

# **AUTOMOTIVE COMPOSITES CONSORTIUM STRUCTURAL COMPOSITE UNDERBODY**

*Libby Berger, Hannes Fuchs*

*General Motors Research and Development, Multimatic Engineering Services Group*

## **Abstract**

The Automotive Composites Consortium Focal Project 4 (ACC FP4) is a joint program between GM, Ford, and Chrysler to develop structural automotive components from composite materials. Part of this project is a structural composite underbody capable of carrying crash loads. Phase 1 of the Composite Underbody project was the selection of a material and process system (MPS). The selected MPS is compression molding of sheet molding compound (SMC), with a vinyl ester matrix and predominately glass fabric reinforcement, with some chopped glass. A high elongation core may be used to increase the integrity of the underbody after a crash event. CAE-based design methodologies were utilized to assess the structural stiffness and impact performance of the initial composite underbody design and the potential mass reduction was estimated for several underbody candidate material scenarios. Phase 2 of the project involves providing a full design of the underbody, including design for durability, and feasible component manufacturing and vehicle assembly scenarios. Weld bonding was selected as the means to join the composite underbody to the steel passenger compartment, and initial testing of the composite-to-steel joint has been completed. A surrogate component was selected to mimic the underbody in processing trials, as well as to provide a model for fabric drape analysis and correlation of analytical and experimental testing. Phase 3 will be fabrication and testing of the targeted underbody.

## **Introduction**

The purpose of the Automotive Composites Consortium Focal Project 4 (ACC FP4) is to guide, focus, and showcase the technology research of the ACC working groups. To this end, we are developing a structural composite underbody. The primary research outcomes of this project are:

- A 2 ½ minute cycle time (100k vehicles per year, 2 shift operation)
- Developing methods of joining and assembly of the underbody to the vehicle
- Processes for fabricating oriented or continuous reinforcement within the time window

Phase 1 of this project, discussed earlier [1-3], was the selection of the materials and processes for the underbody, which involved:

- The development of a design concept, including a means of joining and assembly
- The preliminary design of the concept using three material and process systems,
- The selection of an M&P System based on
  - Manufacturing considerations
    - 2 ½ minute cycle time
    - Technical feasibility of molding
    - Joining and assembly feasibility
  - Technical cost model analysis

Phase 2, which is now underway, is the full design of the underbody, based on a large, rear-wheel drive vehicle. This design includes:

- The whole underbody structure
- Manufacturing plan for the component
- Plan for joining and assembly to the vehicle structure
- Validation of materials, processes, and analysis methodologies and assumptions

Phase 3 will address the fabrication and testing of the underbody.

## **Background**

In Phase 1, a preliminary composite underbody design was developed to replace the steel assembly from the donor vehicle. The preliminary design takes into account three proposed MPS candidates, as well as the general vehicle packaging, and assembly and joining requirements. The vehicle level stiffness performance with the composite underbody is required to have equivalent performance to the donor, while crash performance is required to meet applicable government and industry requirements.

The concept design for Phase 1 must be suitable for predicting preliminary CAE-based structural performance and mass reduction, conducting technical cost modeling, and further Phase 2 detail design and development. The material and process system selected was a glass fabric sheet molding compound (FSMC) with a high elongation core (HEC). The FSMC has been demonstrated in several molding trials. However, the HEC is still under development. Our future processing, material evaluation, and design efforts will focus on this material system.

Our preliminary design and M&P system are based on a set of assumptions:

- Idealized analytical model of the underbody is representative of the as-molded structure.
- Material properties achieved with plaque testing will translate to properties in the complex underbody structure.
- Processing techniques can be developed to preform and mold the FSMC into the complex shapes needed.
- A high-elongation core material can be developed to maintain some continuity of the structure after crash.
- A production-feasible method of fabricating the composite-to-steel weld bonded joints will be developed, with necessary properties and durability.

Phase 2 addresses these assumptions as we move forward with the full design. Our primary means of doing this will be a structural surrogate component with many of the challenges of the underbody. Chrysler has suggested using a tub component for design and fabrication. Although this tub was designed for a Chrysler vehicle, it has not gone into production. The three-dimensional nature of this tool will allow testing of the material drape, preform and molding techniques, and property retention.

A composite-to-steel weld bonded joint [4] has been designed and will be tested statically by the ACC, using super-lap-shear specimens. Dynamic testing of the joint will be done at the Oak Ridge National Lab (ORNL) Test Machine for Automotive Crashworthiness (TMAC) facility. Physical testing methodologies for the surrogate structure, including the weld bonded joints, have been developed, to be compared with structural and crash analysis results.

One point of interest which has been raised about structural applications of composites is how to ensure quality, both after the initial manufacture and through day-to-day usage, or after low-energy impact events. This will require the development of non-destructive evaluation (NDE) techniques that are low cost, robust, and easy to use. Examples of techniques which we will be evaluating for further development are thermal wave imaging, vibro-thermography, embedded microspheres or nanotubes encapsulating a fluorescent dye, embedded fiber optic mesh, and “coin tap” techniques.

Manufacturing a structural composite underbody and assembling it into a vehicle is a radical change in the vehicle assembly process. We are beginning to work on a scenario that will allow this assembly within a generic auto manufacturing facility.

## Composite Underbody Design

Multimatic, the design and analysis supplier for Phases 1 and 2, examined the benchmark steel vehicle underbody (see Figure 1a) to determine the basic construction, attachment requirements, parts count, material selection and gage.

Based on an evaluation of the steel design, and the results of Phase 1 [1-3], the preliminary Phase 2 composite underbody CAD design model was developed to assess manufacturing and tooling requirements, and for further development (see Figure 1b). The composite underbody design integrates 16 stamped steel components into a single molded floor with ribs, and utilizes both carry-over and modified mating components. The model represents the proposed joining concept and component integration. The overall dimensions of the underbody are approximately 1640 X 1470 X 445mm with a variable material thickness ranging from 2.0 to 5.0mm based on the selected MPS and Phase 1 performance requirements.

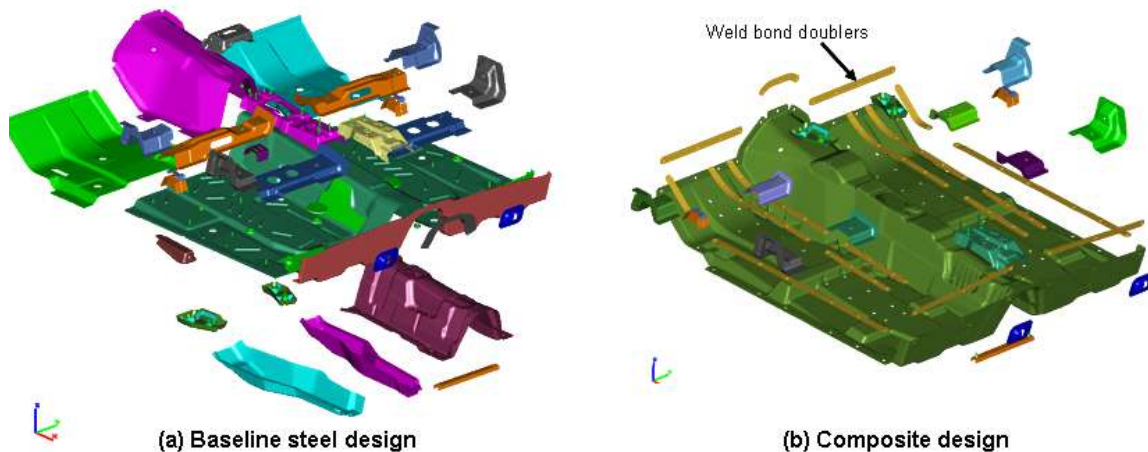


Figure 1: Baseline steel and composite design

## Structural Performance and Mass Assessment

To assess the underbody performance and mass of each candidate material selection, the following development load cases were considered in Phase 1:

- Body-in-White (BIW) static torsional and bending stiffness and modal response
- NCAP 35 mph Full Frontal Impact
- EuroNCAP/IIHS 40 mph Frontal Offset Deformable Barrier (ODB)

- FMVSS214 33.5 mph Side Impact
- FMVSS301 50 mph Rear Offset Impact

The methodology and results of this assessment are reported in [1, 3]. Relative to the baseline steel underbody, it was found that the expected mass savings using glass FSMC with a high elongation core is 14.9 kg, which includes a secondary mass savings of 3.3 kg from the underbody rails. This translates to 33.2% mass savings vs. the baseline steel design. An additional 1.6 kg could be saved by going to a carbon fabric 48 wt% composite with an HEC, however, this would be at a cost of about \$150/kg saved. This surprisingly high cost per mass saved is due to the fact that this application is strength-driven due to the crash loads. In particular, the compressive strength of the carbon composite is not significantly higher than the compressive strength of the FSMC. It is well known that carbon fiber composites result in significant mass savings in stiffness-driven structures, and/or when higher wt% carbon composites (e.g. prepreg) are utilized.

### **Vehicle Assembly / Joining**

Conceptually, the integration of structural composites into a primary metallic structure can be solved via adhesive bonding. This basic joining approach has been successfully implemented in many operations with low volume builds, particular conditioning procedures and special care. In optimal, lightweight, multi-material designs, structural bonding provides enhanced seam integrity, gap bridging or tolerance functions and galvanic separation. However, for automotive line rates and plant infrastructure, several process and quality assurance considerations present concerns and need solutions. In the high volume automotive environment, cycle time, body shop assembly process compatibility, and structural performance are all key requirements, and welding is a primary joining technique.

The combination of welding and bonding, also known as “weld bonding”, is currently being implemented for steel-to-steel joints in some OEM body designs and assembly plants as a means of increasing stiffness, reducing mass, and improving durability. Weld bonding is currently envisioned as the primary joining process to meet the complex automotive requirements for the composite underbody. Specifically, the concept is to attach steel weld bond doublers (see Figure 1b) to the composite to enable spot welding to the surrounding steel structures as well as to attach the structural underbody rails to the composite floor (see Figure 2). The adhesive would be applied prior to spot welding. Not only would weld bonding provide compatibility with current body shop assembly and welding processes for installing the underbody itself, but the spot welds would also serve as peel stoppers in the adhesive joints, provide fixturing during adhesive cure, and enhance overall joint durability and robustness. Figure 3 illustrates a typical weld bond joint, as would be found at the rocker location shown in Figure 2.

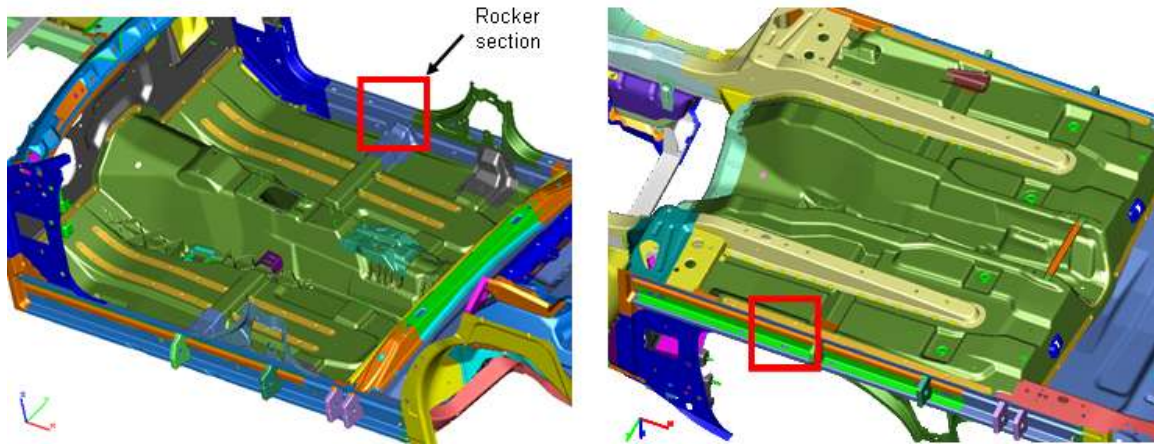


Figure 2: Composite underbody assembled into donor vehicle BIW

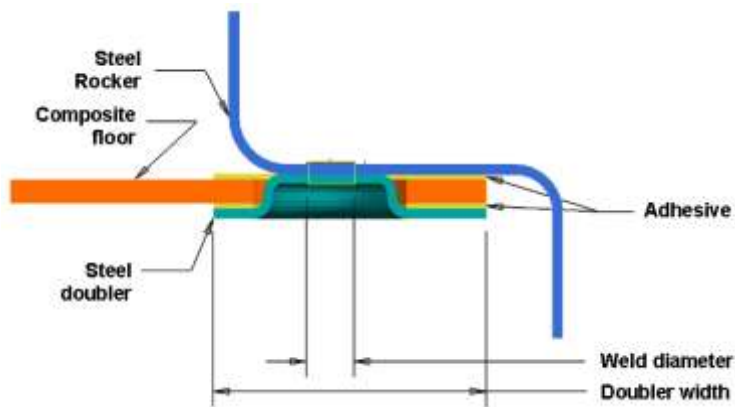


Figure 3: Typical Weld Bond Joint Section at Rocker (see Figure 2)

## Material and Process System Development

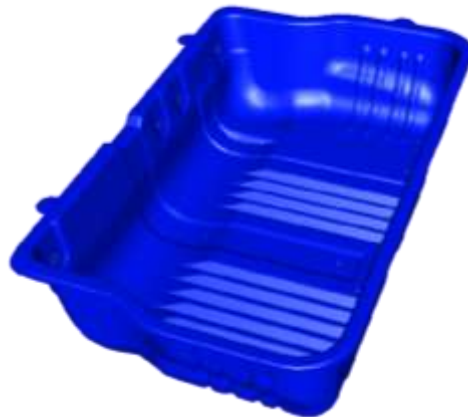
As stated above, a glass FSMC with a high elongation core was selected as our material and process system. While molding trials in 2007 showed that this concept could work, further testing indicated that the originally selected HEC material would not withstand the processing temperatures needed for vehicle assembly. M&P System development in 2008 has focused on finding an acceptable core material. In a plaque molding trial, a variety of core materials were screened, including expanded mesh materials such as steel, poly ethylene terephthalate, and poly vinyl chloride, a polyester roofing fabric, a thermoplastic epoxy film, aluminum screening, and several types of cotton fabric. A number of these showed the desired failure mode of continued low level structural connectivity at high strain after failure. Several of these will be further evaluated in upcoming molding trials.

## Experimental-Analytical Correlation Studies

As part of the development of the Phase 2 design input data, several experimental-analytical correlation studies are planned to develop the analytical material properties and models required for the detailed features of the Phase 2 underbody CAD design. These studies will be used to develop and validate analytical modeling techniques for materials, weld bonded joints, and structural components by correlating physical testing of coupons and surrogate components in environmental, static and dynamic loading conditions.

### Surrogate Component

The surrogate component mentioned above is illustrated in Figure 4, and has a nominal size of approximately 1365 X 785 X 285 mm with a nominal 3.5mm wall thickness and a 2.0 mm perimeter bond flange thickness. This is approximately 45% of the plan view size of the composite underbody with a similar part depth. The tool is a compression tool with shear edges designed for molding glass mat thermoplastics, which should be suitable for molding our glass FSMC material. The surrogate component will be used for material and process development and to mold components for physical and analytical component level performance assessment trials.



*Figure 4: Surrogate Component*

As a first step toward assessing the impact performance of the surrogate component, two test configurations were developed to estimate the impact test mass and speed requirements to achieve “reasonable” tub deformations and loads. For this purpose, portions of the full tub, including representative rocker and underbody rail sections, were selected to represent impacted sections of the full vehicle (see Figure 5). The required initial mass and impact speeds were iteratively determined by means of a dynamic FE analysis to induce similar deformation modes (within the confines of the surrogate component design) as observed in the full vehicle models.

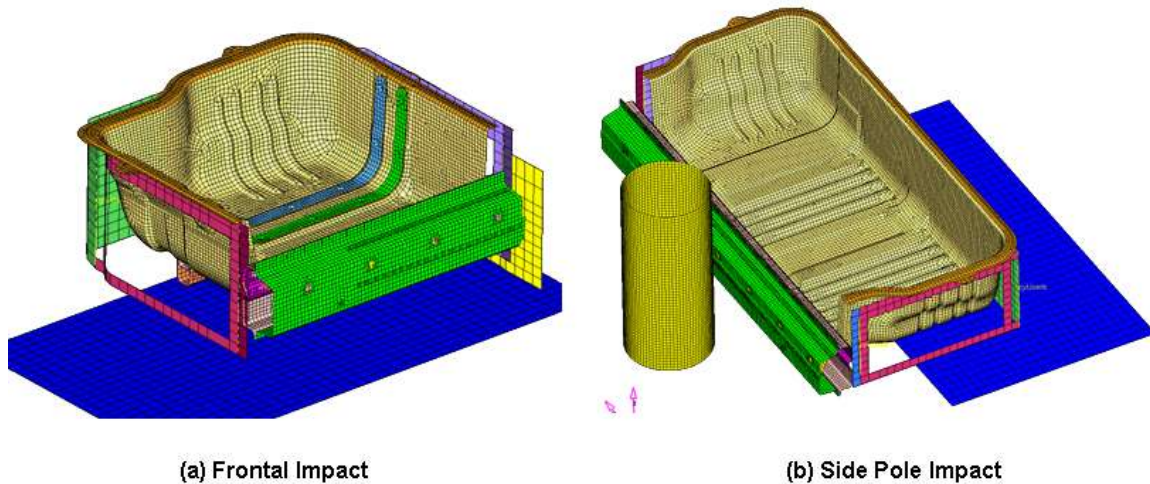


Figure 5: Surrogate Component Impact Models

Further analytical test development is planned once a suitable physical test facility is identified and test capabilities are established. Physical impact testing and performance validation is planned pending the availability of molded surrogate components. A similar approach is under development for the fatigue testing of the surrogate component.

### Material Drape Studies

One of the major questions for processing the underbody is the drape of the FSMC. Woven fabric will not deform as easily as a conventional random SMC, however, large deformations are possible via shearing of the fabric. The simulation of the complex FSMC deformation behavior is possible with certain simplifying assumptions, and the initial drapability of the surrogate component and the underbody has been studied. We have worked with the University of Massachusetts at Lowell to determine the drape characteristics of multiple layers of the FSMC, and to use this in computer models to assess the drapability of the underbody layup determined by the structural requirements, and to facilitate the estimation of the blank size and shape, and preform configurations. The models have been applied to a simple double-dome (with a connecting tunnel) shape, as well as the surrogate component and the full underbody design. The double-dome shape has been molded, and the fabric orientation qualitatively analyzed to validate the modeling. This study includes the characterization of the FSMC material, i.e., the frictional, tensile, and in-plane shearing behavior. This work is presented in more detail elsewhere [5].

A mesoscopic/discrete approach using beams to model the yarns has been used, and shell elements are associated to the beams in order to model the in-plane shear behavior. The drapability of both the surrogate component and the floorpan has been studied for different fabric orientations (Figures 6 and 7), and valuable observations were made to further improve the drapability of the parts. Based on these simulations, it appears that the proposed structural laminate orientations of  $0^{\circ}/90^{\circ}$  and  $+45^{\circ}/-45^{\circ}$  plies should be achievable, however, with some potential local areas of concern:

- Several regions of high fabric shear ( $>50^{\circ}$ ) are evident in local areas of each part, depending on the ply orientation and the local geometry.

- Local geometric features can lead to significant tensile stress in the yarns and subsequent fiber breakage.
- The location of initial tooling / fabric contact can affect drapability. For example, the corrugations at the bottom of the surrogate component can lead to high yarn tension and fiber bridging if contact is first made across the peaks and the fabric must subsequently be forced into the channels. Preforming the fabric in such a way as to allow for additional fabric in this region may improve drapability.

To minimize the risk of fabric wrinkling and fiber breakage and to make the components manufacturable, it may be required to alter the part shape through the use of “gentler” geometry features, alter the fabric ply orientation(s), add additional fabric performing operations or separate smaller plies, or a combination of these.

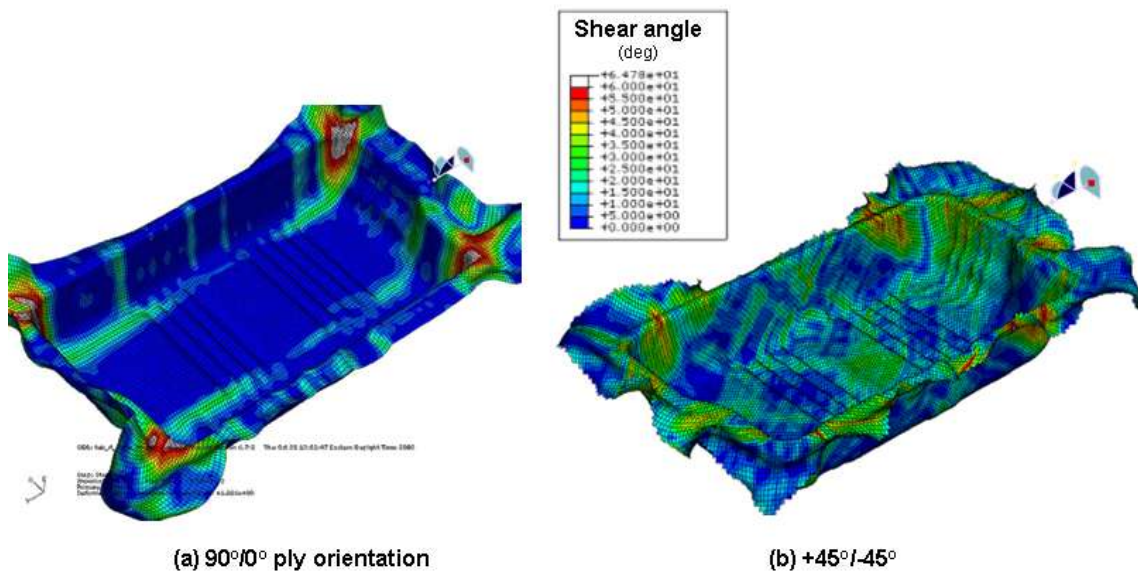


Figure 6: Shear angle contours for the draping simulation of 90°/0° & +45°/-45° surrogate component plies

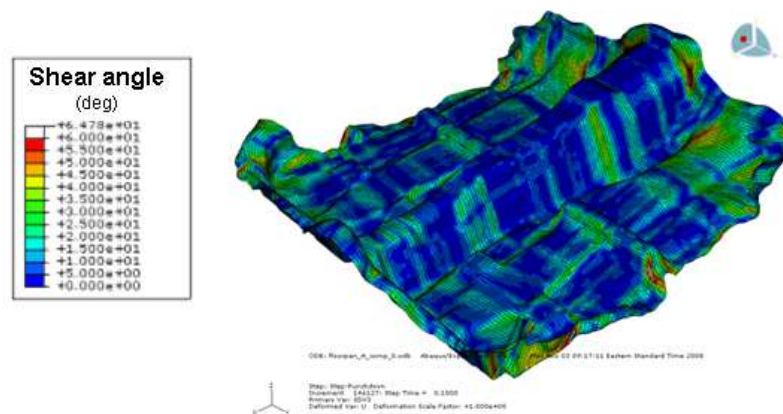


Figure 7: Shear angle contours for the draping simulation of a +45°/-45° floorpan ply

## **Weld Bond Studies**

A key element of the underbody design is the composite-to-steel weld bond joining concept as shown in Figure 3. To gain confidence in the vehicle level joint performance, quasi-static, impact, and fatigue loading conditions will be accessed via analysis and physical testing. Test-analysis correlation will be used to establish the best modeling practices and material models to be used for the prediction of weld bond joint performance.

Since it will be necessary for the underbody joints to carry dynamic loads, the adhesive used in the weld bonding must also be able to survive this loading. Two highly toughened adhesives, currently in use by the automotive industry for steel body-in-white weld bond applications, were trialed by the adhesive suppliers. In these trials, the adhesive suppliers were provided laser cut coupons of 50 wt% random chopped glass SMC with the planned resin system. Standard composite-to-composite lap shear tests were conducted to assess general material compatibility and adhesion. Both investigations reported positive results in that the failures noted occurred in the composite substrate and not the adhesive joint interface.

### **Super Lap Shear Coupon**

The primary geometry for evaluating the joint performance is the super lap shear (SLS) coupon. The SLS coupon was originally designed to evaluate quasi-static tensile joint performance, but it is also being considered as a candidate for evaluating dynamic tensile performance, as well as quasi-static bending and torsional durability performance. Several SLS coupons have been fabricated to date for initial performance assessments and test method development. An early SLS coupon is shown in Figure 8.

### **Quasi-Static Performance**

Several analytical studies were carried out to gain insight into quasi-static SLS tensile performance and to further develop the initial coupon design. The initial efforts were focused on:

- Mesh sensitivity
- Adhesive and weld modeling techniques
- Steel gage / grade effects
- Composite material effects (random and fabric SMC)
- Joint strength for tension, shear, bending, and torsion load cases

Preliminary quasi static tension, bending, and torsion testing have been carried out by ORNL and GM R&D for some early SLS coupons. Figure 9 shows the sample data for coupons made with a 7 ply 0/90 fabric and two gages of steel, 0.7mm GMW2 mild steel and 1.6mm DP590. The specimen with 0.7mm steel showed significant yielding of the steel before the joint failure. The specimens with 1.6mm steel, however, appeared to fail in the joint with composite shearing and tearing of weld nuggets accompanied by delamination. The initial test-analysis correlation of the first-off test coupons appears promising in terms of overall load-displacement response and peak load prediction.

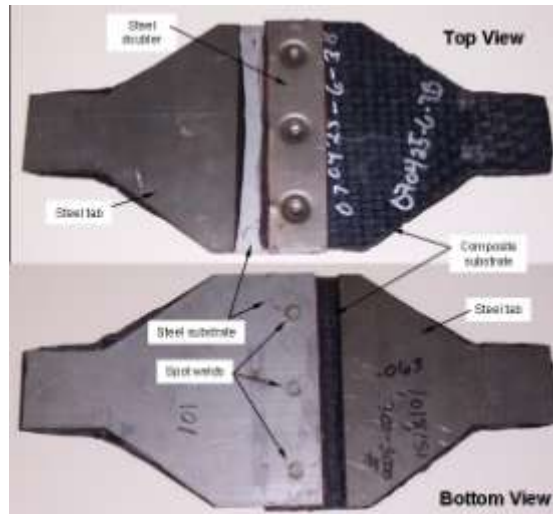


Figure 8: Super Lap Shear Coupon

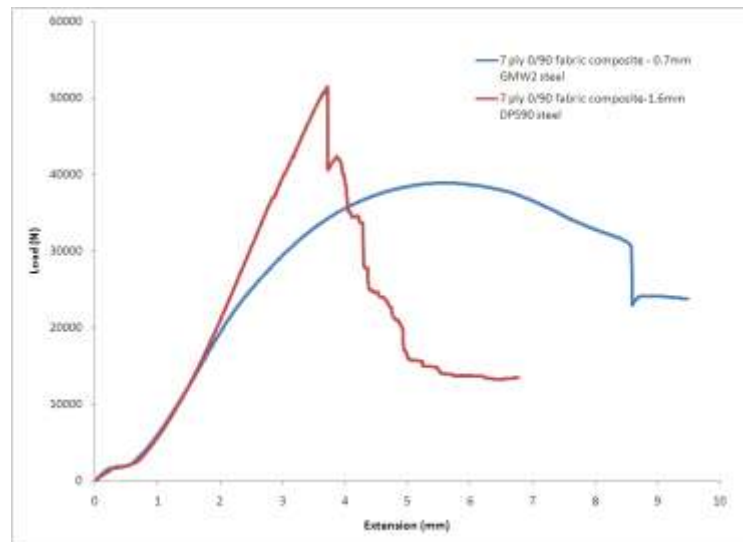


Figure 9. Quasi-static load-extension curve of weld bonded composite-to-steel SLS coupons

## Dynamic Performance

Dynamic tensile testing is planned at the TMAC facility at ORNL. The tensile tests will be carried out at higher strain rates derived from predicted rates observed in vehicle side impact. The initial test efforts will be focused on:

- Coupon, fixture and test methodology development
- Steel gage / grade effects
- Composite material effects (random and fabric SMC)
- Coupon configuration rate effects (welded vs. only bonded)

## **Durability Performance**

To understand the general durability loading conditions in the proposed composite underbody, a vehicle level finite element model with an early composite underbody design was utilized to gain insight into the joint level loading modes. The vehicle model was subjected to simulated worst-case pothole loads and the resulting peel and shear forces were studied in the joint areas. From the analysis results, it was observed that localized mixed mode shear and peel stresses were induced in many joint areas of the underbody, but especially at the end of the weld bond joints and in the vicinity of the local geometric features. Based on these observations, various loading conditions for the SLS coupons were investigated analytically in an effort to generate a range of peel and shear stresses in the adhesive joint. The results of this coupon level study indicated that a range of peak shear and peel could indeed be achieved via bending and torsion testing of the SLS coupon, depending on the gage of the steel substrate, and the test configuration. Further test development is in process to assess the cyclic joint durability under various shear and peel stresses.

Additionally, material coupon fatigue testing has been initiated to generate preliminary S-N response curve for the FSMC material.

## **Summary and Next Steps**

In Phase 1, glass FSMC, with a high elongation core was selected as our material and process system. A preliminary one-piece molded composite underbody design concept was selected, and its structural performance was analytically assessed assuming surrogate material properties and several stiffness and crash development load cases. In Phase 2, additional load cases have been considered along with MPS material properties, leading to an overall mass savings of 14.9 kg, or 33%, including secondary mass saved in the sled rails. To achieve the required level of confidence in the analytical performance and mass assessments, further considerations will be made for material rate dependency and environmental effects.

Further development of the FSMC is necessary, particularly for the manufacture of large parts, and for joining of these parts to the steel vehicle structure. Plaque molding trials have provided several materials showing the proper elongation failure behavior, which will be further investigated. Fabric drape analysis has shown areas for which the design may need to be slightly modified.

A surrogate component has been identified, to allow processing studies of a large structure and validation of design and analysis methodologies in a molded and weld bonded part. Dynamic evaluation of weld bond samples is underway, in cooperation with the ORNL TMAC facility.

## **Acknowledgements**

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