AN INTEGRATED AUTOMOTIVE ROOF MODULE CONCEPT: PLASTIC-METAL HYBRID AND POLYURETHANE COMPOSITE TECHNOLOGY

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Abstract

The implementation of metal stampings combined with injection molded 30% glass fiber reinforced polyamide type 6 (PA6-GF30%) for commercial passenger car and truck front end modules has grown in the automotive industry over the past five years. This patented Plastic-Metal Hybrid (PMH) design technology has proven its ability to enable the automotive original equipment manufacturer (OEM) to engage a flexible assembly strategy, decrease capital expenditures and reduce labor hours required to manufacture a vehicle.

The roof module is an opportunity to further develop content by combining adhesives, coatings, film and reinforced polyurethane (PUR) composite materials with PMH technology. The powerful combination provides the OEM a component ready to assemble. Technical and economic benefits to the value proposition include:

- Weight reduction compared to glass
- Design and styling freedom from a box shaped hard top
- In-mold features like brackets, bosses and attachment points
- Different color options
- Removable or open/close window design
- Safety improvement due to lowered center of gravity and benefits in the event of a rollover crash
- Water management and flush finish with the body exterior

This paper presents a roof module concept that utilizes PMH to create a roof frame welded to the body-in-white (BIW) structure that is capable of going though on-line electro-static coating (E-coat) processes. The frame becomes a common footprint upon which a variety of roof modules constructed with PUR composites protected by coating and film can be attached to the vehicle with adhesive.

A roof frame design concept for a generic medium sized vehicle is presented. The concept includes single, double or triple modular panel versions. Each version can be used to manufacture three variations: a base roof, sunroof, or panoramic roof module.

Background

The patented PMH technology was introduced by Bayer in the 1980s. It has been implemented in over 50 vehicles world wide in the last 8 years with no field failures. PMH is a special technique for insert molding. A metal profile is placed in an injection mold and plastic is injected around the profile. The plastic wraps around the edges of the sheet metal or through carefully designed extruded holes or buttons. There are no secondary operations required. The metal does not need to be free of oils or grease. Figure 1 shows the cross section of a typical PMH beam and the patented button design. Audi was the first OEM to implement this technology on an A6 front end module. Since then numerous OEMs have embraced it for a variety of front end module designs. The technology enables the OEM to develop a flexible assembly strategy for vehicles, reduce capital expenditures and assembly labor hours. An OEM estimated total savings at its assembly operation in the millions of dollars based on the implementation of the technology in a single application.

In 2004 the ownership of the PMH patent was transferred to Lanxess Corporation. The technology was expanded to new applications. Audi implemented the technology in a roof frame construction spanning the A-pillars across the top of the windshield [1].

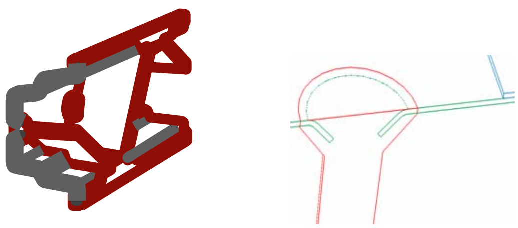

Figure 1: Cross section view of a plastic and metal hybrid beam with button design that mechanically locks the materials together.

The construction used Lanxess Durethan® BKV 30H, (PA6-GF 30%), and was implemented on the A6 body-in-white and met all structural and chemical resistance requirements while reducing weight. Figure 2 shows the PMH roof framework on the front header between the A pillars welded on the assembly line in body-in-white before e-coat.

Figure 2: Plastic and metal hybrid front header on the Audi A6 (photo courtesy Audi Corporation).

Bayer MaterialScience continued the development of plastic, PUR, film, coating, adhesive and sealant technology for implementation in roof modules and other non-traditional roof systems.

Coated Makrolon® polycarbonate (PC) was developed as an alternative to glass for weight reduction and aggressive design and styling solutions. A clear PC fixed window injection molded by the Freeglass company for the DaimlerChrysler SmartCar and a transparent PC body panel on a Mercedes vehicle have been on the road over three years. Other vehicle glazing applications, primarily on vehicles designed, engineered and assembled in European operations have come to the market.

PUR developments have resulted in component level structural materials suitable for roof modules. Developments include a honeycomb structure made from a variety of materials sandwiched between layers of polyurethane with high modulus and low weight. An alternative technology is PUR sprayed in tandem with glass fibers in to an open mold on a thermoformed paint film followed by a compression stage. This technology was recently demonstrated on the Opel Zafira roof module by Webasto.

Recent developments of thick films based on co-extruded PC and PC/acrylonitrile butadiene styrene copolymer (PC/ABS) enable the glass fibers in the PUR to be concealed and deliver a class-A surface. One development uses the thick film as a backing layer laminated on paint film. Alternatively, paint is applied to the thick film in a roll-to-roll dual cure in-line process. The films are subsequently thermoformed and used with the PUR to create the roof module carrier.

Coating developments based on polyurethane (PU) chemistry have focused on technology to help the paint on the film and paint film solutions achieve greater flexibility for deep draw sections. The coating technology not only meets appearance standards but functional requirements for abrasion, scratch and mar, as well.

Adhesive and sealant technology based on PU chemistry has advanced to enable the finished roof module to be glued to the metal roof frame during vehicle assembly. The technology is a proven performer for adhering windshields to the automobile body.

The roof module concept presented in this paper brings together PMH with PUR, co-extruded PC and PC/ABS film, PU based coating, and PU based adhesives and sealants to create an integrated solution. The concept enables a variety of roof modules to be attached to the roof framework which is designed as a common footprint in the vehicle roof structure.

Figure 3 illustrates the common footprint with a variety of possible roof modules for the same vehicle to satisfy customer needs.

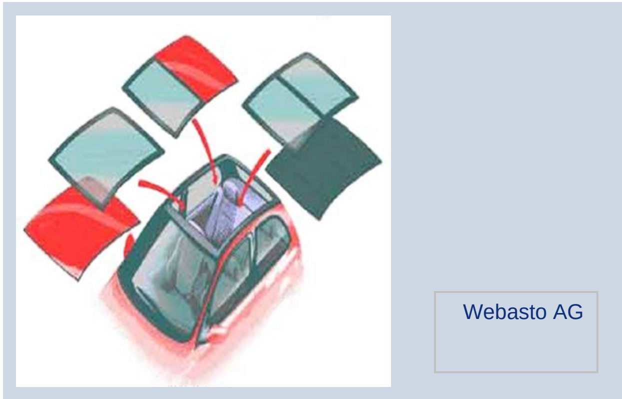

Figure 3: Concept showing a common footprint in the roof structure designed to accommodate a variety of roofs: standard roof, lamellar roof, large panorama roof, and small panorama roof as examples (Illustration courtesy of Webasto)

In this concept the OEM purchases the completed roof modules from a system integrator delivered just-in-time from a facility either co-located or in the vicinity of the vehicle assembly operation. They are brought sequentially to the main assembly line ready to be attached and glued to the vehicle roof framework.

Figure 4 shows a cross-section of the roof module with the film and coating outer surface, PUR carrier and foam and inner surface making up the headliner.

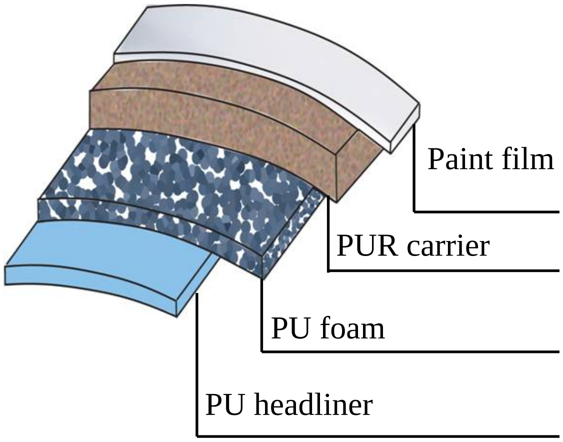

Figure 4: Roof module materials cross-section

Figure 5 shows the roof module fitting on to the common roof framework.

Figure 5: Composite materials roof module fitting into the common vehicle roof framework

Integrated roof module concepts have been under consideration for years. Facets of the technology have become commercial on an increasing array of vehicles. It is now feasible to bring all the needed technologies together for the implementation of a variety of commercially successful roof module to satisfy all the stakeholders: customers, manufacturers and investors.

Composite Structure

Plastic-Metal Hybrid (PMH) Technology

Our roof module concept utilizes PMH to create a common roof framework in BIW to receive the roof module and address roof crush and roll-over requirements. Based on its profile (a U-profile showing the greatest advantages) plastic metal hybrid can increase the strength of a section in bending by nearly 600%. Essentially, the plastic forces the metal to maintain its section properties through the loading and not fail due to localized buckling.

Besides improved strength and energy absorbing capabilities there are other advantages of having plastic as part of the structural system including:

- Reduced components
- Reduced weight
- Increased design flexibility for attachments
- Datum
- Forming from the injection molding process
- Improved damping on the acoustics level translating to four times lower initial decibel reading and immediate damp out versus an all steel structure for a simple hammer test

The PMH system using PA6-GF 30% has proven in several applications it will pass through different OEM E-coat processes without detriment. The technology also offers the ability to use the injection mold to fixture multiple stampings and use the plastic to attach the stampings together. The connections are as strong as or stronger than spot welds. The composite nature of PMH offers the best of both worlds: the strength and ductility of steel and the design flexibility and stiffness of the plastics.

The aim of this concept is to take the PMH technology successfully applied to front end modules and implement it for roof modules as well. Although in our concept PMH is part of the BIW structure and is used to receive the module and handle the structural load requirements of the roof, the design technology could be incorporated in the roof system itself, as well.

A frame of PMH would include the front and rear roof bows and cover areas leading from the A-pillar to the D-pillar making an entire window. The structure would be welded in the BIW structure, much like the PMH Audi A6 roof bow is today. The frame would serve several purposes:

- Reduce weight
- Meet FMVSS requirements
- Handle the body variation to receive the module
- Maintain the contact to the module as the adhesive cures
- Provide attachments for headliner components
- Improve acoustics

PMH opens further opportunities to improve vehicle safety. The side airbag curtains, inflator bodies and gas tubes can be packaged into the PMH roof framework or module. The energy management diffuser tubes can use extruded Texin® thermoplastic polyurethane (TPU) sleeves to move gases emitted when a discharge occurs during an impact event. Figure 6 illustrates how the side airbag curtains could be packaged and deployed from the PMH structure.

Figure 6: PMH side airbag system with TPU sleeves in the energy management tubes packaged in the roof framework

Roof Module Composite Carrier

The roof module concept here considers a vehicle that requires three variations: a base roof, a sunroof, and a panoramic roof. All variations have a common composite materials construction for the portion that provides the class-A surface and a place for insertion of the sunroof and panoramic roof materials formed from PC.

Our discussion of the common composite materials begins on the inner surface with basic polyurethane headliner materials common in the industry today. Several installation concepts were identified in The ITB Group *Automotive Roof Systems and Modules* study [2]. In a concept developed and patented jointly with JCI and Alusuisse, the headliner is brought in through the space where the windshield will be attached later and glued to the roof from beneath and trimmed. The headliner approach for our concept is best illustrated by a solution developed by ArvinMeritor. Here the headliner is part of the roof module assembly and is delivered in a folded state. It is brought to the roof framework in a top-load installation and in a three step process the headliner is unfolded into place and the module is fastened to the side rail. The PU foam in the headliner addresses tactile and acoustic requirements.

The next layer in the composite is the carrier. Our concept envisions two possible constructions. Figure 7 shows a picture of Baypreg®, a PUR honeycomb sandwich construction. Materials like aluminum, cardboard or PC formed into a honeycomb are placed between random glass fiber mats. The sandwich is impregnated with PU then cured and formed in a low compression process.

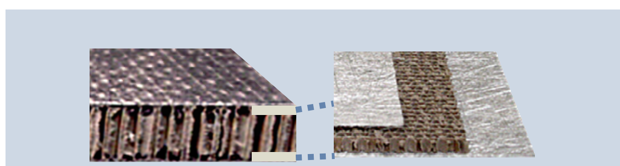

Figure 7: Honeycomb matrix between random glass fiber mats saturated with polyurethane

The PUR system is an integral part of this composite technology that produces parts with a high stiffness to weight ratio. Composites made with this system are manipulated easily allowing developers almost unlimited freedom in manufacturing a wide variety of part designs and configurations [3]. The technology is particularly well suited for large relatively flat panels and is used today, for example, by Toyota Motors in cloth wrapped roof sunshades. Figure 8 shows how paint film adheres to the composite to create a class-A surface.

Figure 8: Paint film over composite polyurethane for class-A surface

Baydur® STR, a PUR composite structural reaction injection molded (S-RIM), is another material solution for the carrier. This system involves a robotic arm cutting long glass fiber (LGF) roving and depositing them with PUR on to the backside of thermoformed paint film placed into an open mold. When the deposition is completed the next stage involves the mold closing with low pressure compression to cure the composite and form the part. Figure 9 shows the finished composite PUR S-RIM with LGF on the left and the robotic arm depositing the materials into the open mold on the right.

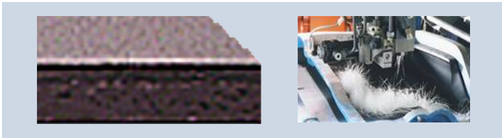

Figure 9: PUR Composite S-RIM

An example of the PUR S-RIM with LGF system used on a commercial vehicle today is the DaimlerChrysler Smart second generation roof module made by ArvinMeritor.

Film and Coating

Recent developments include Bayfol® TP231, a co-extruded PC and PC/ABS film. The film has enabled the manufacture of automotive components made from the PUR reinforced composites. The 1000 micron carrier film serves as a backing layer laminated on paint films. The film chemistry is designed to adhere well to the PUR substrate as well as the color and clear coat layers on the paint film outer surface. Figure 10 shows a cross section represented by the orange and green layers. This developmental co-extruded film offers very high heat resistance, enabling class-A surfaces.

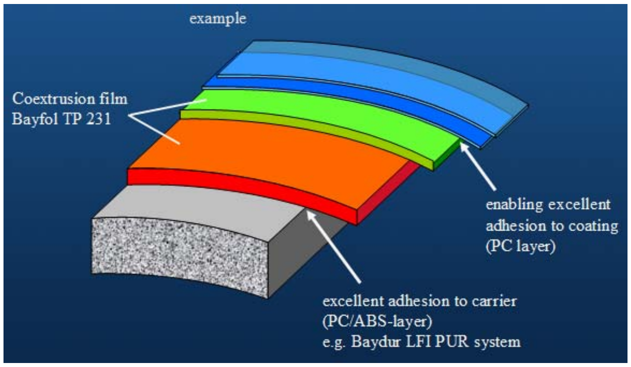

Figure 10: Co-Extruded Thick Film Laminated to Paint Film

There are a couple of scenarios under development for the film technology as it could be used for roof modules. One involves paint film technology. In this case the co-extruded PC and PC/ABS film is used as a backing layer, or carrier film, in the paint film product. An example of this technology is certain Fluorex® Paintfilms manufactured by Soliant. Figure 11 shows another cross section view that illustrates the paint film composition and how it is adhered to the polyurethane roof module carrier depicted in gray. The blue layer in the illustration shows the co-extruded PC and PC/ABS thick backing layer film. It adheres well to the PUR carrier structure on the bottom. The paint film color and cover coats are laminated to the top of the co-extruded PC and PC/ABS as well.

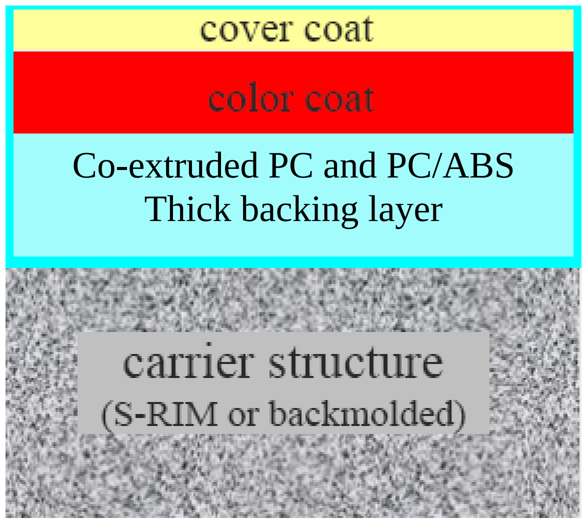

Figure 11: Cross Section - Paint film cover and color coats laminated on PC and PC/ABS co-extruded thick backing layer and adhered to the PUR carrier structure

Another scenario involves the PC and PC/ABS co-extruded material as a carrier film upon which the coating is applied in a continuous roll to roll process. The film and coating composition is cured in a two stage process. The first stage cures the film enough to be rolled without adhering to itself. The film is then cut and thermoformed for use in the part forming process. Figure 12 is a schematic of the first stage roll to roll film and coating process.

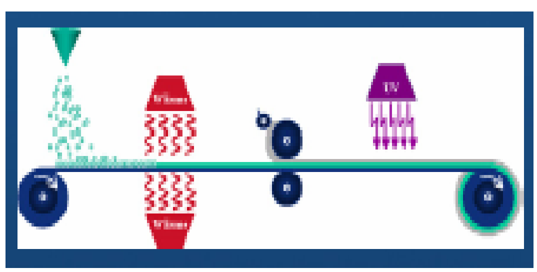

Figure 12: Painting carrier film in a roll to roll process

The second stage occurs after the film is thermoformed to the shape of the roof module component. This second drying step, or thermal treatment, is a UV cure that hardens the outer surface of the paint on the film to its ultimate strength and hardness.

In this scenario there is opportunity to utilize polyurethane coating chemistry for the paint to maximize its ability to stretch over deep draw applications.

Glazing

In the sunroof and panoramic versions of our roof module the use of PC is considered as an alternative to glass. Benefits include weight reduction, design and styling freedom, safety and security. Figure 13 shows a current DaimlerChrysler MCC Smart vehicle rear side window manufactured by the Freeglass company in Germany from PC. The part features curves that would have been difficult to manufacture in glass. The transparent section is framed in opaque black molded in a second stage. Figure 14 shows how the PC is used as a transparent body panel on a current DaimlerChrysler Mercedes-Benz C Class Coupe. The part is manufactured by Dynamit Nobel in Germany and glued in place.

Figure 13: SmartCar PC fixed rear window

Figure 14: Mercedes-Benz C-Class Coupe PC transparent rear body panel

Advances toward implementing PC in sun and panoramic roofs have been made in commercial vehicles. Figure 15 shows the Smart ForFour vehicle featuring transparent PC roof panels.

Figure 15: Smart ForFour with PC roof panels (photo courtesy of DaimlerChrysler)

To overcome issues relating to PC for glazing, Exatec, LLC has developed Exatec® 900, a unique hard coat system. Exatec accelerated weathering data and models predict a greater than 10 year lifetime, depending upon geographic region and on-vehicle orientation, for automotive window applications. In addition the superior abrasion resistance offered by this coating system can be coupled with printing and defroster solutions. The capacity and technology to fabricate PC glazing is evolving in all global regions. Future roof systems and modules are opportunities for businesses seeking to expand or invest in facilities to manufacture PC glazing.

Adhesives and Sealants

Rapidly curing and strong bonding adhesives and sealants based on PU chemistry for attaching the roof modules to the vehicle framework are readily available today. Although our roof module concept incorporates glue tracks in the PMH roof framework ready to receive the component in final assembly, they could also be designed into the PUR materials used in the roof module carrier.

The use of PU energy management foam in conjunction with PMH or the PUR composites used in the roof module carrier can further address acoustical sealing, increase strength and improve performance during impact events. According to quasi-static bending test data generated by Bayer MaterialScience comparing trapezoid and hexagonal shaped metal stampings of various thickness with cavities filled with two different densities of energy management PU foam, it clearly showed increasing forces to bend in both geometries and densities. Figure 16 shows the final deflection of thin wall/344 kg/m^3 in the background was substantially less that the thick wall/empty assembly at approximately 15% lower mass. The final deflection is similar between the thick wall/empty and thin wall/128 kg/m^3 filled assembly at approximately 30% lower mass, shown respectively in the foreground and middle ground. Figure 17 is the same test samples shown from a longitudinal view.

Figure 16: Side View - Impacted Samples (photo courtesy of Bayer MaterialScience)

Figure 17: Longitudinal Views - Impacted Samples

The Integrated Roof Module Concept

This roof module concept began with computer-aided design (CAD) data from an OEM's medium sized vehicle currently sold in the market. The math data was transposed to create an integrated modular roof concept for a generic vehicle. The vehicle is designed for assembly in three versions: base roof, sunroof and panoramic roof.

Roof module concepts have been presented in graphical form before [4]. The purpose of this initiative was to base the work on existing CAD data to clearly demonstrate how a real integrated roof module could be engineered for assembly. Figure 18 shows the OEM's basic CAD data for the upper roof frame.

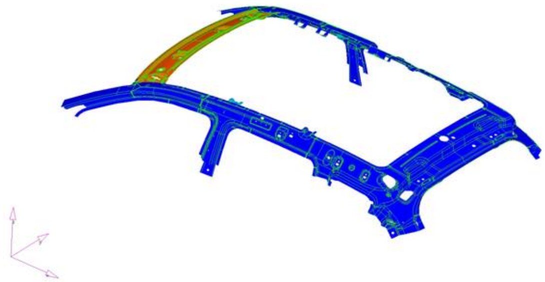

Figure 18: Upper Roof Frame CAD data

In the first phase the design assumptions included:

- Need to generate first outer surface
- Door construction is glass over door structure
- BIW needed with front and rear roof rails to go through e-coat
- Previous cross-car structure needed to be implemented, included in module
- Need to define a locating strategy
- Implement snap fits to hold module to frame allowing time for adhesive to cure
- BIW tolerance is +/- 4.5mm fore, aft and cross-car

In phase two the inner surface and packaging the rest of the bill of materials (BOM) was to be addressed. BOM considerations included:

- Integrated antenna
- Digital Video Discs (DVD) brackets
- Roof header console and brackets
- Sun visors and retainers
- Wire Harness
- Trim ring
- Noise, Vibration, & Harshness (NVH)
- Coat hooks
- Intrusion Module
- Heating, Ventilation, & Air-conditioning (HVAC) ducts and outlets absorber PU foam pads
- System head impact foam
- Grab handles featuring snap lock design
- Side airbags

Figure 19 shows a bottom view of the roof module upper frame concept and Figure 20 shows the top view.

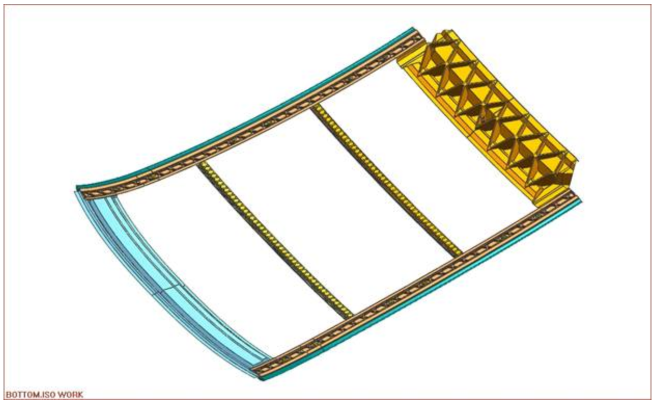

Figure 19: Bottom View - Roof Module Upper Frame Concept

Figure 20: Top View - Roof Module Upper Frame Concept

In these views the front of the car is positioned to the left. The PMH technology that provides the roof structure is clearly seen in the cross-hatch design around the perimeter. The cross car rails at the B and C pillar are optional for additional structure and could be made from PMH technology or alternatively have thin metal stampings integrated into the PUR composite material on the roof carrier layer.

In figure 21 the PU headliner and the PUR carrier with film and coating are combined with the PMH roof module frame with a list of construction materials suited for the different modules. In the view the headliner is shown on the bottom of the stack followed by the PMH frame and finally the roof carrier construction on the top.

Figure 21: Roof Panel Constructions (from top to bottom)

Roof Materials

- PC glazing
- PC and PC/ABS film
- PUR composite materials
- In-mold color
- Film Insert Molding (FIM)
- PU coating
- PU adhesives and sealant

PMH Structural Frame

Baynat®, PU Head Liner

A decision was made to develop three concepts based on a single, double and triple panel roof frame. The reason was to demonstrate how flexible the design technology could be in implementing this solution. Within each concept it was shown how to design a base roof, sunroof and panoramic roof.

Figures 22-25 show the most complex three panel design concept. By selecting the panels the roof module can be a base, sunroof, or panorama. The panels are tied together with a material strip that could be made from weatherable PU RIM or acrylonitrile styrene acrylate (ASA) material attached to the PMH or metal cross car beams and double as luggage rack connections.

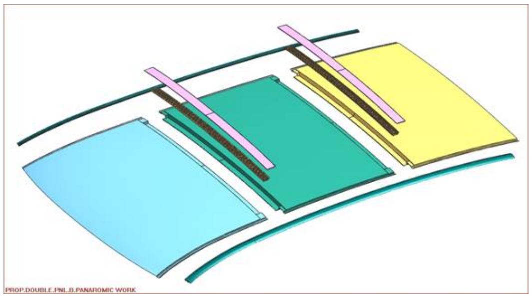

Figure 22: Top view – Three Panel Base Design

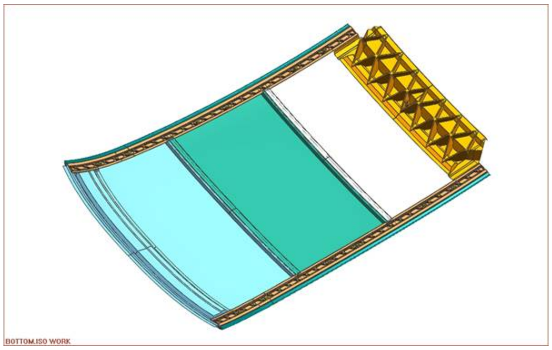

Figure 23: Bottom view – Three Panel Base Design

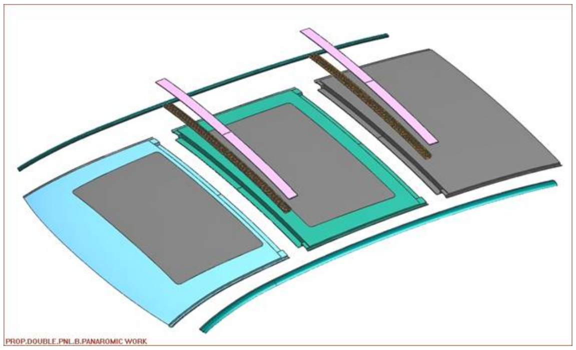

Figure 24: Top view - Three Panel Panorama Design

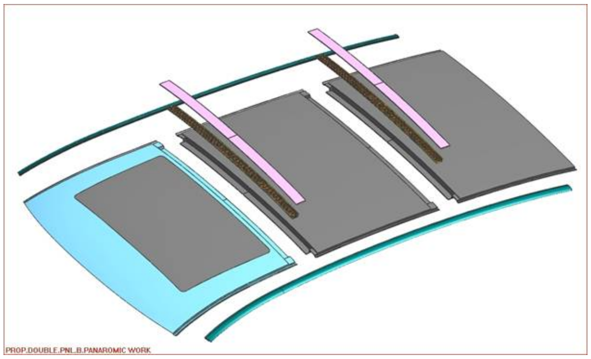

Figure 25: Top view - Three Panel Sunroof Design

Conclusions

PMH enabled the cost effective implementation of front end modules. The same benefits can be realized for other applications like roof modules.

The materials and technologies necessary to technically and economically implement an integrated roof module system on a production scale are available now. A roof module system will enable the OEM to offer a wider variety of styles and options for a vehicle while reducing OEM labor hours and number of assembly stations. Also, the modular assembly reduces the footprint on the assembly floor and decreases capital investment at the OEM level.

Future developments will focus on economic analysis, film and coating development, and supply infrastructure for a vehicle with production intent. Bayer MaterialScience continues to evolve its Roof System ideas into more defined engineering solutions with additional concepts that broaden its economic and technical viability. Particular emphasis will be on developing the engineering data to enable the adoption of PUR composite systems for roof modules and other non-traditional roof systems.

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