was necessary to rebalance the engine to further reduce the cranktrain mass and to avoid crankshaft torsional vibration potentially created by an unbalanced crankshaft.

After testing and inspection, it was determined that all components successfully passed. No change occurred to the center-to-center distance, bend or twist on any parts, indicating that the components were structurally sound and no buckling or bending occurred.

2.3.5 Conclusions

- Base material investigation and small scale forging trials resulted in the choice of AA2618 material due to excellent thermal stability, fatigue properties and forgability.
- ATMP processing resulted in a 25% improvement in fatigue behavior with improved thermal stability.
- The conrod was redesigned based on preliminary material properties and achieved a 46% mass reduction compared to baseline forged steel design.
- Numerical simulation and validation testing confirmed that the material and design provide an adequate safety factor against component failure.
- Bore coatings were selected to improve durability of parts. Henkel electroceramic coating (ECC) showed most promising results; polymer coatings passed tests but

need to be improved with respect to compression resistance.

- The aluminum connecting rods successfully completed engine durability testing with no major issues.
- A total mass reduction of 3.57kg (7 lbs. 13.9 ozs.) was achieved after rebalancing the engine.

The total mass reduction compared to the volume production forged steel part was 46%. While this magnitude mass reduction will differ for each conrod design based on the physical loading and engine variables, it is representative of a typical reduction that can be expected.

This significant mass reduction in the connecting rod would enable an engine manufacturer to also optimize ancillary components which would be under less stress. These components include the crankshaft, block structure and bearings. In addition to reducing the overall vehicle weight, cranktrain mass reduction directly results in an engine which accelerates faster and has increased response. Although it was outside of the scope of this project to quantify the effect, it is possible that these modifications may improve fuel economy and reduce CO_2 emissions.

2.4 Low-Cost Resin System for Lightweight Polymer Matrix Composite (PMC) Components (130174)

Safety requirements are never going to go away, and the demand for ever-lighter vehicles means that whole new families of materials will be required to accommodate the design obligations.

Among the most promising of these new materials are polymer matrix composites (PMCs). These high-tech materials are made by embedding reinforcing fibers into a plastic polymer matrix, resulting in very sturdy, but very light, reinforcing materials. The lightness and strength of PMCs have made them extremely popular in aerospace, but cost and manufacturing issues have deterred widespread adoption in automotive. To realize their potential in this space, PMCs must be cheaper and take less time to manufacture than comparable metal parts.

The team set out to improve cost and cycle time challenges associated with PMCs. Across two phases of extensive experimentation and testing, the team accomplished a number of significant wins likely to ensure a bright future for PMCs in automotive:

- Digital M&S optimized PMC manufacturing cycle time by 30%.
- PMC performance compared to metal parts repeatedly demonstrated in simulations.
- 3X cost reduction was achieved through various chemical and process optimizations.

Aggressive use of HPC to perform thousands of M&S runs for each experiment was crucial in the strides made by the team. HPC drastically reduced R&D investment by virtualizing a massive portion of the research and validating experiments many dozens or hundreds of times more than would be possible in a traditional environment.

Overall, the team determined beyond doubt that low-cost, high-speed manufacture of automotive PMC components is feasible, and made many steps toward that goal. With further research into promising new technologies and approaches revealed by this project, the team is confident PMCs can be a valuable addition to the engineer’s arsenal in the challenge of developing light, strong, safe, fuel efficient vehicles.

Introduction of PMC components is desirable mainly because these materials offer weight benefits without sacrificing the strength requirements. PMC usage has increased significantly in the aerospace industry, but only modestly for automotive applications. A major drawback for using PMCs in automotive applications is the typically long cycle times associated with part manufacturing. Low-cost processing methods have matured significantly in the last decade, but typical costs are still higher than comparable metal parts. Costs along with the slow processing cycle of PMCs are the two major deterrents against their wider usage in both the aerospace and automotive markets. To make PMC application more affordable, this project exploited attributes of the dicyclo-pentadiene (DCPD) for liquid resin infusion process. As a natural technology flow down PMCs would be an attractive lightweight material alternative for the automotive industry. DCPD resin cured with catalyst offers a unique balance of properties for composites made using low-cost, out-of-autoclave, vacuum-assisted resin transfer molding (VARTM) processes. Typical resins used for VARTM processes need to have low process viscosity and long pot life to enable high-fiber volume parts. Low toughness and high cure temperatures typically accompany these characteristics. In the case of DCPD, it not only has low viscosity and high toughness, but the resin toughness is also five times higher than the toughest epoxy used in composites today. Low cure temperatures of DCPD also allow for low-cost tooling. The resin is cured to green state at 49°-82°C (120-180°F) for 1-2 hours at which time it can be removed from the mold and placed in an oven for free standing post cure. Post cure conditions can vary from 121-204°C (250-400°F) depending on desired glass transition temperature (Tg) 107°-152°C (225-305°F).

The first two phases of the project focused on DCPD selection based on catalyst concentration and extensive material characterization, leading to models development from the material data and usage of numerical analysis tools to guide the infusion process and understand the design boundaries. The third phase focused on mitigating the key technical challenge of DCPD bondage with other material systems. Copper was of particular interest to the General Electric Global Research Center (GE-GRC). Final phase was optimizing the cure cycle and meeting the key electrical conductivity data, followed by validation of performance of a prototype gradient coil in a laboratory environment. During the course of the project the following milestones were achieved:

- Environmentally safer and infusion-friendly catalyst handling and incorporation method developed for DCPD.
- Optimized cure cycle developed in conjunction with modeling, experiments and usage of Isight tool.
- Process models developed to evaluate DCPD resin infusion and cure.
- Feasibility of bonding DCPD with inter-phase material proven.
- Materials performance validated in a simulated component test.
- DCPD resin with carbon fiber composite panels mechanical properties completed by Plasan Carbon Composites.

This project demonstrated feasibility of a low-cost resin system like DCPD starting with applied research (TRL 2) through technology development and lab testing of components/ process (TRL 4). Results provide evidence that performance targets may be attainable based on projected or modeled systems. With feasibility having been demonstrated on the project, as the technology maturity level develops DCPD resin system is well placed to serve a variety of markets in composite applications as a lowcost resin system alternative.

2.4.1 Conclusions

Some key conclusions from the material characterization, process modeling and optimization work are provided below:

Latency & Work Life – The X3 resin formulation has a work life of ~3 days at room temperature once catalyzed, and storage of the catalyzed resin at cold temperatures appears to extend its useful life. The application of heat can complete cure of the resin within hours. The cure conditions are comparable to those used for anhydride-cured epoxy systems in terms of time and temperature requirements.

Viscosity – The resin has a low viscosity, allowing it to flow easily and infiltrate small gaps.

Toughness – The X3 resin has inherently good plane-strain fracture toughness. Many epoxy compositions used in elevated temperature encapsulation or composite applications are inherently brittle, and require additives to achieve comparable toughness (e.g. functionalized rubbers, poly-glycols, or thermoplastics). These additives can influence other properties of the epoxy, such as viscosity, cost, and glass transition temperature (Tg).

Catalyst Handling – Suspension of the X3 catalyst in mineral oil allows it to be handled and incorporated in the resin without the use of solvents such as dichloromethane. This avoids the health concerns and issues of in-process volatility associated with the solvent.

Cure Optimization – Tg data from the cure studies suggest that there may be additional opportunity for optimizing the cure of the X3 resin. There is an interaction between catalyst concentration and the cure cycle, which was not explored in the initial cure optimization study. Later experiments showed that a higher catalyst concentration could result in a higher Tg using a lower temperature cure cycle. It is possible that given sufficient experimental data, the formulation and process conditions could be optimized for particular characteristics using the software tools demonstrated in this study. Cost (strongly related to catalyst use), Tg, cycle time, toughness, etc. could be balanced according to the needs of a particular application.

Cure Shrinkage – The cure shrinkage of the X3 resin is comparable to typical unfilled epoxy resins. It should be noted that epoxy resins used for elevated temperature encapsulation are often filled with particulates, which have the effect of reducing overall cure shrinkage. In this work, the X3 resin was used without the addition of filler.

Adhesion – The X3 resin bonds poorly with many of the materials used in this work. This is a key distinction from epoxy resins. Studies showed that the use of an interfacial layer (sometimes known as a tie-layer, primer, or by another term), compatible with the X3 and the other surface, may be used to improve bonding.

Volatility – The X3 resin is relatively volatile, and has a low odor threshold but a distinctive odor. Ventilation is required for handling. A closed mold is indicated for processing, to prevent significant evaporative loss of resin. Vacuum processing of the resin is possible, but may require careful control of vacuum and temperature levels to prevent evaporation, boiling, and formation of voids during cure.

Process Modeling – Commercially available numerical tools can significantly guide and reduce the time for process development as long as thorough material characterization is done and uncertainties in data are considered properly using tools like OntoSpace™. Infusion analysis and bond strength analyses helped to minimize some key processing risks and set a specification requirement for the bonding between X3 and copper.

Optimization – Front end optimization during process development can center the process before getting it implemented on the floor and make the implementation of a new resin system like X3 cost effective. As a case study in the cure cycle optimization, OntoSpace™ and Isight tools were used to reduce the baseline cure cycle time by 30%.

2.5 Thermal Processing of Aluminum Alloys (130175)

Aluminum alloys have been widely used in automotive and aerospace since the 1960's for lightweight applications requiring high strength. These alloys are susceptible to warping and cracking during manufacturing processes. This unpredictability of the stresses upon aluminum alloys have been cause for concern. Being able to predict weakness and avoid costly scrap and design loops carries heavy financial and safety potential for future manufacture of aluminum alloy parts.

The project focused on the development of an accurate predictive software tool that could be used to streamline manufacturing processes for aluminum alloy part production, with the goal of reducing scrap loss, energy, and labor costs while improving the economics of fabrication of aluminum alloy parts. Such a software tool can change the production economics such that material change from steel to aluminum may become viable. Heavier steel components may be replaced by lighter weight aluminum components resulting in reducing vehicle weight and improving overall performance while not compromising safety.

DOE has supported efforts to reduce automobile weight in order to improve fuel economy for many years. The scope of this project fit this goal by virtue of the promise to improve the economics of aluminum parts use in automobiles through the predictive capability offered by the software.

The purpose of the project was to develop a software tool capable of predicting the distortion, residual stress state and microstructural phases for heat treated aluminum alloys. To maintain focus for achieving this goal, the commonly used age hardenable 7075 aluminum was selected as the demonstration material. A collaborative project was designed, with Case Western Reserve University (CWRU) performing experiments to characterize the mechanical properties of the heat treatable alloy, and Deformation Control Technology, Inc. (DCT) developing the predictive software tool. DCT had developed a finite element based tool for steel alloys, and this tool was modified to model solution treatment, age hardening and over-aging of alloy 7075. Once the framework of DANTE® was modified for aluminum and an appropriate database was developed for alloy 7075, the tool was applied to simulate the heat treatment of a commercial forging that resembled a "Tee" shape. The model results were compared to dimensional measurements made on the forged shape in the as-forged and after heat treatment conditions.

2.5.1 Main Findings

An experimental test program was conducted at CWRU to broadly characterize alloy 7075 in the solution treated, over-aged and age hardened conditions. The testing program included room temperature electrical resistivity measurements for these microstructures at various times during heat treatment, hardness and tension tests also conducted to determine properties at various times during heat treatment, microstructural characterization, and dimensional change data.

Kinetics models were developed and implemented into DCT's DANTE® software for prediction of the heat treatment response to 7075 aluminum parts. The kinetics models covered the commercially important transformations of solution treatment, age hardening and over-aging. The mathematical relationship was simplified by defining critical temperature ranges of importance for each transformation, and assuming that these diffusion controlled reactions had a linear formation rate based on the natural logarithm of time.

The mechanical test data, augmented by published mechanical property data for 7075 aluminum, was used to determine DANTE® mechanical parameters for the solution treated, age hardened and over-aged conditions. These parameters are used by the modified Bammann-Chiesa-Johnson internal state variable (ISV) model implemented in the DANTE® software. These parameters describe the phases plasticity characteristics, including yielding, hardening and recovery mechanics.

A comparison of model results with measured results for dimensional change showed close agreement for dimensional change during age hardening, cf. strain of 0.0004 predicted by the model, and 0.0004 to 0.0006 measured from test samples at CWRU.

Total dimensional change for the "Tee" forging and the model showed the same trends, but the values were different. This difference was due to heat transfer differences between the actual process and the perfect conditions of the model. Both the part and the model showed that bending occurred. Also, circular cylindrical section warped and non-uniformity of the cylinder surfaces developed.

For this part, thermal stress during quenching was the main source of distortion in the aluminum parts, as shown by the model results.

2.5.2 Outcome

The feasibility of using predictive software for aluminum part heat treatment design was successfully demonstrated. Simulation of solution annealing resulted in over-aged material converting to solution treated material over a realistic time period. Quenching was shown to be sufficiently fast that the solution treated structure was retained. During subsequent age hardening, the solution treated phase converted to the age hardened phase. The mechanical properties changed appropriately as the phase makeup of the part changed. Also, the dimensions of the part changed appropriately. The result was that the stress state during the entire heat treatment was known.

Further work is needed to enhance the model capabilities and the accuracy of the data used to drive the models. The relationship between mechanical strength and hardness needs to be tuned. A main feature to add is the accelerating effect of cold work on the age hardening kinetics. It is well known that cold worked parts age non-uniformly, and this can lead to significant distortion during age hardening.

2.5.3 Benefits

This process and materials engineering project clearly demonstrated important benefits. Specifically, a comprehensive, validated software tool for predicting phase distributions, dimensional change, stress state during processing and potential cracking problems due to heat treatment. With a predictive software tool, process conditions and/or alloy grade selection can be defined to avoid cracking and distortion problems while still achieving desired microstructures. The benefits of using this software tool are many.

The ability to investigate dimensional change issues during process design before costly production mistakes or deficiencies have been experienced. This saves development time and cost, as well as allowing part shape to be optimized.

An optimum part shape allows minimum heating times during solution annealing and age hardening to be used. This minimizes energy usage. Finishing operations are also minimized, and this keeps material usage at a minimum.

A predictive software tool provides a method for reducing part rework and scrap.

A fully developed software tool can result in large energy and cost savings. A 10% savings in energy applied to aluminum alloy parts production means a savings of 8.6T BTU's annually, which is roughly $77M annually. This is based on 50% of the annual aluminum production going into discrete parts.

The process model can be used by designers and manufacturing engineers to address the following manufacturing issues affecting energy use inefficiencies and waste.

2.5.4 Conclusions

A software tool to predict the response of age hardenable aluminum alloys has been developed and demonstrated for 7075 aluminum. The tool capabilities include prediction of residual stress, dimensional change and phase amounts and distributions. The tool can be used to determine proper heat treat schedules so that scrap and energy usage can be minimized.

Feasibility for the use of a process engineering design tool to promote energy efficient production of aluminum alloy parts has been demonstrated for 7075 aluminum.

Design tool utility can be expanded through further work specifically in development of a more accurate and more comprehensive database for age hardenable aluminum alloys. At this point, the accuracy of the shrinkage calculation during age hardening is acceptable. Other data, such as thermal expansion, should be re-checked. The main source of distortion and potential cracking is thermal stress during quenching of solution treated material.

The thermal conductivity of aluminum is sufficiently high that critical thermal gradients are typically experienced only during quenching. Cracking is typically only an issue for large bulky products that are solution treated and quenched, such as ingots.

2.6 Ultra-Lightweight Sandwich Composite Constructions for Autobody Applications (130176)

Sandwich composite structures common in aerospace applications offer exceptional SWRs; but they have not yet been investigated and adapted for automotive applications.

The new core and facing material combinations chosen for this investigation were uniquely suitable for the requirements of automotive structural applications.

This project modeled revolutionary new ultra-lightweight sandwich composite structure technologies for significant weight reduction in vehicles. These structures achieved strength targets and accomplished weight reductions far beyond those feasible using present stamped steel/aluminum welded car body construction methods.

The purpose of this R&D project effort was to develop strategies for sandwich composite construction technologies for significant weight reduction for automotive applications and to develop computationally efficient models to predict the behavior of sandwich composites using model-based brokerage portals.

2.6.1 Static Behavior and Modeling Introduction

Prior to this research these composites were limited to the aerospace industry due to its high cost and manufacturing difficulties. A new low-cost material and its understanding of behavior under various conditions would allow composite materials for several applications in multiple industries. For applications in the automotive industry weight savings and strength of structure influenced the work with respect to lightweight sandwich composite materials. This research work focused on the analysis of glass fiber reinforced polymer (GFRP)/balsawood sandwich composite panels subjected under flexure.

Sandwich composite panels were analyzed under three-point flexure tests for understanding flexural behavior and failure mechanisms. Study on effect of padding to avoid locally induced stresses on skin were also analyzed with Teflon and rubber pad.

Curing Sandwich Composite Without External Adhesive – E-glass/epoxy pre-pregs were directly layered on the core and cured together. Good adhesion at the skin and core interface was found in all the sandwich beams with balsa core, as the epoxy from the pre-preg flows into the pores in balsawood creating a strong bond.

Failure Mode Assessment of GFRP/Balsa Sandwich Composite – Sandwich composite with soft core such as regular balsa exhibited failure due to indentation of skin, which was followed by skin failure or core failure. In case of sandwich beam with end-grain balsa core, skin failure was the dominant mode of failure. With adequate span length, core shear failure and de-bonding of skin-core interface was not a concern with balsa core sandwich composite. The failure modes were also correlated with flexural behavior of sandwich structure (load-displacement curve) which was helpful for full structural analysis.

Effect of Core Grain Orientation on Sandwich Composite – Bending stiffness, strength and failure modes were strongly influenced with core grain orientation in the sandwich composite. Sandwich panels with end-grain balsa core offered better energy absorption, but catastrophic skin failure with huge load drop was observed. Overall shear resistance of balsa was considerably good with least resistance when loaded tangentially to balsa grain direction.

Effect of Padding on Sandwich Composite Beam – Overall flexural behavior of sandwich composite was not affected with the use of padding. Failure mode could change from skin failure to core shear failure, as direct stress on skin was distributed.

Finite Element Analysis (FEA) – Good correlation in all the sandwich composite models was found between FEA and experimental results. FEA confirmed the bi-modulus behavior of E-glass/epoxy laminates. In sandwich beam with soft core (regular balsa), before skin failure higher stress concentration was found next to the loading pin, whereas in sandwich beam with end-grain balsa core maximum stress was found below the loading-pin. Stress contour of sandwich beam with padding showed reduction in normal stresses on top-skin with influence of shear stress on more area in the core. Also, local bending of skin was reduced for same flexural deflection with the use of padding. It was difficult to conclude on core shear failure using FEA results, as more research on balsa wood is required.

2.6.2 Dynamic Behavior and Modeling

A number of tests under different impact energies were conducted where the results of these tests show that the damage modes are fiber fracture at upper and lower skins, delamination between adjacent glass-epoxy layers, core shear fractures and face/core de-bonding. In addition to the single impacts, repeated impact response of the samples was also investigated. The delamination area was one of the parameters that was used in the evaluation of the impact response of composite sandwich panels. Therefore, it was necessary to use precise methods to estimate the size of damage, in this case the damage was very clear. Visual inspection was possible and best for end-grain balsa/glass fiber sandwich composites.

Due to the symmetry of the sandwich composite plate geometry, boundary conditions and loading, one quarter of the plate was simulated. Tensile and compression testing for both core and face sheets in fiber and cross fiber were conducted to determine the properties of end-grain balsawood core and glass fiber/epoxy. There were three main failure mechanisms observed, including delamination, fiber breakage and matrix cracking, after the specimens were subjected to impact.

This work was done to investigate damage behavior of sandwich composite plates comprising of E-glass/epoxy composite laminate face-sheets and end-grain balsawood core under low velocity impact. The experimental data was utilized to build a FEM to predict the behavior of the sandwich composite. Deflection time response, load time and kinetic energy time were presented experimentally and numerically. Good agreements were obtained by comparing numerical and experimental results.

2.6.3 Web Portal for Computational Analysis

Nimbis Services, Inc., under contract from the NCMS, developed, maintained, and supported a secure cloud portal for on-demand procurement and access to technical computing applications.

The web portal set up by Nimbis was effective and allowed the team to freely use the necessary software to perform analyses for both the static and dynamic models. The target HPC platform for the portal was the Glenn cluster at Ohio Supercomputer Center (OSC). The pilot LAMP users of the Nimbis LAMP portal at OSC were Wayne State University (WSU) students and researchers. The FEA M&S applications provided through the portal included ABAQUS, ANSYS, LS-DYNA, and Hypermesh. The portal supports batch solvers running parallel jobs on a cluster of compute nodes and interactive pre-and post-processing of job inputs and outputs running on a graphics processing unit (GPU) node. Academic licenses for the application software were provided by OSC to WSU users. The web portal set up by Nimbis was effective and allowed the team to freely use the necessary software to perform analysis for both the static and dynamic models.

2.6.4 Conclusions

Sandwich composites offer significant weight reduction for structural parts for automobiles. The key findings and outcomes achieved in the project were:

- Sandwich composite with soft core such as regular balsa exhibited failure due to indentation of skin, which was followed by skin failure or core failure. In case of sandwich beam with end-grain balsa core, skin failure was the dominant mode of failure. With adequate span length, core shear failure and de-bonding of skin-core interface was not a concern with the balsa core sandwich composite.
- Bending stiffness, strength and failure modes were strongly influenced with core grain orientation in the sandwich composite. Sandwich panels with end-grain balsa core offered better energy absorption, but catastrophic skin failure with huge load drop was observed.
- Good correlation in all the sandwich composite models was found between FEA and experimental results. FEA confirmed the bi-modulus behavior of E-glass/epoxy laminates. In sandwich beam with soft core (regular balsa) before skin failure, higher stress concentration was found next to the loading pin, whereas in sandwich beam with end-grain balsa core maximum stress was found below the loading pin.
- This work was done to investigate damage behavior of sandwich composite plates comprised of E-glass/epoxy composite laminate face-sheets and end-grain balsa-wood core under low-velocity impact. The experimental data was utilized to build a FEM to predict the behavior of the sandwich composite. Visual inspection was presented of the delamination area due to low velocity impact. Deflection time response, load time and kinetic energy time were presented experimentally and numerically. Good agreements were obtained by comparing numerical and experimental results.
- The web portal set up by Nimbis Services was effective and allowed the team to freely use the necessary software to perform analysis for both the static and dynamic models.

The benefits of the R&D effort identified glass fiber composite/balsa core sandwich composites and their processing methods for automotive applications in stiffness critical applications. Design tools such as computational modeling schemes have been realized that will allow development of the sandwich construction for both static and impact performance. The computational schemes also allow predicting the response of the composite under both flexural loading and dynamic planar impact. These R&D results confirm that material, process method, and design for performance can be successfully realized for this class of composites for weight reduction in automotive composite application.

2.7 Lightweight Fiber Composite Structures with Embedded Communications (130177)

The purpose of this project funded was to investigate the feasibility of using a high-volume, low-cost, composite manufacturing process for the embedding of fiber-optic cabling in a continuous-fiber composite floor pan for high-speed communications within the vehicle. Continuous-fiber composites or “aligned fiber” technology is considered to be the technology of choice for manufacturing lightweight vehicle components.

It was accomplished using a combination of experimental methods and FEM to explore the formability of unidirectional prepreg non-crimp fabrics (NCF). The experimental project provided the necessary data to characterize the mechanical behavior of the fabric during a forming process and to provide data for investigating the credibility of the FEM to describe the behavior of the fabric during the forming process. As opposed to a fabric draping model that can only consider the kinematics of the fabric behavior, the forming models used in the current project also consider the mechanical behavior of the fabric during the forming process. This inclusion of the mechanical behavior gives the model the ability to predict if and where defects such as fabric wrinkling, fabric folding and fabric tearing may occur in the formed part. The output of the forming simulation provides a high-fidelity map of fiber location and orientation throughout the thermostamping process. The simulation tool has the potential to accommodate a seamless transition from the forming of the part to a structural analysis of the cured composite. The result is a structural model of a formed composite that is a one-to-one match with that of an actual manufactured part. The structural modeling methods currently used by industry require the engineer to make assumptions about fiber directions and locations over large areas of the formed composite structure in the FEM – often called a zone-based model. Thus, the zone-based approach comprises the fidelity of the model and often requires the use of knockdown factors to compensate for uncertainties in the modeling method, which will result in an overweight design. Only upon subsequently pursuing a time consuming and expensive trial-and-error test project can the design of the composite structure be made so as to determine an optimal weight. Such a compromise of the structural model is not required for the simulations completed in the current project. The simulation methodology not only assists in removing the concern of uncertainties in the quality of the formed part, but it can also be used to link the structural response back to the manufacturing process. Thus, the simulation tool can be used to guide the manufacturing process to get a desired target structural behavior, such as overall effective stiffness of the formed part as well as localized increases or decreases in stiffness.

A hybrid finite element discrete mesoscopic approach was used to predict the quality of the final part based on manufacturing processing parameters. This approach required that the mechanical behavior of the fabric and the friction between the fabric layers and the metal tooling be well characterized as a function of fabric architecture. Two prepreg fabric architectures were considered for the forming of the composite parts: a double-bias stitched NCF fabric and a unidirectional glass NCF. The stitching in the double-bias fabric was found to facilitate excessive wrinkling of the fabric when sheared whereas the unidirectional NCF did not experience out-of-plane buckling during shear. However, the lack of stitching to keep the unidirectional fibers in place did allow for the yarns to spread and bunch during forming, i.e. swim. The unidirectional fabric exhibited a different shear response than what has been observed with traditional woven fabrics, i.e. the shape of the load-deformation curve was flipped.

To prevent wrinkling during the composite forming process, it was necessary to develop in-plane tensile forces in the fabric. These in-plane forces are a result of inter-ply and fabric-to-tool frictional forces. Fabric-to-fabric and tool-to-fabric friction characterization tests were performed to obtain the static and dynamic friction coefficients for a layer of fabric sliding against another layer of fabric and for a layer of fabric sliding against the tooling surface, respectively. Friction testing was completed for steel and aluminum tooling surfaces for a variety of surface finishes, and the friction was concluded to be a function of temperature, rate and normal force. Friction was observed to be a function of surface finish at room temperature but was independent of surface finish at the processing temperature of 50°C (122°F). Thus, it was concluded that the viscosity of the resin at the processing temperature was relatively low and provided uniform lubrication between the mating surfaces regardless of the surface finishes considered in this project.

The experimentally determined material properties were incorporated into an ABAQUS/EXPLICIT FEM via user-defined material subroutine, VUMAT. Each ply was modeled as an independent layer so the relative movement of adjacent plies and the movement of the yarns within a ply could be considered by the model. By modeling each fabric layer independently, the composite design engineer has the freedom to remove or add plies and to rearrange the stack-up easily.

To demonstrate the credibility of the simulation method, the virtual forming of a hemisphere was completed, and the results of the simulations were compared to experimentally formed parts. The simulations compared well with the experimental parts upon a visual inspection. When using the unidirectional unstitched NCF to form a deep draw as that of a hemisphere, there was a tendency for the yarns to “swim” during the forming process leading to spreading and bunching of the yarns. The simulation captured this “swimming” phenomenon very well.

The FEM was subsequently used to explore the possibility of forming a composite part with an inter-laminate fiber-optic cabling for high-speed communications within a vehicle. The initial efforts to characterize the “formability” of embedded fiber-optic cabling in composite panels progressed through iterative modeling exercises and one forming experiment at Philadelphia University. The initial fiber-optic forming studies indicated some limitations relative to the formability of a fiber-optic cable. These limitations are primarily driven by part geometry and the bend radius of the currently available optic fiber/cable.

The project then progressed to exploring the feasibility of making selective cuts in the fabric. These cuts aid the forming process by reducing the tensile strains in the fabric as it conforms to out-of-plane features in the part, e.g. ribs. The Lincoln MKZ hood inner was identified as the demonstration part for the application of the simulation to using selective cuts.

Because out-of-plane waviness is a serious concern when forming a composite using a fabric reinforcement, the ability of the model to consider the relationship between the bending stiffness of the fabric and the potential to form waves was explored using the proposed simulation methodology. The model showed that it was capable of predicting the formation of out-of-plane waves and the subsequent deformation of the waves to develop folds. Thus, with an understanding of the processing conditions that can lead to the formation of waves, steps can be taken in the design of the manufacturing process to avoid the conditions that lead to these defects.

The preprocessing and simulation software developed as part of this LAMP research project will support the applications development phase of a new automotive program and enable the "Design for Manufacture" approach demanded by today's OEMs in the early product development project phase. Manufacturing simulation models currently exist for metals forming and injection molding of plastics. This innovative software will help drive the use of aligned fiber composites in a variety of applications and markets beyond automotive including military and heavy truck. This continuous fiber forming software will have a significant impact on the practical realization of continuous fiber composites in high-volume automotive applications.

MAG Industrial Automated Systems (MAG-IAS) built technology demonstrator equipment capable of producing surrogate parts and established an alliance with a part fabricator partner that is now willing to provide a surrogate part mold and forming press. The mold geometry was for a Lincoln MKZ hood inner. MAG located the technology demonstrator equipment at the partner's site to produce surrogate prototype parts. Simulations of the forming of the hood inner using selective cuts in the fabric to reduce the tensile forces that can develop due to "hills and valleys" in the part geometry were conducted. The simulations showed that the potential for fabric tearing could be eliminated through the use of the selective cuts without compromising the structural quality of the formed part.

Initial steps into exploring the ability of the simulation tool to link the structural stiffness of the formed part back to the manufacturing process were taken. Flat composite plates with one, three and five plies were modeled using the cured material properties of the polymer matrix and the fiberglass yarns. Corresponding plates of the same ply configurations were tested. The correlation of the mode shapes and natural frequencies of the cured composite plates between the experimental data and the FEMs concluded that the link between the manufacturing process and the resulting structural performance can be accomplished.

2.7.1 Conclusions

The mechanical behavior of a non-stitched unidirectional prepreg fabric and a stitched double-bias prepreg NCF that would be used for the manufacture of automotive parts in a thermostamping process was characterized through a series of mechanical characterization tests and forming experiments and then simulated using a discrete mesoscopic FEM. The mechanical behavior of the fabrics, which consisted of the tensile stiffness of the yarns and stitches, the in-plane shear stiffness, and the friction behavior between contacting layers of fabric as well as the tooling surface, was implemented into the ABAQUS/EXPLICIT FEM of the fabrics using 1-D beam and 2-D shell elements via a user-defined material subroutine VUMAT. Even though ABAQUS/EXPLICIT was chosen for this project, the process was not limited to just this software. It could be used with any commercially-available finite element package that allows for user-defined material models such as LS-DYNA.

Uniaxial tensile tests were performed to capture the tensile stiffness of the fabric yarns. Shear frame tests were completed to measure the in-plane shear stiffness of the fabrics at room and at the processing temperature of 50°C (122°F). The unidirectional fabric exhibited different shear behavior compared to what has been observed in the past with traditional woven fabrics. The through-thickness stitching of the double-bias fabric played an important role in its in-plane shear and out-of-plane wrinkling behavior. The in-plane shear stiffness was significantly higher when the stitching was oriented parallel to the direction of deformation as compared to when it was oriented perpendicular. A friction test apparatus previously developed at University of Massachusetts – Lowell (UML) was used to determine the static and dynamic coefficients of friction at the processing temperature between contacting layers of fabric and between a layer of fabric with the tooling surface. Once the mechanical behavior of the fabrics was characterized and implemented into the FEMs for each, simulations of the shear frame test were successfully completed as a validation of the modeling methodology. The through-thickness stitching in the double-bias fabric was modeled to allow for accurate representation of the shear stiffness in the forming simulations based on its orientation.

The modeling methodology used in this project was originally developed for a United States Council for Automotive Research (USCAR) project. The methodology has been shown to work well for stitched unidirectional, biaxial and triaxial NCFs used in the manufacture of wind turbine blades. The modeling approach, however, had not been demonstrated for unstitched unidirectional prepreg fabrics. Thus, to further investigate the validity of the modeling approach using the unidirectional fabric, forming simulations with various geometries were performed. The results from a physically formed hemisphere part were qualitatively compared to those of the finite element simulation. The FEM predicted very well the fiber bunching and separation defects noticed during the forming experiment. Forming simulations with an automotive rear tub and a floor pan were also performed using the unidirectional prepreg fabric to explore further the ability of the FEM to conform to complex geometries and fine tune various input parameters used in the FEM. The results from the forming simulations showed large shearing in the regions where the fabric deformed to conform to the deep-draw curvatures of the parts. It was concluded from the characterization tests that the shear capability of this fabric is fairly low and exceeded its locking angle which led to the formation of out-of-plane wrinkling defects. Therefore, the unidirectional fabric is best suitable for the formation of parts with a fairly flat geometry such as the outer of an automotive hood, trunk lids, and doors.

While the outer of a hood is a fairly flat surface that would be well suited for the unidirectional fabric, the hood inner contains many structural elements that could present challenges during the manufacturing process. Forming simulations using an x-hat section from a structural member of a hood inner were completed. A significant difference in the drapability of the unidirectional fabric was observed based on the fabric orientation. The maximum shear deformation for the 0°/90° fabric orientation was below the locking angle for the unidirectional prepreg material of approximately 20°. The ±45° layup, however, was above the locking angle and approximately twice the maximum shear angle observed with the 0°/90° configuration. Thus, the 0°/90° orientation would be more favorable when making this part.

In addition to tracking the deformation and final orientation of the yarns during forming, the simulation tool could further be used by the part designer to explore changes in the geometry of the part to prevent defects from forming. Forming simulations using an international double-dome benchmarking tool were performed to explore the capabilities of the FEM to accommodate the presence of cabling and the tooling modifications required to do so. Even though the protective coating of the currently available fiber-optic cables for vehicle applications is not suitable for the high temperature of 150°C (302°F) needed to cure the unidirectional prepreg fabric after it has been formed, a hypothetical representation of the cable was modeled. The significantly larger thickness of the protective coating compared to the fabric yarns prevented pressure from being applied to the fabric layers when the mold was fully closed which led to the formation of pocket defects around the area of the cable. Modification to the tooling helped avoid the formation of the gap defects in that area. The mesh density of the fabric just around the cable also was refined to allow the shell elements to conform tightly to the shape of the cable without significantly increasing computational time.

The forming simulations performed in this project using the FEM were excellent examples of its potential to be used as a design-aid to simulate the composite forming process. Such a design-aid tool could be used to investigate the effect of changes to the tooling geometry as well as to improve the manufacturing process by exploring various process parameters such as the number of fabric layers used and their orientation to allow for a part to be formed without defects such as wrinkles, folds, or tearing while maintaining a short cycle time.

2.8 Simplified Computational Fluid Dynamics (CFD) Analysis of Tow Vehicle & Trailer Bodies (130181)

Small and medium-sized manufacturers in Ohio are under constant economic pressure to deliver high-quality, low-cost products. Many large manufacturers have embraced simulation-driven design to achieve a degree of market advantage. Simulation-driven design replaces physical product prototyping with less expensive computer simulations, reducing the time to market, while improving quality and cutting costs.

CFD analysis is commonly used by major automotive and truck manufacturers; however, small to medium-sized suppliers in niche markets such as trailers and after-market devices often lack the resources to harness such HPC-enabled technologies. The low level of usage is due to a combination of lack of expertise as well as a scarcity of necessary in-house computational infrastructure. Typically, high barriers to entry exist in undertaking any aerodynamic development program, either in designing and building scale models, utilizing full-scale wind tunnels, or starting a CFD program.

To address the barriers that small manufacturers typically face, OSC a member of the OH-TECH Consortium, and industry partners launched this project in 2011. The goal of the project was to address these issues by developing an easy-to-use and inexpensive way to leverage HPC resources in the automotive industry.

The Truck Add-On Predictor portal allows trailer designers and parts suppliers to model the airflow and the corresponding aerodynamic forces over a tractor/trailer through the application of OpenFOAM®, an industry-standard, open source CFD code developed and supported by the commercial company OpenCFD Ltd. By understanding the forces on the various surfaces, designers and suppliers can reduce the weight of key structural components, replace them with other materials or utilized novel shapes while potentially increasing the aerodynamic efficiency of the trailer. The use of CFD analysis speeds up time-to-market for suppliers and saves money by eliminating much of the costly and inefficient physical testing process.

The portal was developed in multiple phases:

- User Interface and Pre-Processing
- Job Submission and Stability Analysis
- Graphical User Interface (GUI)
- Portal Testing.

The first phase involved creating a simulation based on various parameters predetermined by the project team and provided by the user.

The second phase involved creating a process for submission of a job to the server. After submission, project partners SimaFore and TotalSim identified parameters within trial results that might be changed to optimize the results for future simulations.

During the third phase, partners finalized the design of a portal platform through which users can launch multiple simulation runs. Project partner Nimbis Services worked with OSC to develop an easy-to-access interface.

The final stage of portal development involved testing the Predictor. TotalSim performed a vast quantity of tests to improve initial aspects of the portal and the prediction capability of the CFD tool.

A complete Truck Add-On Predictor product, the major deliverable of the project, now exists on the Nimbis portal, listed with other OSC Blue Collar Computing (BCC) products in the Nimbis Services Marketplace and including a BCC store registration form detailing user terms and conditions.

2.8.1 Results

The actual Truck Add-On Predictor remains available online via the Nimbis Services Marketplace. Notable capabilities of this portal include:

- Inclusion of a baseline truck/trailer geometry contributed by SOLUS and rough wireframe of the model available for download.
- User access to default simulation results from a suite of J1252 runs at 65 mph that can be altered for additional design variations.
- Inclusion of an arbitrary number of add-on STL files.
- Calculation of a wind-averaged drag coefficient for a suite of J1252 runs during post-processing stages.
- Production of a CSV report of important model parameters and CFD results.
- Production of an HTML report with high level slice pictures and data.
- Comparison of results for two or more CFD simulations.
- Completion of a simulation stability analysis after each run.
- Flexible tiered payment structure including subscription and pay-as-you-go pricing.
- Software-as-a-Service model.

2.8.2 Benefits

The completion of the Truck Add-On Predictor project has produced a number of tangible benefits and deliverables and will continue to be a valuable asset to manufacturers and parts suppliers during the remainder of its lifecycle. These benefits include:

- Increased ease-of-access to HPC-based M&S.
- Reduced cost of services.
- Reliability of design predictions.
- Cycle time savings.
- Inter-organizational collaboration.

2.9 Ultra-Lightweight Sandwich Composite Constructions for Autobody Applications – A Predictive Simulation Approach (130182)

This project demonstrated that lightweighting via sandwich constructions can be achieved and predictive tools are in place to allow utilization of this technology for automotive composite parts.

A composite is defined as a combination of two or more different materials; each one of them keeps its own distinctive properties, to create a new material with properties that cannot be achieved by any of the components acting alone. Using this definition, it can be determined that a wide range of engineering materials fall into this category. For instance, concrete is a composite because it is a mixture of Portland cement and aggregate. Fiberglass sheet is a composite since it is made of glass fibers imbedded in a polymer.

Composite Laminates –can be defined as layers of fibrous composite material which are joined together to provide required properties like in-plane stiffness, bending stiffness, strength and coefficient of thermal expansion. The individual layers consist of high modulus, high-strength fibers in a polymeric metallic or ceramic matrix material. Typical fibers include graphite, glass boron and silicon carbide, and some matrix materials are epoxies, polyimide, aluminum, titanium.

Layers of different materials may be used, resulting in a hybrid laminate. The single plys generally are orthotropic or transversely isotropic with the laminate then exhibiting anisotropic, orthotropic, or quasi-isotropic properties.

Sandwich Composite – consists of two thin stiff laminates bonded with a low density material in between. ASTM defines a sandwich structure as follows "A structural sandwich is a special form of a laminated composite comprising of a combination of different materials that are bonded to each other so as to utilize the properties of each separate component to the structural advantage of the whole assembly."

In a sandwich composite, skin will be adhesively bonded to the core for transferring the load between the components, thereby one skin acts in compression as the other skin acts under tension and the core resists the shear loads. This provides high stiffness, bending rigidity, SWR and energy absorbing capability to the structure. The bond must be strong enough to resist shear and tensile stresses in the sandwich panel.

The sandwich panel can be compared to an I-beam, as the skin corresponds to flange of the I-section beam and the core corresponds to the web.

Currently, various type of cores such as polymeric foam, honeycomb, aluminum foam, and balsa have been used, and they have different damage behavior when subjected to a low-velocity impact.

Impact by foreign objects can be expected to occur during structure life such as tool drops on a sandwich structure. In this case impact velocity is small but the mass of the tool is large. Impact also can be occurred by high energy events such as ballistic penetration. Low-velocity impact may induce damage in composite structures like matrix crack, fiber fracture, fiber kinking, and delamination, which may significantly reduce the strength of the material and finally cause the material to fail without any warning. A FEA per LS-DYNA was utilized to predict the response of composite laminates and balsawood sandwich composite car hood samples under dynamic loading.

The project involved experimental and numerical investigation of impact response of E-glass/vinyl-ester laminate car hood panel and sandwich composite car hood panel comprised of E-glass/toughened vinyl-ester composite laminate face-sheets and balsawood core under low-velocity impact.

Low-velocity impact tests were performed by driving the impacting pendulum by using a pneumatic device at a velocity of 30.6 kph (19 mph) to evaluate the impact response of the laminated and sandwich composite car hood panels. The composite car hood panels were tested at various speeds until adequate visual damage was seen. Impact test results which included load-time and load-deflection history from experimental study performed at 200KJ impact energy are presented. Hypermesh was used to develop the CAD and FEMs. LS-PREPOST was used to setup FEA as per LS-DYNA control cards.

Computational procedures were developed to predict the impact performance of the automotive structures with sandwich constructions. Experimental and predicted results matched well in terms of load-deflection response and kinetic energy.

The project utilized the production knowledge base of MAG-IAS and computational FEA portals of Nimbis in conjunction with WSU's knowledge of composite structural analysis, materials performance and understanding of anisotropic properties of composites.

This project provides new information about lightweight sandwich composites for potential applications in the automotive industry with greater confidence.

3. Manufacturing Risk Assessment

3.1 Manufacturing Risk and Vulnerability

The objective was to identify which, among the nine LAMP projects in Section 2 of this report would require a detailed and sophisticated risk analysis assessment. The goal was not to actually conduct the risk assessment itself, but to essentially short list those projects which would require a detailed risk assessment. In order to achieve this objective, the first step was to evaluate all the projects from a standard risk management perspective and if possible assign an overall risk rating from a manufacturing viewpoint.

What Constitutes Manufacturing Risk and Vulnerability

There are several areas which are pertinent to manufacturing risk: workforce risk, workmen's compensation risk, product recall and liability risk, environmental exposure risk and supply chain network risk. In the context of this analysis, the focus was on three main risk areas – product recall and liability, environmental exposure, and supply chain network. This was because the projects (if implemented in a production scenario) would entail no new risks along the dimensions of workforce, or workmen's compensation risks.

Risk 1 (R1) – Product Recall and Liability

Unique liability challenges exist for businesses in relation to the manufacture, sale, and distribution of products that would be the result of the newly developed manufacturing processes described in these projects. This includes warranty issues relating to the performance of the products.

Risk 2 (R2) – Environmental Exposure

With an increase in the U.S. Environmental Protection Agency's (EPA) enforcement activities, new environmental reporting requirements and uncertainty regarding climate-change laws and regulations, financial assurance and other emerging issues, most industry sectors are seeing an increase in their environmental exposures. The manufacturing processes described in these projects were evaluated against conventional manufacturing in order to determine potentially new environmental risks. If the processes did not substantially differ from traditional and well established processes, added risk was assumed to be minimal.

Risk 3 (R3) – Supply Chain Network

Supply chain risks include everything from natural hazards, terrorism, pandemics, and data security to demand variability and supply fluctuations. In this case however, NCMS only focused on risk brought about from supply fluctuations because of newer and advanced materials employed in the described manufacturing processes.

For each of the projects, the potential risk along these three dimensions was examined in order to determine which projects would require a more thorough and sophisticated risk analysis.

Each project was scored with a rating system of 1-10. Lower scores reflect no need for further pursuit of a detailed and sophisticated risk analysis assessment.

3.1.1 Automotive Component Manufacture in Titanium (130171)

R1 – Product Recall and Liability Risk: The project describes the use of titanium for automotive components. The major contributors to recall and liability risk would stem from a wear or corrosion triggered potential failure of the components. Titanium has a higher SWR than steel (the competing material), but it is still of lower strength per *volume* than most steel grades. Strength should be accounted for in part redesign, but does not pose a risk. However since, titanium is extensively used in the aerospace industry, specifically for its high SWR and high corrosion resistance, this particular risk is not a significant issue. **Score 2/10**

R2 – Environmental Exposure Risk: All processes used in the manufacture of the components described in the project are well-established, traditional processes such as welding, forming and machining. A new process involving electrically-assisted machining was recommended, which would only reduce the machining time and hence not have an adverse impact on environmental factors. Therefore, this particular risk dimension is also not a significant one. **Score 2/10**

R3 – Supply Chain Network Risk: Current worldwide supply base of titanium provides 150-200 metric tons (330.690-440.920 lbs.)/year of the material, most of which is consumed in the aerospace industry. The U.S. supplies about 40% of the world mill products. However, should the automotive industry adopt titanium on a large scale and in a very short period of time, there may be a ***moderate to high risk*** originating due to potential shortages. There is very little excess capacity in the supply base and at current volumes it would not be able to handle a requirement of more than 0.9kg (2 lbs.)/vehicle. Additionally, the issue of supply timing would be a critical factor. Currently the average supply timing for titanium alloy parts varies between 4 to 6 weeks. In the automotive industry where many parts are sourced to be delivered “just-in-time” for manufacturing, this would cause significant bottlenecks. **Score 7/10**

Overall Risk Score: 3.7/10.0

3.1.2 Lightweight Material Usage Optimization for Multi-Mode Safety, Noise, Vibration, Hardness and Durability Performance using High Performance Computing (HPC) (130172)

The objective of this project was to optimize the design of a vehicle body by utilizing structural composites. The simulations provided a virtual proving ground and the results indicated a saving of 3kg (6.6 lbs.) of body structure mass while increasing crash performance by 12%. No new manufacturing processes were envisaged – simply the possibility of using advanced structural composites in vehicle body parts were systematically investigated.

R1 – Product Recall and Liability Risk: For the crash test scenarios examined – roof strength (FMVSS 216) and side impact (IIHS Side Impact) – a sequence of optimizations were able to define part designs in two areas. The first solution was able to reduce body structure weight while maintaining constant performance. This design was built upon iteratively to generate the final, optimal solution which increased performance 12% while actually reducing the body structures mass. Therefore no significant increases in recall or liability risks are expected. **Score 2/10**

R2 – Environmental Exposure Risk: No new manufacturing processes are recommended in this project. The goal was to substitute currently manufactured structural composites into existing vehicle designs. Due to this reason, no *new* environmental impact is expected from the manufacture of individual parts. **Score 2/10**

R3 – Supply Chain Network Risk: If the recommended changes in vehicle parts from conventional materials to structural composites are adopted by the vehicle manufacturers, this would require an increase in investment for composite production equipment at the suppliers. Additionally, it would also require investment in hardware/software and personnel training to prepare engineers and designers at supplier companies to meet scaled up demand for such parts. All these additional investments could potentially slow down the adoption of the technology or discourage existing suppliers from making rapid investments. This could result in some initial supply problems should the industry decide to adopt such advanced materials in their production vehicles. **Score 5/10**

Overall Risk Score: 3/10

3.1.3 Ultra-Fine Grained/Nano Aluminum Material for Connecting Rods (130173)

This project evaluated the potential for using a non-traditional material for internal combustion engine connecting rods with a view to reduce the mass of the part. Aluminum alloys offer a significant mass reduction compared to steel alloys owing to their lower density; however, if used for a structural component such as a connecting rod, special requirements including fatigue resistance and thermal stability must be met. The base aluminum material was processed to improve microstructure and physical properties, which resulted in a 25% improvement in fatigue strength. The total mass reduction compared to the volume production forged steel part was 46%. The target market for this type of connecting rod is the hybrid and range extender performance engines.

R1 – Product Recall and Liability Risk: The modified components were tested in both physical and virtual environments. It was determined that all components successfully passed testing. No change occurred to the center-to-center distance, bend or twist on any parts, indicating that the components were structurally sound and no buckling or bending occurred. Based on this conclusion from the report, it is estimated that recall and liability risk that could potentially stem from large scale production would be fairly low. **Score 3/10**

R2 – Environmental Exposure Risk: The modified parts were produced by making custom modifications to existing forging processes. However, these processes are not expected to significantly alter the environmental performance of the manufacturing plant as they do not require new chemistries, or process steps. They mostly require changes to process parameters and therefore are not expected to adversely contribute to the existing environmental impact such plants currently have. **Score 3/10**

R3 – Supply Chain Network Risk: Although the manufacturing processes are slightly more involved than traditional connecting rod material, the target market envisioned for this product is somewhat small in the current market (hybrids and performance engines). Also the raw materials involved (aluminum) is widely available. Therefore, any supply chain risks should automotive companies adopt this technology are also expected to be minimal. **Score 3/10**

Overall Score: 3/10

3.1.4 Low-Cost Resin System for Lightweight Polymer Matrix Composite (PMC) Components (130174)

This project describes the use of PMC for automotive components. Similar to the use of titanium described in 130171, the end goals of replacing currently used standard metal parts with advanced materials is the same: reduce weight without compromising safety and performance. Risk assessment for this project will be similar to 130171.

R1 – Product Recall and Liability Risk: The major contributors to recall and liability risk would stem from potential failure of the components. PMC has a higher SWR than steel (the competing material). Strength should be accounted for in part redesign, but does not pose a risk. However since, PMC is extensively used in the aerospace industry, specifically for its high SWR and high corrosion resistance, this particular risk is not a significant issue. **Score 2/10**

R2 – Environmental Exposure Risk: Similar types of composite structures are currently manufactured commercially for the aerospace industry. Degassing from resin processing is a reasonable well-managed environmental issue and large-scale manufacturing of such composites would not pose a challenge to meeting current environmental regulations. **Score 2/10**

R3 – Supply Chain Network Risk: As mentioned before, the aerospace industry sources and manufactures large volumes of similar composite structures. Unlike titanium, discussed earlier, there are no capacity issues should the automotive industry decide to adopt these materials for their products. Therefore, the overall supply chain network risk for manufacture of sandwich composites is projected to be quite low. **Score 2/10**

Overall Risk Score: 2.0/10.0

3.1.5 Thermal Processing of Aluminum Alloys (130175)

The purpose of the project was to develop a software tool capable of predicting the distortion, residual stress state and microstructural phases for heat treated aluminum alloys. The feasibility of using predictive software for aluminum part heat treatment design was successfully demonstrated. A fully developed software tool can result in large energy and cost savings. A 10% savings in energy applied to aluminum alloy parts production means a savings of 8.6T BTU's annually, which is roughly $77M annually. The following is a summary of the risks along the three main dimensions.

R1 – Product Recall and Liability Risk: There is no major change from the current manufacturing process of parts. Therefore any recall or liability risks are in line with existing risks of aluminum part manufacturing. **Score 2/10**

R2 – Environmental Exposure Risk: Applying the same logic as R1, because there are no deviations from current manufacturing processes in terms of any new quenching agents or heat treatment processes, it is expected that the environmental impact of adopting the recommendations from this research should be the same as current processes. **Score 2/10**

R3 – Supply Chain Network Risk: Some key recommendations from the project include monitoring of quenching process and improved systems for racking the processed parts. Improved monitoring requires investment in sensors and other related technologies. Upgraded racking systems are also important to minimize distortions of heat treated parts. Finally, current suppliers may also need to upgrade their software, hardware and personnel training in order to be able to fully support the design, analysis and production of these minimized distortion parts. All these additional investments could potentially slow down the adoption of the technology or discourage existing suppliers from making rapid investments. This could result in some initial supply problems should the industry decide to adopt such advanced alloys in their production vehicles. **Score 5/10**

Overall Risk Score: 3/10

3.1.6 Ultra-Lightweight Sandwich Composite Constructions for Autobody Applications (130176)

This project describes the application of sandwich composite materials in the automotive industry. The aim was to develop strategies for sandwich composite construction technologies for significant weight reduction for automotive applications and to develop computationally efficient models to predict the behavior of sandwich composites using model-based brokerage portals.

R1 – Product Recall and Liability Risk: The structural integrity of the investigated sandwich composite construction is significantly high and by themselves, any parts constructed using these composite would be fairly robust. However, this project did not investigate system level behavior of such composites. Specifically, there could be some potential issues while joining these composite structures to other traditional materials such as steel or aluminum. **Score 3/10**

R2 – Environmental Exposure Risk: Similar types of composite structures are currently manufactured commercially for the aerospace industry. Degassing from resin processing is a reasonable well-managed environmental issue and large scale manufacturing of such composites would not pose a challenge to meeting current environmental regulations. **Score 2/10**

R3 – Supply Chain Network Risk: As mentioned before, the aerospace industry sources and manufactures large volumes of similar composite structures. Unlike titanium, discussed earlier, there are no capacity issues should the automotive industry decide to adopt these materials for their products. Therefore the overall supply chain network risk for manufacture of sandwich composites is projected to be quite low. **Score 2/10**

Overall Risk Score: 2.33/10.0

3.1.7 Lightweight Fiber Composite Structures with Embedded Communications (130177)

The purpose of this research was to characterize the mechanical behavior of unidirectional and biaxial NCFs that could be used for forming of composite automotive parts with embedded cabling by performing simple tensile, shear and friction tests. The project was mostly simulation based, with the goal of verifying if a simulation tool could be used as an effective design-aid in building parts using NCF materials.

R1 – Product Recall and Liability Risk: The high SWR, corrosion resistance and tailored energy absorption characteristics compared to traditional metal formed parts indicates that a general in-field failure risk would be similar or lesser than currently used metal formed parts. The study built simulation models (and developed generic physical testing processes) to predict the final orientation of the yarns in the formed part as well as the formation of defects. Knowing the final orientation of the yarns provides a more accurate representation for determining the structural properties and permeability of the composite part. Using this knowledge in addition to real-world testing and validation analysis would result in a greatly reduced probability of recall and/or liability risk.
Score 2/10

R2 – Environmental Exposure Risk: Various manufacturing processes have been developed to produce NCF materials. The automotive industry has been exploring this technology for years using different manufacturing methods such as Resin Transfer Molding (RTM), VARTM, and Resin Film Infusion. As a result, no new processes need to be developed, only a proper selection of processing parameters need to be determined. Therefore, the environmental risk from manufacturing the experimental part are no higher than current production risks for similar widely used materials. **Score 2/10**

R3 – Supply Chain Network Risk: Liquid Resin Infusion technologies infuse resin into a dry fabric preform as a means of a cost-effective way to produce high-quality parts in high volume. Thermostamping process, which is similar to sheet metal stamping, is another attractive manufacturing process of composite parts. Thermostamping is especially attractive to the automotive industry due to its high efficiency. Parts can be formed and cured to their final shape in a single step within a short cycle time. Therefore it appears that supply risks, should the industry adopt such non-traditional materials would also be low. **Score 2/10**

Overall Risk Score: 2/10

3.1.8 Simplified Computational Fluid Dynamics (CFD) Analysis of Tow Vehicle & Trailer Bodies (130181)

This project describes and demonstrates a platform for the design and development of composite materials using HPC to improve fuel efficiency of tow vehicles and trailers. The aim was to pilot a low-cost analysis and simulation platform where add-on manufacturers (typically small and medium manufacturers) could quickly design and develop add-ons to improve truck fuel efficiency. An “app” style predictor that leverages existing HPC resources was developed and made available for small and medium manufacturers to utilize in their R&D stages. Risk assessment is performed assuming that these small and medium manufacturers will rapidly begin to engage the app to develop and market add-on products. Risk analysis is focused on the add-on products that could potentially be developed using the described process/platform.

R1 – Product Recall and Liability Risk: The structural integrity of the composite based add-on construction is significantly high and by themselves, any parts constructed using these composites would be fairly robust as described in other projects involving composites. Additionally, these add-on products are not utilized as structural members, but only as air flow optimizing features. Specifically, there could be some potential issues while joining these composite structures to other traditional materials such as steel or aluminum. However this project did not investigate a complete system level behavior of such composite add-ons. **Score 3/10**

R2 – Environmental Exposure Risk: Similar types of composite structures are currently manufactured commercially for the automotive and aerospace industry. Degassing from resin processing is a reasonable well-managed environmental issue and large scale manufacturing of such composites would not pose a challenge to meeting current environmental regulations. **Score 2/10**

R3 – Supply Chain Network Risk: As mentioned before, the aerospace industry sources and manufactures large volumes of similar composite structures. Unlike titanium, discussed earlier, there are no capacity issues should the automotive industry decide to adopt these materials for their products. Therefore the overall supply chain network risk for manufacture of composite add-ons is projected to be quite low. **Score 2/10**

Overall Risk Score: 2.33/10.0

3.1.9 Ultra-Lightweight Sandwich Composite Constructions for Autobody Applications – A Predictive Simulation Approach (130182)

This project is very similar in scope to the more extensive project on Ultra-Lightweight Sandwich Composites (130176), the risk assessments will therefore be identical.

R1 – Product Recall and Liability Risk: **Score 3/10**

R2 – Environmental Exposure Risk: **Score 2/10**

R3 – Supply Chain Network Risk: **Score 2/10**

Overall Risk Score: 2.33/10

Summary Table of Assessments of All Projects (Scale 1-10)

Project #	Project	Product Liability and Recall Risk	Environmental Exposure Risk	Supply Chain Risk	Overall Score
130171	Automotive Component Manufacture in Titanium	2	2	7	3.7
130172	Lightweight Material Usage Optimization for Multi-Mode Safety, Noise, Vibration, Hardness and Durability Performance using High Performance Computing (HPC)	2	2	5	3.0
130173	Ultra-Fine Grained/Nano Aluminum Material for Connecting Rods	2	2	7	3.7
130174	Low-Cost Resin System for Lightweight Polymer Matrix Composite (PMC) Components	2	2	2	2.0
130175	Thermal Processing of Aluminum Alloys	3	2	2	2.33
130176	Ultra-Lightweight Sandwich Composite Constructions for Autobody Applications	2	2	2	2.0
130177	Lightweight Fiber Composite Structures with Embedded Communications	3	2	2	2.33
130181	Simplified Computational Fluid Dynamics (CFD) Analysis of Tow Vehicle & Trailer Bodies	3	2	2	2.33
130182	Ultra-Lightweight Sandwich Composite Constructions for Autobody Applications – A Predictive Simulation Approach	3	3	3	3.0

4. Web-Based Information Clearing House

NCMS developed a website at http://lamp.ncms.org that provides the public with information regarding LAMP funded projects and activities. The site tells the story of what LAMP is, provides informative videos and the latest news in lightweight materials, summaries of completed and other related projects completed with links to project executive summaries.

5. Product Development Education and Outreach

NCMS has developed a website at http://doitindigital.com as a portal to provide the public with information about and access to digital manufacturing tools, training, and events. Phase I of the site was used as an outreach mechanism aimed at informing, engaging, and enticing manufacturers to adopt the digital manufacturing technologies through affordable pay-as-you go and bundled package pricing models. The site currently contains several informative videos about digital manufacturing, information about the Grid initiative, who is involved, Digital Manufacturing events, initiative timeline, and contact info. Also, using feedback from targeted user base, NCMS developed an visual design and a technical requirements document to be used as a guideline for Phase II of the website; implementation of digital manufacturing tools, training, and events marketplace and community.