A MODULAR AUTOMOTIVE ROOF SYSTEM DESIGN CONCEPT
BASED ON POLYURETHANE COMPOSITE TECHNOLOGY

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Abstract

There is a growing trend in the automotive industry to offer more “non-traditional” roof configurations to the consumer. In many cases the non-traditional roof contains glass, guides, drives and other hardware that increase the cost and weight of the vehicle. Consequently, suppliers are being challenged to offer designs that use lightweight materials, integrate or eliminate components, while maintaining or improving overall structural and dimensional performance of the vehicle.

Based on a standard "body in white" roof structure, the innovative concepts described in this paper use molded polymers and composite materials that allow a vehicle to be fitted with a wide variety of roof “modules”, each having customized performance, content and value. The modules are designed to integrate components, eliminate post painting, increasing vehicle rigidity, and reduce weight.

Conceptual designs illustrated in this paper will include two different vehicle architectures and two different roof module constructions. Three different composite materials will be reviewed for their suitability in the roof module. Detailed section views are included to illustrate important part design features, attachment methods, performance considerations, and general composite “know-how”.

The concept’s value proposition is examined in four areas: cost, weight, safety and assembly. Technical and economic benefits to the value proposition include weight reduction, design and styling freedom, in-mold features, attachment points, color options, fixed or moveable window design, and improved roll-over safety due to the lowered center of gravity. Since the modular roof system starts with a component that is ready to assemble it offers a path forward for the supply chain, which enables OEMs to decrease capital expenditures and reduce labor hours required to manufacture a vehicle.

The backbone of the value proposition is a recently conducted case study, comparing a traditional vehicle to the same vehicle fitted with a composite polyurethane roof module. The two piece roof module examined in the case study is constructed using long fiber technology, and results in a vehicle that is lighter, stiffer, has a lower center of gravity, while offering greater design freedom and integration flexibility than traditional roof materials and design solutions.

In addition to polyurethane composites, the paper includes references to adhesives, coatings, co-extruded polycarbonate and polycarbonate/acrylonitrile film, and polycarbonate thermoplastic glazing.
Background

In 2005, in response to the growing trend in the automotive industry to offer more “non-traditional” roof configurations to the consumer, Bayer MaterialScience (BMS) introduced a basic modular roof frame design concept. It was for a generic medium-sized vehicle that could be manufactured in three variations: a base roof, a sunroof, or panoramic roof module. Each variation could be made with single, double, or triple panel versions. It was concluded materials and process technologies to implement an integrated roof module on a production scale were available. A commitment was made to further develop engineering solutions and knowledge toward polyurethane composites for roof system structural components [1].

New roof system polyurethane composite structural components are in production. The Opel Zafira roof manufactured by Webasto in Europe is made from BMS Baydur polyurethane composite (PUR) with the long fiber technology (LFT) processed behind a polycarbonate (PC) based film [2]. It is a Class “A” finished module ready for assembly by the automotive original equipment manufacturer (OEM). This application is a good example of the emerging material and design technology based on PUR composites and PC film that enable component integration, eliminate post painting, increase vehicle rigidity, reduce weight, and improve vehicle safety. Figure 1 shows an exterior view of the Zafira. Figure two shows the roof from an interior perspective.

Encouraged by the industry trend and commercial implementation, Bayer furthered its design initiative by establishing two different architectures and two different roof module design constructions. Three different composite materials were reviewed for their suitability. Detailed section views were developed to illustrate important part design features, attachment methods, performance considerations, and general composite knowledge. The concept’s value proposition was also developed and examined in four areas: cost, weight, safety and assembly. Technical and economic benefits to the value proposition include weight reduction, design and styling freedom, in-mold features, attachment points, color options, fixed or moveable window design, and improved roll-over safety due to the lowered center of gravity. The backbone of the value proposition is a recently conducted case study, comparing a traditional vehicle to the same vehicle fitted with a composite polyurethane roof module. The two piece roof module examined in the case study is constructed using LFT, and results in a vehicle that is lighter, stiffer, has a lower center of gravity, while offering greater design freedom and integration flexibility than traditional roof materials and design solutions.
Architectures & Design Concepts

Fundamental assumptions were developed and used as the basis for the new “non-traditional” roof concept:

- The roof module is provided “whole” by a tier-one supplier or system integrator
- The module drops onto the roof frame, aligns using dowel pins, and is attached permanently using glue
- If different car platforms use the same roof system they can use the same modules
- The modules can have any glazing style: none, panoramic, fixed, moving, etc.
- The module integrates typical passenger compartment options: dome light, HVAC, sun shade, electronics, air bags, etc.
- The module is supplied to the OEM with the headliner attached
- The OEM must provide “trim” pieces of headliner to finish the perimeter of the interior (outboard of the roof module)
- The trim pieces can be installed before the roof module, possibly from outside/above
- The roof frame must be re-designed as part of this roof system

Figure 3 depicts the “traditional” roof systems that consists of a sheet metal roof skin spot welded to the roof frame and to cross-car braces. In this system the roof is installed before e-coating or painting.

Figure 4 shows a “traditional” roof frame structure featuring conventional geometry standard on a production SUV. This structure was used as the baseline upon which to develop the two basic architectural approaches for the “non-traditional” concept.
conventional (baseline) roof frame geometry is a standard production SUV roof frame

Figure 4: Traditional Roof Frame Structure

The first “non-traditional” architectural approach was named “Over-the-Top” because the roof module overlaps the roof frame. The second approach is named “Recessed” because the roof module fits into the roof frame opening. Figure 5 illustrates the two basic architectural approaches designed to offer the OEMs design and styling choices.

Gives OEM Design/Styling Choices

“Over-The-Top”
(roof module overlaps roof frame)

“Recessed”
(roof module fits into roof frame opening)

*Bayer Concept

Figure 5: Two Basic Architectural Approaches
Figures 6 and 7 show details of the respective approaches and illustrate how the module appears when installed. Cross-sections A, B and C show the detail for the side, front header and rear header, respectively.

**Figure 6:** “Over-the-Top” Architectural Approach

**Figure 7:** “Recessed” Architectural Approach
The concept involved offering two design options for either architecture. One option consisted of a single molded part and was named “One Piece Design”. The other option consisted of two molded parts glued together and was named the “Clam-shell Design.” Figure 8 illustrates the design options that could be used with either architecture.

![Figure 8: Roof Module Design Options](image)

Advantages of the “One Piece Design” include:

- The composite polyurethane substrate can be molded between the paint film and the headliner cloth in a single molding process, eliminating fasteners and reducing assembly steps.
- A perimeter seal can be molded onto the above, which will simultaneously seal the edges of the composite material, and provide sealing against the car body (roof line)
- Integration of assembled parts: dome light, wiring, etc. is possible
- Simple design concept
- Light weight, but stiff construction
- Potential increase in vehicle rigidity & torsion
- Potential increase in roll over resistance
- Reduced parts inventory

Figure 9 illustrates the “One Piece” design approach. Note that structural steel spanning between the “B” pillars can be encapsulated into the polyurethane composite to maintain or increase roll-over integrity. Detailed cross-sections showing the sides of the module and attachment to the door were developed. Four distinct “One Piece” design concepts were developed for the “Over-the-Top” system architecture to represent various performance and economic solutions. The concepts were named: Traditional Look, Fixed Glazing, Robust/Metal Module Design, and Robust/ST Foam Roof Frame. Additionally, three distinct “One Piece” design concepts were developed for the “Recessed” system.
architecture to represent various performance and economic solutions. These concepts were named Integral-Wire-Way.

Figure 9: “One Piece” Design Approach (Bayer MaterialScience)

Figure 10 is an example of the “One Piece” design concept for the “Over-the-Top” system architecture that represents the “Traditional” Look.

Figure 10: “One Piece” Design Concept, “Over-the-Top” System, “Traditional” Look
Figure 11 is an example of the “One Piece” design concept for the “Recessed” system architecture that represents one Integral-Wire-Way solution. Details of the other solutions are contained in the presentation that accompanies this paper.

The second option offered for either system architecture is the “Clam-shell” Design. Advantages of this design include:

- Best suited for applications requiring a higher level of parts integration into the roof module
- Exterior piece/part is molded directly behind a multi-layer paint film, saving post painting
- Interior piece/part is molded directly behind the headliner cloth, eliminating the headliner foam
- Interior piece can have molded-in features such as air ducts, wiring tracks, sun shade recess, sun roof motor supports, other hardware supports, etc.
- Interior piece, if constructed of BMS Baypreg PUR composite with a paper honeycomb core, since it’s not exposed to the elements
- All hardware items are easily mounted on to the interior piece
- Exterior piece is glued on to the interior piece, after hardware mounting, creating a very rigid structure
- Potential increase in vehicle rigidity & torsion
- Potential increase in roll over resistance
- Reduction of parts inventory

Figure 12 illustrates the “Clam-shell” design approach with outer and inner panels. Notice the detail of wire ways and heating, ventilating and air-conditioning (HVAC) duct work that are formed into the inner panels. Five distinct “Clam-shell” design concepts were developed for the “Over-the-Top” system architecture to represent various performance and economic solutions. The concepts were named: Traditional Look, Rivet Attachment, Integral HVAC Ducts, Moveable Glazing, and Head Impact.
Protection. Additionally, four distinct “Clam-shell” design concepts were developed for the “Recessed” system architecture to represent various performance and economic solutions. Three concepts were named Robust Module, Integral-Wire-Way, and the fourth was a “Special” design concept named Integral Airbag.

Figure 12: “Clam-shell” Design Concept, Outer and Inner Panels

Figure 13 is an example of the “Clam-shell” design concept for the “Over-the-Top” system architecture that represents the Moveable Glazing solution. Here Makrolon PC is the material of choice for the movable sun roof and the sliding shade is made with polyurethane composite with a paper honeycomb core and wrapped in cloth.

Figure 13: “Clam-shell” Design Concept, “Over-the-Top System, Move-able Glazing
Figure 14 shows the “Special” design concept for the “Recessed” system architecture named Integral Airbag. This design concept features an airbag package encapsulated into the roof module with medium density polyurethane (PU) foam. Details of the other solutions are contained in the presentation that accompanies this paper.

Value Proposition

The basis for the value proposition is the design concept's universality and versatility that enables module interchangeability. Each module has its own customized performance, content, and economics. The concept allows the automotive OEM maximum flexibility in product planning and manufacturing. The various design concepts discussed previously in this paper are placed on an X and Y graph in Figure 15. The X axis is the module content from low to high. The Y axis is module performance, again, from low to high. The module design named “one-piece traditional”, closest to the point of origin on the graph shows the least content and performance, with presumably the least cost. At the other end of the spectrum is the “special integral airbag” design that features the highest level of content and performance, with presumably the most cost. In between could be and endless array of combinations for the OEM to choose from. At the product planning stage the OEM chooses several roof modules with different levels of merchantable content. Later the vehicle buyer considers the roof options, makes a choice and the order is sent to the factory for a specific module to be assembled for this customer. In each case the roof module is delivered to the OEM sequentially and ready for assembly. The roof module could be assembled inside the main vehicle assembly operation in a feeder line owned by the OEM or “co-located” with a system integrator or other tier-one supplier. The roof modules could also be assembled in a separate facility within close proximity to the main OEM assembly operation for just-in-time (JIT) delivery.
The value proposition also offers the opportunity to address vehicle safety. An average of 3,700 deaths and serious injuries occur annually in rollover accidents in which the victims are belted and the roof is crushed, according to the National Highway Traffic Safety Administration (NHTSA). No subset of rollover statistics is under greater scrutiny by NHTSA, which may propose tougher, new roof-strength standards to replace the current ones enacted in 1971 [3]. Appropriate modular roof designs could effectively address this issue with the customer ultimately deciding the cost/benefit solution right for them.

The basic value proposition was coined in the new phrase “uni-versital” body-in-white (BIW) header. The concept enables module interchangeability; each module having customized performance, content, and economics. The uni-versital BIW header is illustrated in Figure 16.
Value Proposition – DaimlerChrysler Dodge Caravan Case Study

A case study was used to examine the value proposition in four areas: cost, weight, safety and assembly. The analysis was based on the comparison of an existing “beam/skin” construction to a “structural plate” construction made from PUR LFT. The scope was a comparison of the existing Dodge Caravan to the same vehicle fitted with a PUT LFI roof module. The attributes that were studied included:

- **Performance, FEA simulations:**
  1. knee load
  2. wind load
  3. torsion stiffness
  4. modal analysis

- **Weight**

- **Value**

The FEA results and conclusions showed that in the knee load simulation, the PUR LFT roof was 82% stiffer than the steel roof. The analysis measured the deflection simulated by one knee at a 115 kg load at the temperatures of 23°C and 85°C. In the wind load simulation done at 100 mph at 23°C and 85°C, the deflection results were considered almost identical. The roof torsion loading was measured at 23°C and 85°C with results showing the PUR LFT roof was 40% stiffer than the steel roof. The modal analysis was done with the roof only from the beltline up, 1st mode. The analysis showed that further optimization was possible. The results and conclusions from the FEA simulations are shown in Figure 17.

![Figure 17 FEA Results and Conclusions (Bayer MaterialScience)]
A weight comparison showed the vehicle installed with the PUR LFT roof module is 5.6 kg lighter than the existing vehicle with the all-steel roof. Figure 18 summarizes the details of the weight comparison analysis.

- existing all-steel roof (from beltline up, featureless) ............ 102.4 kg
- Baydur/LFT roof module (i.e. PC glazing, steel pillars & roof frame) ....... 96.8 kg
  - 2 molded Baydur/LFT parts only .................................. 12.5 kg
  - 4 Makrolon windows .................................................. 2.5 kg
  - remaining steel structure, pillars, and roof frame ........ 81.8 kg
  - 4 tempered glass windows (reference only) ................. 3.6 kg

Materials' Details:
- Baydur/LFT composite includes 45% glass @ 75 pcf molded density
- all surfaces are 3.0 mm thick
- Makrolon windows are 5 mm thick (could be optimized to be thinner)
- existing roof sheet metal is 1.55 mm thick
- existing steel cross-car beams are 0.77 mm thick

The case study summary and conclusions showed that the PUR LFT structural plate compared to the existing construction resulted in:

- At lower weight and higher performance, the PUR LFT solution enabled more features and value
- At equal feature count and value, the PUR LFT solution offered lower weight and higher performance
- The PUR LFT solution enables “structural plate” constructions and more design freedom compared to the beam/skin designs.
Figure 19 shows details of the case study summary and conclusions of the PUR LFT structural plate compared to the existing construction.

### Conclusions

At lower weight & higher performance, Baydur/LFT enables more features & value.

At equal feature count & value, Baydur/LFT offers lower weight & higher performance.

*Baydur/LFT enables “structural plate” constructions and more design freedom vs. beam/skin designs.*

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**Figure 19 Case Study Summary & Conclusions (Bayer MaterialScience)**

An analysis of the case study comparing the existing Dodge Caravan roof to a PUR LFT design resulted in these key conclusions:

- PUR LFT enables a “structural plate” construction and improved design freedom compared to the metal beam/skin construction
- The PUR LFT “structural plate” design is over 25% stiffer in torsion rigidity than the existing metal beam/skin design
- The PUR LFT roof module is 5.6 kg lighter than the existing beam/skin construction of the Dodge Caravan
- At lower weight and higher performance, the PUR LFT roof solution enables more features and value
Sample Application – Opel Zafira

The General Motors Opel Zafira roof is in production with a modular design. The structural carrier is made by Webasto with the PUR-LFT process. A black PC film is placed over the substrate material to deliver a Class A exterior appearance. Figure 20 shows the current construction.
Figure 21 illustrates an Opel Zafira roof concept based on a “Clam-shell” design. This concept features injection molded PC glazing and uses a PC and PC/ABS co-extruded film laminated with paint film to deliver a variety of custom colors to match the vehicle body. On the interior is a high level of integration featuring storage compartments and lighting.

Conclusions

The Opel Zafira is an example of a vehicle with a “non-traditional” roof system in production today. The carrier is made with a PUR LFT composite with PC film delivering black high gloss exterior appearance and performance. Paint film developments show the promise to open the pallet to a variety of custom colors with good adhesion and appearance on the PUR LFT composite. Future vehicles currently in the concept design and engineering phase incorporate PC glazing for panoramic roofs. These vehicles will feature advanced styling, integration and modular assembly.

Fresh design and material concepts developed by Bayer MaterialScience show different vehicle architectures that enable component integration, post painting elimination, increased vehicle rigidity, and weight reduction. The value proposition’s “uni-versital” BIW header concept enables module interchangeability and allows the OEM to select a variety of customized roof modules with different levels of performance, content, and economics for a vehicle. Careful selection of merchantable content with assembly flexibility will provide an economic incentive to the OEM.
Case study analysis demonstrated a PUR LFT based roof module system when compared to an existing vehicle roof offers:

- A “structural plate” construction with greater design freedom compared to the metal beam/skin construction
- The “structural plate” design is over 25% stiffer in torsion rigidity that the existing metal beam/skin design
- The roof module is 5.6 kg lighter that the existing metal beam/skin construction
- More features and value can be offered at lower weight and higher performance

**Bibliography**

