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CALM Studies Roof Lightweighting

Different concepts get different scores

Automotive lightweighting comes in many forms and is emphasized across the thousands of components that make up the vehicle. Some areas of the vehicle are more important than others. Wheels, for example, represent rotational mass, multiple per vehicle and also unsprung weight.

The roof is another, as it is the highest point on the vehicle, and a heavy roof raises the vehicle center of gravity, reducing vehicle stability and ride control. The Center for Automotive Research, known as CAR, decided to study the vehicle roof and the opportunities to reduce weight, referred to as the Roof Lightweighting Study.[1]

Working within its Coalition for Automotive Lightweighting Materials (CALM[2]) group, which is made up of more than 30 organizations, the team formalized a plan to study the vehicle-roof construction and the means to reduce weight, while taking into account the cost, capital investment, global material availability, ease of processing in the paint shop, integration to adjacent structure, field repair and recyclability.

The baseline roof is on a 2011 Honda Accord and is made up of mild steel in its structure and the large sheet panel over the top. The group down-selected to three concepts. The first replaces mild steel with advanced high-strength steels. The second utilizes a mix of high-strength steel, aluminum sheet and polymer composite roof bows. The third is an extension of the second, replacing the aluminum sheet with carbon fiber weave. Each concept demonstrates attractive weight reduction, though only the first concept, using advanced steels, met all of the design criteria.

Background, Motivation & Objective, Scope

The emphasis on cost-effective weight reduction is always top of mind for automotive manufacturers because the purpose of the vehicle and the consumer needs are evolving. The trend now is on mobility solutions, and under that umbrella, there is ACES, which stands for automated, connected, electric and shared vehicles. In addition, governments around the world and within municipalities are putting restrictions on, even laws limiting, the use of internal combustion engines (ICE) within city limits and across countries via greenhouse gas (GHG) regulations.

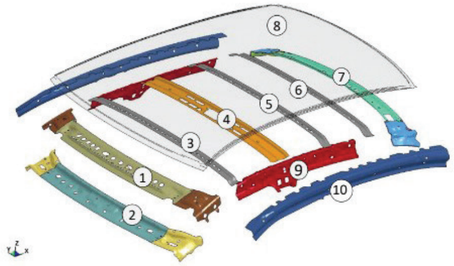
Much of the ACES vehicle is in development. Yet the electrified portion is easy to understand in that there is a limitation in charging infrastructure, combined with longer than desirable charging times. The need to extend the vehicle range is real and tangible. A lower weight vehicle will travel further on a charge. So, let's lose weight!

In addition to the integration and cost aspects already noted, the roof is a Class A surface, which comes with stringent aesthetic requirements, and it plays a critical role in passenger safety during rollover and side-impact events.

To complete a study like this, you need ground rules to limit the number of options under consideration. One limit was on the manufacturing readiness level (MRL). The team selected

Design Space

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



Sl 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	1.65	DP 350-600 MPa
10	Roof rail Outer	1.75	DP 350-600 MPa

Note: Both left hand (LH) and right hand (RH) parts are considered for design space.
IF = Interstitial free (IF) Steels
DP = Dual Phase Steels

Baseline:

- Design space Mass = 22.4 Kg
- 100% steel
- Joining – Spot-welds and adhesive bonding between roof and roof bows

FIGURE [1] / Baseline Roof – 2011 Honda Accord

Level 5 as the minimum, which is in the pre-production phase, and states "basic capability demonstrated."

The computer-aided engineering (CAE) analysis requires that each concept match or exceed baseline performance of:

- Roof crush
- Bending
- Torsion
- Dent

Out of the scope of this study was physical testing, absolute cost and redesign of the supporting body structure.

The report also points to prior literature on vehicle-roof structures, and I am glad that these were presented before reading the study. Typically, in technical papers, these are references listed on the bottom, and it takes a great deal of attention to reach them and appreciate the authors and the content. In this study, the reference studies are readily available, coming from Lotus Engineering, EDAG, FEV working for the EPA, a CAR survey and Politecnico Di Torino (Polytechnic University of Turin, Italy) on polymer composite roof structures.

After researching prior work on roof-weight reduction, the team selected the 2011 Honda Accord as a baseline vehicle because its roof is comprised of mild steel materials and presumably, in part because the vehicle information is readily available. Even the National Highway Traffic Safety Administration (NHTSA) provided crash-simulation models. Figure 1 shows the baseline roof construction

The baseline details include the steel types and ranges of properties, thickness, and as you will see, the weight of each component. The weight of the adhesive is negligible and not listed.

The Engineering

The CAE tools today are really critical to the rapid development of vehicles, and within the vehicle, the material, the design and the joining method between materials. The saying goes in Detroit automotive, "If we can't model it, we can't use it." That is easy to say, yet not so easy to accomplish.
Take the case of adhesives. The supply base provides shear, peal and the common test samples and results. Yet, what are the load-carrying characteristics under non-linear loads as in a side impact or a rollover event with three times the vehicle weight crashing down? The non-linear event challenges the load cases, the boundary conditions and the material property data.

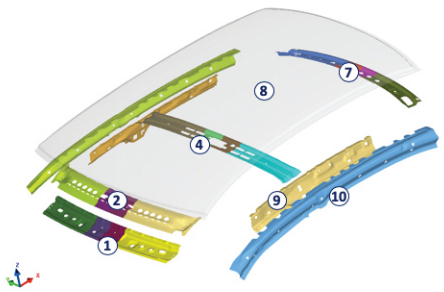
For this study, the non-linear properties of the materials were taken into account, with exception to the joints. Directional properties were used for each layer of the composites. The material is made up of multiple layers in 0 and 90 degree configuration.

The three concepts are evaluated by these baseline performance targets:

LOAD CASES	BASELINE
Mass	22.4 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	6.9kN/mm
Dent Resistance (plastic strain)	1.2%

FIGURE [2] / Baseline performance targets

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
4	Roof Bow	1.2	PHS 1500MPa or Gen-3 980 MPa
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	1.2	PHS 1500MPa or Gen-3 980 MPa
10	Roof Rail Outer	1.4	PHS 1500MPa or Gen-3 980 MPa

Mass Summary

Model	Weight
Baseline Model Mass	22.4 kg
Optimized Roof Mass	17.4 kg
Total Savings	**5 kg**

22% 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

FIGURE [3] / Concept 1

Performance Criteria

The roof crush test is based on Federal Motor Vehicle Safety Standard (FMVSS) 216. A design of experiments was performed based on the surface response sensitivity using these parameters:

- Gauge or Thickness
- Material Grade
- Shape or Cross Section

The roof crush is most affected by the front header and the nearest roof bows. Interestingly, the roof rails are not ranking high in the sensitivity plot.

Though the only system studied was the roof, clearly the load cases take the entire vehicle into account.

Coincidently, the BIW stiffness-torsion loading was most difficult to meet as only Concept 1 using optimized steel passed. The other two concepts missed the target by 22 percent and 26 percent respectively. In all the tests, each roof concept utilized consistent A-, B- and C-pillars, with the pillars carrying significant loads. The future effort plan includes the B-pillar and its optimization with intention to enable Concepts 2 and 3 to meet the torsional stiffness target.

Materials

There is a large variety of materials available to the automobile roof designer, from structures underneath to the large panel to the attachment method. However, for this particular study, Motivation #2 is to provide CALM members a platform to showcase their material and manufacturing technology to the automakers.

The CALM members include lightweight-material producers such as AK Steel, Arconic, BASF, DuPont, Henkel, NAGASE, SABIC and U.S. Steel. Fastening and joining solutions from 3M, ARaymond, Coherent, Dow, DuPont, Eastman, Henkel, KOBELCO, PPG and Sika. Tier 1 integrators like Faurecia, Gestamp, IAC, Magna, Martinrea and Shiloh. An impressive list with considerable capability.[2]

Three Concepts to Reduce Roof Weight

Concept 1 is all-steel like the baseline, yet because it replaces mild steel with press hardened steel (PHS 1500 Mpa) or Gen3 980 Mpa, considerable efficiencies were achieved. The baseline had four roof bows, whereas the conversion to high-strength steel only requires one roof bow.

Almost 20 percent of the 4.91 kg saved came from the 0.65-mm thick 490 Mpa roof panel, the large sheet over the top. Joining the parts is the same even with the change in the steels. Spot welds are used for the roof bows to the roof rails, and adhesives are used to secure the roof panel.

The total weight savings was 22 percent from the baseline, and it passes all the design criteria. The cost is a

The BIW Stiffness-Torsion loading was most difficult to meet as only Concept 1 using optimized steel passed.

Category	Scale	Roof Rails	Cross Bows	Roof Panel
		Material: PHS	Material: PHS	Material: DP Steel
Mass Reduction Contribution of Total 5 kg reduction		41.55%	39.10%	19.35%
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

FIGURE [4] / Concept 1– Design, Manufacturing and Supply Chain Impact

10-percent increase over mild steel, well within the normal targets for weight reduction. As Figure 4 shows, Concept 1 is a very robust solution.

The joining is well understood. There is a global supply chain. There is low impact on the processes in the assembly plant. The repair facilities know how to fix these materials, and there are existing recycling processes in place. An optimized steel roof is an elegant solution because it is simple, cost effective, easy to implement. It met all target performance criteria, and it meets most weight-reduction initiatives.

Coincidently, the 2018 Honda Accord also used an all-steel design,[3] though its design looks to be even more conservative than Concept 1, as it is closer to the baseline. The 2018 Accord has four roof bows, though using 1500 Mpa in the center arch, 780 Mpa on the front header and 340 Mpa on the roof panel.

Concept 2 is a mixed-material solution, and the design returned to the number of roof bows in the baseline (four), though three are steel, yet at a lower strength than in Concept 1. The fourth bow is a ribbed, glass-fiber PA6 nylon with a glass-fiber unidirectional tape (GF UD). The front and rear headers are also made of this glass-fiber composite, with 0 and 90 degree layers, with the GF UD tape.

A complication with the composite is the means to attach it to the side rails. The composite roof bow is attached to a steel end connector, presumably with adhesive. The end connectors are then MIG welded to the steel rails. The end connectors add additional weight, and when combining the weight reduction using composites, the net weight reduction is just 0.7 kg. With a cost delta of $4X for composites over mild steel, only premium vehicles would find it worth the effort.

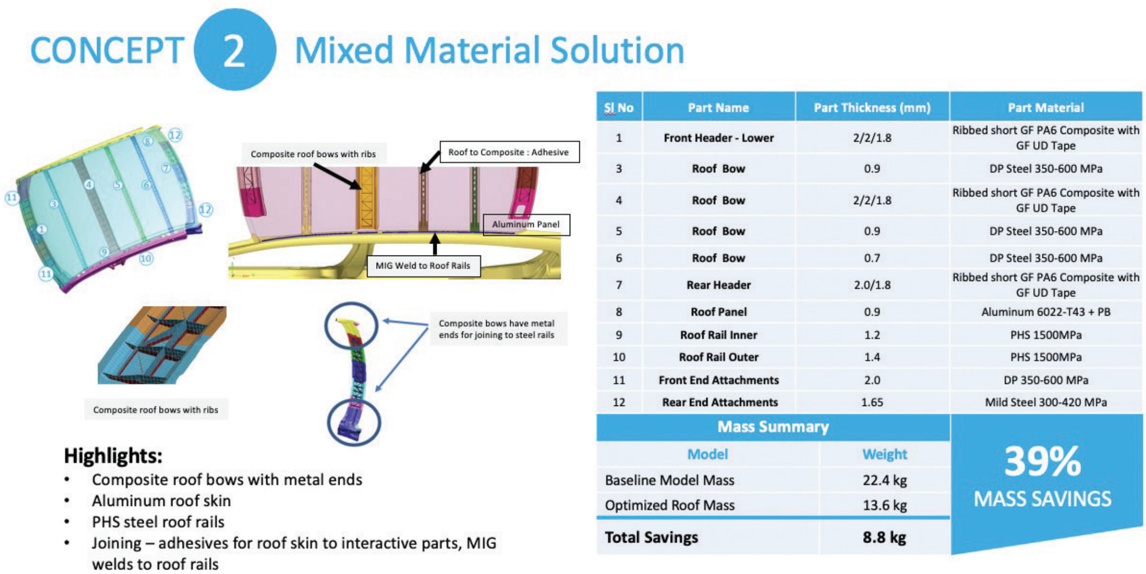
The big weight savings in Concept 2 comes from the panel conversion to 6022-T43 + PB aluminum sheet with properties[4] of 130 Mpa YS, 250 Mpa UTS, 26 percent elongation, 0.9 mm thick, delivering a whopping 64.2 percent weight reduction!

Concept 2 meets all performance besides the torsional stiffness as shown (see Figure 6).

The authors included a note stating, "If our design space was bigger, we could meet target torsional stiffness by taking a small hit on the percentage of mass reduction achieved." It is not known how much mass would be added nor if this roof concept would pass all criteria without redesigning other body structures, such as the B-pillar, which is not within the scope of this effort.

Concept 3 is the final concept, and also a mixed-material solution that is very similar to Concept 2, except that the aluminum sheet is replaced by a carbon fiber roof panel.

A carbon fiber roof is pushing the innovation button, yet there is not a whole lot of weight saved compared to the aluminum roof in Concept 2. Just 0.2 kilograms are reduced with the carbon fiber roof. This would bring



Sl No	Part Name	Part Thickness (mm)	Part Material
1	Front Header - Lower	2/2/1.8	Ribbed short GF PA6 Composite with GF UD Tape
3	Roof Bow	0.9	DP Steel 350-600 MPa
4	Roof Bow	2/2/1.8	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	2.0/1.8	Ribbed short GF PA6 Composite with GF UD Tape
8	Roof Panel	0.9	Aluminum 6022-T43 + PB
9	Roof Rail Inner	1.2	PHS 1500MPa
10	Roof Rail Outer	1.4	PHS 1500MPa
11	Front End Attachments	2.0	DP 350-600 MPa
12	Rear End Attachments	1.65	Mild Steel 300-420 MPa

Mass Summary		
Model	Weight	39% MASS SAVINGS
Baseline Model Mass	22.4 kg	
Optimized Roof Mass	13.6 kg	
Total Savings	8.8 kg	

FIGURE [5] / Concept 2

LOAD CASES	BASELINE (TARGET PERFORMANCE)	CONCEPT 2 PERFORMANCE	MEETS/EXCEEDS BASELINE PERFORMANCE (within 5%)
Mass	22.4 kg	13.6 kg	
Roof Crush	3.7 SWR, 62 kN	3.8 SWR, 63 kN	YES
Frequency–Torsion	50 Hz	50 Hz	YES
Frequency–Bending	37 Hz	37 Hz	YES
Stiffness–Torsion	27.6 kN-m/deg	21.4 kN-m/deg	78% of baseline
Stiffness–Bending	6.9 kN/mm	7 kN/mm	YES
Dent Resistance (plastic strain)	1.2%	1%	YES

FIGURE [6] / Concept 2 results

Sl No	Part Name	Part Thickness (mm)	Part Material
1	Front Header - Lower	2/2/1.8	Ribbed short GF PA6 Composite with GF UD Tape
3	Roof Bow	0.9	DP Steel 350-600 MPa
4	Roof Bow	2/2/1.8	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	2.0/1.8	Ribbed short GF PA6 Composite with GF UD Tape
8	Roof Panel	1.5	CFRP
9	Roof Rail Inner	1.2	PHS 1500MPa
10	Roof Rail Inner	1.4	PHS 1500MPa
11	Front End Attachments	2.0	DP 350-600 MPa
12	Rear End Attachments	1.65	Mild Steel 300-420 MPa

Mass Summary		
Model	Weight	40% MASS SAVINGS
Baseline Model Mass	22.4 kg	
Optimized Roof Mass	13.4 kg	
Total Savings	9 kg	

FIGURE [7] / Concept 3 Roof Construction

The most prominent aluminum-body vehicle on the planet, the Ford F-150, converted a three-piece steel stamped front roof header to a one-piece aluminum extrusion and cut a whopping 2.9 kg.

the total weight savings to 9 kilograms, which is a 40-percent total roof weight reduction—a big headline, yet with the asterisk for not passing the torsional stiffness requirement. Like 2, it is not known how much weight would be added to pass all the criteria.

Future Work

The future work identified by the CALM Group:

- an all-aluminum roof concept
- to test all concepts under a side-impact load
- to evaluate modifications to other structural components, such as the B-pillar, to enable Concepts 2 and 3 to meet the torsional requirements
- to evaluate the materials for a panoramic sunroof

These all sound very good, though after seeing Tesla transition from the all-aluminum body on the Model S to a mixed-material body on the more affordable Model 3, I think the future is really in mixed materials.

Closing Thoughts

CALM's intent is to provide an unbiased study for OEMs. For this reason, they do not provide conclusion statements or recommendations. The purpose of this study is ultimately to drive change. Will the OEMs design the next-generation vehicle with a lower weight roof, and will they use materials and concepts proposed in this study?

My opinion is that there are many areas of the vehicle that could use a weight-reduction effort. The OEMs will use Concept 1 first because it easy and cost effective. If they want more weight reduction, they will replace the steel panel in Concept 1 with aluminum, keeping the efficient high-strength steel support structure. Some OEMs are more conservative than others. Yet, we have already seen in the 2018 Honda Accord where Honda redesigned the 2011 Accord more conservatively than Concept 1.

The most prominent aluminum-body vehicle on the planet, the Ford F-150, converted a three-piece steel stamped front roof header to a one-piece aluminum extrusion and cut a whopping 2.9 kg. A huge amount of weight savings on the header, yet no extrusions were proposed in the three concepts because there are CALM members who produce aluminum extrusions. This will be studied in other CALM efforts.

Concept 3 was largely an extension of 2, yet utilized fewer composite roof bows, more high-strength steel, and it replaced the aluminum sheet with carbon fiber composite. The resulting 1-percent improvement in weight savings doesn't move the needle for the additional cost and complexity.

The goal of this study was to assess multiple materials to reach a weight-savings goal according to a set of performance metrics. The first two parts were met. There were mixed materials, and there was weight savings. The last item was left incomplete. Only the Concept 1 reached all target metrics.

This begs the question, *if the torsional stiffness target was reduced by 26 percent such that all concepts could reach it, how much weight would have been reduced by Concept 1?* Unfortunately, as it is, the media doesn't read the fine print, and they run to social media and their newsletters to publish results that are really incomplete. LW

REFERENCES

1. www.cargroup.org/publication/roof-lightweighting-study/
2. www.cargroup.org/calm-program/calm-roster/
3. www.repairerdrivennews.com/2019/06/26/37520/
4. www.manualzz.com/doc/9466000/6022-spec-sheet

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