LIGHT METAL-PLASTIC BODY-IN-WHITE SOLUTIONS FOR AUTOMOTIVE

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Paper Number 17-0126

ABSTRACT

Engineered systems in today's automobiles are often designed and built to meet conflicting and complex requirements. While mobility is a car's primary function, accomplishing that in an energy-efficient manner and ensuring the safety of the occupants are critical requirements. Automotive OEMs, therefore, are aggressively working on making vehicles lighter without compromising its safety. Meeting such complex requirements often requires solutions encompassing innovative designs, manufacturing processes and multi-material systems.

This paper focuses on the development of lightweight metal-plastic body-in-white (BIW) solutions. A generic vehicle validated for high-speed crash scenarios such as full frontal impact, side deformable barrier impact, side pole impact and rollover (roof crush resistance) is chosen for the feasibility study of developing hybrid lightweight solutions using metals and thermoplastics. Various weight reduction opportunities by either replacing the existing metal reinforcements in the BIW or by replacing a complete sub-system such as B-pillar were explored using metal-plastic hybrid combinations. Developed reinforcements include those in the floor rocker, rails, floor etc. A combination of high heat unfilled thermoplastic resins (tough and ductile) or fiber reinforced thermoplastic resin (high stiffness and strength) and metal are chosen appropriately depending on the requirements. For instance, an unfilled thermoplastic resin over-molded with multiple metallic inserts was chosen to replace the incumbent energy-absorbing members in the floor rocker for side impact, and fiber compounded thermoplastic resin over molded with a metallic insert is chosen to replace the existing B-pillar with comparable crash performance. The developed lightweight hybrid B-pillar replaces a multi-piece B-pillar made of high-strength steel. The metal inserts in the hybrid systems are exploited for assembly ease in the BIW structure. Such a solution not only offers part integration possibilities with equivalent crash performance as that of the baseline system, but also opens the door for replacing the high-strength steel used in the BIW with a medium-strength steel.

A significant weight reduction potential (approximately 30%) is observed as the baseline BIW structures were down-gauged with overmolded thermoplastics. Thermoplastic material overmolded on steel plays a crucial role in avoiding localized buckling of the BIW structures and in absorbing impact energy as and when required.

The developed solutions – validated using CAE studies – are further correlated using component level studies with a generic 800 mm long metal-plastic system weight 1.6 kilograms. This system is subjected to 3-point

bending and force vs. deflection characteristics and the deformation kinetics in the above loading scenario is correlated using sub-system level CAE studies.

INTRODUCTION

Automotive safety regulations, in general, can be categorized as those that ensure occupant safety and those that regulate pedestrian safety. While the latter is achieved by designing an optimum bumper and a bonnet, the former warrants a combination of appropriate design of vehicle body-in-white (BIW) and incorporation of additional safety features such as airbags, seat belts, etc. inside the vehicle. As the BIW accounts for majority of the mass of a vehicle, it also plays an important role in defining the energy/fuel needs of a vehicle.

While there are significant developments in solar energy, fuel cells and other such renewable sources of energy, fossil fuels still remain the most common and preferred source of energy for automobiles. This continues and the ever-increasing use of fossil fuels has serious undesirable impact to our environment resulting in global warming and more importantly on the sustainability of humankind. Thus, to make sure that the current usage of fossil fuels does not jeopardize the potential for people in the future to meet their energy needs, the U.S. government (later supported by other regulatory bodies in different parts of the world) introduced the concept of Corporate Average Fuel Economy (CAFE) standards in 1975 [1]. Its primary objective is to reduce the energy consumption by increasing the fuel economy of light trucks and cars, which also indirectly results in reducing greenhouse gas emissions. An in-depth study of worldwide statistical data indicates that automobile manufacturers need to come up with bold solutions in the next few years, as CO2 emission reduction targets for the next 10 years are nearly double of what has been achieved in the last 10 years [2].

Studies and surveys performed by several institutes [3] show that light weighting is so far the most promising option for automobile manufacturers to address 2025 CAFE industry standards (refer Figure 1). It is worthwhile to note that some of the survey respondents focus on multiple technologies and hence a cumulative score of more than 100% as one could observe in the figure. Lightweighing, though seemingly relatively simple, is not the most convenient option to implement in a vehicle due to several factors mentioned below.

1. It can have an adverse effect on other factors such as the dynamic stability and noise, vibration and harshness (NVH) performance of the vehicle.
2. Strength and stiffness of application/part being replaced with a lighter solution should not be compromised as it can negatively impact the long-term performance and more importantly the crash performance of the vehicle.

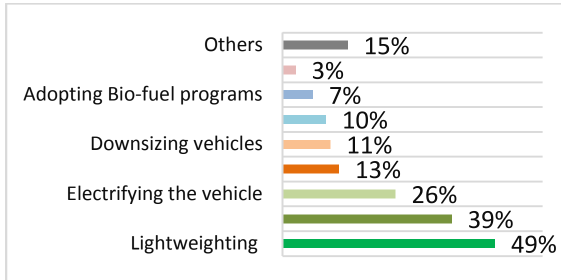

Figure 1.Technologies being focused by industries to help to meet 2025 industry standards. Adapted and recreated from [3].

This paper investigates one of the short-term lightweighting approaches for automobiles. The approaches explained in the paper are focused on replacing hang-on parts with a lightweight and optimally designed system while making sure that this replacement does not result in reduced crash performance of the car.

The remaining part of this paper is divided into five sections as follows. The first section explains why the body-in-white (BIW) reinforcements are targeted for the lightweighting of automobiles. The next section of the paper deals with identifying a realistic weight reduction potential in an automobile using BIW reinforcement concepts. This is performed by developing solutions for one of the vehicle platforms for which a validated computer aided engineering (CAE) model was developed by the National Crash Analysis Center at George Washington University. The third section includes the preliminary crash performance evaluation of the conceived lightweight vehicle, and the comparison of the performance with the baseline solution. The next section explains how the performance of such lightweight BIW reinforcement solutions can be validated using component level tests. The last section contains an overall summary, thoughts on future work required and some concluding remarks.

AUTOMOTIVE LIGHTWEIGHTING

It is estimated that a vehicle's typical subsystem mass distribution is led by the body [4]. On average, it amounts to 37% of the total mass of a vehicle. This is followed by the chassis (30%), powertrain (14%), interior (12%), electrical (4%), and the remaining 3% contributed by Heating, Ventilating and Air Conditioning (HVAC) and powertrain cooling systems. A similar distribution are reported by other research papers too [5-6]. Though the numbers and ranking reported by other studies can vary, most of those studies unanimously show that body and chassis contribute to roughly 65% of the total mass of the car. It is, therefore, important that one view the BIW as a major lightweighting region of the car. Numerous options including alternate materials, optimum geometrical configurations and diverse manufacturing methods are being investigated in the literature to take out the mass from the BIW without compromising the car's performance [7-10]. Automobile manufacturers also need to make sure that the resulting increase in cost is maintained within acceptable levels.

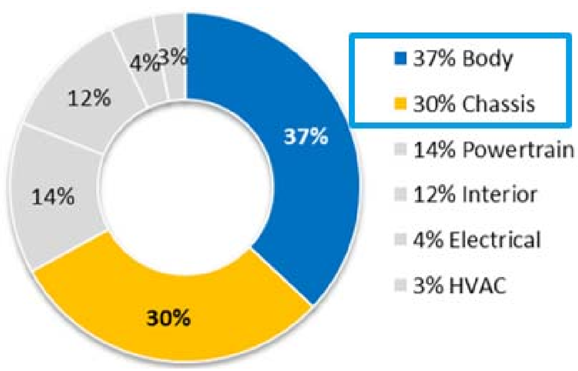

Figure 2. Mass distribution in a typical automobile. Adapted and recreated from [4].

Each application in an automobile is unique in its own way. Interior trim applications, which are typically made of plastics, need not offer high stiffness and strength, but should provide the aesthetics and premium looks for the occupant sitting inside the car and should also have provisions for sufficient storage holders. Similarly, polyurethane foam used in seats should offer the passenger sufficient comfort and cushioning effect. Likewise, a car's BIW has to provide sufficient support and mountings to other parts in a car including the engine and powertrain, suspension, body panels, glazing and so on. The BIW is also the major energy-absorbing member in an automobile in the event of a high-speed crash. Figure 3 shows typical materials used and a few major relevant applications using the same in an automobile. As you would notice, each material has its own pros and cons, making it more appropriate or not appropriate for certain applications. For example, it would be highly challenging to achieve the required cushioning and comfort of a seating system using high strength steel (HSS). Similarly, it would be tough to imagine polyurethane foam replacing the BIW, which is typically made using steel, HSS or aluminum. Certain applications can be designed and made of multiple materials. The BIW of a car is a one such application. A typical low-cost and heavy vehicle uses conventional stamped steel parts to constitute its BIW. More expensive and probably lighter cars use HSS or aluminum for manufacturing its BIW. Even more expensive cars such as sports cars, which demand the lightest possible vehicle with superior dynamic stability, use composites predominantly to make most of its parts. Figure 4 shows cost implications and lightweighting potential in a car using different materials. It is worth noting that the conventional medium strength steel is used as the baseline for this comparison.

Materials	Typical Applications
Steel	Structural parts requiring strength and formability needed, e.g., side intrusion beams
HSS	Structural parts, but additional strength comes with increased difficulties in molding, e.g., B-pillar
Plastics	Exterior and interior parts with no requirements for structural strength, e.g., fascia or covers
Aluminum	Structural or functional parts, e.g., sub frames or beams
Composites	Structural parts requiring high strength, e.g., frame, hood, or tailgates

Figure 3. Various materials, applications and why those materials are used for those applications in automobiles. Adapted and recreated from [10].

Why BIW Reinforcements for lightweighting?

As mentioned in the earlier section, a vehicle's BIW is typically made using stamped steel parts. Several stamped steel parts are welded together to form the complete BIW. In general, it is difficult to achieve local stiffening or softening effect in a stamped steel parts. This is primarily because the raw material used for the stamping or metal forming operation is a blank with uniform thickness. The only way to vary the stiffness along the length of a stamped steel part is by smart geometrical variations, which beyond a limit is infeasible as it is limited by the draw ratio. This is true with other materials, too, such as aluminum wherein the parts are typically made using an extrusion process. Needless to mention, achieving local stiffness variation in an extruded aluminum part is even more challenging. Automobile designers, therefore, generally make use of local reinforcements in a car's BIW to improve the stiffness and strength at certain selective locations. The center portion of the B-pillar, roof, A-pillar center and rocker as shown in Figure 5 are a few, examples of such reinforcements [11]. Similar reinforcements exist in other parts of the BIW such as rails, floor and C-pillar. These reinforcements are typically made of HSS and are separately welded onto the part.

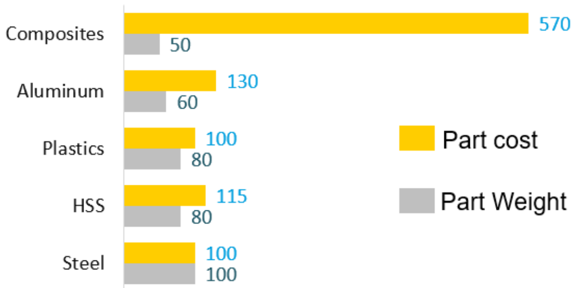

Figure 4. Impact of lightweight materials on the part cost for a typical automotive application. Adapted and recreated from [10].

Each reinforcement in the BIW has different functions. For example, in the case of the B-pillar, the reinforcement is provided in the center to prevent the undesired local buckling of the B-pillar during a side impact and a roof crush/roll over scenario. The rocker reinforcement absorbs the greatest share of energy during a pole impact event. A reinforcement in a rail can absorb energy during a high-speed frontal crash. It may also provide an additional local stiffening effect in the vertical direction at engine mount locations in the rails. These reinforcements in the rails, therefore, can also reduce the transfer of engine vibration to the BIW of the vehicle to a greater extent. Considering all these factors, one can say that BIW reinforcements can be appropriate applications to target for lightweighting in an automobile as:

1. Replacement of BIW reinforcements with lighter and hybrid reinforcements does not require any major changes in the existing assembly line.
2. Potential weight reduction possibilities are significant as multiple reinforcements are present in a vehicle.
3. One does not need to be concerned about joining techniques as the same welding process or adhesives can be used to join the new solution to the BIW.

Figure 6 shows a schematic representation of few potential BIW reinforcement applications using a thermoplastic, metal-plastic or composite-plastic solution. Details of the development of such solutions for a realistic vehicle platform and the potential weight reduction possibilities is demonstrated in the next section.

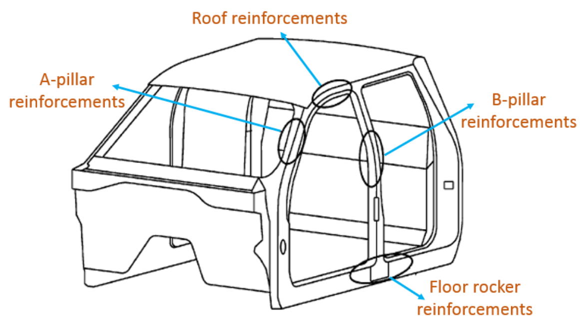

Figure 5. Few BIW reinforcements in typical automobile. Adapted from [11].

Figure 6. A realistic representation of BIW reinforcements in a vehicle using plastic, metal-plastic and other hybrid concepts.

DEVELOPMENT OF BIW REINFORCEMENTS

This section aims to demonstrate the weight-reduction potential in a realistic vehicle platform by replacing a few of its BIW reinforcements by lighter plastic or hybrid solutions. A finite element model of one of the car models developed by FHWA/NHTSA National Crash Analysis Center at George Washington University [12] is used as a baseline vehicle for this study. The identified vehicle is a sedan weighing approximately 1070 kg. This vehicle was chosen for the study because:

1. This vehicle was one among the well correlated vehicle finite element (FE) models from the set of several available.
2. This vehicle model has reinforcements in the A-pillar vertical member, front rails, B-pillar, and rocker. Thus, the weight reduction potential by replacing all four reinforcements can be studied.

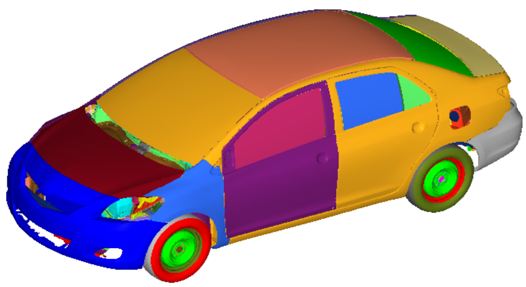

Figure 7. Identified vehicle models for the lightweight BIW reinforcement development study. Adapted from [12].

As mentioned earlier, four reinforcements were selected to study the lightweighting potential in this vehicle platform. These are floor reinforcements, reinforcements in the vertical A-pillar, front rail reinforcements, an integrated and lightweight rocker solution and a metal-plastic B-pillar system replacing four out of the existing 5-piece B-pillar in the vehicle. While lighter solutions are achieved in the first two applications purely by replacing the existing steel inserts by injection molded thermoplastic systems, the last three applications realize the weight reduction by combining a multiple steel stamped solution to a single-piece metal-plastic over molded solution. The metal in the metal-plastic solutions are down-gauged significantly compared to the existing solutions, and thermoplastics are molded onto it to compromise the reduced stiffness as a result of the down-gauging of the steel part. These solutions, therefore, not only offer significant lightweighting opportunities, but also offer part integration possibilities in many cases. Figure 8 to Figure 11 show the details of the conceived lighter solutions. Appropriate meshing, morphing and preprocessing software [13] was used to conceive these solutions so that they fit within the packaging space available in the vehicle. The engineering techniques/approach used to reduce the mass of reinforcements are as follows.

1. Metal sheets are typically downgraded to at least 1 mm or 0.8 mm depending on the grade of the steel used. This provides a significant weight saving as the baseline solutions are typically 1.5 or 2 mm thick.
2. Plastics honey combs are over molded on this down gaugeed steel stamp parts to avoid the local buckling of these structures

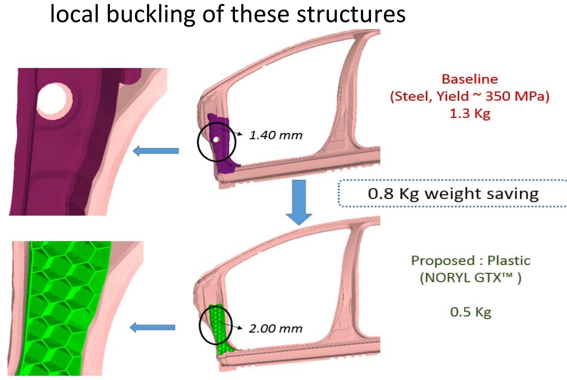

Figure 8. Existing reinforcement in the A-pillar and proposed thermoplastic reinforcement. Total weight reduction of 1.6 kg/car. Reinforcement dimensions – 450 mm * 110 mm * 60 mm.

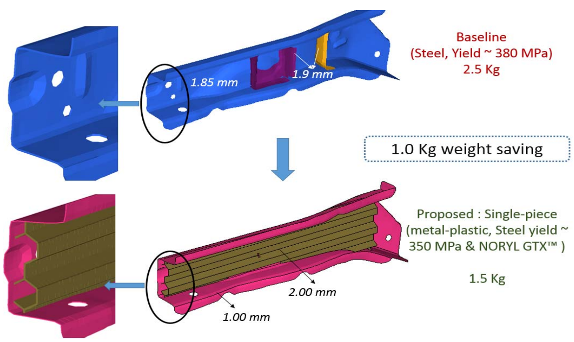

Figure 9. Existing 3-piece steel front rails and proposed metal-plastic lighter front rails. Total weight reduction of 2.0 kg/car. Reinforcement dimensions – 550 mm * 120 mm * 70 mm.

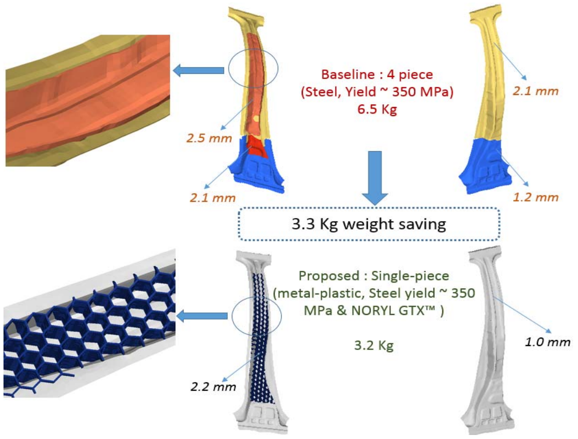

Figure 10. Existing 4-piece steel B-pillar and proposed metal-plastic single-piece B-pillar. Total weight reduction of 6.6 Kg/car. Reinforcement dimensions – 1000 mm * 140 mm * 115 mm.

It is worth noting that the assembly sequence is only minimally altered by introducing these lighter solutions. For example, in the case of the B-pillar, the top and bottom portions still have isolated metal sections, which can be welded onto the existing BIW. In many cases, the assembly is actually made simpler as several parts are integrated in the proposed solutions. Furthermore, based on the requirements, materials can be selected capable of passing the e-coat bath for anti-corrosion.

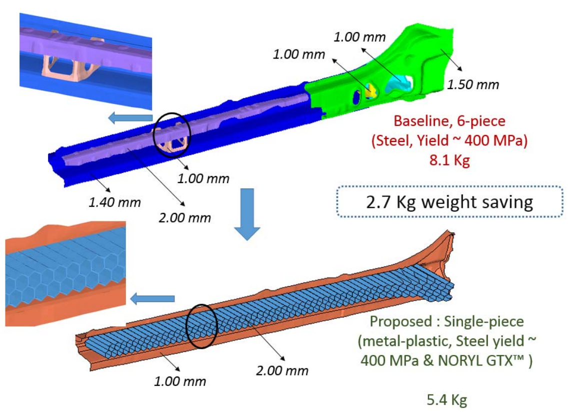

Figure 11. Existing rocker outer and reinforcement solution and proposed metal-plastic rocker outer & reinforcement. Total weight reduction of 5.4 Kg/car. Reinforcement dimensions – 1650 mm * 150 mm * 120 mm.

Figure 12 shows a summary of weight reduction possibilities achieved in the considered vehicle using the aforementioned four lightweight solutions. Based on these developed solutions, it is observed that approximately 15.6 kg of a car weighing close to 1070 kg can be reduced by this technology. Similar technologies, when evaluated for another vehicle can yield different numbers, but the message remains the same.

Applications	Representative Picture	Part Weight: Baseline	Part Weight: Proposed	Weight reduction (Kg / car)	% Weight reduction	Other Remarks
A-pillar vertical reinforcements		1.3	0.5	1.6	62	
Front Rail		2.5	1.5	2	40	Part integration
B-pillar		6.5	3.2	6.6	51	Part integration
Floor Rocker		8.1	5.4	5.4	33	Part integration
Total weight Reduction				15.6	42%	

Figure 12. Summary of weight reduction potential in a car using BIW reinforcement concepts.

NUMERICAL PERFORMANCE EVALUATION

As mentioned in the earlier sections, BIW caters to multiple functionalities in an automobile. This section, however, only focuses on evaluating a few major high-speed crash scenarios during which the BIW plays a crucial role in absorbing a significant portion of the impact energy, and thus mitigating the injury of the occupant to a greater extent. A performance evaluation for the secondary functionalities of the BIW is beyond the scope of this paper.

The vehicle with the conventional BIW inserts and the same vehicle with the four newly proposed, alternate lightweight solutions are subjected to 56 km/h full frontal impact [14] 50 km/h side IIHS deformable barrier impact [15], 30 km/h pole impact [16] and roof crush impact scenario [17]. LSDYNA a commonly available explicit solver is used for these simulations [18]. The metal and plastic parts of the vehicle were modelled using MAT 24, a commonly used piecewise linear plastic material model in LSDYNA. A strain-based failure model was used to model the failure of these parts. To avoid the complexity, the delamination of plastics in the metal-plastic hybrid inserts was not modelled. Figure 13 shows the expected impacts of replacing the BIW parts with the conceived lighter solutions on the four major crash scenarios explained above. A tick mark in any column or row indicates that the corresponding solution (shown in the respective row) can have a significant impact on the respective (shown in the column) crash impact performance of the vehicle.

		Full frontal crash	Side IIHS deformable	Side Pole Impact	Roof Crush Impact
A-pillar vertical reinforcements			✓		✓
Front Rail		✓			
B-pillar			✓	✓	✓
Floor Rocker			✓	✓	

Figure 13. Replacement of BIW parts with lighter solution and their impacts on the crash performance of a car during various crash scenarios.

High speed full frontal Impact

The acceleration experienced by the occupant or measured by the accelerometer positioned close to the left/right rear seat floor is an important criteria evaluated in a full frontal impact at 56 km/h. Typically, for a safer car, the deceleration levels have to be maintained below 40 g. The deformed/crushed vehicle configurations at the maximum intrusion points are shown in Figure 14. Figure 15 shows the deformed configuration of the relevant part of rail which is replaced with a lighter solution. Both figures indicate that the vehicle behavior and its performance is not drastically affected. The acceleration measured near the left rear seat as shown in Figure 16 also substantiate this fact. The reduced acceleration in the case of the proposed solution is mainly because the rails absorb more energy than just buckling about a point in the rear as in the case of the baseline solution.

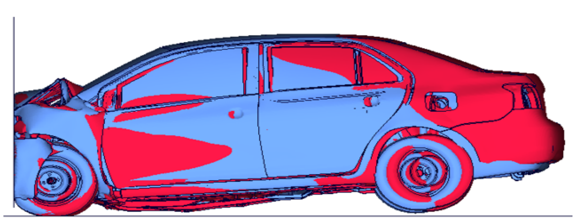

Figure 14. Deformed configuration of the baseline vehicle and a vehicle with lighter front rail insert solutions in a high-speed frontal impact

Side Impact @ 50 km/h using IIHS barrier

Side impact to a vehicle using Insurance Institute for Highway Safety (IIHS) deformable barrier impact emulates a crash scenario between two vehicles in orthogonal directions. The function of BIW components – including the B-pillar, A-pillar, door, rocker, etc. – in this case is to limit the side intrusion in a vehicle. This is extremely important as there is hardly any space available between the occupant and the side structural parts of the car, and any direct contact of the structural member to the occupant's body can cause severe injuries to the occupant. It is also important that these side members are not over-designed so that the occupant will experience high side accelerations in these cases. In order to make sure that the proposed solutions do not adversely affect the side impact performance of the vehicle, IIHS deformable barrier is impacted to both vehicle configurations at 50 km/h.

Figure 17 shows the deformed configurations (at maximum intrusion point) of the baseline solution and the proposed solution respectively. As one can make out from the figure, the performance of the vehicle with lightweight systems is very much comparable to that of the original configurations. Section views (refer Figure 18) along the width of the car at the B-pillar location also demonstrate that the lightweight B-pillar, rocker and floor reinforcements behave very similar to the behavior of those respective parts in the baseline vehicle configuration. This is further supported by the force vs. intrusion curves during the side impact scenario as shown in Figure 19. The proposed solution generates higher peak force and relatively higher force levels towards the end of the impact mainly because of the additional stiffness from the plastic over molds in the B-pillar inserts.

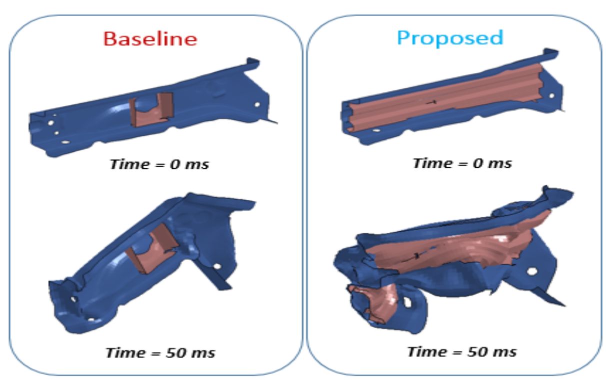

Figure 15. Deformed configurations of the left rails in case of baseline and the proposed solution in a high-speed frontal impact

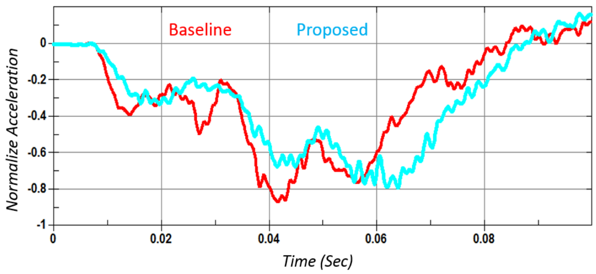

Figure 16. Normalized acceleration measured near the left rear seat in a high-speed frontal impact. This gives an indication of acceleration experienced by the occupant. The proposed solution shows better crushing resulting in reduced occupant acceleration.

Side Rigid Pole Impact at 29 km/h

Pole impacts are performed in a vehicle mainly to safeguard the occupant during the event of its impact with a rigid tree or any other relatively slender, vertical and rigid structures on either sides of the road. The major challenge in this case is to make sure that the required amount of energy is absorbed by the vehicle's structural members before the pole comes in direct contact with the occupant's body. The rocker, one of the very first portions that comes in contact with the rigid pole, plays a crucial role in limiting the intrusion in a vehicle during such an event. The two vehicle configurations are therefore compared for its rigid side pole impact performance. Figures 20, 21 and 22 show the performance of the vehicle in this impact situation. Observations and conclusions from these results are no different from what was observed in the earlier impacts. It is worth noting that the force levels are again higher in the case of proposed solution. These force levels can be reduced, if required, to reduce the acceleration experienced by the occupant. Softer plastic honeycombs will help to achieve this.

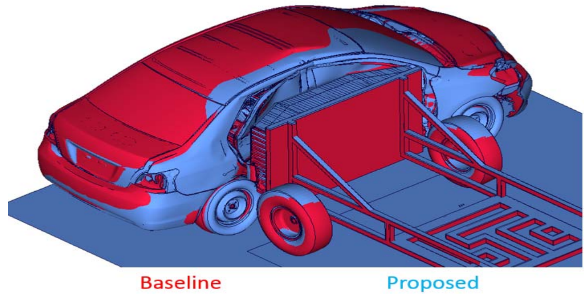

Figure 17. Deformed configuration (at maximum intrusion time) of the baseline vehicle and a vehicle with lighter solution subjected to IIHS deformable barrier side impact.

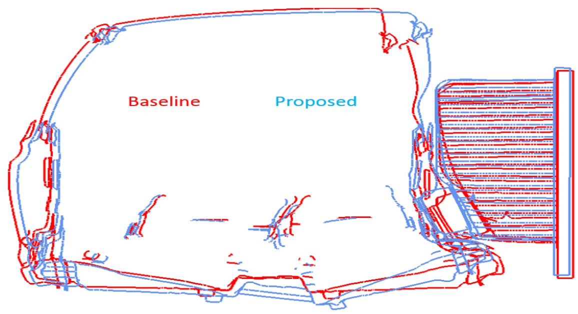

Figure 18. Sections views along the width of the car at the B-pillar section. Both baseline and the proposed configurations seem to behave in a similar way. The proposed solution also shows promises of reducing the side impact intrusions.

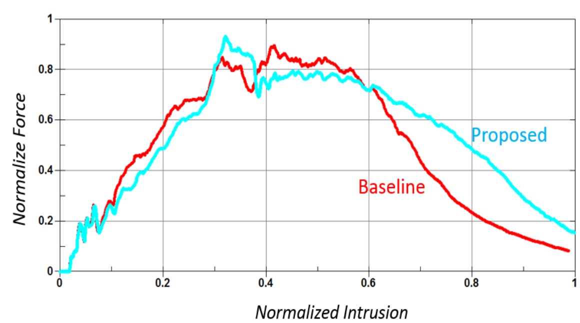

Figure 19. Normalized Force versus Intrusion curves during the IIHS side deformable barrier impact.

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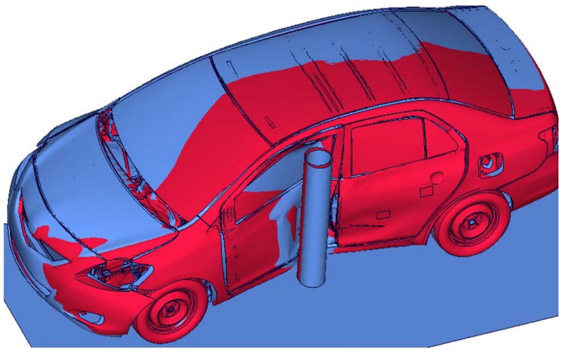

Figure 20. Deformed configuration (at maximum intrusion time) of the baseline vehicle and a vehicle with lighter solution subjected to rigid pole impact.

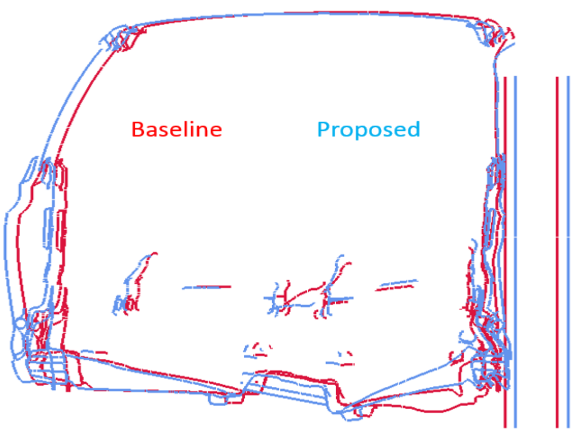

Figure 21. Sections views along the width of the car at the B-pillar section during a rigid pole impact. Both the baseline and proposed configurations seem to behave in similar ways. The proposed solution also shows promise of reducing side impact intrusions.

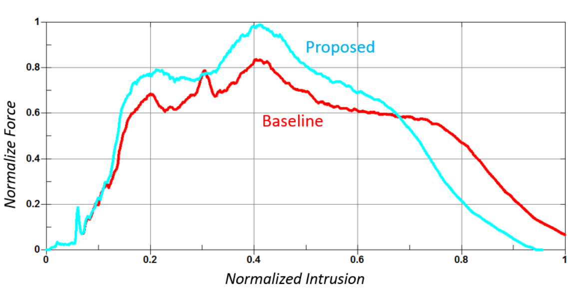

Figure 22. Normalized Force versus Intrusion curves during the rigid pole impact.

Roof Crush Resistance

The objective of roof crush performance evaluation is to make sure that the occupant has sufficient headroom before the vehicle's structural parts (mainly the roof, A-pillar and B-pillar) deform to absorb the energy during a rollover situation. Different regulations evaluate the roof crush in different ways. In general, the vehicle is supposed to be performing well for the roof crush requirements if it can generate a peak force of at least 2.5 times (> 2.5 times the weight of the vehicle – marginal performance and > 4 times the vehicle's weight – good performance) the weight of the car before the roof intrudes by 5 inches. Rigid plate impacts to the roof of the baseline and lightweight vehicle are performed as per the regulatory protocols and the performance curves and vehicle behaviors are shown in Figure 23 to Figure 25. Results again demonstrate that a lightweight BIW reinforcement solution does not necessarily reduce the roof crush performance of the vehicle. The maxim value of the strength to weight ratio in the case of the proposed solution is higher within 5 inches (about 127 mm) of intrusion. This is mainly because of the additional stiffness from the plastic honeycomb parts.

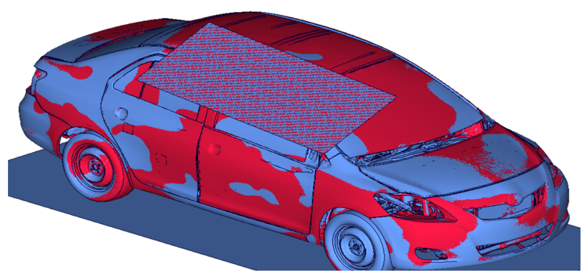

Figure 23. Deformed configuration (at maximum intrusion time) of the baseline vehicle and a vehicle ith lighter solution subjected to roof crush impact.

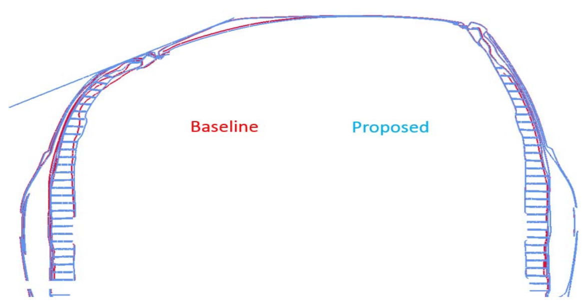

Figure 24. Sections views along the width of the car at the B-pillar section during a roof crush impact.

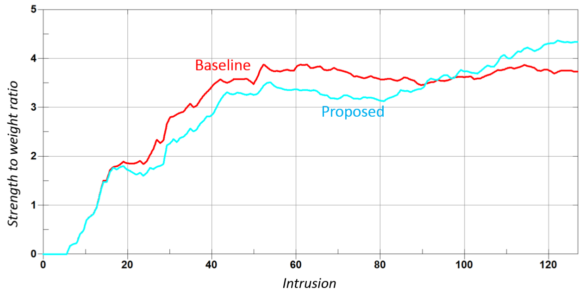

Figure 25. Strength to weight ratio versus Intrusion curves during the roof crush

EXPERIMENTAL STUDIES

Component-level validation

Full vehicle level tests demand higher investment in hardware and take longer time. Therefore, in this section, component level tests on a representative all-plastic and metal-plastic hybrid beam are performed for both static and dynamic scenarios, and are correlated with CAE results. The chosen test specimen is a C- section filled with plastic ribs. For an all-plastic beam, both the channel section and ribs are made of plastic whereas for metal-plastic hybrid beam channel section is made of metal – which is then over molded with plastic to form inner ribs. These test samples are represented in Figure 26. Two load cases (static & dynamic) as shown in Figure 27 are considered.

1. Three point bending load case with indenter moving at 10mm/min. As the speeds are relatively low, this scenario may be considered as static loading.
2. An impact with indenter weighting 23 kg with a speed of 13.5 kmph. This represents a dynamic impact scenario.

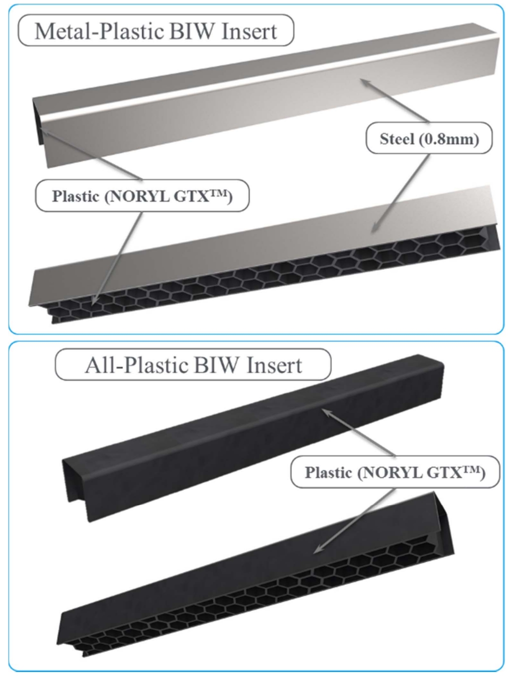

Figure 26. All-plastic and metal-plastic samples used for experimental validation.

Experimental Setup: Static Loading

Two custom-made fixtures support BIW inserts and an indenter loads the insert as shown in the Figure 28. This 3-point bending scenario represents most of the loading that is being applied in BIW insert in the event of a crash. In the component level, these loads are applied using a 100 kN capacity hydraulic press with integrated measurement system from INSTRON. An indenter as shown in the Figure 28 is used to transfer load from hydraulic press to the specimen. A thick layer of foam covering the indenter ensures uniform transfer of load from indenter to the specimen. Force cells with displacement sensors are mounted on the indenter to capture the force and displacement. The beams are loaded with the bottom support fixed and the indenter is allowed to move in the downward (bending) direction at a speed of 10m mm/min. To capture and understand how the specimen fails during these loading scenarios, the bottom face of the beam is focused within the scope of a high-speed camera.

Experimental Setup: Impact Loading

A medium energy uniaxial impactor is used to apply impact load onto the BIW insert. Impact energy supplied to BIW insert can be adjusted to desired level by adjusting mass and/or speed of impactor. The hardware can be adjusted for different impact objects and clamping possibility. High-speed camera is again used to capture deformation and failure of BIW insert subjected to impact loads. The uniaxial impactor can slide along a uniaxial guidance system. The guidance system is mounted on an impactor frame. A Hydraulic cylinder launches the impactor frame with a specified speed. Launch of impactor frame triggers data acquisition system to measure force, intrusion and acceleration. BIW inserted is supported in an orientation such that the impact happens at the center of the beam. A schematic representation of such a system is shown in the Figure 29.

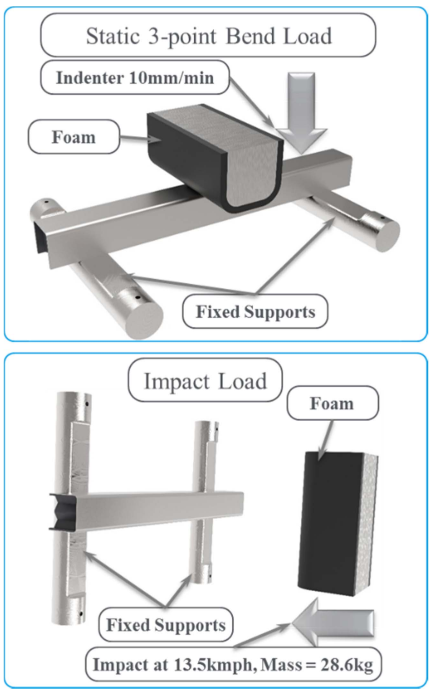

Figure 27. Three point bend and impact load applied to BIW insert.

Effect of e-coat on metal plastic hybrid:

As most of the vehicles have BIW made of steel, they are often subjected to electrophoretic painting process (e-coat) to mitigate the potential long-term corrosion issues and to improve the adhesion of paints on its surface. In this process, BIW is typically immersed in an aqueous solution containing paint emulsion. Paint emulsion gets condensed onto the part by applying electrical voltage. All the surfaces where the solution can reach get painted. Coating thickness is controlled by the magnitude of applied voltage. One of the most important steps of e-coat process is curing. Depending upon the type of paint used, curing temperature can be anywhere between 180^{o}C to 200^{o}C for 20 minutes to 30 minutes. It is also worth noting that BIW can be exposed to different environmental conditions (humidity, excess temperature) in the use phase of a car. Hence, it is important to ensure that metal-plastic BIW reinforcements are immune to such conditions. To study the combined effect of e-coat curing and moisture absorption of the metal-plastic hybrid BIW insert, the BIW insert is exposed to the following conditioning cycle:

1. Oven is preheated to 200^{o}C.
2. BIW insert is kept in the preheated oven for 30 minutes.
3. Insert is cooled to room temperature.
4. Insert is exposed to 95% relative humidity for 40 hours
5. Insert is kept at 50% relative humidity until equilibrium or for 40 hours

Conditioned specimens are also tested for both static and impact loading and their performances are compared against non-conditioned samples.

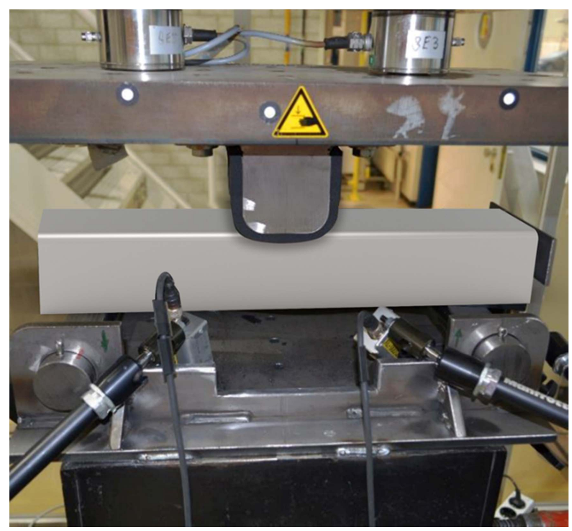

Figure 28. Experimental setup of the 3-point bend loading for BIW inserts.

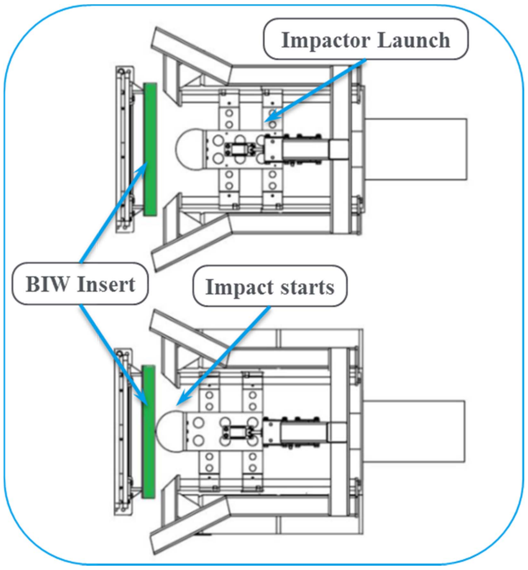

Figure 29. Schematic representation medium energy uniaxial impactor.

Static Loading

Samples are tested with and without e-coat conditioning to study the effect of e-coat cycle on metal plastic hybrid sample. Three samples are tested with e-coat conditioning and three samples are tested without e-coat conditioning at 21°C. An average representative of the three test iteration is been considered for reporting. The test result in the form of a normalized force vs. a normalized intrusion curve is shown in Figure 30. It is worth noting that the e-coat conditioning cycle slightly improves the load-bearing capacity of the metal-plastic hybrid insert at room temperature (21°C). One possible explanation of such behavior is that the e-coat conditioning cycle causes annealing to the molded region of the hybrid insert. This results in relaxation of the process-induced residual stress, which ultimately results in improving the strength of molded part and thus improving the load-bearing capacity. Research [19] confirms improvement in mechanical properties of the molded part due to different level annealing temperature.

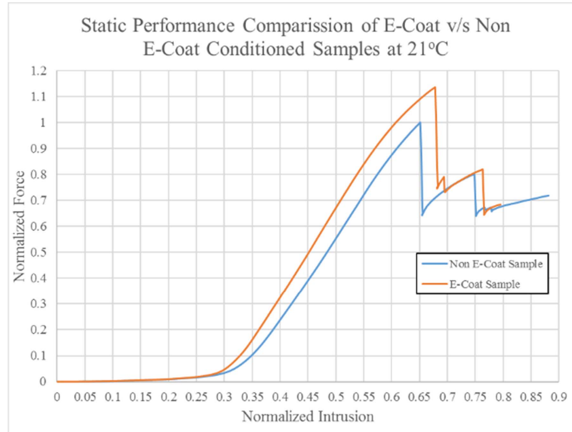

Figure 30. Normalized Force vs. Normalized Intrusion curve for static test considering e-coat sample and non e-coat sample at 21 deg C.

Another set of testing is performed at -20°C with and without e-coat of metal plastic hybrid sample. Two samples are tested with e-coat and two samples are tested without e-coat. An average representative of the three test iteration is been considered. Test result in the form of normalized force vs. normalized intrusion curve is shown in Figure 31. It shows that the e-coat cycle has very little effect on performance at minus 20°C.

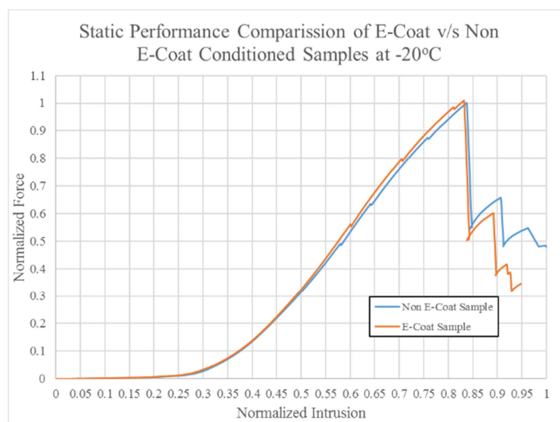

Figure 31. Normalized Force vs. Normalized Intrusion curve for static test considering e-coat sample and non e-coat sample at -20oC.

To confirm that e-coat has little or no influence on the performance of metal-plastic reinforcements, one more set of experiments are performed at 80°C with and without e-coat conditioning of metal plastic hybrid sample. Two samples are tested with e-coat and two without. The test result (refer Figure 32) shows that the e-coat cycle has very little effect on performance at 80°C.

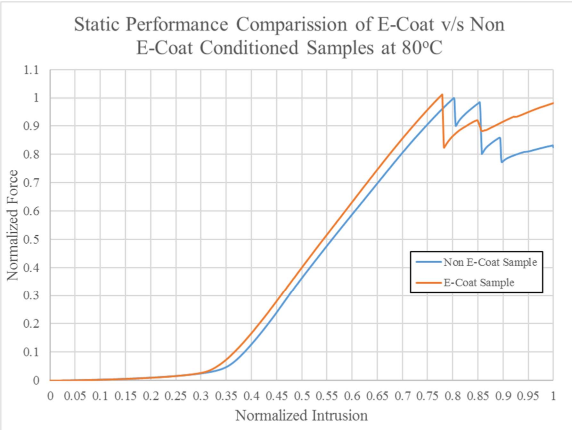

Figure 32. Normalized Force vs. Normalized Intrusion curve for static test considering E-coat sample and non E-coat sample at 80 deg C.

Figure 33 shows comparison of the static performance of the metal-plastic BIW insert at -20^{o}C, 21^{o}C and 80^{o}C. As one would expect, energy absorption of the sample is best at 21^{o}C, whereas load-bearing capacity is highest at -20^{o}C.

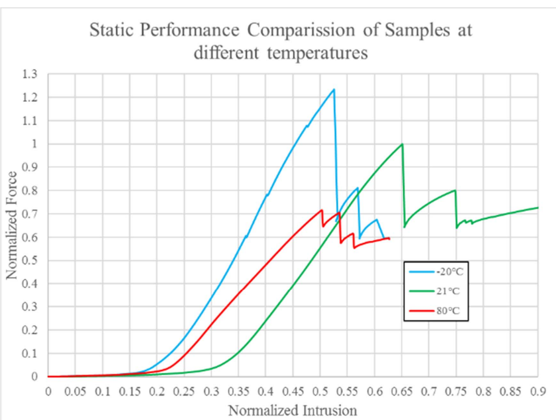

Figure 33. Normalized Force vs. Normalized Intrusion curve for static test at -20 deg C, 21 deg C and 80 deg C.

Impact Loading

The effect of the e-coat cycle on impact performance of the metal plastic hybrid insert is also studied. Impact testing as described in the previous section, is performed at 21^{o}C for samples with and without e-coat. Test results in the form of normalized force vs. normalized intrusion curve is shown in Figure 34. These results reinforces that the e-coated metal-plastic hybrid insert shows similar performance as that of non e-coated sample at room temperature.

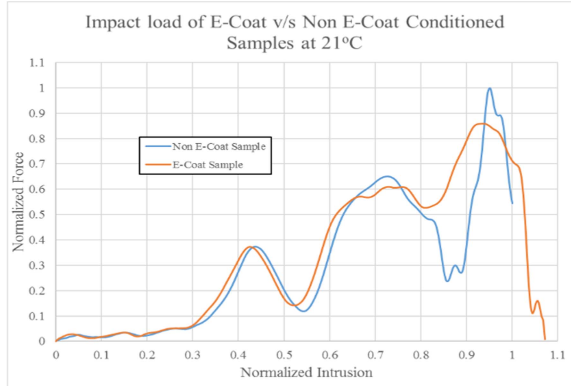

Figure 34. Normalized Force vs. normalized Intrusion curve for impact test considering e-coat sample and non e-coat sample at 21 deg C.

Correlation Studies

Experimental validation of predictive methodology is required to build confidence in vehicle level simulation. Finite element (FE) simulations are performed for static three-point loading scenario for all-plastic beam and metal-plastic beam and the results are compared with the experimental results explained in the previous section. CAE versus test results for plastic beam is plotted in Figure 35. The effect of foam is ignored in normalized force vs. normalized intrusion for both prediction and testing. Correlation of normalized force vs. normalized intrusion for the all-plastic beam is found to acceptable. There is an excellent match for stiffness (initial slop of the curve) of the insert. Predicted strength (maximum force) is within 2% of tested strength, and predicted intrusion at failure is within 4% tested intrusion at failure. FE model could also predict the location and nature of failure with reasonable level of accuracy. Figure 36 shows predicted and tested failure location for all-plastic insert.

CAE versus test results for metal-plastic beam is plotted in Figure 37. Effect of foam is ignored in normalized force vs. normalized intrusion for both prediction and testing. Correlation of normalized force vs. normalized intrusion for metal-plastic insert is reasonably good. The FE model could predict the stiffness of the metal-plastic insert (initial slop of the curve) with very good accuracy. Predicted strength (maximum force) is within 6% of tested strength. Predicted intrusion is about 28% off as compared to the test. The discrepancy in prediction of failure mode is primarily due to the unknown adhesion property at the metal-plastic interface. The interface was modeled using cohesive surface behavior in ABAQUS[†] with stiffness and strength of interface as 20% of stiffness and strength of plastic. A detailed investigation of adhesion between metal-plastic hybrids is beyond the scope of this paper, and hence excluded from subsequent sections.

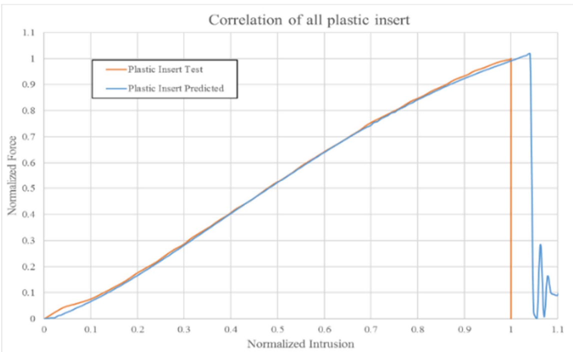

Figure 35. Predicted versus experiment correlation for an all-plastic insert subjected to three-point bending. A very good correlation is observed for all-plastic insert.

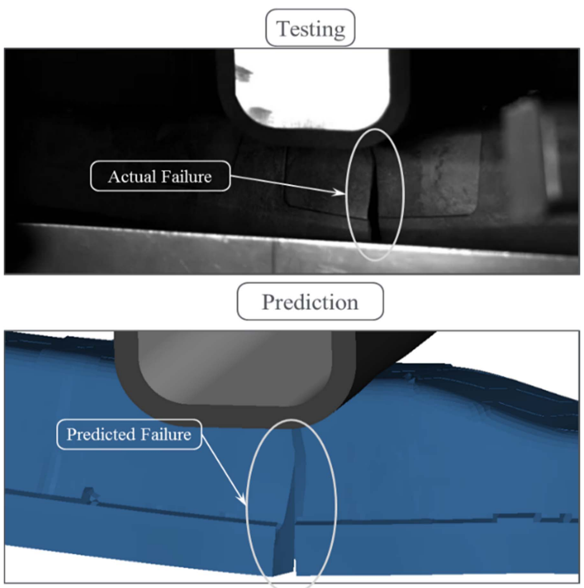

Figure 36. Failure modes and zones for all plastic insert. It is worth noting that the failure happens almost at the same region, and is always in tension.

Predicted location of failure is correlating reasonably well with actual failure location observed in the test for metal-plastic insert. Figure 38 shows predicted and tested failure location for the metal-plastic insert in three-point bending scenario.

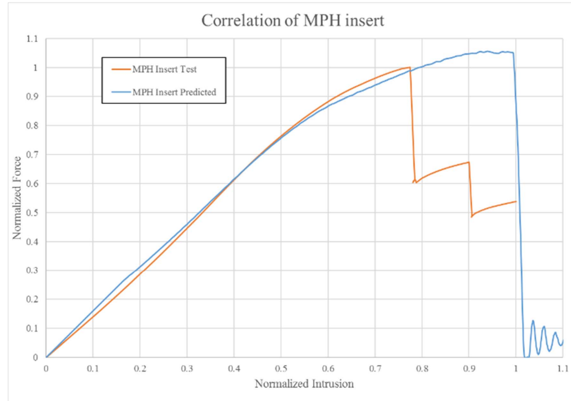

Figure 37. Predicted vs. experiment correlation for metal-plastic insert subjected to three-point bending. Failure prediction can be improved by improving the adhesion between metals and plastics in PMH.

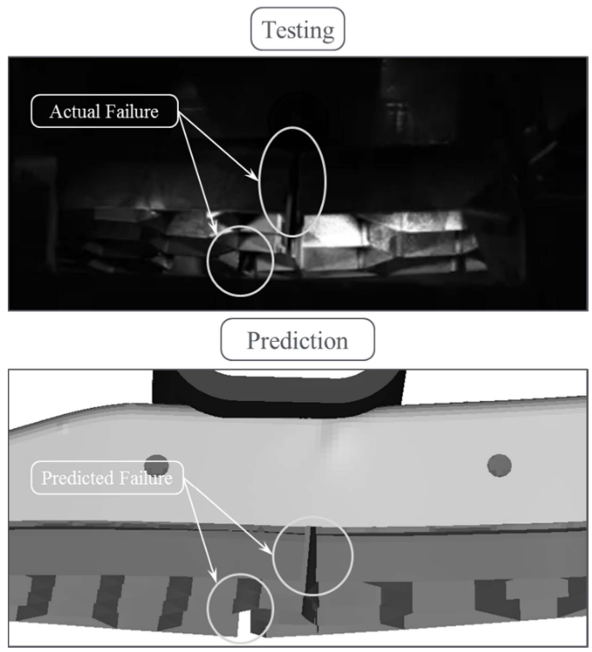

Figure 38. Failure zones for metal-plastic insert showed reasonable correlation between prediction and experiements.

CONCLUSIONS

This paper focused on the development of BIW reinforcement solutions using multi-material systems including engineering thermoplastic materials and metals. Various design and material configurations – including plastic and metal-plastic structural members – mounted on the BIW – are evaluated through CAE studies for various crash scenarios such as high-speed frontal crashes, side impact, pole impact and rollover. These CAE studies performed on a generic vehicle shows that up to 15 kg weight can be taken out by replacing four reinforcements from a midsize sedan weighing nearly 1070 kg. Approaches to correlate the CAE studies using component level testing and validation of generic reinforcements are also investigated. Data from all of this work indicate that the use of lighter metal-plastic BIW reinforcements can achieve significant weight reduction (up to 30%) in a vehicle, while also ensuring no compromise in crash performance. Further work can include detailed validation of component level high-speed tests, investigation of the assembly of proposed BIW reinforcements and their performance evaluation for secondary requirements such as NVH, creep, long-term durability and so on.

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ACKNOWLEDGMENTS

The authors would like to acknowledge National Crash Analysis Center at George Washington for providing FE model of the car model used in the paper. The car model, which is validated for most of the high-speed crash scenarios, is extensively used in this paper to demonstrate the concepts presented in the paper. Authors also would like thank various internal reviewers for providing valuable and constructive feedbacks about the manuscript for further improvement.