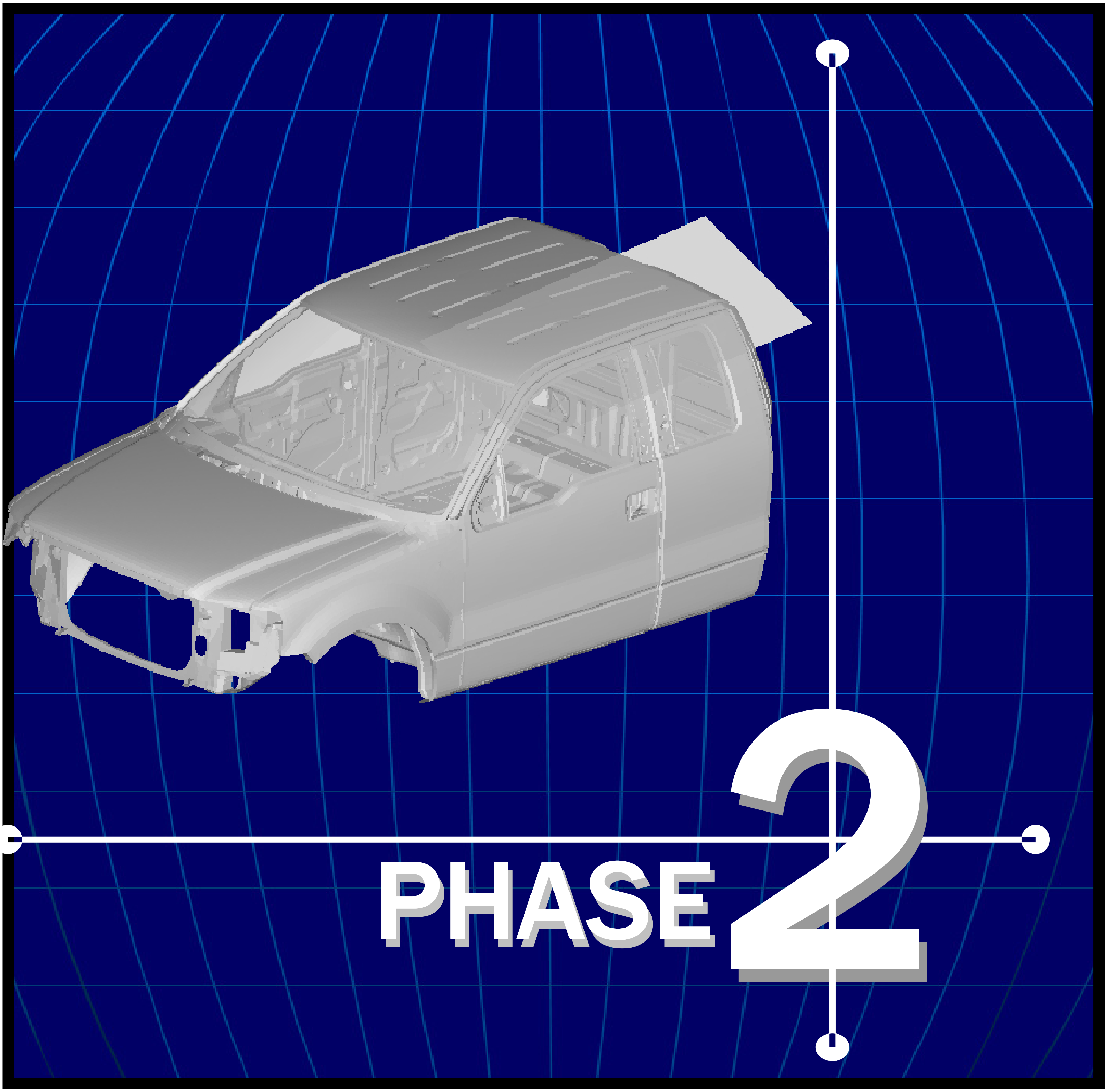

Mass Efficient Architecture for Roof Strength (MEARS)

Phase II Executive Summary

A design optimization study of an automotive roof structure for advancing safety

A/S P Auto/Steel Partnership

EXECUTIVE SUMMARY

PROGRAM GOAL

The goal of the Phase II project was to continue to develop a mass efficient roof structure on the B-pillar less, light truck structure that was the used in Phase I.

These goals included:

- Providing a mass efficient design of the roof structure by further optimizing the Phase I Composite Insert Nylon Steel Design through use of analytical multi-objective optimization.
- Developing designs that continue to meet the enhanced FMVSS 216 roof strength requirements as proposed by the MEARS team.
- Investigation of alternate steel only design concepts that would meet the requirements in a mass efficient manner.
- Investigation of continuous bonding methods including laser welding and weld bonding to gain further mass efficiencies.
- Providing a final design concept that is manufacturing feasible by conducting metal forming simulations and process evaluations on parts that are new or use ultra high strength steels like Boron Steel or Dual Phase Steels.
- Developing a cost model and perform a detailed cost analysis of the final design concept accounting for the manufacturing process and assembly changes in the design.
- Presenting a final design concept that represents an Optimal Design Concept of Mass Efficient Architecture for Roof Strength Performance.

PROGRAM STRUCTURE

In order to achieve these goals, The MEARS team structured the program into the following phases or milestones as shown below:

- Refine CAE Phase I Model (Milestone 1)
- Steel only Design Investigation (Milestone 1A)
- Correlate Composite Reinforcement Performance with Physical Test Results (Milestone 2)
- Refine Existing Geometry to Enhance Roof Strength Performance (Milestone 3)
- Investigate the Performance Improvements of Continuous Bonding (Milestone 4)
- Feasibility Studies (Milestone 5)
- Determine Cost Impact of Design Changes (Milestone 6)
- Final Report (Milestone 7)

PHASE I STUDY FINDINGS

The Phase I final design concept model was validated in terms of the overall load carrying capability at the beginning of the Phase II study. With the use of advanced high strength steels throughout the greenhouse, and the introduction of Composite Nylon Inserts in key areas, the Phase I final concept model was able to carry a normalized load of 3.06. Through design optimization, the mass of the steel components in the roof structure reduced by 5.2 kg. The overall mass of the roof structure including the nylon inserts was 1.3 kg higher than the donor model. More significantly, this Phase I final concept model allowed the roof structure to hold a 40% higher normalized load.

Table 1 below details the metrics of these two models.

Model	Normalized Load	Mass of Roof Structure (kg)
Donor	1.8	36.1
Phase I Final Design Concept	3.06	37.4

TABLE 1: Donor Model and Phase I Final Concept Model - Comparison Table

OPTIMIZATION OF THE STEEL DESIGN WITH COMPOSITE NYLON INSERTS

The Phase I Final Concept Model was used as the baseline for this study. The composite inserts that were developed in Phase I were optimized for size and shape. The surrounding greenhouse structure was also included in the optimization effort in order to achieve a more mass efficient solution. Of all the designs developed, five designs were shortlisted as potential final design concepts in this phase of the study. The five concepts developed all met the load requirements and had varying degrees of mass savings and cost efficiencies. Table 2 below shows the mass of the roof structure for each of the five design concepts and mass savings compared to the Phase I Final Concept Model.

Model	Normalized Load	Mass of Roof Structure (kg)	Mass Savings (kg)
Phase I Final Design Concept	3.06	37.4	N/A
Phase II Composite Nylon Insert Steel Design Concept #1	3.0	32.2	5.2
Phase II Composite Nylon Insert Steel Design Concept #2	3.0	36.4	1.0
Phase II Composite Nylon Insert Steel Design Concept #3	3.0	36.7	0.7
Phase II Composite Nylon Insert Steel Design Concept #4	3.0	36.3	1.1
Phase II Composite Nylon Insert Steel Design Concept #5	3.0	31.7	5.7

TABLE 2: Composite Nylon Insert Steel Design Concepts – Mass Comparison

COMPOSITE BODY SOLUTIONS CORRELATION DATA

Overall, material development and partial bonding modeling techniques are still being enhanced as more data is collected and more tests are conducted. As it stands right now, the data that has been established is correlated back to a variety of three point bend tests, along with some full vehicle tests.

The effects of partial bonding were examined and it has been determined that when a composite body solution was not fully bonded, the performance of the overall structure could be reduced significantly. Generally, there was no clear methodology to predict a ratio of performance (stiffness) compared to the percent of bonding for a specific composite body solution. It was determined that if areas of partial bonding are known and incorporated into an analysis model, then good correlation can be achieved between a physical structure and analytical results.

OPTIMIZATION OF AN ALTERNATE STEEL ONLY DESIGN

Due to the higher costs generally associated with using composite body solutions, a roof structure design that used only steel was considered a more widely acceptable solution. The Phase I Final Design Concept Model was used as a baseline and starting point for this study. The Composite Nylon Inserts were removed, and the gauge and material grade were optimized to develop design concepts that met the overall roof strength load requirements.

Only one of the numerous design concepts developed using steel only options performed well enough to be considered in the final model ranking phase of this study. The solution meets the load requirement, but a slight mass increase occurred when compared to the Phase I Final Concept Model. The design was 1.4 kg heavier, and used an extensive amount of Ultra High Strength Steels (UHSS) in order to achieve this minimal increase in overall mass of the roof structure.

Table 3 below shows the mass of the roof structure for the steel only design compared to the Phase I Final Concept Model.

Model	Normalized Load	Mass of Roof Structure (kg)	Mass Penalty (kg)
Phase I Final Design Concept	3.06	37.4	N/A
Phase II Alternate Steel Design Concept #1	3.0	38.8	1.4

TABLE 3: Alternate Steel Design Concept Solution – Mass Comparison

LINEAR STATICS BASED OPTIMIZATION

Linear statics based optimization showed a lot of initial promise, though many factors limited our overall ability to use this method to guide our design optimization process. It served as more of a confirmation to what had been already learned through detailed non-linear optimization.

Topology optimization showed results very similar to our non-linear optimization efforts. It indicated that higher gauges and design changes to improve stiffness in the C-Pillar area were critical to the structure meeting the load requirements.

Similarly, the volume topology showed to be a quick way of establishing the nylon insert locations. Lastly, the shape optimization provided an interesting approach for developing shape changes and identifying shape variables for optimization. Unfortunately, the package, styling and manufacturing feasibility (as is often the case) limited our ability to continue this investigation further.

In conclusion, linear statics based optimization for complex non-linear problem is a relatively new approach with a lot of research activity in the recent years, some providing very interesting results. In this project, these approaches showed similar trends to the non-linear optimization results, and therefore, served as a confirmation of the results obtained from the non-linear optimization. We strongly feel further research and development activity in this area would potentially uncover new, quicker and more effective ways to establish linear statics based optimization to solve complex non-linear problems.

CONTINUOUS BONDING EVALUATION

Weld bonding did not show any benefit to enhance roof strength performance. Two factors work against the use of weld bonding for this application. First, overall stiffness of structure only showed minimal gains. Secondly, the inclusion of the weld bonding process adds significant cost to structure.

Similarly, laser welding does not show any significant benefits in enhancing the rood strength for mass savings. Through evaluation of the effects of laser welding, it was determined that doubling the greenhouse welds improved the load carrying capability around 6%. However, since it adds a lot of cost to the assembly process. Therefore, doubling the amount welds in the structure is not economical.

By optimizing the number of welds added to the structure to those with load of 5 kN or greater, the number of added welds was held to 20. This achieved an additional 0.5 kg of mass savings in the Phase II Composite Nylon Insert Steel Design Concept #1 model while meeting roof strength requirements. This design was called Phase II Composite Nylon Insert Steel Design Concept #5. (Table 4)

Model	Normalized Load	Mass of Roof Structure (kg)	Mass Savings (kg)
Phase II Composite Nylon Insert Steel Design Concept #1	3.0	32.2	-
Phase II Composite Nylon Insert Steel Design Concept #5	3.0	31.7	0.5

TABLE 4: Phase II Spot Weld Optimization - Mass Benefits

MODEL RANKING

At the end of the Phase II study, five design concepts stood out as potential solutions and were considered as candidates for the final concept model. Four of these potential solutions used Composite Nylon Inserts. The other potential solution was a steel only design. A ranking matrix based on mass, cost efficiency, and manufacturing feasibility was developed to select a final model. The selected models contained a combination of composite nylon inserts, new design concepts, advanced and ultra high strength steels and spot weld optimization.

Phase II Concept Nylon Insert Steel Design Concept #5 was ranked as the best design. It was accepted as the Phase II Final Design Concept. This model showed the most mass savings while meeting the enhanced roof strength performance requirements.

COST STUDY

A cost study conducted at the end of the design phase indicated that the Phase II Final Concept Model has an added cost of $69.48 when compared to the Donor Model. The steel components of the Phase II Model accounted for $30 of the cost while the remaining was attributed to Composite Nylon Inserts. However, the Phase II Final Concept Model has a roof structure that is 4.4kg lighter than the Donor Model.

Lastly, the Phase II Final Concept Model roof was able to withstand a load that is 40% greater than the Donor Model under the enhanced FMVSS 216 requirement.

MANUFACTURING FEASIBILITY STUDIES

Formability assessment of the greenhouse components utilizing ultra high strength steels were conducted for the Phase II Final Design Concept.

The Boron Steel components, A-Pillar Middle, Roof Rail Outer, and C-Pillar Inner showed good formability when crash formed using both one-step and incremental forming analysis. Some localized areas of concern where high percentage thinning was observed, which can be easily addressed using radii concessions during part re-design.

The A-Pillar Inner does not show any major split or severe thickness reduction areas when using DP 590 steel material. Only a small area showed some minor splitting that was in the binder area of the blank.

The results of these studies were compared to simulation results for the equivalent parts from the donor model. It was determined that the designs generated during the Phase II portion of the project exhibited similar forming characteristics of the component of the donor model.

Therefore, the team determined the Phase II Final Design Concept was feasible to manufacture.

PHASE II PROJECT CONCLUSIONS

The Phase II Final Design Concept Model had a mass savings of 5.7 kg when compared to the Phase I Final Concept Model and 4.4 kg compared to the Donor Model. In order to achieve the mass savings, a combination of design changes, advanced and ultra high steel materials, additional spot welds and composite nylon inserts were included in the design. The study determined that the C-Pillar stiffness contributed the most to the overall roof structure strength. Composite Nylon Inserts and Boron Steel, coupled with design changes were used to help strengthen this area, allowing gauge reductions and material substitutions to occur throughout the greenhouse structure to achieve the final mass savings. Table 5 below compares the Phase II Final Design Concept with the Donor Model for load capability and mass of the roof structure.

Model	Normalized Load	Mass of Roof Structure (kg)
Donor	1.8	36.1
Phase II Final Design Concept	3.0	31.7

TABLE 5: Phase II Final Design Concept Summary