6. Application of Innovative Materials

A. Carbon Fiber SMC for Class 8 Vehicle Hoods

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Contract No.: 4000010928

Objective

- Develop carbon fiber sheet molding compounds (SMC) and processing techniques which will enable serial production of Class 8 truck hoods with structural integrity, class A surface quality, significantly reduced mass, and competitive in costs with existing glass fiber SMC molded components.

Approach

- Accumulate material property data to establish reliable design properties that can be utilized for engineering design analysis.
- Perform finite element analysis of a carbon fiber SMC based Class 8 hood design.
- Evaluate consistency and repeatability of carbon fiber SMC material properties, processing techniques, and surface quality.
- Evaluate mass savings and costs.
- Confirm predicted results by constructing prototype hoods and performing accelerated endurance tests.
- Determine if a business case can be made for a carbon fiber hood to proceed into serial production.

Accomplishments

- Built twelve (12) prototype hoods using existing production tools to evaluate processing characteristics of various combinations of lightweight materials and successfully processed the hoods through the VTNA production paint process.
- Determined that the cycle time for carbon fiber SMC was comparable to glass fiber SMC (one minute of chemical cure) and exhibited similar flow and mold characteristics as structural grades of glass fiber SMC. This is compared to several hours of effective cure with an epoxy/autoclave system with minimal flow.
- Found from the prototype hoods that the bond strength between carbon fiber SMC components and the lightweight glass fiber SMC components varies substantially, the weakest link being the mid- and low-density

glass fiber SMC components. The interlaminar strength of the low-density fiberglass SMC (loaded with hollow glass microspheres) was considerably lower than expected, leading to poor bond performance.

- Found that the published tensile and flexural strength properties of lightweight glass fiber SMC materials are unreliable due to the methods used in determining and calculating the properties.
- Developed a preliminary carbon fiber SMC material performance specification.
- Developed a preliminary adhesive bond specification for carbon fiber SMC and lightweight fiberglass SMC bonded assemblies.
- Completed the engineering detail and assembly drawings for a lightweight hood assembled from carbon fiber inner reinforcement structures and mid-density fiberglass SMC surface panels.
- Successful Finite Element Analysis of the carbon fiber reinforced lightweight hood assembly.
- Meridian Automotive Systems designed, built, installed, and tested a small scale carbon fiber SMC compounding line to supply materials to support this research and development project.
- Obtained formal quotations for production tools, detail hood parts and hood assembly costs.
- Performed cost and weight evaluations comparing the carbon fiber reinforced hood to the same hood constructed of typical fiberglass SMC.
- Performed a business case analysis for the carbon fiber reinforced hood and determined that the cost premium for the carbon fiber hood was too high and the lightweight hood could not proceed into production.
- Conducted a roundtable discussion to identify barriers and possible solutions to using carbon fiber SMC materials in automotive production applications.

Future Direction

- Encourage and follow the development of new low cost carbon fiber material production processes.
- Evaluate low cost carbon fiber materials and surface treatments as they become available.
- Evaluate the long term supply stability of low cost carbon fiber materials.
- Look for opportunities to utilize low cost, light weight, high strength carbon fiber materials in automotive applications.

Introduction

The mass of light automotive and commercial heavy-duty vehicles can be reduced utilizing modern lightweight, high performance composite materials. The reduction in vehicle mass translates into an increase in fuel efficiency. Currently, polymeric carbon fiber composites are utilized in low volume, high performance applications such as spacecraft, aircraft, and racecars. Carbon fiber reinforced composites can reduce vehicle body mass by 40% to 60%. However, market conditions and technical barriers inhibit their use in high volume automotive applications.

Class 7 and 8 trucks offer a lower production volume, lower technical barriers, and financial incentives that can justify a modest price premium for competent lightweight materials. The aim of this Project is to accelerate the commercial implementation of high performance, lower cost carbon fiber SMC (sheet molding compound) material body components for Class 7 and 8 trucks. As utilization of carbon fiber SMC develops and the technology matures, it is foreseeable that carbon fiber SMC will migrate into the high volume automotive market.

The Project was initiated by performing a comparative finite element analysis of a hood configuration made of glass fiber SMC material that had been validated through modeling, accelerated endurance tests, and field test. Based on expected carbon fiber physical and mechanical properties, hood structural and surface component material thicknesses were reduced through several iterations to determine the effect on hood system stress states and displacements. Modal analyses were performed to determine mode shapes, and complete vehicle models were utilized to obtain dynamic responses in the frequency domain. Fatigue life comparisons were made based on the complete vehicle model transient analyses.

Based on the initial investigation, it was concluded that a competent hood could be produced with a 40% to 60% reduction in hood mass if a carbon fiber SMC material could be produced that would consistently provide the physical and mechanical properties targeted.

Carbon Fiber SMC Material Search and Comparative Testing

A search was initiated to find suppliers of polymers and carbon fibers combined in a useable sheet molding compound (SMC). Materials from Zoltec, SGL, Toray, Grafill, and others were evaluated. Early on, two significant obstacles became evident; completely wetting out the carbon fiber and defilamentizing the fiber bundles. Suppliers were worked with to optimize chemistry and processes to consistently provide carbon fiber SMC material with the targeted material properties. Recent work with carbon fiber supplier Toho utilizing large tow industrial fibers indicated some cost reduction may be reached with minor reductions in some mechanical properties.

Class A Surface Quality Development

Previous work pursuing the development of Class A surface quality carbon fiber SMC indicated that a substantial effort would be required in materials and process development to achieve the desired quality level. Because of the anticipated higher cycle times and additional processing steps, the projected cost of carbon fiber SMC for Class A surface components was estimated to be too high for commercial truck applications. Therefore, development of carbon fiber SMC for exterior Class A surface quality components was held in abeyance in order to pursue lower-cost, lightweight, low and mid-density glass fiber reinforced SMC for Class A surface components. In searching for a lightweight material that would provide Class A surface quality, a low-density, glass microsphere loaded glass fiber SMC was found that showed promise. However, prototype hood parts made from the material did not develop the mechanical properties indicated on the material specification sheet. Hood assembly bond strengths were also significantly lower than expected.

Assembly Process Evaluation

To evaluate the processing characteristics of various combinations of lightweight SMC materials, 12 prototype hoods were built using the production tooling from an existing hood. The prototype hoods were fabricated using low-density and mid-density glass fiber SMC Class A surface quality outer panels, with inner reinforcements constructed of glass or carbon fiber reinforced SMC. The prototype hoods were used to assess manufacturing process variability, dimensional stability, and adhesive bonding characteristics. To evaluate the viability of the lightweight materials in the production environment, the hoods were run through the normal assembly plant production processes and evaluated for surface quality, paint quality, and bond read-through. No unusual production assembly process problems were found.

Cost and Weight Evaluation

Initial concept work concluded that a 40% to 60% weight reduction was within range, as samples in the required reduced material thickness were successfully molded. Preliminary cost estimates of the carbon fiber SMC hood indicated a higher than expected cost premium based on the then current best estimate of CF SMC material costs. Therefore, alternative constructions utilizing carbon fiber only in areas requiring high strength and stiffness were pursued. During the course of the Project, carbon fiber costs continued to rise and are now at a level almost three times their cost at the beginning of the Project. When the formal quotes for the carbon fiber hood were reviewed, it became apparent that a business case for the hood could not be made. It was then decided to cease work on the carbon fiber hood.

Conclusions

The Project has made good progress in identifying materials and processes that could be utilized in automotive body structural applications. Molding and bonding processes are very similar to existing glass fiber SMC processes, requiring only minor adjustments in process variables. Most of the potential weight reduction was achieved. Good progress was made in the development of carbon fiber SMC materials for Class A surface quality applications. However, the lengthened process for Class A surface quality components was projected to be too expensive for commercial vehicle applications, and development was not pursued further.

The main impediments to the utilization of carbon fiber SMC in automotive applications are the cost and supply stability of the carbon fiber material. Compared to the commodity glass fiber, which is a competitively priced, mature, mass produced unspecialized product available in adequate supply, carbon fiber is an emerging specialty product available from few sources in limited supply at market driven prices. Further, much of the carbon fiber currently produced is utilized in government supported applications (aerospace, aviation, military, security, marine, and energy), which to some degree removes competitive pricing pressure. It appears that a breakthrough process for mass producing carbon fiber from a readily available and stable source of raw materials is required to bring carbon fiber costs down to levels that can be utilized in automotive applications.

B. Application of Carbon Fiber for Large Structural Components

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Contractor: Pacific Northwest National Laboratory
Contract No.: DE-AC06-76RLO1830

Objective

- To develop selective reinforcement technology that can be applied to large truck components to improve specific stiffness and strength while reducing overall component weight.

Approach

- Determine how well the low-cost carbon fibers can be hybridized with glass fibers to provide substantial weight and cost reductions in large cab components.
- Develop a system for preforming carbon and glass fibers together that will allow components to take maximum advantage of the capabilities of selective reinforcement alignment and property contribution.
- Develop models for the analysis of hybrid chopped fiber preforms and composites that allow the thermal and structural properties to be developed and compared to experimental analysis.
- Perform structural testing to define the limits of applicability of the carbon/glass hybrid reinforcement materials to the large structures and develop guidelines for applications that may be utilized by original equipment manufacturers (OEMs).
- Design and develop critical sub-section components of large structures to use in correlation to the predictive models, and to validate the structural application criteria. Determine the capability of the materials to be fabricated in full-scale components and determine the performance of these full-scale components in real application scenarios.

Accomplishments

- Developed the first Class A structural carbon composite panels for truck applications.
- Developed hybrid carbon composite with improved impact performance over fiberglass composites.
- Demonstrated thin (2.5mm) panel fabrication and resin transfer molding capability.
- Demonstrated panel molding with varying cross-sections from 2.5 mm to 7 mm in a single component.
- Performed panel molding with various filler types and loading, and selected optimum fillers for achieving Class A surface.
- Performed mechanical and impact tests on a range of panels.
- Developed and performed process trials with a new tooling system that allowed system to work together, and improved thermodynamic control for achieving mechanical and impact properties.

- Completed optimization of the resin system using different fillers.
- Tested and validated thickness constraints on panels for achieving structural performance on surface coated thin hybrid panels.
- Tested and validated barrier coat and optimized for surface profile.
- Completed modeling of tooling flows.

Future Direction

- Scale up to test production component as selected by CRADA partner.
- Fabricate test tooling for production level component.
- Verify tooling performance and long-term viability.

Introduction

Current interest in the attractive properties arising from the combination of polyester and urethane resin chemistries has prompted investigation into efficient manufacturing methods using a blended polyester/urethane system. By mating this material to a glass/carbon hybrid fiber preform an optimization of properties from all of the constituents can be achieved at a relatively low cost, especially if the laminate production can occur within a short cycle time. Using combinations of these materials, test panels were manufactured at different lengths to provide specimens and validate the feasibility of molding large (>5ft) and thin (<3mm) components. Close monitoring of developing manufacturing procedures provided valuable data concerning the behavior of both the resin and fiber hybrids in VARTM and closed molding operations.

Two types of flat laminate panels were produced from two different moldsets. Initially, a 12" x 24" glass-top mold (Figure 1) was loaded with the preform and infused with both neat and filled blended resin systems using VARTM. The transparent mold allowed for visual confirmation of the location and flow path of the hybrid resin at any point during the infusion process. In addition, the mold was fitted with inlet and outlet pressure transducers to record pressure gradients during mold filling. The second mold (Figure 2) was constructed of plywood, MDF, and Melamine facing fitted to a hydraulic press operating at 2500 psi. Visual confirmation of resin flow was confirmed via short tube ports protruding from the upper mold half. The panel preforms were one of two types of cores, with and without chopped carbon fiber. In all cases, temperature was kept between 100-120ºF and the mold cavity was evacuated to 85 kPa prior to injection of the resin with an 11:1 custom piston pump which kept the unmixed resin components at 104ºF also.

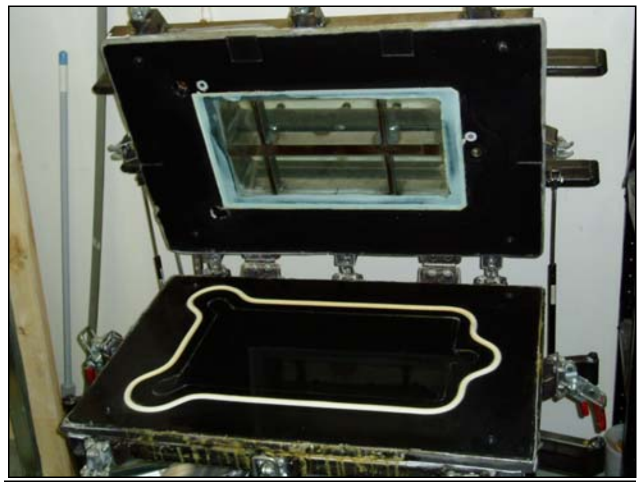


Figure 1. Glass top mold for test trials

Four cores of different thickness and architecture were examined as possible core materials for use with the highly viscous blended resin. CR-1, FM-1, S&F and "M-03" core materials were compared during initial testing. Only the S&F products were capable of providing fully wet out panels less than

Figure 2. Top of long flow path mold

5mm. S&F and “M-03” are 4mm and 3mm thick fabrics respectively, consisting of glass strand mat stitched to a ‘knitted’ polypropylene core, which provides loft to create a flow path for the resin and reduce back pressure within the mold. S&F designed these mats specifically for the purpose of injection molding with high viscosity, highly filled resin systems and the fabric has never been tested previously, with the exception of product development at S&F. Discontinuous carbon fibers were chopped from Toray 12k tows directly onto the cores and held in place with polyester binder. In some cases, final placement and consolidation by hand was required to achieve full panel coverage and even fiber distribution. When filler was introduced to the matrix, calcium carbonate, in powder form, was added to the polyester side of the blended resin. The resin itself was supplied as a proprietary chemistry consisting of a polyester component, compatible urethane component, and catalyst.

Fiber Preform Development and Evaluation

The purpose of this investigation was to evaluate the processability of the blended resin and hybrid fiber/mat raw materials and characterize the required production cycle. During the early stages of testing, the S&F mats performed exceptionally allowing the matrix to fill and fully wet the glass and hybrid preforms in less than half the time of competitor’s core materials (Table 1). Figures 3 and 4 show the difference between inlet and outlet pressures recorded during the RTM process. Both the S&F and M-03 had equal gate and vent pressures in less than 100 seconds, with the thinner

Table 1. Recorded fill times for core materials.

Material	Time to fill 24” x 12” x 0.12” cavity
CR-1	4:38
FM-1	5:20
S&F	1:43
M-03	0:34

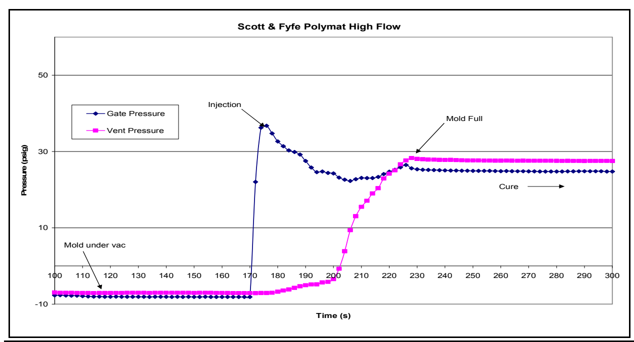


Figure 3. Pressure difference between gate and vent during injection cycle for S&F core material.

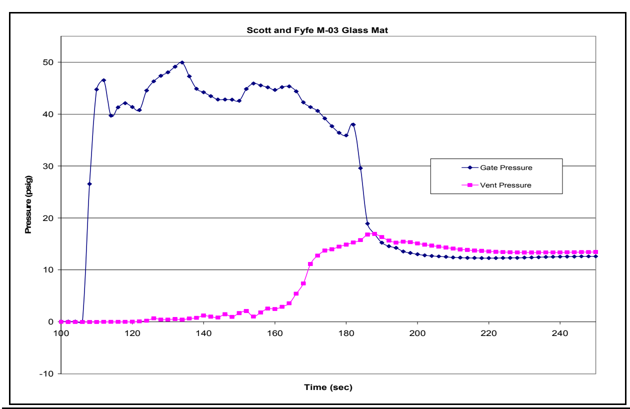


Figure 4. Pressure difference between gate and vent during injection cycle for M-03 core material.

M-03 requiring slightly more time. It is important to note the design of the mold cavity itself is critical to both the fill time and level of filler filtering. Resin must be injected directly into the polypropylene core of the mat, along the material plane. Otherwise the flowrate within the S&F is hindered by a layer of glass strand and it behaves similar to any other core material.

The success of the 6ft panel validates the use of the filled, blended resin system and S&F and M-03 for the production of large components. The injection took less than 4 minutes to complete and the panel was demolded in less than 25 minutes from first injection. Resin ports along the length of the mold indicated an even flow rate along the full length of the panel. When demolded, the preform had been stretched slightly along the inlet width, a problem that was corrected for by pinching the fiber along its edge and cutting a small section away directly in front of the resin gate.

The quality of the final panels was excellent in both the 2ft and 6ft panels. Panel surfaces showed no shrinkage or print through and thickness was as consistent as the molds would allow. Final panel thicknesses were between 2.5 and 3.25 mm when using M-03 and between 3.5 and 4.5 mm when using S&F. The nature of the S&F mat filling from 'behind' the glass mat virtually eliminated washout of carbon fiber during RTM. However, polyester powder was still applied to ease preform handling. Filler improved the shrinkage characteristics slightly, although it would slow the rate of cure, possibly due to absorption of promoter over time. The resin system also performed admirably, wetting and bonding intimately to both types of fibers as well as the polypropylene core. The fast fill rates and high level of promoter reduced cycle times to less than 16 min for the short panels and 25 min for the longer pieces, although the larger mold was frequently at a lower temperature than the glass-top.

Panels produced from the S&F mat and carbon chop were sectioned and subjected to flexural and tensile testing. The results agree quite well with the predicted material properties for hybrid fibers and blended resins. In addition, optical analysis of panel cross sections showed no signs of resin filtering along the length of the panels.

Filler Optimization

Filler optimization is an important part of viscosity minimization for the benefit of lowest achievable fill pressures on large structures. Likewise, maximum filler loading is an important aspect of reducing resin shrinkage for achieving the best possible surface finish (class A).

The results of the design of experiments (DoE) to optimize filler loading with viscosity included four factors of Resin Blend (20/80 to 30/70), Filler Load (25 pphr to 45 pphr). The Filler Ratio (15% to 35% filler A to filler B) measured at 2 and 12 minutes after mixing as a function of viscosity, showed that there is an optimal region of Filler Ratio and Filler Loading within the tested ranges. In Figure 5, the Pareto Chart of the Effects, not including mixing time, shows that the factor of Resin Blend is the largest determinant of viscosity at a given mix time.

Therefore, the most sensitive component of final mix viscosity is the isocyanate to polyester ratios, with some dependence on Filler Load.

The other non-setting factors show fairly narrow ranges of minimum viscosity. The Filler Load seems to have the second largest effect on mix viscosity and, in general, viscosity increases with increasing Filler Load. Filler Load shows a decreased viscosity response between 30 pphr and 40 pphr and a Resin Blend ratio below where an interaction may be occurring with the Filler Ratio.

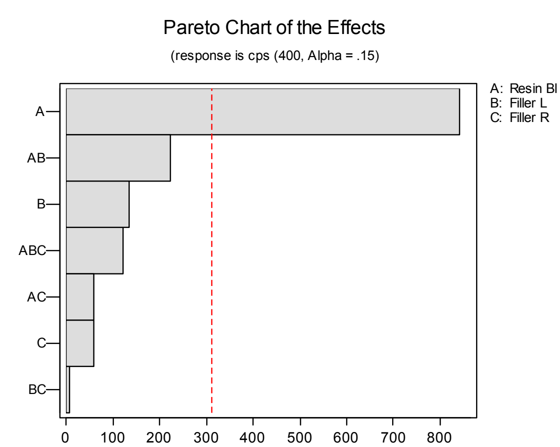


Figure 5. A Pareto chart illustrating the combined and individual effects of the different constituents of the mixes.

Filler Ratio, the percentage of Optifil JS within the blend of Optifil JS and Optifil T, gives a minimum viscosity within the range of 20% to 25% depending on the total Filler Load in the mix and set-time. This interaction results in the viscosity's minimum shifting from 25% to 20% in Filler Ratio as the Filler Load shifts from 30 pphr to 40 pphr. It is also affected by the setting of the resin over time by shifting the optimum Filler Ratio back from 20% to 25%. This same shift with set-time can be seen in the Resin Blend vs. Filler Ratio above. Is this shift an interaction between the surface of one of the fillers and a resin component?

The approach to this screening study was intentionally broad within the area; we now know a more optimal range for the factors tested. The next step needed to verify and improve the data's resolution is a full factorial concentrated around a focal point of: Filler Ratio of 23% JS, Filler Load of 35%, a Resin Blend minimizing isocyanate but controlled for its effects on the final composite properties and mixing times of 2, 7, and 12 minutes.

Flow Modeling

Flow modeling utilized Polyworx software for simulations in the flat plate tools for determining preform permeability based on temperature, pressure and viscosity. Figure 6a and b illustrates the pressure and flow patterns in the long flat plate tool. The flow and pressure patterns were even. The information determined from the flat panels was correlated to experimental data which gave us the information needed for inputting into the more complicated test as well.

The Freightliner test tool was then modeled using the permeability numbers determined from the flat panels and the other resin input variables.

Modeling of the test tool was then used to see the correlation between model and experiment for scaling up complexity in the part. Figure 7, illustrates multiple time snapshots of fill percentages and how that correlates to the actual fill time and flow behavior with partial shots. The correlation of three minute fill times from model to experiment is inline with each other.

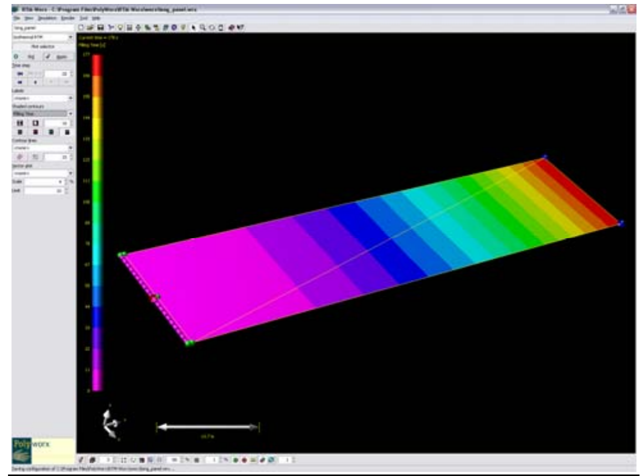


Figure 6a. Modeled flow pattern in 18" x 72" panel mold

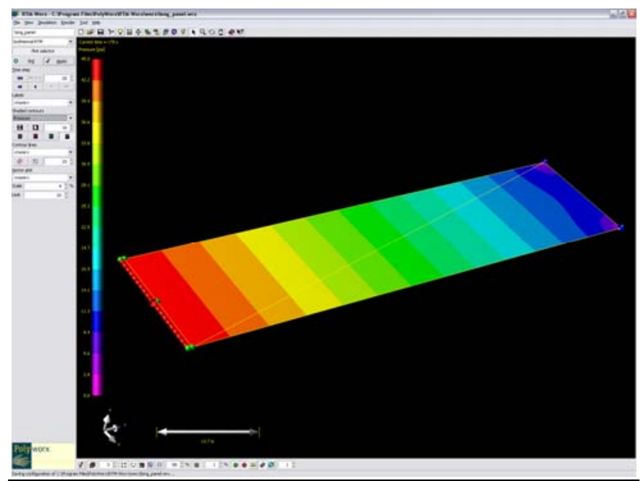
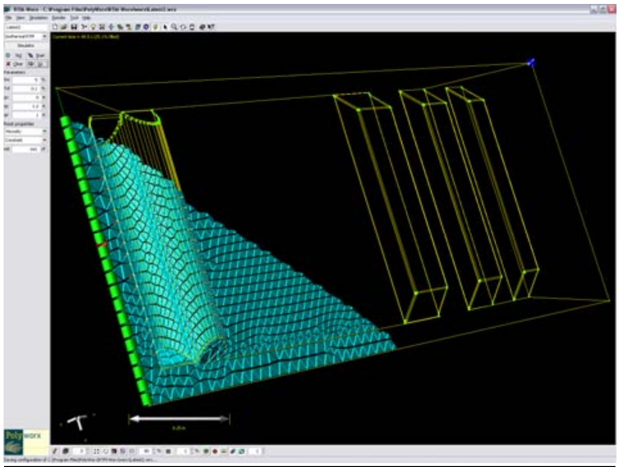


Figure 6b. Modeled pressure pattern in 18" x 72" panel mold

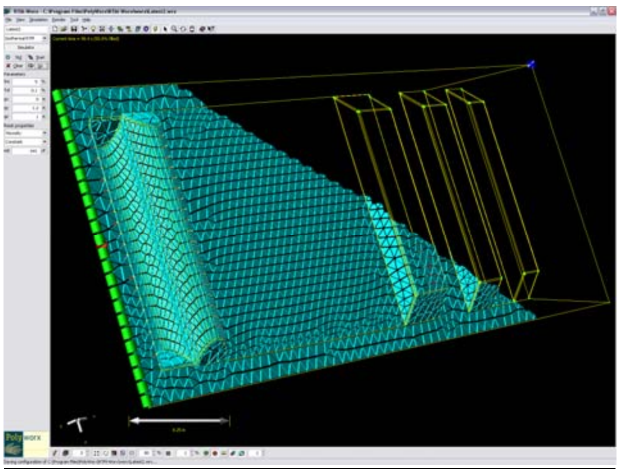
The next task will be to model a large structure that will be fabricated in FY06. These simulations will help us in determining flow patterns and fill times with the current material configuration. This will give confidence that the design will work prior to tool build.

Conclusions

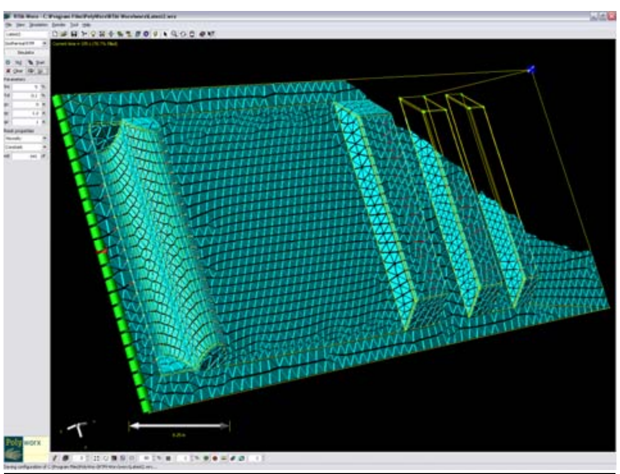
The flow trials gave us valuable insight as to how fast large panels will fill. The rheology studies indicate time sensitivity when the two resin components are mixed and have the largest influence on the viscosity. There is an optimum ratio of the two fillers at 25 pphr that will help in reducing filler cost and viscosity. The viscosity data



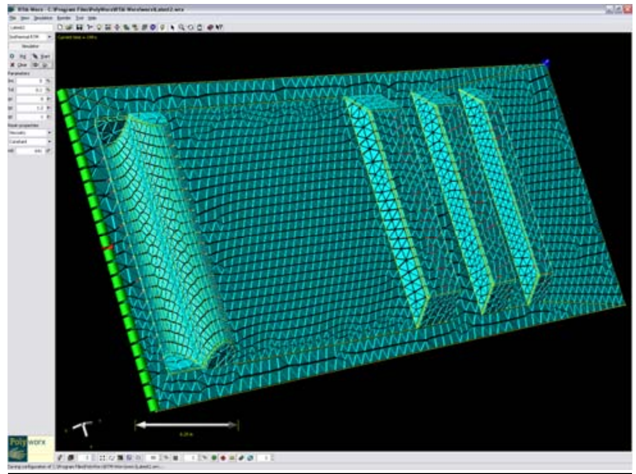
Permeability = 0.008 sq-cm, ~25% Fill, t = 48.5sec.



Permeability = 0.008 sq-cm, ~50% Fill, t = 98.4sec.



Permeability = 0.008 sq-cm, ~79% Fill, t = 155sec.



Permeability = 0.008 sq-cm, ~100% Fill, t = 199sec.

Figures 7 a,b,c,d. Illustration of the flow pattern at different fill percentages.

became very useful with the modeling which illustrated the fill time and pressure gradients within the part. These models and the correlation data gave us the information needed to be able to model large structures prior to building the tool. This will help reduce the risk of the unknown with any large, complicated and expensive tool.

Future work will model a large composite structure and build the tooling. Experimental correlation will be evaluated on the large molded parts. A large tool will be fabricated for testing the moldability and mechanical testing of large parts. A series of factors associated with optimizing details of the process technology are being worked, and the CRADA partner is developing an approach to mold full-scale parts that will ultimately go on over-the-road trials. These parts have been chosen to demonstrate the most challenging aspects of the process capability, namely highly structural, Class A surfaces in direct line-of-sight, with some complex process details required for success. Tooling quotes and negotiations are ongoing, and several aspects of the process are anticipated to go forward for patent protection.

C. Hybrid Composite Materials for Weight-Critical Structures

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Contractor: Pacific Northwest National Laboratory
Contract No.: DE-AC06-76RLO1830

Objective

- Develop and demonstrate (1) the application of hybrid composites and composite/metal hybrids to heavy-duty vehicles and (2) the capability to integrate these materials choices into moderate-volume production.
- Develop and demonstrate the potential for major weight savings (>50% on a component basis) in critical structures applicable to truck cabs and support components.
- Demonstrate the basis for use of hybrid metal-composite systems to reduce weight via proof-of-principle experimentation.
- Develop full-scale prototype components for vehicle testing and validation.

Approach

- Investigate the potential of new materials and manufacturing technologies to effect major weight reductions for heavy-duty vehicles.
- Assist in demonstrating the applicability of composites and composite/metal hybrids to operational vehicles with little or no cost impact.
- Provide the experience base to develop the design and analysis tools, as well as the scientific understanding of the factors affecting molding and materials performance.
- Provide the materials suppliers with a market that can stimulate demand, leading to an increase in their production capacity. This will help reduce materials costs by creating higher volumes. Develop and assemble full-scale hybrid material prototype door system for heavy vehicle test and evaluation.

Accomplishments

- Completed three sets of prototype hybrid door components, which were delivered to Pacific Northwest National Laboratory (PNNL) by the subcontractors. The key components include sand cast magnesium door inners (Style and Tech) and molded hybrid glass/carbon fiber upper door frames (Profile Composites).
- Developed bonding fixture, bonded the initial hybrid door components, and verified dimensional conformance.

- Assembled the first door and performed static load analysis. Initial results indicate that the hybrid door assembly exceeded the targeted 50% improvement and exhibited a 64% improvement.
- Assembled additional door for cab fit and function, and full-length cab door durability testing.

Future Direction

- Assemble three prototype hybrid material doors for testing by PACCAR. Plans call for cab door durability tests to be conducted in 2005, these tests are currently underway.
- Based on component design and assembly tasks, update door manufacturing cost models for PACCAR (PNNL and Mercia).
- Compile a final report at the conclusion of the prototype demonstration phase.

Introduction

Current materials and manufacturing technologies used for heavy vehicle door systems are often dictated by the high cost of tooling and the relatively low production volumes for Class 8 trucks. Automotive-style stamped door designs, whether of steel or aluminum, require multistage stamping dies that are generally cost-prohibitive at lower production volumes (<50,000 units per year). Alternate materials, such as glass-reinforced sheet molding compound (SMC), require less expensive tooling and can provide a Class A finish; but the relatively poor specific properties of SMC tend to compromise design and result in a heavier door system. For many production truck cabs, a simple aluminum extrusion frame is used with a flat aluminum sheet riveted to the frame. Although this approach does not require expensive tooling, the use of constant cross-section extrusions in the frame is less than optimum, and it requires more assembly labor than other approaches. PACCAR, a world leader in Class 8 truck design and manufacturing, teamed with PNNL to explore alternate “hybrid” door system designs that minimize tooling cost and per/part door cost, while providing a lightweight, structurally stiff, automotive-style door.

Project Approach

The initial approach to development of the hybrid door system was to perform a structural analysis of an existing PACCAR door design and to determine what the design and performance goals should be for new-generation door systems. PACCAR provided a number of weight, cost, and performance parameters that it considered important for future door designs. PNNL was tasked to survey existing and emerging materials and manufacturing approaches that could be applied to a new door design. Following completion of this survey and analysis of existing door designs, PNNL, with design assistance from Mercia, Ltd., developed a series of five door design concepts that included combinations of large die castings, extrusions, carbon- and glass-reinforced composites, and conventional SMC and stamped aluminum exterior panels.

Following a concept review meeting with PACCAR, an optimized hybrid door design concept was selected. The door concept was then defined using computer-aided-design tools and analyzed with finite element models to validate performance, weight, and cost. After determining that the prototype design met or exceeded all performance and projected cost targets, PNNL and PACCAR selected methods to produce prototype components for the full-scale assembly and testing phase of the project. The finite element model of the prototype door system is shown in Figure 1.

Following completion of the design selection phase of the project, full-scale hardware components were developed and shipped to PACCAR Technical Center for assembly and testing. In addition, to the static deflection tests, a complete door was assembled and mounted in a Class 8 truck cab for fit and functional tests (Figure 2). Subsequently, the door was placed into a door durability cab test which is currently being run to completion.

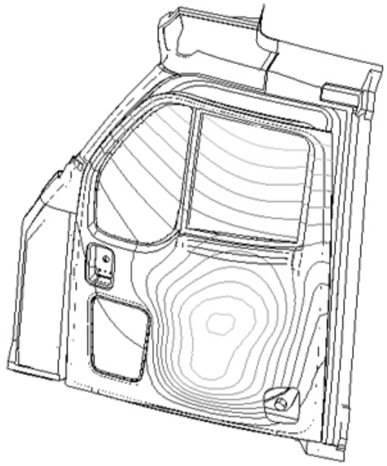

Figure 1. Finite element model of prototype door system under simulated loading conditions.

Figure 2. Prototype door assembled in Class 8 cab for functional testing.

Conclusion

The prototype development of hybrid door components for an advanced heavy truck door was completed by the team and its selected subcontractors. Prototype assembly has been completed by the team, including inspection and assembly fitting, as well as adhesive bonding development. Three prototype doors have been assembled by the team for cab testing and evaluation during calendar year 2005. Static testing and cab functional test and evaluation have been completed. A prototype door is now undergoing cab durability testing. The hybrid door design that will be prototype-tested reduces door weight by 37%. If the hybrid design were to move into production, the use of a stamped aluminum outer panel (cost-prohibitive during the prototype stage) would improve structural performance, reduce cost to project goals, and increase weight savings to 55%.

D. Advanced Composite Structural Cab Components

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Contractor: Oak Ridge National Laboratory
Delphi/ORNL Contract No.: 4000009401

Objective

- Develop an advanced composite cab structural component for a Class 8 tractor:
- Develop the design and the manufacturing process for utilizing continuous-oriented, fiber-reinforced composites for affordable commercialization within 5 years of beginning the project.
- Reduce the existing mass by at least 30% from 22.8 kg to 15.96 kg.
- Meet or exceed the performance of the existing cab structural component.
- Meet customer target cost.

Approach

- Perform a Value Analysis/Value Engineering (VAVE) workshop to generate options for design and manufacturing.
- Perform finite element analysis (FEA) to develop and optimize design options.
- Perform a process cycle study and make prototype panels to develop Class B surface requirements.
- Conduct Design Failure Modes Effects and Analysis (DFMEA).
- Construct prototype parts and verify proposed design using a design validation (DV) test.
- Release final designs, construct production tools, perform Process Failure Mode and Effects Analysis (PFMEA), and undergo Process Validation (PV) of the production phase.
- Commercialize and start of production.

Accomplishments

- Completed "Proof-of-process" study with generic "block" mold, which demonstrates feasibility of infusing thin-walled laminates; then completed " Pre-PV" study with production foam core and prototype composite mold for areas 3&4 of lower B-Pillar.
- Completed DV testing of prototype components in full cab build. (Door slam test had gone through 3 life cycles and sustained no structural issues) Completed fastener torque studies in molded sample blocks.
- Updated the system DFMEA with suppliers and customer.

- Refined FEA models to include material properties from actual material test data, developed local composite reinforcements to improve stiffness, and studied the effect of processing tolerances for an affordable product.
- Simplified construction in air duct area by making air duct a separate, post mold fastened part.
- Reduced metal usage by eliminating large steel plate and using more localized attachments with composite reinforcements.
- Produced assembly drawings, CAD models, design details, and specifications for quote packages.
- Selected production source for final assembly.
- Reduced flange areas to 3mm thick (current production flange varied from 6 to 12 mm thick).
- Performed cure-cycle study, made composite panels, conducted Class B surface activities.
- Made plaques and part skins using conductive gel coat to demonstrate elimination of post mold spray conductive primer. Validated conductive gel coat to replace post mold, spray primer system (resulted in an overall 10% total mfg cost savings).
- Finalized metal hardware material specifications.
- Determined optimal machining process parameters (tool shapes, feeds, and speeds for drill/tap of composite laminate over metal hardware) without any delamination or degradation to the laminate.
- Created 2D lay-flat fabric patterns from 3D part geometry with slits and darts to minimize fabric shear and to optimize the overall fabric blank size.
- Completed environmental testing.
- Finished final design math model and process.

Future Direction: Applicable only after receiving Purchase Order

- Conduct PFMEA with sourced supplier and customer.
- Finalize specifications, assembly and detail drawings.
- Release final design, release remaining production tools, and PPAP validate the production phase.
- Begin production.

Introduction

Significant strides forward were made on the Advanced Composite Structural Cab project. Within Delphi, the project had moved from a development activity to an implementation team and with the progress outlined in this report below, both cost and mass targets were achieved.

To accomplish the project objectives the Delphi-led team had to replace the present production liquid compression molded two component post-bonded assembly made of non-oriented chopped fiberglass with a single RTM processed foam core structure enclosed with a thin-laminate of oriented and continuous length fiberglass.

Design and Process Failure Modes and Effects Analysis

A system-based design failure modes and effects analysis (DFMEA) was initiated in early 2003 and had periodically been updated as the production intent design had been refined. This included a review at Delphi's OEM partner's assembly plant with representation from Engineering, Quality, and Purchasing. Another DFMEA was reviewed in June 2004 with the OEM engineers after the DV tests were completed. The suppliers of individual components and final molder have responsibility for performing the PFMEA and creating process control plans after final sourcing. Delphi participates in each FMEA.

Pre-Production Validation Development: Resin Cure Times and Thin-Walled Infused Laminates

In order to determine the proper tooling and cure cycle, Delphi and Reichhold, a leading resin supplier, conducted multiple cure-cycle studies. The goal was to make a resin recipe that would meet a 22-min full-cure cycle at 120ºF. Initial studies completed in February 2004 indicated that a processing temperature of 120ºF cure cycle was possible.

One of the major design obstacles of this project was the processing of thin (1.0-1.5 mm) laminates with resin transfer molding (RTM) to produce high quality parts. Some of the concerns originated around tolerances and geometric stack-ups of all the components within the molded assembly. Secondary concerns included the response of the foam core, tooling, and hardware during infusion, multiple layers of fabric and the reinforcements that were located between various foam cores.

In order to expedite the "Pre-Production Validation" (production validation = PV hereinafter) development, a small section of the molded assembly was selected rather than working with the complete assembly. The "Pre-PV" development used results from early "Proof-of-Concept" development.

"Proof-of-Concept" development utilized a rectangular box (4"x6"x16"), a cross section of which is shown in Figure 1. This shape closely represents one of the longest infusion sections of the actual component. The tool was designed to infuse the 16" length with an injection and a vacuum port on opposite ends. The cover of the tool was made of clear glass to allow visual inspection and video taping of the resin flow front.

Almost 50 individual infusion runs were conducted with very positive end results. In the course of the "Proof-of-Concept" study, it was determined that laminate thicknesses of less than the 1.5mm were achievable. The limiting factors in achieving thin laminates were the tolerances of the tooling and the foam cores, but even on areas where the fabric was pinched due to irregularities or multiple plies, it was still possible to infuse. In order to maintain regular laminate thicknesses between the top and bottom surfaces due to pressure gradients, special geometries were added to the foam cores. With respect to internal supports and multiple plies, the development showed a process that was able to fully infuse any of the combinations we were able to create. A close-up view of a "Proof-of-Process" through-part reinforcement is shown in Figure 2.

Other notes from this process development were that pressure/vacuum values as well as the foam density were optimized. With a low-density foam core, vacuum assist and low resin pressure, consistent processing results were obtained with few air voids and an infusion time of 1 minute. High pressure resulted in foam compression allowing more resin into the part and did not shorten the injection time. Finally, a modified resin with less inhibitor was used to allow the cure cycle (from mixing to cured part) to meet an acceptable cycle time (<22 minutes) at a heated tool temperature of <120ºdeg F.

The next step in developing the "Pre-PV" molding process was to build a larger tool with actual part geometry (foam core areas 3 & 4) to ensure "Pre-PV" process capability. Two production level foam core tools were made to allow refinement of the process on actual production geometry tool. Figure 3 shows a view of an open Aluminum based RTM "Pre-PV" tool. Figure 4 shows the first part made out of the Aluminum based "Pre-PV" tool and Figure 5 shows a cutout portion view of a molded part section from the Aluminum "Pre-PV" tool. The part was made using production intent resin with low inhibitor level and production intent foam. The resulting composite part was very close to the targeted weight.

Hardware: Secondary Machining Operations

A key design element to minimize cost was insert molding of the metal fasteners into the foam cores. Another factor for affordability was to ensure that drilling and tapping time were optimized. To ensure optimal drill & tap cycle time after parts were made, a study was conducted. Figure 6 shows a robotic machine cell that was utilized to optimize drilling method. Various drill bits and speeds were determined to help remove chips, and countersink

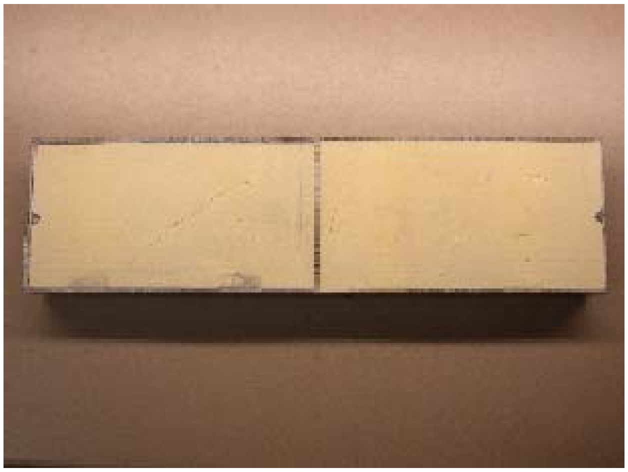

Figure 1. "Proof-of-Process" Mold Block.

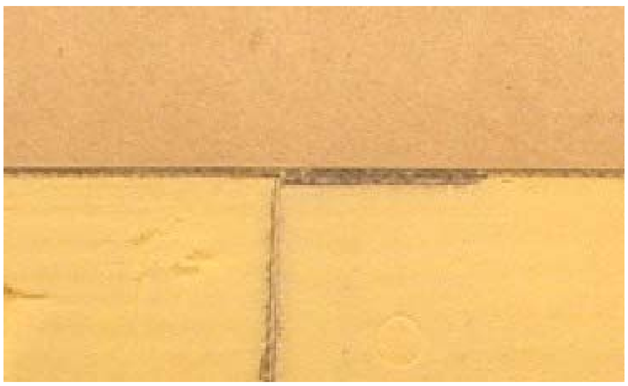

Figure 2. Close-up view of "Proof-of-Process" composite block with reinforcement.

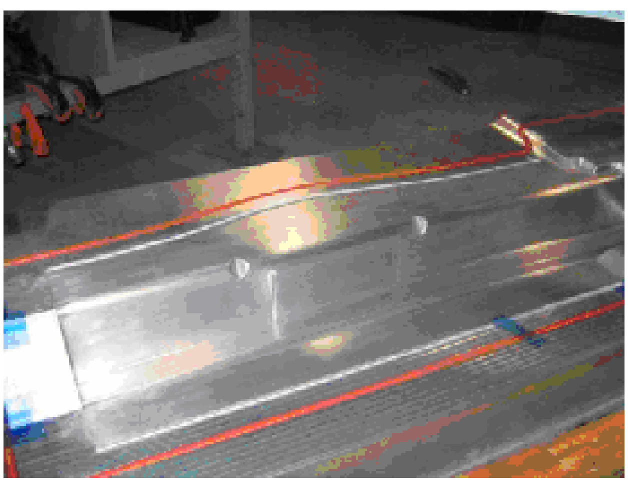

Figure 3. Open view of Aluminum based RTM "Pre-PV" tool for sections 3&4

Figure 4. First "Pre-PV" part made out of Aluminum based RTM tool.

Figure 5. A cutout portion of molded "Pre-PV" part from Aluminum tool.

Figure 6. Drill & tap time study fixture for hardware molded test block.

methods were developed to avoid composite damage during tapping.

Analytical Work - Finite Element Analysis and Fabric Pattern Development

The production design direction has been finalized, and FEA and CAD data files are undergoing final updates before production release. FEA indicates that all performance requirements will meet or exceed requirements.

Fifteen individual fabric pieces are required in the molding operation. The initial lay-flat patterns developed did not drape well over the foam cores or into the molding tool. Alternative lay-flat software is being investigated.

Cost Reduction: Conductive Gel Coat

A systematic review of the final assembly cost indicated that masking; conductive spray primer and finish were areas with great cost reduction potential. By implementing a conductive gel coating in the composite molding, preliminary estimates showed that finished assembly cost could be reduced by up to 10%. Delphi identified a conductive gel coat system that had already been approved by the OEM partner in other applications and fabricated flat panels production representing exterior part surfaces (see Figure 7) with this conductive gel coat. These samples were forwarded to the OEM partner for oven and environmental conditioning. Following this conditioning, surface finish and resistivity will be evaluated.

Figure 7. Exterior surface showing conductive Gel- coat.

Testing Activities

Fastener testing - Tests for torque and pullout load had been conducted on several M5 and M6 threaded fastener designs in composite panels with steel plates. Other sizes were also tested per their application category (e.g., FMVSS, heavy load bearing, interior to the door seal, exterior to the door seal).

The foam block with hardware after drilling and tapping can be seen in Figure 8. To ensure that new hardware will work, a hardware bonding study and corrosion resistance were conducted.

Figure 8. Hardware molded block after drilling & tapping

Torque and pullout load between composite and metal hardware embedded in foam was determined using various surface preparations for metal hardware. The torque fixture used for the study is shown in Figure 9. The purpose was to determine that threaded fasteners meet FMVSS requirements. The results showed that all various surface

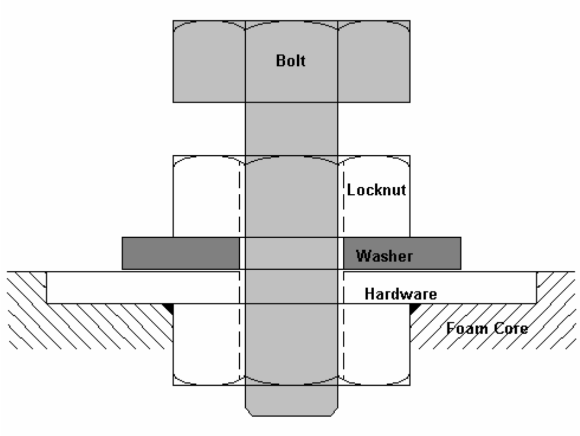

Figure 9. Torque test fixture for hardware molded test block.

preparations were acceptable for bonding with the proposed composite materials.

Expansion testing - Blocks of the same composition of composite and foam design have been heated to process temperatures of 225ºF for one hour with no effects to the part due to differences in expansion rates of the differing materials.

Environmental testing – Environmental testing was conducted on both composite test blocks and cut-away sections of prototype parts. The effect on the foam, the hardware, and the laminate was determined. The results, as expected, verified that the foam and composite laminate construction protect the hardware from the environment and resisted moisture penetration into the structure.

To meet the corrosion requirement it was decided, and approved by the customer, that we use SS material for machined and tapped holes outside the seal and carbon steel material in areas inside the seal. The corrosion resistance test was performed per OEM's standard practice on drilled metal fasteners (Fig. 10). The results showed that Dupont's E-Coated steel exhibited similar results as current production parts. Since the cost difference was minimal, the team decided to use E-coat to keep within the customer specifications.

Figure 10. Hardware molded block after corrosion.

Summary

These are the highlights for the progress during the first three years of this project (FY02-FY04).

1. Reduced laminate thickness from 3.0mm to 1.5mm using 30% fiber volume with production intent resin and process. The visual inspection looked good. Mechanical testing of the panels was performed and the test properties were used to refine the FEA model of the Cab Structure.
2. Reduced component mass by 32% over current composite technology.
3. In-molded hardware met process requirements.
4. Proved 1.5mm thick process capability in a portion of the cab structure by molding just area 3&4 with "Pre-PV" tools, including the use of foam cores from production sections 3&4 foam core tools.
5. Used in-mold conductive gel coating to reduce process steps and material cost of a post-mold conductive spray primer.
6. The cab structure using VARTM thin-walled laminates over foam cores with embedded metal hardware has successfully completed cab shake testing. This same cab structure completed the final stages of Design Validation testing, again with no failures. Also, torsion and pullout testing have met specifications.

7. Met all mass, performance, and cost objectives.

The advanced cab component technology demonstrated a 32% weight savings while maintaining superior structural performance and cost competitiveness. The customer successfully completed all verification testing. However, due to commercial concerns with the Tier 2 supplier, production plans were halted. In FY2005, the project was novated from Delphi to the National Composites Center. During FY2005, the customer also completed laboratory tests simulating a lifetime of opening the cab door against its stops. The test component exceeded requirements. Discussions continue with the customer on potential application of the technology for new products. The customer is also considering bringing the molding of this cab structure in-house, instead of using a Tier 1 or Tier 2 molder. Without renewed DOE funding this project is being closed out. Currently, this customer is unable to resource this development on its own.

E. Advanced Composite Structural Chassis Components

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Contractor: Oak Ridge National Laboratory
Contract No.: DE-AC05-00OR22725

Objectives

- Develop an economical, long-fiber-reinforced manufacturing procedure utilizing continuous and/or oriented chopped fibers for structural chassis components for Class 7 and 8 trucks.
- Reduce mass of these components by 30% minimum.
- Commercialize and annually produce these components, reducing vehicle mass by about 50 kg/vehicle and significantly increasing North American carbon fiber demand annually, within 5 years of beginning the project.

Approach

- Conduct Value Analysis/Value Engineering workshop(s) to conduct function analysis and brainstorm solutions using composites for each component function.
- Develop Finite Element Analysis (FEA) models at both the component and system level. Conduct structural optimization (topology and shape/sizing) on components for “material efficient” designs.
- Build and test prototypes.
- Develop production viable product along with processes for required cost and volumes.
- Secure production orders for the components developed within the scope of the project.

Accomplishments

- Received customer production part approval of two different models of lateral links. Completed first order of more than 1000 lateral links. Submitted samples and obtained initial order from second commercial vehicle customer. Composite lateral links are 66% lighter than current steel, resulting in almost 5 kg/system mass savings.
- A new lower cost version of lateral link has been designed and performed favorably in initial testing. Additional testing and product validation testing is currently ongoing.
- Proof-of-concept composite-reinforced, thin-wall steel tube main support successfully completed all cycles in the side load testing and brake load testing.
- Tier 1 partner used team’s composites research and design concepts to develop and commercialize an aluminum z-beam, which resulted in over 27 kg mass savings per system. Combined with the mass savings of the lateral link, this project has realized 32 kg of the 50 kg target for system mass reduction at the end of FY 2003.

- Completed testing the proof-of-concept reinforced main support. This product has the potential for over 20 kg additional mass savings.

Future Direction

- Complete the cost model for reinforced main supports.
  - Select the appropriate partner for commercialization.
- Investigate and validate lower cost lateral link designs and processes.
  - Select the appropriate partner for commercialization.

Introduction

In response to a request for proposals from Oak Ridge National Laboratory (ORNL) in February 2001, a submission from Delphi Corporation led to the award of a subcontract for the development of advanced composite structural chassis components with the objectives listed above.

Sponsored by the DOE, the subcontract was initially scheduled to run for three years with an estimated cost of $2.5M. This project is a 50/50 cost share between ORNL and industry. In this project, Delphi Corporation, the world's largest automotive Tier 1 supplier, partnered with an industry-leading Tier 1 supplier to the truck and trailer industry and focused on three components in a chassis/suspension system: lateral links, main supports and z-beams.

Lateral Link Status

A key project milestone (limited-volume commercialization) for the lateral link was realized in FY 2003 with the acceptance by Delphi of the first 1000-piece order from its Tier 1 partner. Two different models of the link (different lengths for different applications) were approved through the production part approval process (PPAP), and several hundred are in use in the field.

Glass and standard modulus carbon-fiber-reinforced prepreg are the materials utilized in the manufacture of the links. The bulk of the material is carbon-fiber reinforced to obtain the buckling stiffness required. Tubes are mandrel roll-wrapped, cured, and threaded. Metal inserts are then bonded in each end. The glass prepreg is employed for the threading operation and as protective outer layer.

Current composite links offer a 67% mass reduction and outperform the mainstream steel in buckling load capacity and three-point bending, and they also have a significantly higher natural frequency. Examples of both link assemblies are shown in Figure 1.

Figure 1. Typical steel and composite lateral link assemblies.

Although the lateral link can be deemed a success both technically and commercially, costs are still somewhat prohibitive for applications other than lower-volume niche markets. Beginning in 2003, efforts were made to develop lower-cost designs and processes to broaden the market potential and increase the impact on fleet fuel efficiency. Two options that were built as prototypes were hybrids (thin-walled steel overwrapped with composite) and pultrusion. Cost models for the hybrid design were not favorable, and costs for pultruded designs are still being analyzed. Initial pultruded test samples failed to satisfy the test requirements.

Because many of the properties of the composite tube are significantly superior to those of the steel, a lower-cost roll-wrapped option has been investigated. In this option, the number of carbon fiber unidirectional layers will be reduced as well as strategically placed to be in the most effective location for the required load cases. The glass fabric on the inner diameter will be placed only at the ends instead of along the entire length. It is anticipated that this will yield up to a 20% cost reduction.

Preliminary test results demonstrate favorable results.

The team attempted to validate lower-cost lateral links for a second Tier 1 partner through building and testing the prototypes. This second Tier 1 tested to higher standards than did the first Tier 1. As a result, the design did not pass its DV testing. A redesign would have been required, but a costly and high-risk development program would have been required to achieve the target piece price. Thus, the development was stopped.

Main Support Status

A significant amount of design effort was spent on the main support. The main thrust of this design was toward carbon-fiber reinforcement of a relatively thin-walled steel tube. Although the design of the tube reinforcement remained stable, much difficulty was encountered in obtaining a solution for the interface between the tube and the mounting hardware and brackets.

The initial all-composite interface design was not cost-effective. When all steel hardware was used in the design, mass targets were not met. As a compromise, a hybrid interface was designed in which thin steel brackets were welded to the tube (see Figure 2). These brackets were then reinforced with composites with the rest of the tube.

The current prototype design yields a mass savings of approximately 30% or 23 kg per system.

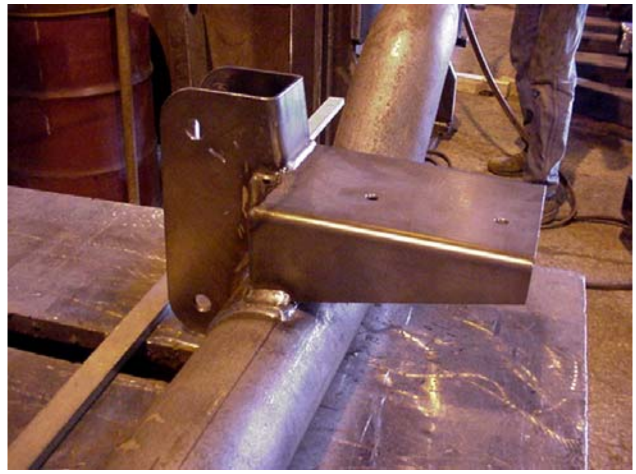

Figure 2. Steel interface-bracket assembly on subplate welded to tube.

Six steel framework subassemblies (Figure 3) were fabricated. The first composite-reinforced assembly is shown in Figure 4 prior to any finishing work.

These prototypes are fabricated by placing dry fabrics with specific fiber orientations around the tube and brackets. The entire support is then enclosed and infused with epoxy resin. For production, mold tooling would be used for application of the reinforcement material.

Figure 3. Prototype steel framework ready for composite fabrication.

Figure 4. First composite-reinforced main support just out of cure oven, prior to any finishing work.

The prototype reinforced main supports satisfied or exceeded all test goals. Commercialization of this component in the chosen application was stopped when Delphi's Tier 1 partner expressed interest in a multi-piece design for its next generation of products. Unfortunately, these designs were not affordable for development with the use of advanced composites. Alternative applications were investigated and pursued by Delphi with other potential Tier 1 partners.

Z-Beam Status

At the beginning of FY 2003, Delphi's Tier 1 partner announced its intention to commercialize an aluminum version of the z-beam based on FEA topology optimization completed for a composite design. The cast aluminum solution reduced the mass by approximately 7 kg and was at cost parity with or below the current cost of welded steel designs. Because four z-beams are used in each system, total system mass was reduced by 28 kg.

Based on the success of the aluminum, work was suspended on composites. Composites were considered again for a heavy-duty application, but cost models were not favorable, and work was suspended.

In FY 2005, this program was novated to the National Composite Center in anticipation of finding new Tier 1 partners for main support commercialization. The National Composite Center has found a couple of other Tier 1 partners ready to carry forward commercialization of a main support. In fact, one came to the National Composite Center on September 15, 2005 for a workshop to narrow down which product to propose. Thus, we had requested to keep this project open for re-initiation of activities to start when a new project could be defined with this new Tier 1. However, the DOE budget could not be realized. As such, this project is being closed out.

Summary

Three polymer composite-intensive components were investigated for a heavy truck auxiliary axle system. Lateral links were developed and commercialized in low volumes, saving approximately 5 kg or 66% of incumbent steel member's mass. High carbon fiber prices have prevented their widespread adoption. The initial composite design for z-beams (trailing arms) morphed into an aluminum member that was commercialized at a cost lower than the incumbent steel member, while reducing mass by approximately 27 kg per vehicle. A proof-of-concept main support was developed, with potential mass savings around 20 kg.