# Roof Lightweighting Study

## Coalition for Lightweight Materials

**Updated Report**

CENTER FOR AUTOMOTIVE RESEARCH


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# Cover Letter

The CAR's Coalition for Automotive Lightweighting Materials (CALM) is a collaboration of more than thirty industry leading organizations working to support the cost-effective integration of mixed materials to achieve significant reductions in mass through the joint efforts of the material sectors and the auto manufacturers.

Vehicle mass reduction or "lightweighting" has been deemed very important by automakers because of many benefits including performance and fuel economy. The arrival of automated, connected, electrified, and shared (ACES) technology will make lightweighting more important in the future because of added weight and range anxiety in battery electric vehicles (BEVs).

The CALM group selected the vehicle roof structure for a co-development lightweighting study because it provides an opportunity for mixed-material application. The baseline vehicle for this research is the 2011 Honda Accord which has a mild steel roof structure. The design space contains twelve parts including the roof panel, roof bows, roof rails, and the headers.

Lightweighting ideas submitted by various CALM members were tested on various qualitative and quantitative parameters such as manufacturing readiness, joining feasibility, reparability, ability of computer simulation, etc. The project team selected four concepts after filtering through various combinations of the lightweighting ideas. All four concepts were studied by computer aided engineering methods including finite element analysis and design of experiments. The performance of the lightweight concepts were compared to the baseline.

# Major updates in this version

1. New aluminum intensive concept.
2. Updated baseline to include front and rear header to roof-rail connections. (see note)
3. The mass reduction percentage calculation is updated as per the new baseline for all concepts.
4. Torsional stiffness corrected for all concepts.
5. Performance for all concepts are now within 95% confidence level of the baseline performance.

**Steps taken to fix torsional stiffness performance**

1. Increased composite bow thickness (2.5mm from 2.0mm previously)
2. Additional adhesives
3. Better quality data card for CFRP and increased composite roof panel thickness

Note: The baseline change was required due to the addition of new aluminum intensive concept. For the new concept, since the roof bows were updated to aluminum, the front and rear header connecters were also optimized to aluminum and integrated with the headers. This reduces complexity as the aluminum bows can be directly joined to the steel roof rails. For all other concepts, the connectors are kept same as the baseline (i.e. steel) since downgauging them would have affected the performance.

Including the connecters in the baseline increases the baseline mass to 25.69 kg.

# Executive Summary

| | ROOF RAIL | ROOF BOWS | ROOF PANEL | WEIGHT (kg) | MASS REDUCTION % |
|---|---|---|---|---|---|
| BASELINE | Mild Steel | Mild Steel | Mild Steel | 25.7 | baseline |
| CONCEPT 1 | Press Hardened Steel or Generation-3 Steel | Press Hardened Steel or Generation-3 Steel | Dual Phase Steel | 20.8 | **19%** |
| CONCEPT 2 | Press Hardened Steel or Generation-3 Steel | Aluminum, 6xxx series | Aluminum, 6xxx series | 13.01 | **49%** |
| CONCEPT 3 | Press Hardened Steel or Generation-3 Steel | Short Glass Fiber (GF) Injection Molded Polyamide (PA6) with GF Unidirectional (UD) Tape | Aluminum, 6xxx series | 15.5 | **40%** |
| CONCEPT 4 | Press Hardened Steel or Generation-3 Steel | Short GF Injection Molded PA6 with GF UD Tape | Carbon Fiber | 15.3 | **40%** |

# Performance

| Load cases | Baseline | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|---|---|---|---|---|---|
| Mass | 25.7 kg | 20.8 Kg | 13.01 Kg | 15.5 kg | 15.3 kg |
| Roof Crush | 3.7 (SWR) /62 kN | 3.6 (SWR) /61.4 kN | 3.6 (SWR) /59 kN | 3.9 (SWR) /65 kN | 3.6 (SWR) /60 kN |
| Frequency- Torsion | 50 Hz | 50 Hz | 47.76 Hz | 50 Hz | 51 Hz |
| Frequency- Bending | 37 Hz | 36 Hz | 37.25 Hz | 37 Hz | 37 Hz |
| Stiffness – Torsion | 27.6 kN-m/deg | 27.3 kN-m/deg | 28.35 kN-m/deg | 28.51 kN-m/deg | 27.92 kN-m/deg |
| Stiffness – Bending | 6.9 kN/mm | 6.8 kN/mm | 7.17 kN/mm | 7.2 kN/mm | 7.5 kN/mm |
| Dent Resistance (plastic strain) | 1.2% | < 1% | <1% | < 1% | <1% |

# Background

Vehicle mass reduction or lightweighting is an important concept pursued by the automakers since the dawn of the automotive industry. Lightweighting has many benefits including better acceleration, increased fuel economy, reduced green house gas (GHG) emissions, better handling, etc. Vehicle performance is sensitive to the power to weight (P/W) ratio. Therefore, reducing weight while keeping the power constant can drastically improve performance. Also, the fuel economy is improved if the P/W ratio is maintained by reducing power and weight concurrently. Automakers often find a middle ground between improving performance and fuel economy.

The arrival of Automated, Connected, Electric, and Shared (ACES) vehicles and global regulations on GHG emissions will put more pressure on automakers to design lightweight vehicles since ACES technology can add significant weight to the vehicles. For example, a vehicle with 10 gallons of fuel on board weighs an additional 63 pounds, and it gradually drops that weight as the fuel is combusted. A BEV battery pack may contain 100 kWh of energy and weigh 1400 pounds. Other components that may add weight include sensors, thermal management system, sensor cleaning system, comfort and infotainment features, redundant parts for safety, etc. The added weight needs to be compensated by lightweighting other vehicle components to maintain performance.

# Background (cont.)

A vehicle has more than 15,000 major parts. Selecting parts for lightweighting depends on various factors such as mass reduction impact, manufacturability, vehicle crash sensitivity, cost, supply chain robustness, etc. The roof subsystem is deemed very important by automakers to achieve vehicle lightweighting targets. Lightweighting the roof lowers the vehicle's center of gravity which improves its handling. The roof subsystem includes several crash sensitive structural components and also an A-class surface which provides an opportunity for mixed-material applications. Therefore, the CALM team decided to work on the vehicle roof structure for a co-development lightweighting study.

The CALM team selected the roof structure for a lightweighting study to highlight the possibilities of mixed-material for mass reduction. Lightweighting the roof structure not only reduces the vehicle curb weight but also lowers the center for gravity which provides better handling and safety.

## Project Motivation and Objective

1. Prove that mixed-material solutions can save more weight than mono-material solutions and can meet performance

2. Provide CALM members a platform to showcase their material and manufacturing technology to the automakers

3. Provide CALM members networking opportunity with automakers via project presentation

# Project Scope

## In Scope:

- Mass saving ideas in manufacturing readiness level 5 and above
- Mass savings estimate in comparison to the baseline
- CAE analysis to match or exceed baseline performance
    - Roof Crush
    - Bending
    - Torsion
    - Dent
- Directional material cost estimate and qualitative manufacturing feasibility analysis

## Out of Scope:

- Physical Testing
- Absolute Cost

**Manufacturing Readiness Level (MRL)**

| Phase | MRL | State of Development |
|---|---|---|
| Phase 3: Production Implementation | 9 | Full production process qualified for full range of parts and full metrics achieved |
| | 8 | Full production process qualified for full range of parts |
| | 7 | Capability and rate confirmed |
| Phase 2: Pre Production | 6 | Process optimized for production rate on production equipment |
| | 5 | Basic capability demonstrated |
| Phase 1: Technology assessment and proving | 4 | Production validated in lab environment |
| | 3 | Experimental proof of concept completed |
| | 2 | Application and validity of concept validated or demonstrated |
| | 1 | Concept proposed with scientific validation |

# Literature Survey

The vehicle roof structures has been studied in the past by various universities, suppliers, automakers, and other independent organizations.

Lotus Engineering in a lightweighting study on the 2009 Toyota Venza studied aluminum stampings for roof panel and magnesium castings for roof bows. The idea saved 11 kg from the mild steel baseline.

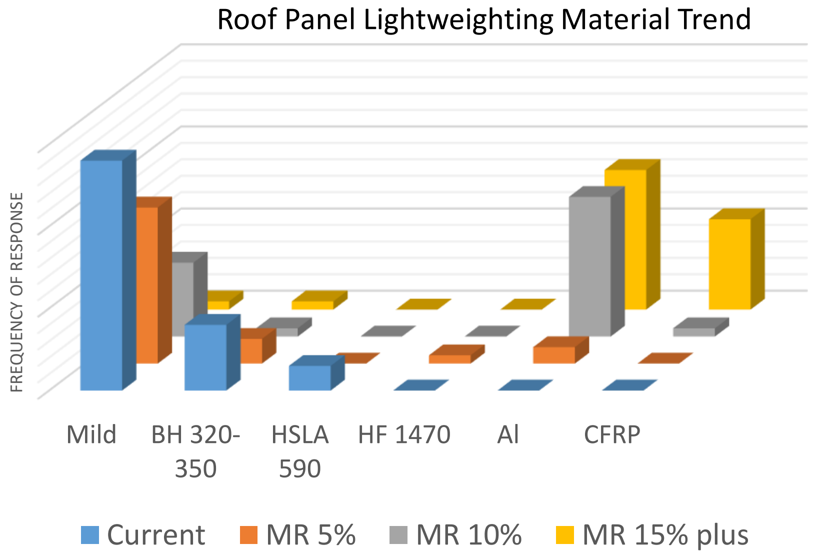
EDAG in a lightweighting study on the 2011 Honda Accord utilized aluminum for the roof panel and advanced high strength steel for the bows and roof rails. The aluminum roof panel achieved 45% weight savings over the steel baseline.

EPA and FEV in a lightweighting study on the 2011 Chevrolet Silverado utilized aluminum 5000 series for the roof panel.

NHTSA and EDAG in a lightweighting study on the 2014 Chevrolet Silverado utilized aluminum to save 38% weight over the mild steel baseline.

CAR survey of 42 vehicles from nine automakers revealed mild steel as most popular material for roof panel today. To achieve lighweighting automakers are most likely to use aluminum for up to 15% curb weight reduction and polymer composites beyond 15% curb weight reduction.

Borazani et al. studied sandwich structure with unidirectional carbon/epoxy composite face-sheets and foam core. They managed to reduce vehicle roof panel mass by 68% while maintaining the same structural performance with the steel solution having equal value of strength-to-weight ratio (SWR).




Source: CAR survey of 42 vehicles from nine automakers

# Literature Survey

A short-fiber polypropylene resin developed by Asahi Kasei plastics was implemented in the 2010 Cadillac CTS sunroof, reducing weight by 12% and component cost by 24%.

The 2015 Volkswagen Golf Hatchback added an optional carbon fiber roof to drop 18-20 pounds of weight from the vehicle.

In 2016, Mercedes-Benz began use of a natural fiber roof frame for their new E-class, being 40% lighter than roof frames made of metal.

The 2016 Cadillac CT6 was GM's first use of laser welding aluminum on a roof, an effort to better optimize mass in their vehicles.

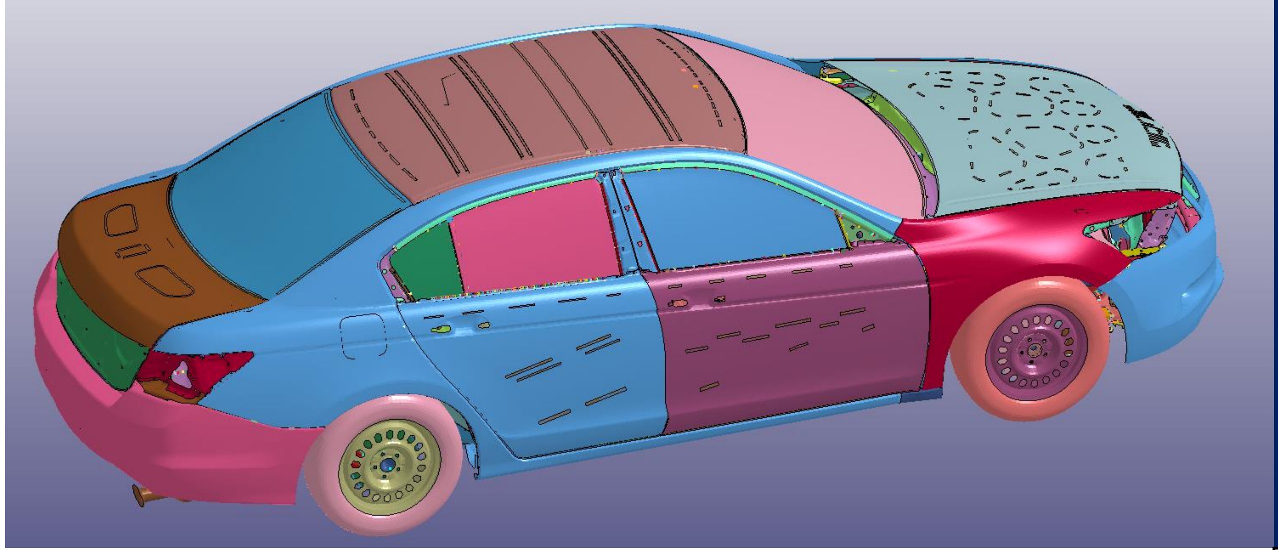
The 2014 GM Silverado utilized zinc-coated (galvanized) steel for the roof for better corrosion resistance.

# Research Method

The project was done in the following steps:

1. Conduct a literature survey of roof lightweighting trends
2. Define scope of the project
3. Select a baseline vehicle
4. Collect roof lightweighting ideas from suppliers using a standard form
5. Analyze and sort the data
6. Select ideas to study via roundtable discussions with the CALM team
7. Hire an independent engineering firm to do the CAE analysis
8. Work with the CAE firm to combine submitted lightweighting ideas into three concept solutions
9. Analyze the lightweight concepts using FEA analyzes against the baseline performance targets
10. Report the results to the CALM team and automakers
11. Make changes based on the feedback
12. Write and Publish a report

# Baseline



Source: NHTSA

## 2011 Honda Accord 4DR LX

VIN: 1HGCP2F3XBA055835
Engine Number: K24Z2-4018756
Control Number: 061145
Exterior Color: Alabaster Silver
Interior Color: Black
Transmission: Automatic

| | |
|---|---|
| Wheelbase (in) | **110.2** |
| Length (in) | **194.9** |
| Height (in) | **58.1** |
| Width (in) | **72.7** |
| Track (in, front/rear) | **62.6/62.6** |
| Curb Weight (lbs) | **3279** |

Highlights:

- Freely available from NHTSA
- Model updated to meet IIHS small overlap requirements
- Mild steel roof structure

FEA Model Available at: https://www.nhtsa.gov/crash-simulation-vehicle-models

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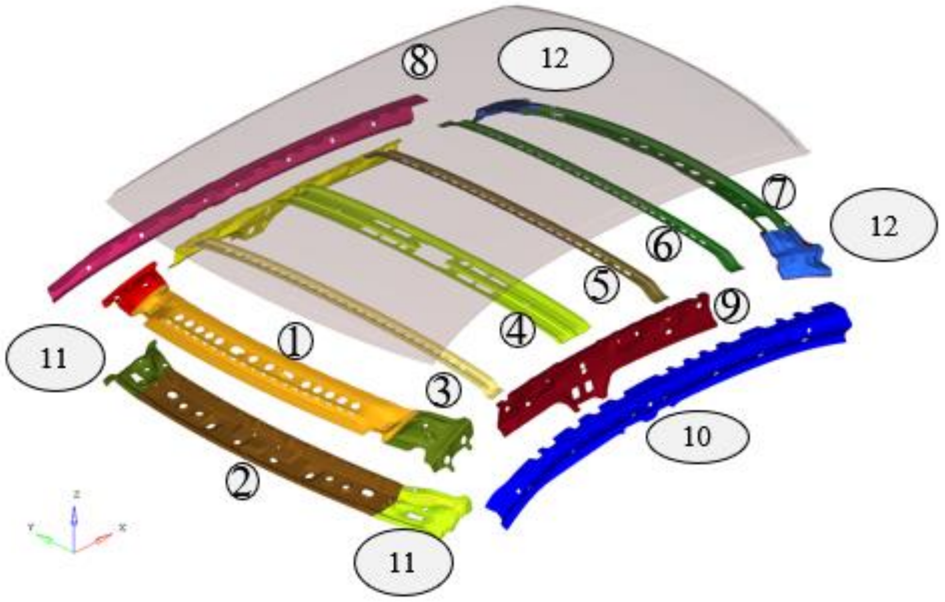
# Design Space

Roof along with all the roof bows and roof rail considered for the optimization.




| S.No. | Part Name | Thickness (mm) | Material |
|---|---|---|---|
| 1 | Front header - upper | 0.9 | IF 300-420 MPa |
| 2 | Front header - Lower | 0.7 | DP 350-600 MPa |
| 3 | Roof  Bow | 1.2 | IF 300-420 MPa |
| 4 | Roof  Bow | 1.2 | DP 500-800 MPa |
| 5 | Roof  Bow | 1.2 | IF 300-420 MPa |
| 6 | Roof  Bow | 1.2 | IF 300-420 MPa |
| 7 | Rear Header | 1.2 | IF 300-420 MPa |
| 8 | Roof Panel | 0.7 | IF 140-270 MPa |
| 9 | Roof rail Inner (LH/RH) | 1.65 | DP 350-600 MPa |
| 10 | Roof rail Outer (LH/RH) | 1.75 | DP 350-600 Mpa |
| 11 | Front header attachments (LH/RH, four parts) | 2.0 | DP 350-600 |
| 12 | Rear header attachments (LH/RH, four parts) | 1.65 | IF 300-420 |

IF = Interstitial free (IF) Steels
DP = Dual Phase Steels

Baseline:

- Design space Mass = 25.7 Kg
- 100% steel
- Joining – Spot-welds and adhesive bonding between roof and roof bows

# Load Cases

The primary functional requirements for the roof and roof structure are to:

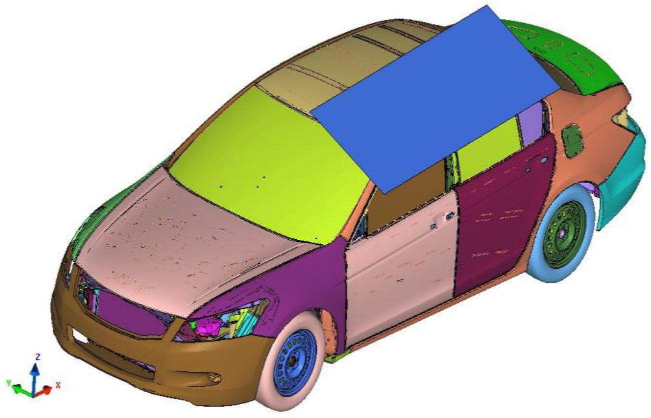
- Provide protection for the occupants from the elements
- Meet federal roof crush regulations (FMVSS 216)
- Contribute to the structural performance of the body
- Contribute to maintaining the dimensional accuracy of the body

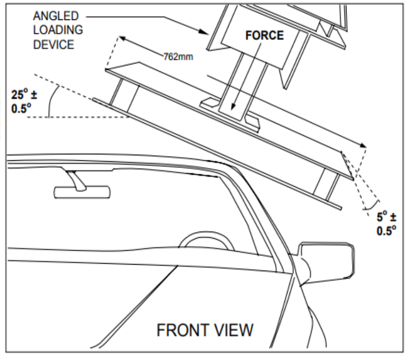
Based on the roof structure's functional requirement, the CALM team selected the following load cases to study for this project:

1. Roof Crush
2. Roof Panel Dent
3. Body-in-White (BIW) bending stiffness and frequency
4. BIW torsional stiffness and frequency

*It was recommended by the CAR's Technical Advisory Council (TAC) and few automakers that side impact is an important functional requirement affected by the roof structure. CAR will study this requirement in future projects.*

# Load Cases

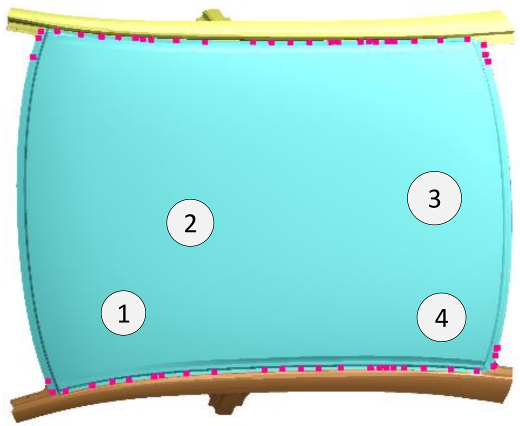





**Roof Crush**

FMVSS 216 - In the test, the strength of the roof is determined by pushing an angled metal plate down on one side of the roof at a slow but constant speed and measuring the force required to crush the roof. The force applied relative to the vehicle's weight is known as the strength-to-weight ratio. The peak Strength-to-Weight ratio (SWR) recorded at any time before the roof is crushed five inches is the key measurement of roof strength.

**SWR value of three and above is considered good by NHTSA.**

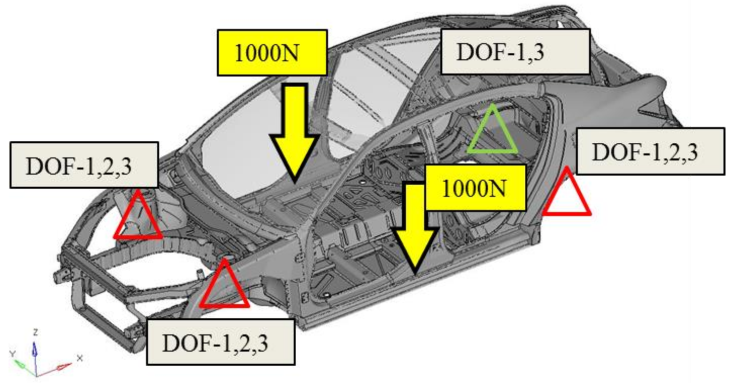



**Roof Dent**

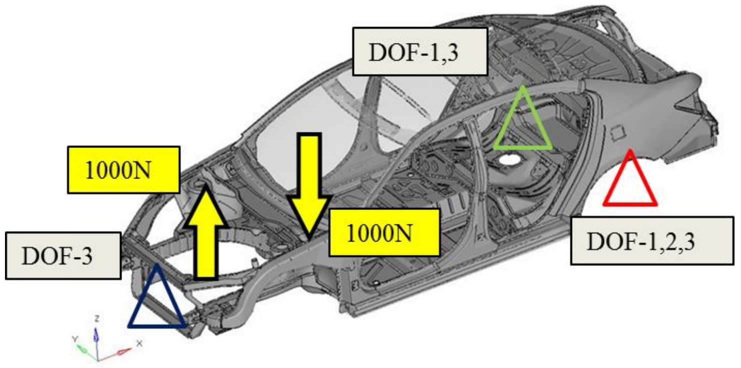
A Spherical ball of 25.4mm indented on roof with 150N force and the response is recorded in terms of resistance force offered and plastic strain to identify any permanent deformation.

**Lower plastic strain value is better as it represents less plastic deformation.**

# Load Cases




**BIW Stiffness – Bending**




**BIW Stiffness - Torsion**

**Bending Static Stiffness**: The Body-in-White (BIW) is constrained at the four shock mounts positions. A load of 1000N applied at rockers.

**Bending Frequency**: The body has resonant frequencies for which a small dynamic force at the resonant frequency can cause large deformations. Although the number of frequencies is infinite, we will calculate lowest frequency of bending.

**Torsion Stiffness**: The BIW is constrained with minimal boundary conditions, at the middle of the front bumper and at the rear shock mount. Force of about 1000N is applied in the opposite direction on the Vertical axis in the shock tower mount. This will induce a static moment on the front shock tower with the rear spring mounts constrained in all translation degree of freedoms.

**Torsion Frequency**: calculate the lowest frequency (mode) of torsion.

# Design Optimization

Design of Experiments (DOE) Based on Surface Response Sensitivity

Response Measured: Peak Force for Roof Crush (FMVSS 216)

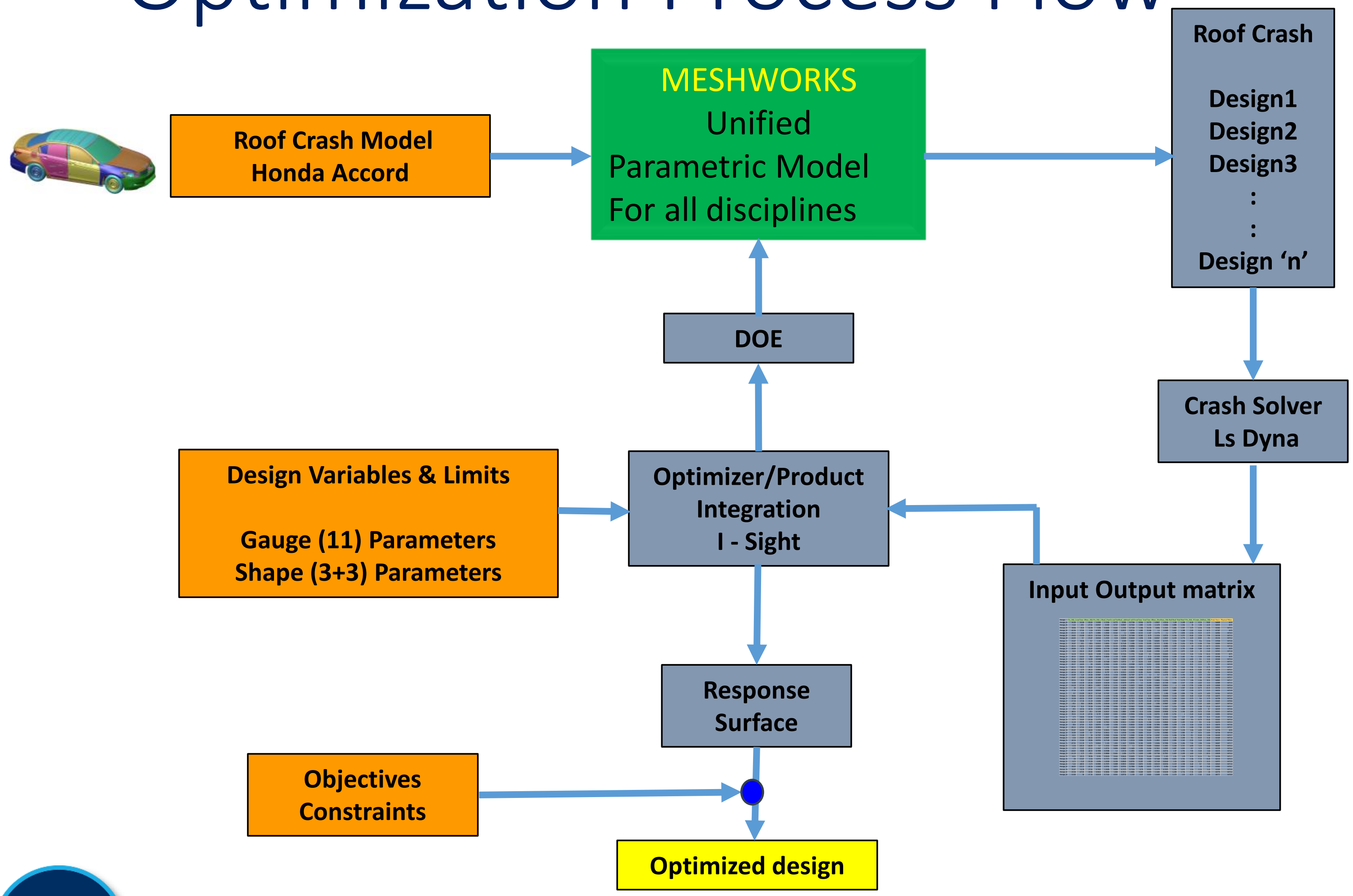
DOE Parameters

✓Gauge or Thickness

✓Material Grade

✓Shape or Cross Section

# Optimization Process Flow




For roof crash analysis, we have considered Force as target. i.e. 3 times of the vehicle curb weight

# DOE & Optimization

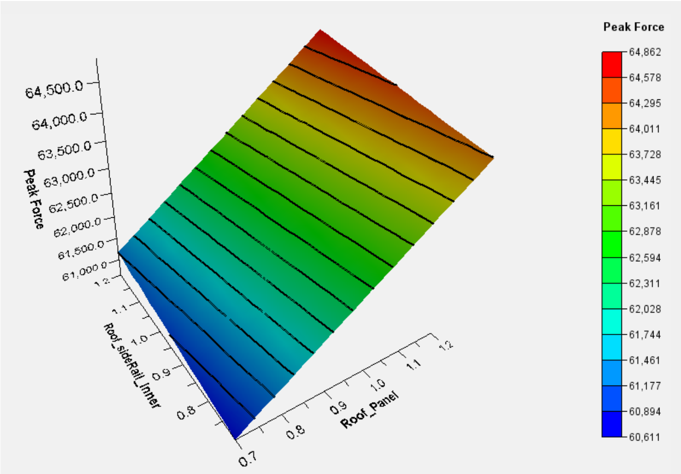
**Input-Output matrix**

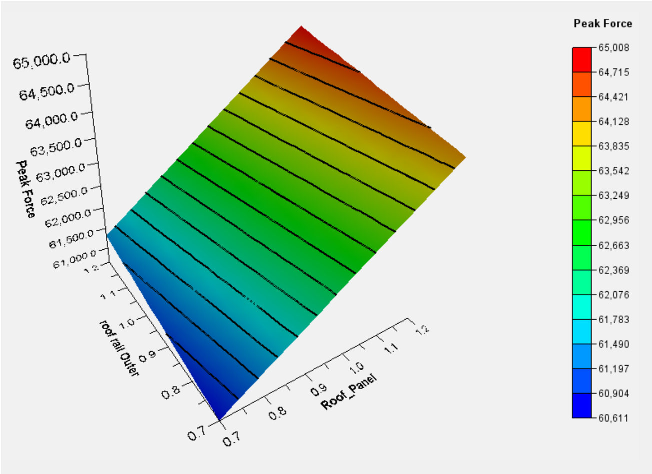
**Design Input**

**Solvers Output**

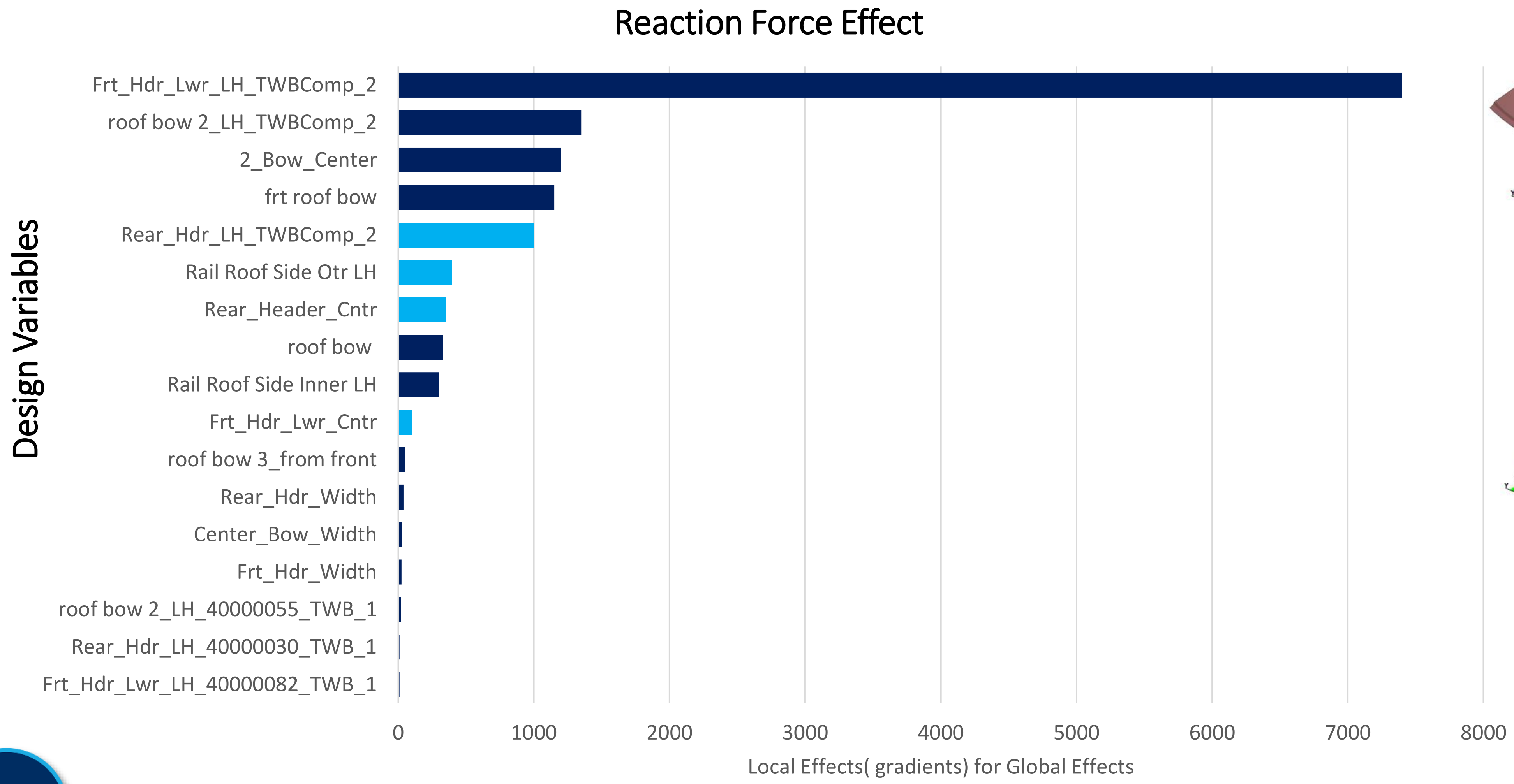
| Design | Frt_Hdr_Lwr_LH_40000082_TWB_1 | roof bow 2_LH_40000055_TWB_1 | Rear_Hdr_LH_40000030_TWB_1 | Frt_Hdr_Lwr_Cntr | Roof_Panel | frt roof bow | Roof_sideRail_Inner | roof rail Outer | roof bow 3_from front | roof bow 4 | Rear_Header_Cntr | Rear_Hdr_LH_TWB Comp_2 | Rail Roof Side Inner LH | Rail Roof Side Otr LH | Frt_Hdr_Width | Center_Bow_Width | Rear_Hdr_Width | Peak Force | Physical Mass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Design_01 | 41.04 | 41.04 | -24.63 | 1.0582 | 1.1104 | 0.773 | 0.991 | 0.7746 | 0.954 | 0.773 | 1.0657 | 1.0134 | 1.09 | 1.299 | -6.12 | 6.12 | -8.81 | 64600 | 1582 |
| Design_02 | -5.22 | -29.1 | -27.61 | 0.8567 | 0.909 | 0.757 | 0.8567 | 0.7522 | 1.003 | 1.151 | 1.1478 | 1.0284 | 1.896 | 1.164 | 10 | 1.04 | -4.33 | 62035 | 1582 |
| Design_03 | 18.66 | -8.21 | -14.18 | 1.006 | 0.8269 | 0.412 | 1.1701 | 0.7149 | 1.184 | 0.133 | 0.894 | 1.1925 | 1.806 | 1.597 | 3.73 | -2.54 | -1.04 | 62462 | 1583.1 |
| Design_05 | -41.04 | 27.61 | 2.24 | 0.7672 | 1.0881 | 0.987 | 0.9537 | 0.8716 | 1.085 | 0.166 | 1.2 | 1.0209 | 1.627 | 1.388 | -3.43 | 6.42 | 6.72 | 67307 | 1583 |
| Design_06 | -23.13 | 2.24 | -0.75 | 1.0881 | 1.0582 | 0.543 | 1.2 | 0.894 | 0.313 | 1.167 | 1.1776 | 1.2 | 1.791 | 1.836 | -2.54 | 0.15 | -3.73 | 62902 | 1584.3 |
| Design_07 | 24.63 | -12.69 | -23.13 | 0.7224 | 0.7522 | 0.51 | 1.1179 | 0.7448 | 0.363 | 0.79 | 1.1254 | 1.0731 | 1.194 | 1.373 | -6.42 | 2.54 | 7.91 | 62330 | 1581.5 |
| Design_08 | -44.03 | 9.7 | -15.67 | 0.8343 | 1.1925 | 0.56 | 0.8269 | 0.8418 | 1.036 | 0.56 | 0.8567 | 1.0657 | 1.239 | 1.776 | 4.33 | -8.81 | -9.1 | 65156 | 1583.2 |
| Design_11 | -15.67 | 38.06 | 9.7 | 1.103 | 1.1776 | 0.79 | 0.909 | 1.0507 | 0.248 | 1.101 | 0.8493 | 0.7373 | 1.552 | 1.418 | -7.61 | -9.4 | -2.54 | 67058 | 1582.6 |
| Design_13 | 35.07 | 29.1 | -30.6 | 0.9313 | 1.0955 | 0.527 | 0.7149 | 1.006 | 1.151 | 0.593 | 0.7373 | 0.991 | 1.94 | 1.254 | 0.75 | -1.04 | 7.61 | 63695 | 1582.9 |

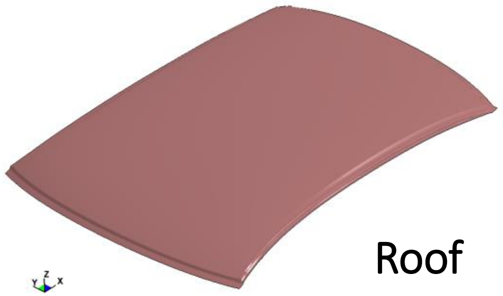
**Response Surface**



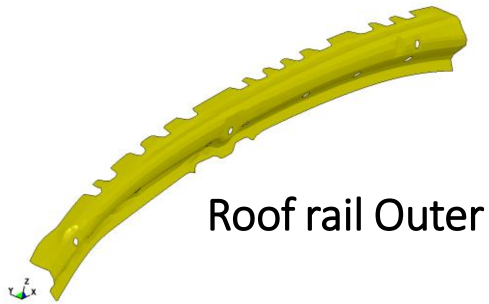



# Surface Sensitivity Plot

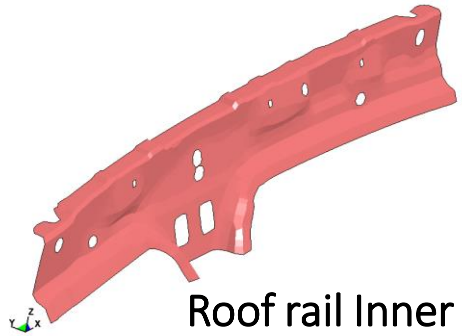


Roof



Roof rail Outer



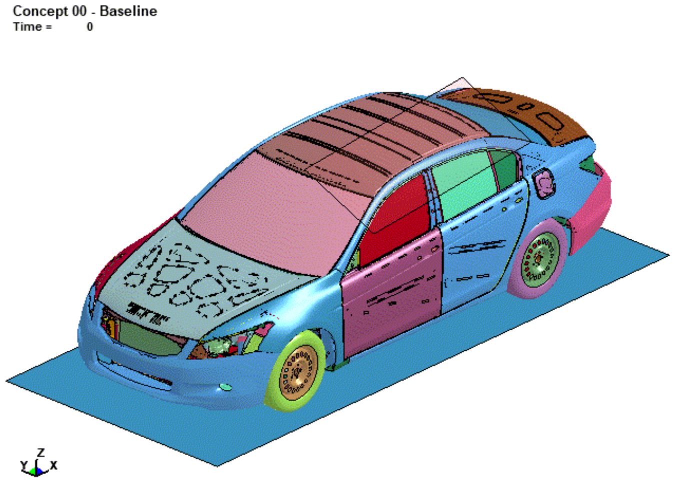
Roof rail Inner

# Baseline Target Performance

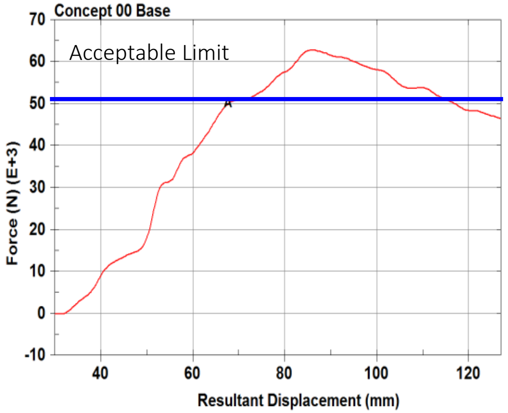
| Load cases | Baseline |
|---|---|
| Mass | 25.7 kg |
| Roof Crush | 3.7 SWR, 62 kN |
| Frequency- Torsion | 50 Hz |
| Frequency- Bending | 37 Hz |
| Stiffness – Torsion | 27.6 kN-m/deg |
| Stiffness – Bending | 6.9 kN/mm |
| Dent Resistance (plastic strain) | 1.2% |

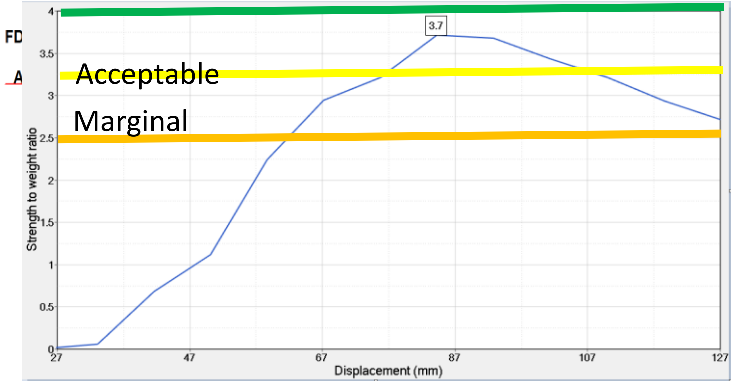
CAE Partner: DEP Smarter Solutions. Realized.

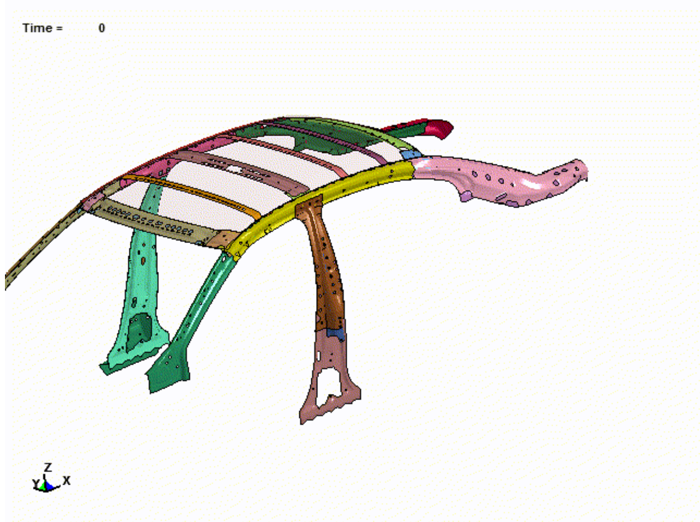
# Baseline Design Results: Roof Crush Resistance



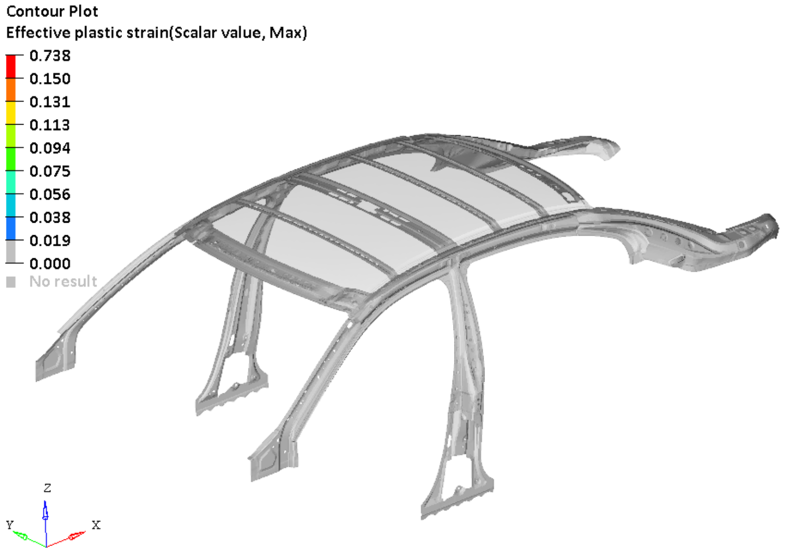

## Force vs Displacement



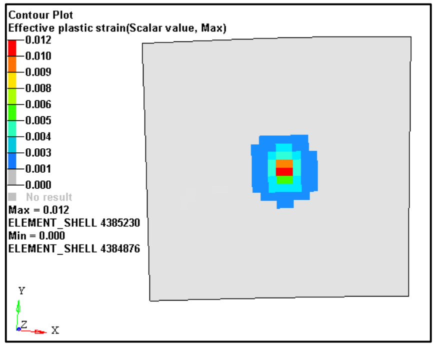




| Criteria | Baseline | SWR |
|---|---|---|
| Peak Force | 62 kN | 3.7 |



# Baseline Design Results: Dent Analysis

1

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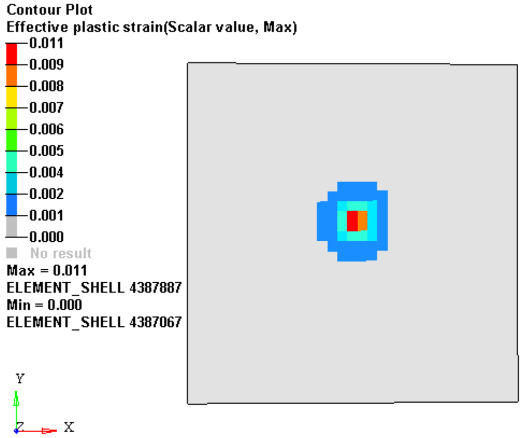


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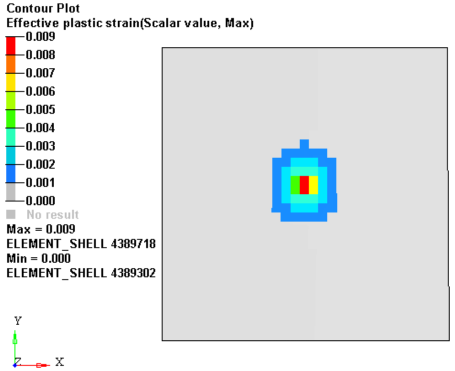


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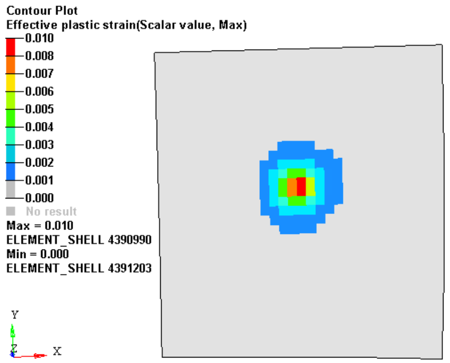
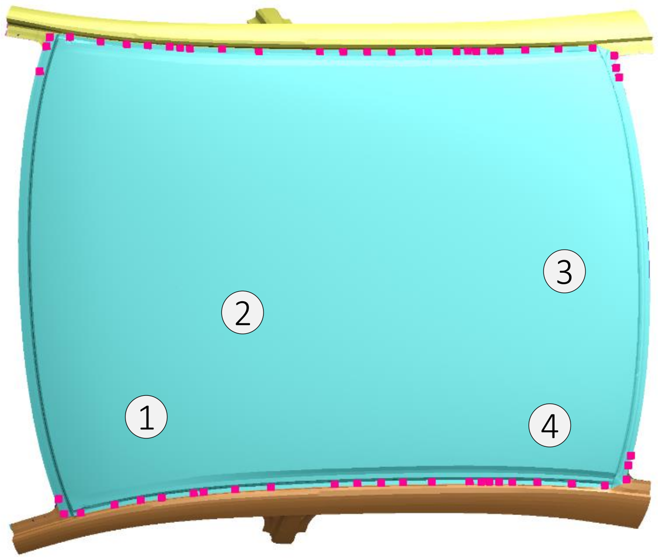



*Dent Indenting Locations :*

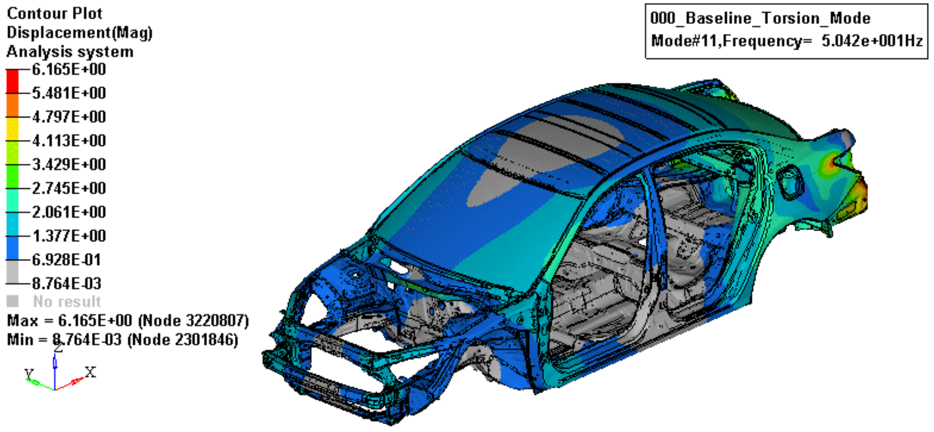



## Result Summary:

| Hit location | Displacement(mm) | Maximum Plastic Strain |
|---|---|---|
| Location-01 | 0.24 | 1.2% |
| Location-02 | 0.20 | 1.1% |
| Location-03 | 0.2 | < 1% |
| Location-04 | 0.22 | 1.0% |

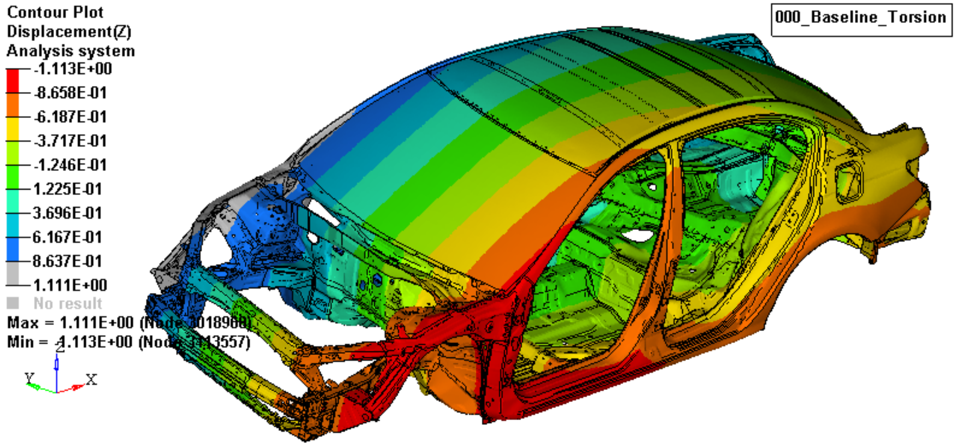
# Baseline Design Results: NVH

## *Normal Mode: Torsion*



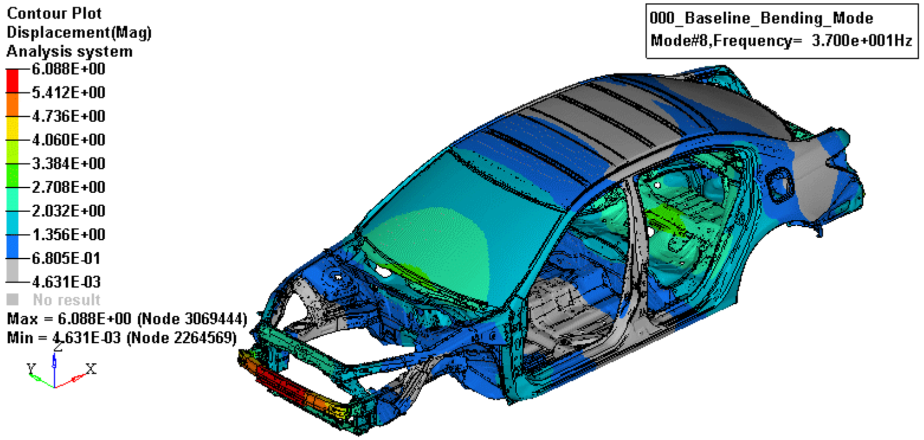

Target: 1st Torsion Mode =50Hz

## *Global Stiffness: Torsion*



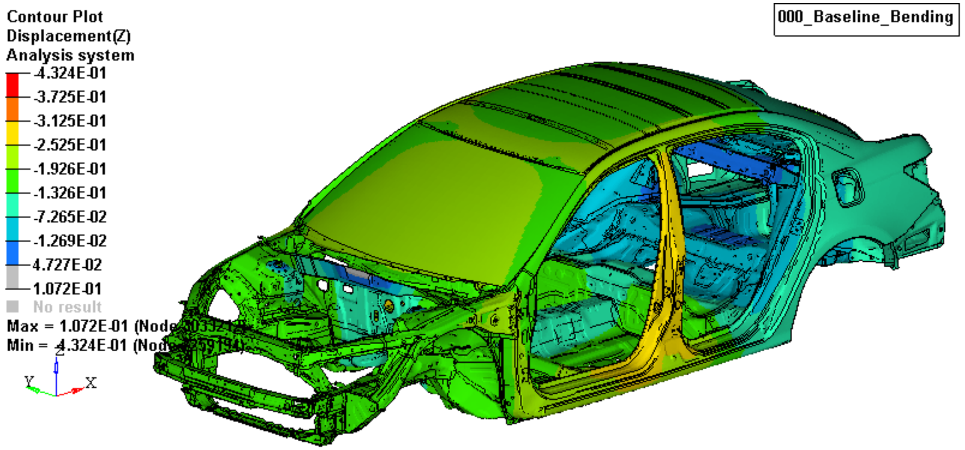

Target: Torsion Stiffness: 27.6 kN-m/deg.

## *Normal Mode: Bending*



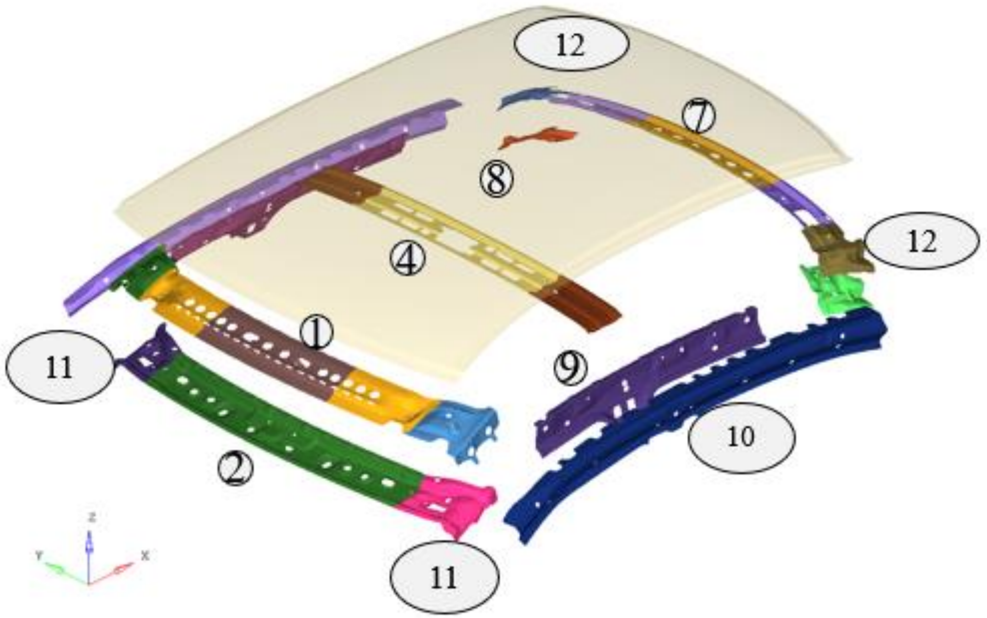

Target:1st Bending Mode =37Hz

## *Global Stiffness: Bending*




Target: Bending Stiffness: 6.9 kN/mm.

# CONCEPT 1 Optimized Steel Solution




| Sl No | Part Name | Part Thickness (mm) | Part Material |
|---|---|---|---|
| 1 | **Front Header - Upper** | 1 | PHS 1500MPa or Gen-3 980 MPa |
| 2 | **Front Header - Lower** | 1.2 | PHS 1500MPa or Gen-3 980 MPa |
| 3 | **Roof Bow** | - | Part Removed in Optimization |
| 4 | **Roof Bow** | 1.2 | PHS 1500MPa or Gen-3 980 MPa |
| 5 | **Roof Bow** | - | Part Removed in Optimization |
| 6 | **Roof Bow** | - | Part Removed in Optimization |
| 7 | **Rear Header** | 0.7 | PHS 1500MPa or Gen-3 980 MPa |
| 8 | **Roof Panel** | 0.65 | Dual Phase (DP) Steel 490MPa |
| 9 | **Roof Rail Inner (LH/RH)** | 1.2 | PHS 1500MPa or Gen-3 980 MPa |
| 10 | **Roof Rail Outer (LH/RH)** | 1.4 | PHS 1500MPa or Gen-3 980 Mpa |
| 11 | **Front header attachments (LH/RH, four parts)** | 2.0 | Dual Phase (DP) Steel 350-600 |
| 12 | **Rear header attachments (LH/RH, four parts)** | 1.65 | Interstitial free (IF) Steel 300-420 |

**Mass Summary**

| Model | Weight |
|---|---|
| Baseline Model Mass | 25.7 kg |
| Optimized Roof Mass | 20.7 kg |
| **Total Savings** | **5 kg** |

**19%**
MASS SAVINGS

**Highlights:**

- Mild steel replaced with Press Hardenable Steel (PHS) and Gen-3 Steels.
- Both PHS and Gen-3 gives similar performance in roof crush.
- Two roof bows eliminated while preserving performance
- Joining – Spot-welds and adhesive bonding between roof and roof bows

Note: Tailor welded blanks were studied for roof bows but the optimization showed best results for uniform thickness.

# CONCEPT 1 Optimized Steel Solution

| | | Baseline | | | Concept 1 | | | | Component Mass Reduction as % of Total Mass Reduction |
|---|---|---|---|---|---|---|---|---|---|
| Sl No | Part Name | Thickness (mm) | Material | Mass (kg) | Thickness (mm) | Material | Mass (kg) | Mass Reduction (kg) | |
| 1 | Front header - upper | 0.9 | IF 300-420 MPa | 0.85 | 1 | PHS 1500MPa or Gen-3 980 MPa | 0.89 | -0.04 | -0.81% |
| 2 | Front header - Lower | 0.7 | DP 350-600 MPa | 0.71 | 1.2 | PHS 1500MPa or Gen-3 980 MPa | 0.9 | -0.19 | -3.87% |
| 3 | Roof Bow | 1.2 | IF 300-420 MPa | 0.53 | - | Part Removed in Optimization | - | 0.53 | 10.79% |
| 4 | Roof Bow | 1.2 | DP 500-800 MPa | 1.1 | 1.2 | PHS 1500MPa or Gen-3 980 MPa | 1.03 | 0.07 | 1.43% |
| 5 | Roof Bow | 1.2 | IF 300-420 MPa | 0.53 | - | Part Removed in Optimization | - | 0.53 | 10.79% |
| 6 | Roof Bow | 1.2 | IF 300-420 MPa | 0.53 | - | Part Removed in Optimization | - | 0.53 | 10.79% |
| 7 | Rear Header | 1.2 | IF 300-420 MPa | 1.09 | 0.7 | PHS 1500MPa or Gen-3 980 MPa | 0.6 | 0.49 | 9.98% |
| 8 | Roof Panel | 0.7 | IF 140-270 MPa | 10.05 | 0.65 | Dual Phase (DP) Steel 490MPa | 9.1 | 0.95 | 19.35% |
| 9 | Roof rail inner - LH | 1.65 | DP 350-600 MPa | 1.2 | 1.2 | PHS 1500MPa or Gen-3 980 MPa | 0.8 | 0.4 | 8.15% |
| 10 | Roof rail Outer - LH | 1.75 | DP 350-600 MPa | 2.3 | 1.4 | PHS 1500MPa or Gen-3 980 MPa | 1.68 | 0.62 | 12.63% |
| 9-RH | Roof rail inner - RH | 1.65 | DP 350-600 MPa | 1.2 | 1.2 | PHS 1500MPa or Gen-3 980 MPa | 0.8 | 0.4 | 8.15% |
| 10-RH | Roof rail Outer - RH | 1.75 | DP 350-600 MPa | 2.3 | 1.4 | PHS 1500MPa or Gen-3 980 MPa | 1.68 | 0.62 | 12.63% |
| 11 | Front header attachments (LH/RH, four parts) | 2 | DP 350-600 Mpa | 1.9 | 2 | DP 350-600 Mpa | 1.9 | 0 | 0.0% |
| 12 | Rear header attachments (LH/RH, four parts) | 1.65 | Mild Steel 300-420 Mpa | 1.4 | 1.65 | Mild Steel 300-420 Mpa | 1.4 | 0 | 0.0% |
| | | | Total Mass | 25.69 | | Total Mass | 20.78 | 4.91 (19%) | 100% |

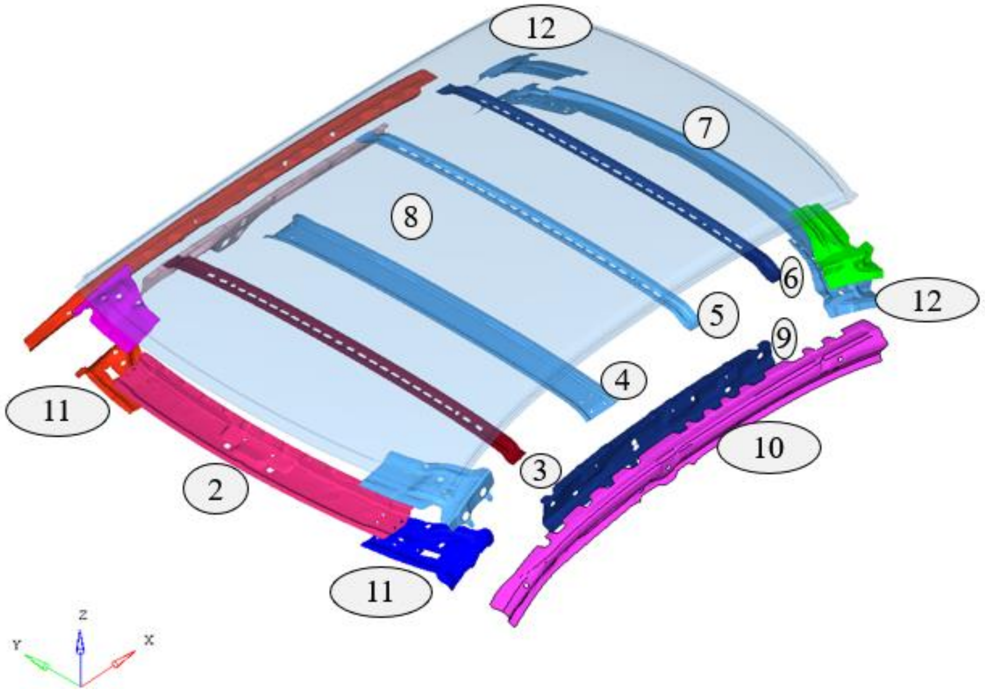
# CONCEPT 1 Performance

| Load cases | Baseline (Target Performance) | Concept 1 Performance | Meets/Exceeds Baseline Performance (95% confidence level) |
|---|---|---|---|
| Mass | 25.7 kg | 20.8 Kg | - |
| Roof Crush | 3.7 SWR, 62 kN | 3.6 SWR, 61.4 kN | ✓ |
| Frequency- Torsion | 50 Hz | 50 Hz | ✓ |
| Frequency- Bending | 37 Hz | 36 Hz | ✓ |
| Stiffness – Torsion | 27.6 kN-m/deg | 27.3 kN-m/deg | ✓ |
| Stiffness – Bending | 6.9 kN/mm | 6.8 kN/mm | ✓ |
| Dent Resistance (plastic strain) | 1.2% | < 1% | ✓ |

# CONCEPT 1 Design, Manufacturing and Supply Chain Impact

| Category | Scale | Roof Rails | Cross Bows and Headers | Roof Panel |
|---|---|---|---|---|
| | | Material: PHS | Material: PHS | Material: DP Steel |
| Mass Reduction Contribution of Total 5 kg reduction | | 42% | 39% | 19% |
| Impact on Design | Low, Mid, High | Low | Low | Low |
| Impact on Body Shop (includes joining) | Low, Mid, High | Low | Low | Low |
| Impact on Paint Shop | Low, Mid, High | Low | Low | Low |
| Initial Capital Investment | Low, Mid, High | Low | Low | Low |
| Incremental Raw Material Cost | Times X (Ref: Mild Steel) | 1.1x | 1.1x | 1.0x |
| Material Availability | USA, NA, Global | Global | Global | Global |
| Material Source | Standard, Branded | Standard | Standard | Standard |
| Skill Training Required | Low, Mid, High (Ref: Mild Steel) | Low | Low | Low |
| Serviceability/Repair | Low Impact, Mid Impact, High Impact | Low Impact | Low Impact | Low Impact |
| Recyclability | Existing, In-development, TBD | Existing | Existing | Existing |

# CONCEPT 2 Aluminum Intensive Solution




| Sl No | Part Name | Part Thickness (mm) | Part Material |
|---|---|---|---|
| 1 | Front Header - Upper | - | Part removed in optimization |
| 2 | Front Header - Lower | 2.4 | AL-6022-T43 + PB |
| 3 | Roof Bow | 1.2 | AL-6022-T43 + PB |
| 4 | Roof Bow | 1.8 | AL-6022-T43 + PB |
| 5 | Roof Bow | 1.2 | AL-6022-T43 + PB |
| 6 | Roof Bow | 1.2 | AL-6022-T43 + PB |
| 7 | Rear Header | 1.8 | AL-6022-T43 + PB |
| 8 | Roof Panel | 0.9 | AL-6022-T43 + PB |
| 9 | Roof Rail Inner (LH/RH) | 1.0 | PHS 1500MPa Steel |
| 10 | Roof Rail Outer (LH/RH) | 1.0 | PHS 1500MPa Steel |
| 11 | Front header attachments (LH/RH, four parts) | 2.8 | AL-6022-T43 + PB |
| 12 | Rear header attachments (LH/RH, four parts) | 2.0 | AL-6022-T43 + PB |

| Model | Weight |
|---|---|
| Baseline Model Mass | 25.7 kg |
| Optimized Roof Mass | 13.01 kg |
| **Total Savings** | **12.69 kg** |

**49.4%**
MASS SAVINGS

**Highlights:**

- Aluminum roof bows
- Aluminum roof skin
- PHS steel roof rails
- Joining – adhesives for roof skin to interactive parts, new welding technology roof bows-roof rails

# CONCEPT 2 Aluminum Intensive Solution

| | | Baseline | | | Concept 2 | | | | Component Mass Reduction as % of Total Mass Reduction |
|---|---|---|---|---|---|---|---|---|---|
| Sl No | Part Name | Thickness (mm) | Material | Mass (kg) | Thickness (mm) | Material | Mass (kg) | Mass Reduction (kg) | |
| 1 | Front header - upper | 0.9 | IF 300-420 MPa | 0.85 | - | Part Removed for Optimization | - | 0.85 | 6.70% |
| 2 | Front header - Lower | 0.7 | DP 350-600 MPa | 0.71 | 2.4 | AL-6022-T43 + PB | 0.75 | -0.04 | -0.32% |
| 3 | Roof Bow | 1.2 | IF 300-420 MPa | 0.53 | 1.2 | AL-6022-T43 + PB | 0.17 | 0.36 | 2.84% |
| 4 | Roof Bow | 1.2 | DP 500-800 MPa | 1.1 | 1.8 | AL-6022-T43 + PB | 0.57 | 0.53 | 4.18% |
| 5 | Roof Bow | 1.2 | IF 300-420 MPa | 0.53 | 1.2 | AL-6022-T43 + PB | 0.18 | 0.35 | 2.76% |
| 6 | Roof Bow | 1.2 | IF 300-420 MPa | 0.53 | 1.2 | AL-6022-T43 + PB | 0.18 | 0.35 | 2.76% |
| 7 | Rear Header | 1.2 | IF 300-420 MPa | 1.09 | 1.8 | AL-6022-T43 + PB | 0.56 | 0.53 | 4.18% |
| 8 | Roof Panel | 0.7 | IF 140-270 MPa | 10.05 | 0.9 | AL-6022-T43 + PB | 4.4 | 5.65 | 44.56% |
| 9 | Roof rail inner - LH | 1.65 | DP 350-600 MPa | 1.2 | 1 | PHS 1500MPa | 0.8 | 0.4 | 3.15% |
| 10 | Roof rail Outer - LH | 1.75 | DP 350-600 MPa | 2.3 | 1 | PHS 1500MPa | 1.31 | 0.99 | 7.81% |
| 9-RH | Roof rail inner - RH | 1.65 | DP 350-600 MPa | 1.2 | 1 | PHS 1500MPa | 0.8 | 0.4 | 3.15% |
| 10-RH | Roof rail Outer - RH | 1.75 | DP 350-600 MPa | 2.3 | 1 | PHS 1500MPa | 1.31 | 0.99 | 7.81% |
| 11 | Front header attachments (LH/RH, four parts) | 2 | DP 350-600 Mpa | 1.9 | 2.8 | AL-6022-T43 + PB | 1.18 | 0.72 | 5.68% |
| 12 | Rear header attachments (LH/RH, four parts) | 1.65 | Mild Steel 300-420 Mpa | 1.4 | 2 | AL-6022-T43 + PB | 0.8 | 0.6 | 4.73% |
| | | | Total Mass | 25.69 | | Total Mass | 13.01 | 12.68 (49.4%) | 100% |

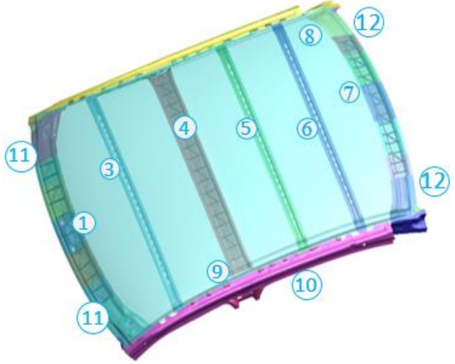
# CONCEPT 2 Aluminum Intensive Solution

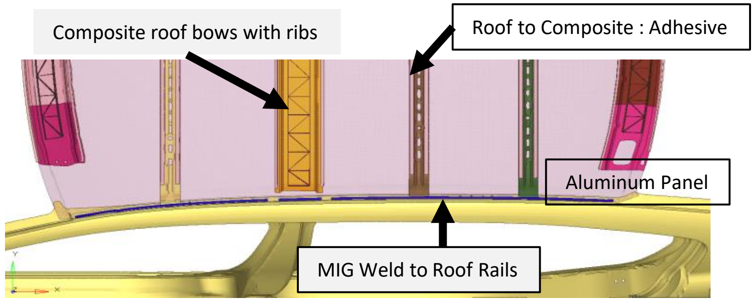
| Load cases | Baseline (Target Performance) | Concept 2 Performance | Meets/Exceeds Baseline Performance (95% confidence level) |
|---|---|---|---|
| Mass | 25.7 kg | 13.01 Kg | - |
| Roof Crush | 3.7 SWR, 62 kN | 3.6 SWR, 59 kN | ✓ |
| Frequency- Torsion | 50 Hz | 47.76 Hz | ✓ |
| Frequency- Bending | 37 Hz | 37.25 Hz | ✓ |
| Stiffness – Torsion | 27.6 kN-m/deg | 28.35 kN-m/deg | ✓ |
| Stiffness – Bending | 6.9 kN/mm | 7.17 kN/mm | ✓ |
| Dent Resistance (plastic strain) | 1.2% | <1% | ✓ |

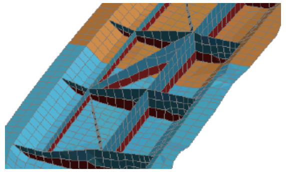
# CONCEPT 2 Design, Manufacturing and Supply Chain Impact

| Category | Scale | Roof Rails | Cross Bows and Headers | Roof Panel |
|---|---|---|---|---|
| | | Material: PHS | Material: Aluminum | Material: Aluminum |
| Mass Reduction Contribution of Total 13 kg reduction | | 22% | 33.5% | 44.5% |
| Impact on Design | Low, Mid, High | Low | Low | Low |
| Impact on Body Shop (includes joining) | Low, Mid, High | Low | Mid | Mid |
| Impact on Paint Shop | Low, Mid, High | Low | Low | Low |
| Initial Capital Investment | Low, Mid, High | Low | Low | Low |
| Incremental Raw Material Cost | Times X (Ref: Mild Steel) | 1.1x | 1.5x | 1.5x |
| Material Availability | USA, NA, Global | Global | Global | Global |
| Material Source | Standard, Branded | Standard | Standard | Standard |
| Skill Training Required | Low, Mid, High (Ref: Mild Steel) | Low | Low | Low |
| Serviceability/Repair | Low Impact, Mid Impact, High Impact | Low Impact | Low Impact | Low Impact |
| Recyclability | Existing, In-development, TBD | Existing | Existing | Existing |

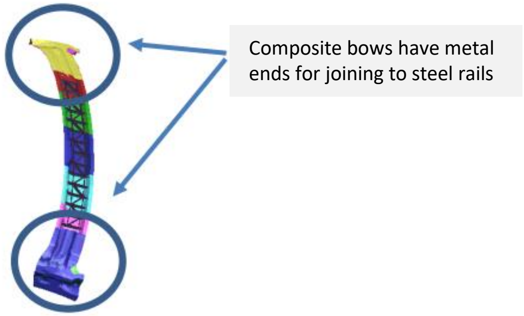
# CONCEPT 3 Mixed Material Solution



Composite roof bows with ribs




## Highlights:

- Composite roof bows with metal ends
- Aluminum roof skin
- PHS steel roof rails
- Joining – adhesives for roof skin to interactive parts, MIG welds to roof rails

| Sl No | Part Name | Part Thickness (mm) | Part Material |
|---|---|---|---|
| 1 | Front Header - Upper | - | Not Applicable |
| 2 | Front Header - Lower | 2.5/2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape |
| 3 | Roof Bow | 0.9 | DP Steel 350-600 MPa |
| 4 | Roof Bow | 2.5/2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape |
| 5 | Roof Bow | 0.9 | DP Steel 350-600 MPa |
| 6 | Roof Bow | 0.7 | DP Steel 350-600 MPa |
| 7 | Rear Header | 2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape |
| 8 | Roof Panel | 0.9 | Aluminum 6022-T43 + PB |
| 9 | Roof Rail Inner (LH/RH) | 1.2 | PHS 1500MPa |
| 10 | Roof Rail Outer (LH/RH) | 1.4 | PHS 1500MPa |
| 11 | Front header attachments (LH/RH, four parts) | 2.0 | DP 350-600 MPa |
| 12 | Rear header attachments (LH/RH, four parts) | 1.65 | IF 300-420 MPa |

**Mass Summary**

| Model | Weight |
|---|---|
| Baseline Model Mass | 25.7 kg |
| Optimized Roof Mass | 15.5 kg |
| **Total Savings** | **10.2 kg** |

**39.7%**
MASS SAVINGS

# CONCEPT 3 Mixed Material Solution

| | | Baseline | | | Concept 3 | | | | Component Mass Reduction as % of Total Mass Reduction |
|---|---|---|---|---|---|---|---|---|---|
| Sl No | Part Name | Thickness (mm) | Material | Mass (kg) | Thickness (mm) | Material | Mass (kg) | Mass Reduction (kg) | |
| 1 | **Front header - upper** | 0.9 | IF 300-420 MPa | 0.85 | NA | NA | NA | 0.85 | 8.33% |
| 2 | **Front header - Lower** | 0.7 | DP 350-600 MPa | 0.71 | 2.5/2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape | 0.56 | 0.15 | 1.47% |
| 3 | **Roof Bow** | 1.2 | IF 300-420 MPa | 0.53 | 0.9 | DP Steel 350-600 MPa | 0.38 | 0.15 | 1.47% |
| 4 | **Roof Bow** | 1.2 | DP 500-800 MPa | 1.1 | 2.5/2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape | 0.62 | 0.48 | 4.71% |
| 5 | **Roof Bow** | 1.2 | IF 300-420 MPa | 0.53 | 0.9 | DP Steel 350-600 MPa | 0.38 | 0.15 | 1.47% |
| 6 | **Roof Bow** | 1.2 | IF 300-420 MPa | 0.53 | 0.7 | DP Steel 350-600 MPa | 0.33 | 0.2 | 1.96% |
| 7 | **Rear Header** | 1.2 | IF 300-420 MPa | 1.09 | 2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape | 0.56 | 0.53 | 5.20% |
| 8 | **Roof Panel** | 0.7 | IF 140-270 MPa | 10.05 | 0.9 | Aluminum 6022-T43 + PB | 4.4 | 5.65 | 55.39% |
| 9 | **Roof rail inner - LH** | 1.65 | DP 350-600 MPa | 1.2 | 1.2 | PHS 1500MPa | 0.8 | 0.4 | 3.92% |
| 10 | **Roof rail Outer - LH** | 1.75 | DP 350-600 MPa | 2.3 | 1.4 | PHS 1500MPa | 1.68 | 0.62 | 6.08% |
| 9-RH | **Roof rail inner - RH** | 1.65 | DP 350-600 MPa | 1.2 | 1.2 | PHS 1500MPa | 0.8 | 0.4 | 3.92% |
| 10-RH | **Roof rail Outer - RH** | 1.75 | DP 350-600 MPa | 2.3 | 1.4 | PHS 1500MPa | 1.68 | 0.62 | 6.08% |
| 11 | **Front header attachments (LH/RH, four parts)** | 2 | DP 350-600 Mpa | 1.9 | 2 | DP 350-600 MPa | 1.9 | 0 | 0.00% |
| 12 | **Rear header attachments (LH/RH, four parts)** | 1.65 | Mild Steel 300-420 Mpa | 1.4 | 1.65 | Mild Steel 300-420 Mpa | 1.4 | 0 | 0.00% |
| | | | **Total Mass** | **25.69** | | **Total Mass** | **15.49** | **10.2 (39.7%)** | |

# CONCEPT 3 Performance

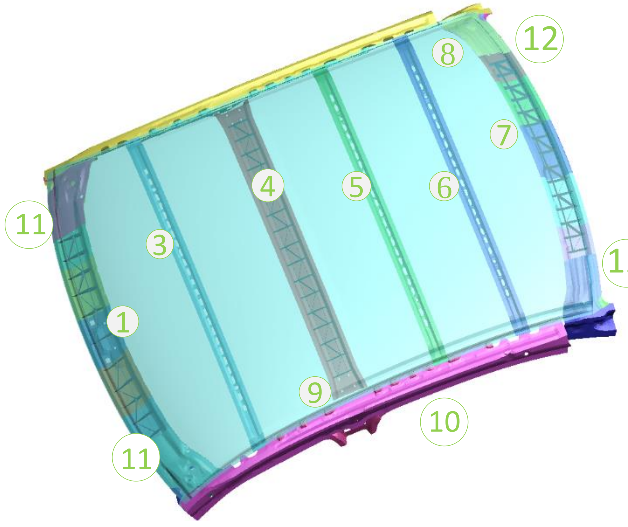
| Load cases | Baseline (Target Performance) | Concept 3 Performance | Meets/Exceeds Baseline Performance (95% confidence level) |
|---|---|---|---|
| Mass | 25.7 kg | 15.5 kg | - |
| Roof Crush | 3.7 SWR, 62 kN | 3.9 (SWR), 65 kN | ✓ |
| Frequency- Torsion | 50 Hz | 50 Hz | ✓ |
| Frequency- Bending | 37 Hz | 37 Hz | ✓ |
| Stiffness – Torsion | 27.6 kN-m/deg | 28.51 kN-m/deg | ✓ |
| Stiffness – Bending | 6.9 kN/mm | 7.2 kN/mm | ✓ |
| Dent Resistance (plastic strain) | 1.2% | < 1% | ✓ |

# CONCEPT 3 Design, Manufacturing and Supply Chain Impact

| Category | Scale | Roof Rails | Cross Bows and Headers | Roof Panel |
|---|---|---|---|---|
| | | Material: PHS | Material: GF Composite with CF UD Tape | Material: Aluminum |
| Mass Reduction Contribution of Total 10 kg reduction | | 20% | 25% | 55% |
| Impact on Design | Low, Mid, High | Low | Mid | Low |
| Impact on Body Shop (includes joining) | Low, Mid, High | Low | Mid | Mid |
| Impact on Paint Shop | Low, Mid, High | Low | Mid | Low |
| Initial Capital Investment | Low, Mid, High (Ref: Steel) | Low | Mid | Mid |
| Incremental Raw Material Cost | Times X (Ref: Mild Steel) | 1.1x | 4x | 1.5x |
| Material Availability | USA, NA, Global | Global | Global | Global |
| Material Source | Standard, Branded | Standard | Standard-branded | Standard |
| Skill Training Required | Low, Mid, High (Ref: Mild Steel) | Low | Mid | Mid |
| Serviceability/Repair | Low Impact, Mid Impact, High Impact | Low Impact | High Impact | Mid Impact |
| Recyclability | Existing, In-development, TBD | Existing | In-development | Existing |

CAR

# CONCEPT 4 Mixed Material Solution




Carbon Fiber Fabric Roof

| Sl No | Part Name | Part Thickness (mm) | Part Material |
|---|---|---|---|
| 1 | Front Header - Upper | - | Not Applicable |
| 2 | Front Header - Lower | 2.5/2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape |
| 3 | Roof Bow | 0.9 | DP Steel 350-600 MPa |
| 4 | Roof Bow | 2.5/2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape |
| 5 | Roof Bow | 0.9 | DP Steel 350-600 MPa |
| 6 | Roof Bow | 0.7 | DP Steel 350-600 MPa |
| 7 | Rear Header | 2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape |
| 8 | Roof Panel | 0.9 | Carbon Fiber UD |
| 9 | Roof Rail Inner (LH/RH) | 1.2 | PHS 1500MPa |
| 10 | Roof Rail Outer (LH/RH) | 1.4 | PHS 1500MPa |
| 11 | Front header attachments (LH/RH, four parts) | 2.0 | DP 350-600 MPa |
| 12 | Rear header attachments (LH/RH, four parts) | 1.65 | IF 300-420 MPa |

**Mass Summary**

| Model | Weight |
|---|---|
| Baseline Model Mass | 25.7 kg |
| Optimized Roof Mass | 15.3 kg |
| **Total Savings** | **10.4 kg** |

**40.4%**
MASS SAVINGS

**Highlights:**

- Carbon Fiber Reinforced Composite (CFRP) roof skin
- Polymer composite roof bows (same as concept 2)
- PHS roof rails
- Joining – adhesives for roof skin to interactive parts, MIG welds to roof rails

CAR

# CONCEPT 4 Mixed Material Solution

| | | Baseline | | | Concept 4 | | | | Component Mass Reduction as % of Total Mass Reduction |
|---|---|---|---|---|---|---|---|---|---|
| Sl No | Part Name | Thickness (mm) | Material | Mass (kg) | Thickness (mm) | Material | Mass (kg) | Mass Reduction (kg) | |
| 1 | **Front header - upper** | 0.9 | IF 300-420 MPa | 0.85 | NA | NA | NA | 0.85 | 8.17% |
| 2 | **Front header - Lower** | 0.7 | DP 350-600 MPa | 0.71 | 2.5/2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape | 0.56 | 0.15 | 1.44% |
| 3 | **Roof Bow** | 1.2 | IF 300-420 MPa | 0.53 | 0.9 | DP Steel 350-600 MPa | 0.38 | 0.15 | 1.44% |
| 4 | **Roof Bow** | 1.2 | DP 500-800 MPa | 1.1 | 2.5/2.5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape | 0.62 | 0.48 | 4.62% |
| 5 | **Roof Bow** | 1.2 | IF 300-420 MPa | 0.53 | 0.9 | DP Steel 350-600 MPa | 0.38 | 0.15 | 1.44% |
| 6 | **Roof Bow** | 1.2 | IF 300-420 MPa | 0.53 | 0.7 | DP Steel 350-600 MPa | 0.33 | 0.2 | 1.92% |
| 7 | **Rear Header** | 1.2 | IF 300-420 MPa | 1.09 | .5/2.5 | Ribbed short GF PA6 Composite with GF UD Tape | 0.56 | 0.53 | 5.10% |
| 8 | **Roof Panel** | 0.7 | IF 140-270 MPa | 10.05 | 1.5 | CFRP UD | 4.2 | 5.85 | 56.25% |
| 9 | **Roof rail inner - LH** | 1.65 | DP 350-600 MPa | 1.2 | 1.2 | PHS 1500MPa | 0.8 | 0.4 | 3.85% |
| 10 | **Roof rail Outer - LH** | 1.75 | DP 350-600 MPa | 2.3 | 1.4 | PHS 1500MPa | 1.68 | 0.62 | 5.96% |
| 9-RH | **Roof rail inner - RH** | 1.65 | DP 350-600 MPa | 1.2 | 1.2 | PHS 1500MPa | 0.8 | 0.4 | 3.85% |
| 10-RH | **Roof rail Outer - RH** | 1.75 | DP 350-600 MPa | 2.3 | 1.4 | PHS 1500MPa | 1.68 | 0.62 | 5.96% |
| 11 | **Front header attachments (LH/RH, four parts)** | 2 | DP 350-600 Mpa | 1.9 | 2 | DP 350-600 MPa | 1.9 | 0 | 0.00% |
| 12 | **Rear header attachments (LH/RH, four parts)** | 1.65 | Mild Steel 300-420 Mpa | 1.4 | 1.65 | Mild Steel 300-420 MPa | 1.4 | 0 | 0.00% |
| | | | **Total Mass** | **25.69** | | **Total Mass** | **15.29** | **10.4 (40.4%)** | |

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# CONCEPT 4 Performance

| Load cases | Baseline (Target Performance) | Concept 4 Performance | Meets/Exceeds Baseline Performance (95% confidence level) |
|---|---|---|---|
| Mass | 25.7 kg | 15.3 kg | - |
| Roof Crush | 3.7 SWR, 62 kN | 3.6 SWR, 60 kN | ✓ |
| Frequency- Torsion | 50 Hz | 51 Hz | ✓ |
| Frequency- Bending | 37 Hz | 37 Hz | ✓ |
| Stiffness – Torsion | 27.6 kN-m/deg | 27.92 kN-m/deg | ✓ |
| Stiffness – Bending | 6.9 kN/mm | 7.5 kN/mm | ✓ |
| Dent Resistance (plastic strain) | 1.2% | <1% | ✓ |

# CONCEPT 4 Design, Manufacturing and Supply Chain Impact

| Category | Scale | Roof Rails | Cross Bows and Headers | Roof Panel |
|---|---|---|---|---|
| | | Material: PHS | GF Composite with CF UD Tape | CFRP |
| Mass Reduction Contribution of Total 10 kg reduction | | 20% | 24% | 56% |
| Impact on Design | Low, Mid, High | Low | Mid | High |
| Impact on Body Shop (includes joining) | Low, Mid, High | Low | Mid | High |
| Impact on Paint Shop | Low, Mid, High | Low | Mid | High |
| Initial Capital Investment | Low, Mid, High (ref: steel) | Low | Mid | Mid |
| Incremental Raw Material Cost | Times X (ref: mild steel) | 1.1X | 4X | 6.5X |
| Material Availability | USA, NA, Global | Global | Global | Global |
| Material Source | Standard, Branded | Standard | Standard-Branded | Branded |
| Skill Training Required | Low, mid, high (ref: mild steel) | Low | Mid | High |
| Serviceability/Repair | Low impact, mid impact, high impact | low impact | High Impact | High Impact |
| Recyclability | Existing, In-Development, TBD | Existing | In-development | In-Development |

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# Secondary Mass Reduction

The concept of mass decompounding or secondary mass reduction recognizes that, as vehicle mass is reduced, there are new opportunities to reduce additional mass and that these often minimize the overall cost increase. Subsystems that may offer potential mass decompounding will vary by vehicle design, but the most common opportunities for decompounding are tires, wheels, powertrain, suspension system, braking system, bumpers, fuel and exhaust systems, steering system, and electrical systems and wiring.

The National Academy of Science (NAS) 2015 report, defines decompounding as:

Decompounding = secondary mass reduction / primary mass reduction.

The NAS report notes that for every 7.14 percent of the primary mass reduction, an additional 2.86 percent of the mass could be removed by decompounding for midsized and large cars.

For light-duty trucks, for every 8 percent primary mass reduction, an additional 2 percent of the mass could be removed by decompounding.

# Plastics and Polymer Composite Technology Suppliers

| Material | Company | Product | Details | Roof Application |
|---|---|---|---|---|
| **Plastics and Polymer Composites** | BASF We create chemistry | Ultratape and Ultramid | **Ultramid**: a 63% glass reinforced, injection molding, high modulus nylon designed to have high strength and stiffness for metal replacement applications.<br><br>**Ultratape**: Glass fiber reinforced thermoplastic tape for use in structural applications which is made out of PA6 and roving glass. Processing by thermoforming and overmolding processes. | Used for Roof Bows - Concept 3 and 4 |
| | سابك sabic | LEXAN™ Polycarbonate Glazing | 30-50% weight reduction over traditional glazing, lower center of gravity for improved ride and handling. | Sunroof/Moonroof |

For individual contact information, please refer Appendix C

# Metal Technology Suppliers

| Material | Company | Product | Details | Roof Application |
|---|---|---|---|---|
| **Press Hardened Steel** | AK Steel | Ultralume | ULTRALUME® Press Hardenable Steel (PHS) is an aluminized Type 1, heat-treatable, boron steel intended for automotive steel applications where high strength (approaching 1500 MPa), design flexibility and collision protection are paramount. | Used for Roof Rails - Concept 1, 2, 3,4 |
| | U. S. Steel | 980 XG3 | USS Generation 3 steel. One with high strength and high formability. One that adapts to your current processes without compromising weldability, while providing the most cost-effective material for a safer and lighter vehicle. | Used for Roof Rails - Concept 1 alternate solution |
| **Aluminum** | ARCONIC Innovation, engineered. | 6022-T43 Aluminum Body Panel Sheet | 6xxx material that meets Class A surface quality requirements and provides an excellent combination of stretch formability, corrosion resistance, dent resistance and enhanced paint-bake strength response. | Concept 2,3 |
| **Parts** | SHILOH. Lightweighting without compromise.™ | Laser Welded Blanks | Fusion laser weld and mash seam resistance blanks. Linear and curvilinear applications | Roof Bows – potential application in concept 1 |

For individual contact information, please refer Appendix C

# Joining Technology Suppliers

| Material | Company | Product | Details | Roof Application |
|---|---|---|---|---|
| **Adhesives** | Henkel | TEROSON EP 5089/5100 | Highly toughened structural adhesive, that performs across wide temperature ranges | structural adhesive for joining roof skin |
| | Sika® | SIKAFLEX® AND SIKAFORCE® | High elasticity, high elongation, i-cure® technology | structural adhesive for joining roof skin |
| | Dow® | Betaforce and Betamate | Composite Bonding Adhesives for Lightweight Multi-material Vehicles | structural adhesive for joining roof skin |

For individual contact information, please refer Appendix C

# Joining Technology Suppliers

| Material | Company | Product | Details | Roof Application |
|---|---|---|---|---|
| **Fasteners** | ARaymond | Weldable Hybrid Inserts | Sheet metal to composite joining | Joining composite bows with roof skin – potential application in concept 3,4 |
| **Steel-Aluminum Welding** | KOBELCO | Element Arc Spot Welding process (EASW) | Multi-layer dissimilar metal joining | Aluminum roof skin to steel roof rails joining – potential application in concept 2,3 |

For individual contact information, please refer Appendix C

# Future Research

- Test all concepts for vehicle side impact.
- Study materials for panoramic sunroof application.
- Study manufacturing cost and initial investment.

# For More Information Contact:

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Download the Detailed CAE Analysis Report

# Appendix A: Multi-Material Joining Techniques

| Joining Technology/Material Combination | Steel-Steel | Steel-Al | Steel-Mag | Steel-Comp | Al-Al | Al-Mag | Al-Comp | Mag-Mag | Mag-Comp | Comp-Comp |
|---|---|---|---|---|---|---|---|---|---|---|
| **Conventional Resistance Spot Welding** | ★ | X* | | | X | | | | | |
| **MIG/TIG Welding** | X | | | | | | | ★ | | |
| **Friction Stir Spot Welding** | X | X | | | X | | | | | |
| **Laser Welding/Lazer Brazing** | X | X | | | X | | | X | | X |
| **Fasteners (SPR, FDS)** | X | ★ | X | ★ | ★ | ★ | ★ | X | X | X |
| **Clinching** | X | X | X | | X | X | | | | |
| **Adhesive Bonding** | X | ★ | ★ | ★ | ★ | ★ | ★ | X | X | ★ |
| **Magnetic Pulse Welding** | X | X | | | X | X | | | | |
| **Vibration Welding** | | | | | | | | | | X |
| **Spin Welding** | | | | | | | | | | X |
| **IR Welding** | | | | | | | | | | X |

Al=Aluminum Mag=Magnesium Comp=Polymer Composites MIG=Metal Inert Gas Welding TIG=Tungsten Inert Gas Welding * Proprietary Technologies

★ Most Common X Applicable

# Appendix B: Adhesives Information

| Epoxies | Acrylics |
| --- | --- |
| • Epoxy adhesives are some of the most commonly used adhesives in most of the manufacturing industries<br>• This is primarily because of the high strength bond formation post curing.<br>• The bonding between two surfaces may be accelerated using heat or ultraviolet radiation. | • High bonding strength on plastic and metal<br>• However, they tend to have lower vibration/impact resistance than epoxies (thus, lower fatigue resistance) and lower performance at extreme temperature. As a result, it is not advisable to use them for transport vehicles. |
| **Cyanoacrylates** | **Urethane** |
| • Cyanoacrylates tend to provide decent shear strength for bonding of rubber and plastics (with the help of primers); but they are often rigid and show impact and peel resistance. | • Urethanes are quite flexible, but have lower strength in general.<br>• They can be relatively good binding agents for plastic and rubber<br>• Prices are lower compared to other adhesive types. |

Source: Frost Sullivan -Innovations in Multi-material Joining

**Adhesive Benefits**

- Improved stiffness and performance under impact and fatigue loading in body-in-white applications.
- Enables multi-metal design and flexibility in structure lightweighting due to ability to bond dissimilar substrates.
- Stress distribution may allow for the down gauge of metals.
- Ability to join high strength materials that are frequently sensitive to stress concentration.

# Appendix B: Adhesives Information

## Material Selection Driven by Desired Application Properties

| | | | |
|---|---|---|---|
| High modulus<br>High strength<br>Medium elongation | Structural bonding | | |
| | | Semi-structural<br>Elastic bonding | |
| Low modulus<br>Low-medium strength<br>High elongation | | | Sealing /<br>Elastic bonding |
| **Application examples** | **Body structure, structural components** | **Roof, Hood, Closures hang on panels** | **All flange joint sealing, hang-on parts Flaps, Spoiler** |

Source: Audi A8

Source: BMW

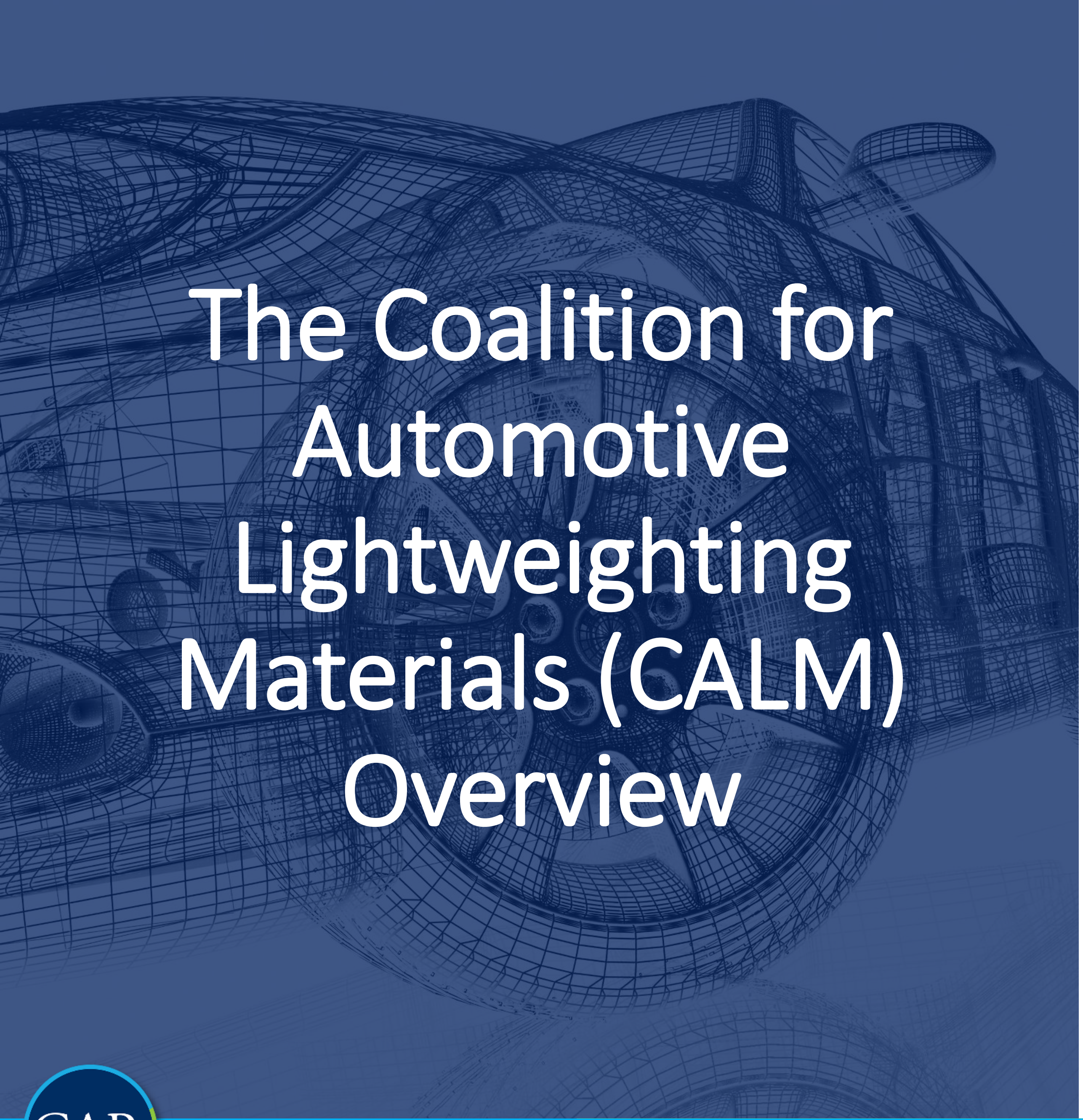
Source: Henkel

# Appendix C: Supplier Contacts

| Company | Product | Person | Title/Department | Email |
|---|---|---|---|---|
| 3M | Bonding Solutions | Scott Taylor | Automotive Market Technology Manager | jstaylor@mmm.com |
| AK Steel | Steel Products | Scott Stevens | Manager, Applications & Advanced Engineering | scott.stevens@aksteel.com |
| ARaymond | Mechanical Fasteners | Chris MURPHY | Product Line Manager | Chris.Murphy@araymond.com |
| Arconic | Aluminum Products | Greg Fata | Global Automotive Technical Director | Gregory.Fata@arconic.com |
| BASF | Plastics and Polymer Composites | Kipp Grumm | Technology Leader Thermoplastic Composites | kipp.grumm@basf.com |
| DowDupont | Plastics and Polymer Composites | Frank V. Billotto | Strategic Marketing, Transportation Assembly | fbillotto@dow.com |
| Faurecia | Interiors and Clean Mobility | Yang Cao | Faurecia Clean Mobility | yang.cao@faurecia.com |
| Henkel | Bonding Solutions | Kevin Woock | Corporate Director, Portfolio Management | kevin.woock@henkel.com |
| Kobelco | Steel and Aluminum | Elijah Kakiuchi | Senior Technical Advisor, Multi-Material Division | kakiuchi.elijah@kobelco.com |

# Appendix C: Supplier Contacts

| Company | Product | Person | Title | Email and Phone |
|---|---|---|---|---|
| Magna | Part Supplier | Tim Skszek | Senior Manager Advanced Materials and Manufacturing | Tim.Skszek@magna.com |
| Nagase | Plastics and Polymer Composites | Gabriel Knee | Senior Manager Materials | gabriel.knee@nagase-nam.com |
| Plastic Omnium | Plastics and Polymer Composites | Bertrand Hache | Product Line & Innovation Director | bertrand.hache@plasticomnium.com |
| PPG | Paints and Coatings | James F. Ohlinger | Manager, Global Application Process Design | ohlinger@ppg.com |
| Sabic | Plastics and Polymer Composites, Glass | Matthew D. Marks | Sr. Manager, Market Development and Technical Service | matthew.marks@sabic.com |
| Shiloh | Part Supplier | Kalyan Palanisamy | Director, Product Application Engineering | kalyan.palanisamy@shiloh.com |
| Sika | Bonding Solutions | Kent Fung | Senior Market Field Manager | fung.kent@us.sika.com |
| Uniseal | Bonding Solutions | Jayne Allerellie | Product Manager | jayne@uniseal.com |
| US Steel | Steel Products | Vasant Pednekar | Product Application Engineer | VRPednekar@uss.com |



# The Coalition for Automotive Lightweighting Materials (CALM) Overview

## Appendix D: About CALM

CALM is a collaboration of more than thirty industry leading organizations working to support the cost-effective integration of mixed materials to achieve significant reductions in mass through the joint efforts of the material sectors and the auto manufacturers. Supporting organizations participate in the CALM working group through an ongoing, annual commitment funded by participating CAR Affiliate organizations.

# Appendix D: CALM Member Companies

AK Steel
Altair
ARaymond MORE THAN FASTENING
ARCONIC Innovation, engineered.
BASF We create chemistry

DOW
DUPONT
faurecia
Gestamp
GRUPO ANTOLIN

Henkel
KOBELCO
lift Where Manufacturing Technology and Talent Matter
MAGNA
MARTINREA

MICHELIN
PLASTIC OMNIUM
PPG We protect and beautify the world™
سابك sabic

Semblex
SHILOH Lightweighting without compromise.™
BUILDING TRUST Sika
USS U. S. Steel

CAR

# Appendix E: Acknowledgement

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Shashank Modi – Research Engineer, MMT Group, CAR

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