ANALYSIS AND OPTIMIZATION OF A POLYURETHANE MATRIX COMPOSITE AUTOMOTIVE DOOR.

Christos Derdas[1*], Georg Kaesmeier[2], Joern Holle[3], Georges Romanos[4], Frank Kerstan[5]

[1]Global Engineering Center, Henkel AG & Co KGaA, Gutenbergstraße 3 Garching, Germany
Email: christos.derdas@henkel.com, Web Page: http://www.henkel.com
[2]Forward Engineering GmbH, Infanteriestraße 19, Munich, Germany, Country
Email: kaesmeier@forward-engineering.com, Web Page: http://www.forward-engineering.com
[3]Forward Engineering GmbH, Infanteriestraße 19, Munich, Germany, Country
Email: holle@forward-engineering.com, Web Page: http://www.forward-engineering.com
[4]Global Engineering Center, Henkel AG & Co KGaA, Gutenbergstraße 3 Garching, Germany
Email: georges.romanos@henkel.com, Web Page: http://www.henkel.com
[5]Henkel AG & Co KGaA, Henkelstraße 67. Düsseldorf
Email: frank.kerstan@henkel.com, Web Page: http://www.henkel.com
*Corresponding author

Keywords: polyurethane, adhesives, automotive door, crash, lightweighting

Abstract

Mass production of composite automotive components represents one of the most important opportunities for lightweighting in the automotive industry. Towards this goal, polyurethane matrix resins are a very attractive candidate due to their low viscosity, snap-cure capability, and the increased fracture toughness and environmental resistance properties. This paper focusses on the application of engineering and more specifically CAE towards the optimization of a composite automotive door for the Roding Roadster, a small series production sports car manufactured by Roding Automobile GmbH. This paper will describe the modelling and optimization efforts conducted in order to achieve the required mechanical stiffness and intrusion resistance characteristics of such a door, during a common development project by Henkel AG & Co KGaA and Roding Automobile GmbH, which involves the use of a resin marketed by Henkel (Loctite® MAX 3 resin), along with composite CAE expertise. After the FE model description and the establishment of a baseline for the intrusion performance of the door, the design and optimization actions for the upgrade of the intrusion performance of the door at the minimal weight costs are presented.

1. Introduction

The current megatrend of sustainability in transport is creating significant momentum towards the adoption of lightweight materials in automotive structures. Of all the lightweight materials available to today's design engineer, composites are the one promising the highest specific properties and as such the highest subsequent weight reduction. This makes composite materials properties highly attractive to the automotive industry, especially since there is the drive to reduce CO2 emissions, which are directly linked to the weight of a vehicle. One of the main factors impeding the widespread adoption of composites in the automotive industry is the need to make manufacturing of composites compatible (in production rates and in price), with the requirements of the automotive industry.

Out of the multitude of processes available for composites manufacturing, the one that demonstrates most promise to achieve the production rates of the automotive industry is the process of High Pressure Resin Transfer Molding (HP-RTM). Keeping that in mind, Henkel AG& Co KGaA is marketing polyurethane resins which have been intelligently designed for HP-RTM. Apart from being designed

Excerpt from ISBN 978-3-00-053387-7

specifically for mass production, which requires low viscosities and very low curing times, the Loctite® MAX resins are also characterized by significantly high fracture toughness, making them an ideal matrix material for composite matrices.

In addition to the innovative Loctite® MAX resins, Henkel AG & Co KGaA, offers a significant portfolio of adhesives along with engineering capability, testing and prototyping facilities to customers. The engineering work involving an internal development projects named the "The Roding door project" is presented here, where Henkel's engineering capability is used to simulate and optimize an automotive door for the Roding Roadster.

In general, polyurethane resins have been studied in comparison to epoxies in [1], where among other conclusions, they have been found to provide higher ILSS properties than epoxies (67.2 MPa vs 48.1 MPa for polyurethane and epoxy respectively).

In terms of automotive doors, several optimization efforts have been published. In [2], the authors perform modelling of the FMVSS214 crash test and extract data of dummy mechanical loading useful for performing optimization studies in the design of a door's side impact beam. In [3], a multiobjective design optimization procedure is adopted to explore the static design of a door. Wu, Liang and Lee[4] , presented the optimization of side crash beams for doors using accelerated simulations of FMVSS-214S. Li and Belingrandi[5], performed a direct change-over of a steel door to composites, which lead to a 39% reduction.

In this paper, after the FE model description and the establishment of a baseline for the intrusion performance of the door, the design and optimization actions for the upgrade of the intrusion performance of the door at the minimal weight costs are presented.

2. Materials and methods

2.1. General Approach

In order to proceed with the optimization runs for the penetration resistance of the door, initially a *MAT_58 (MAT_LAMINATED_COMPOSITE_FABRIC) LS-DYNA 3D Input card has been calibrated. Afterwards, the input has been used to perform simulations of the FMVSS214S NTHSA test procedure. Conclusions are drawn on lamination seuqnce but also impact energy management systems present in the design of the door.

2.2. Materials

Initially prototype plates were manufactured in Henkel's High Pressure Resin Transfer Molding test facility in Heidelberg. The plates were manufactured, using the Loctite® MAX 3 Polyurethane resin, which is specially designed for this type of manufacturing process.

Two types of reinforcements were used for test plates. UD Zoltek PANEX35, 0/90 PANEX35 Chomarat Non crimp Fabrics. Nominal fiber volume fraction for all plates was 50%. Apart from the normal characterization tests (Tension 0 , Tension 90, Compression 0, Compression 90, Shear), an extra compression tests for a +-45 degrees laminates were conducted as part of the material characterization campaign. Additionally, for validation reasons, tests were conducted for a laminate sequence of $[0/90, \pm 45\ 0/90]_s$ .These tests were namely Open Hole Tension, Compression and ASTM D5379-type testing It should be mentioned here that the $[0/90, \pm 45\ 0/90]_s$ lamination sequence lies outside the scope of testing for the ASTM D5379 test standard. However, it was conducted in order to provide some validation against shear-like loads.

Excerpt from ISBN 978-3-00-053387-7

2.3. Methods

To perform the analysis of the FMVSS214S model, initially the parameters for a *MAT_58 material card for the aforementioned composite were validated through FE models. In this paper just the most important elements of the validation will be presented for reasons of brevity.

2.3.1 *MAT_58 (*MAT_LAMINATED_COMPOSITE_FABRIC) calibration process description

*MAT_58 is a well-documented material model used for simulating composite failure under impact and impact-like phenomena. In [6], one can find the whole set of parameters required for implementation of the material model in an Finite Element Analysis. At the same time, in [7] one can find a comparison between different material models, associated with composites in LS-DYNA and the capabilities inherent in each. Of the whole parameter set –and assuming a shell element model is used-, the ones that would require accurate evaluation would be SC (which is the true shear strength), ERODS (which is a parameter used for book-keeping purposes) and the post compressive failure residual stress levels.

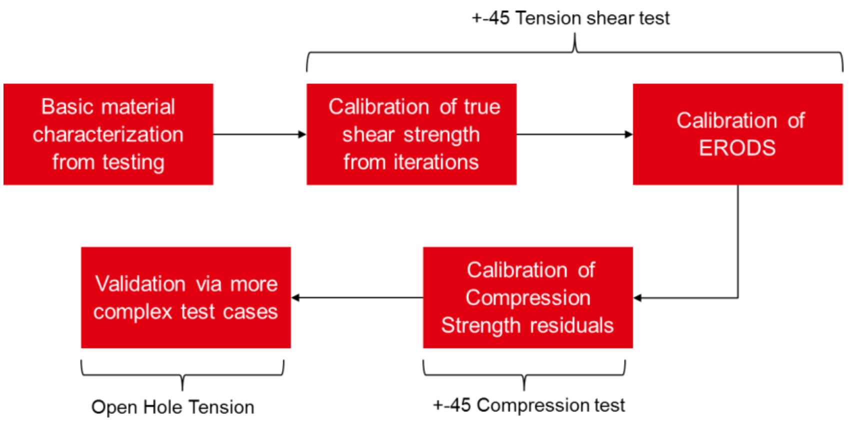

Figure 1: Method graphical description

2.4 The Roding Automobile Door

In order to develop engineering capability and to gain a better understanding of the requirements, needs and pain points of customers duringthe design of composite automotive structures, Henkel AG&Co KGaA, has internally initiated a project involving the design, analysis, optimization and manufacturing of a prototype door for the Roding Roadster. The prototype, using the mass production HP-RTM suited Loctite® MAX 3 resin, has been exhibited in JEC World 2016. Here, some engineering aspects of the project are being documented.

The Roding Roadster's door design used is based upon a two shell concept : the inner and outer door shells which are bonded together using the Loctite® UK 2015 adhesive. The initial design of the door contains a high strength steel tubular beam which acts as the loadpath for transferring frontal crash loads and at the same time is a side impact protection passive safety element. Additionally, for the lower hinge, a reinforcement element takes up the role of spreading hinge loads to the whole inner shell (Figure 2).

The composite shells have a laminate sequence of [0 0 45 90]. The reinforcement is comprised from biaxial (0/90) NCF fabrics, manufactured using Zoltek PANEX35 fibers. Different areal weight fabrics are used throughout the laminate sequence, giving a final thickness of 2mm. The area around the door

Excerpt from ISBN 978-3-00-053387-7

latch is reinforced with extra fabrics and has a thickness of 3.2 mm, with a laminate sequence of [0 0 45 90 45 0].

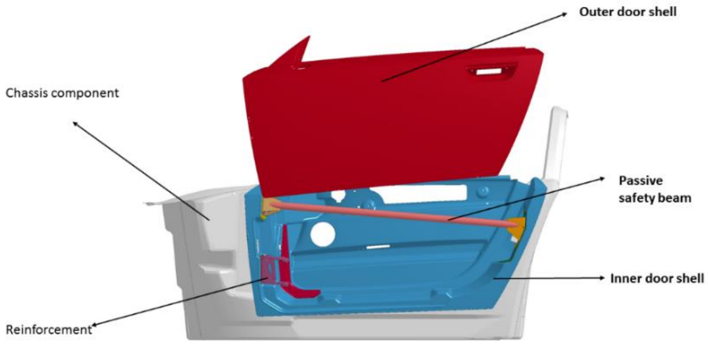

Figure 2: Components of the door design

2.4.1 Engineering Objective

The engineering objective of the project is to produce a design of a door that would comply to safety requirements for a mass produced automobile. In order to achieve this, one of the load cases taken into account –and being the focus of this paper- is the FMVSS214S[8] test, using LS-DYNA analysis. One of the advantages –in terms of modelling - of the FMVSS214S is that it does not require, the use of a whole car FE model, as opposed to actual side impact load cases, which need to take into account the whole chassis structure in order to produce results that would be useful for conclusions extraction. Of course all design iterations considered, easily surpassed static requirements like door sag, oil canning or eigenfrequency.

2.4.2 FMVSS214S (static) test

The FMVSS214S requirement involves a steel cylinder with a diameter of 304.8 mm(12 inches) moving at a constant velocity towards the door. Intrusion force measurements are extracted and the standard requires that at 152 mm of intrusion, the intrusion force should exceed 10000N, at 304 mm of intrusion, the intrusion force should exceed 16000N and at 457 mm of intrusion the intrusion force should exceed 37000N. The 457 mm intrusion needs to occur at a time of 0.080 sec. The test is not a crash test per se, however it represents a formidable challenge for the side crash energy management systems of an automotive door. It was judged that for assessing the door structural performance, the first two test requirement points were sufficient. Further optimization needs may occur for the third requirements point, however they would involve minor laminate modifications, like reinforcement of the crash element attachment points, or small changes in the way the crash elements interface with the inner shell.

2.5 Finite Element Model

In order to proceed with the FE analysis of the door, a Finite Element model for LS-DYNA 3D has been developed. The inner and outer shells, where modelled using reduced integration shell elements with a side length of 4 mm. Material model employed was *MAT_58.

Excerpt from ISBN 978-3-00-053387-7

The adhesive joint between two shells (inner and outer) was modelled using a cohesive contact interface (*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK). The mechanical behavior of Loctite® UK 2015 was derived from mechanical testing and implemented as cohesive fracture parameters in the model. Steel components like the connectors between the steel crash element and the inner door shells, were modelled using solid elements. The material model used was *MAT_3 (*MAT_PLASTIC_KINEMATIC). For the baseline assessment, the crash element was modelled using solid elements. Due to its geometry, the re-designed crash element, was modelled using shell elementsThe FMVSS214-S intrusion device and the chassis components were modelled as rigid, so as to reduce computational costs (Figure 3).

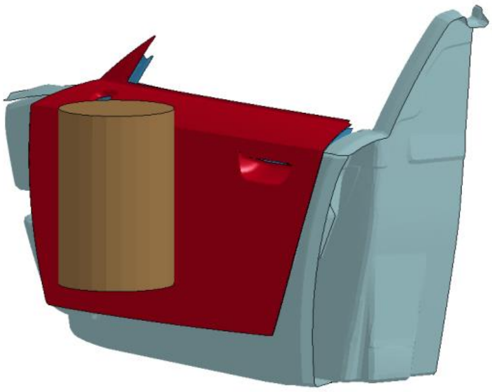

Figure 3: FMVSS214S model

3. Results & Discussion

3.1 Validation results

The shear test standard used for deriving shear properties for the composite material used in the door, was DIN EN ISO 14129, which essentially employs the ±45 degrees tension method for deriving shear behavior. Apart from the stress which is corresponding to 5% shear strain (and which is classified according to the standard to be the measured shear strength), the maximum engineering shear stress was also extracted. Since *MAT_58, incorporates provisions for non-linear shear behavior, The 5% shear strength was used as the limit for non-linearity and the true shear strength was iterated in order to capture the experiment's engineering (measured) shear stress levels. It should be noted here that ,as expected, FE analysis input should be true (logarithmic) stresses. This sometimes is either overlooked in materials with small plastic regions. In other cases , this requirement is covered by using the well known ture stress-true strain transformation formulas, which are valid only for small strains. Since this does not apply for the ultimate (post failure) shear strain. The ultimate shear stress (SC) was needed to be iterated, until the maximum force reached the maximum values attained by testing. The material models validation results are briefly presented in Table 1.

Table 1: Comparison of results vs experiments for FE modeling

Test case	FE Model (MPa)	Experimental (MPa)	Variation (%)
Open Hole Tension	316	343	7.87%
Iosipescu	150	141	-5.81%
Compression	565	540	-4.63%

Excerpt from ISBN 978-3-00-053387-7

As it can be seen, the differences are not significant between FE analysis and experiments. Maximum variation occurs for the Open Hole tension specimen, where higher discrepancies would be expected, since, apart from the expected in-plane failures, delaminations can also be expected. Failure modes predicted by Finite Element Modelling were consistent throughout the models.

3.2 Door Intrusion analysis and optimization

3.2.1 Door intrusion- Initial Design

The initial design of the Roding Automobile Door includes an almost horizontal crash bar (named passive safety bar), designed to act as both a loadpath for frontal crash loads and at the same time to act as an intrusion prevention member. Additionally, a reinforcement exists in the bottom side of the door, essentially structurally connection the lower hinge area with a reinforced laminate area. Figure 3 points out these design features.

The results from the base analysis of the FMVSS214S test, up to the intrusion level of 304 mm is provided in Figure 4

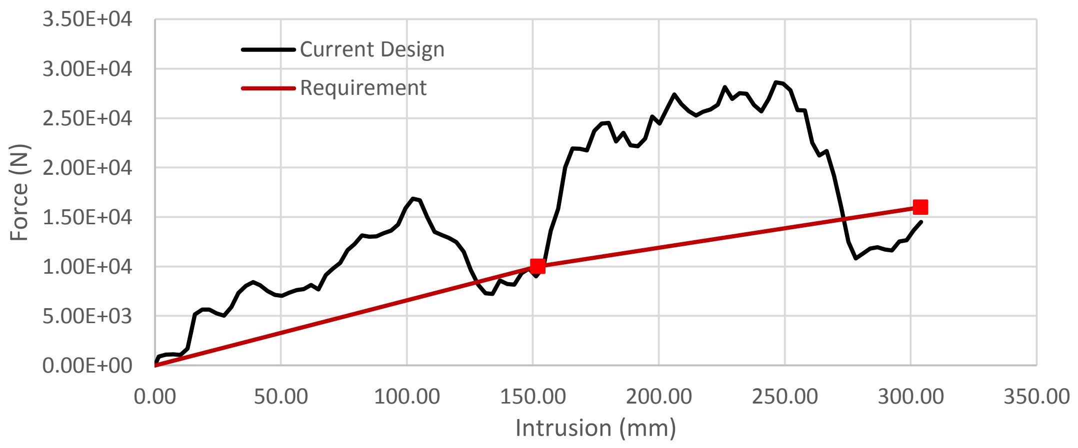

Figure 4: Force Displacement Profile of the FMVSS214S model

As it can be seen from Figure 4, the target intrusion force levels requirements (10 KN @ 152 mm intrusion and 16 KN @ 304 mm intrusion, are not met. Further, there appears some damage on the composite outer shell essentially exposing the crash element to the intrusion device.(Figure 5). This exposure of the crash element to the intrusion device, plays a detrimental role, since it concentrates forces on a small length of the crash element, instraed of spreading them, and of course significantly loads -up to failure- the interface components of the crash element to the inner shell.

Excerpt from ISBN 978-3-00-053387-7

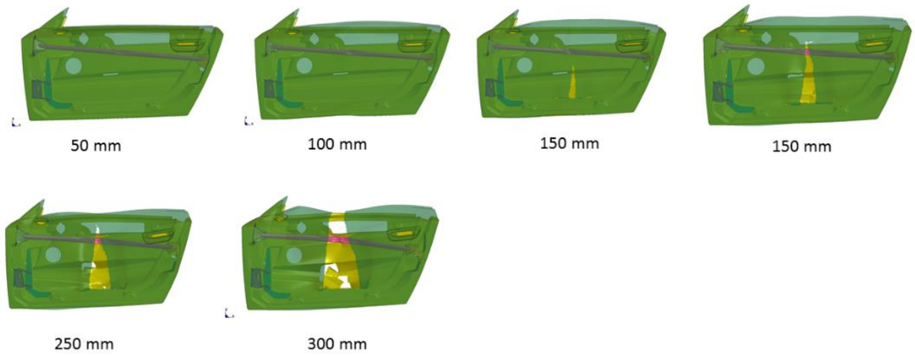

Figure 5 Timeline of the model

In order to cover for the requirements, the option of investigating a new redesigned passive safety structure, which would provide advanced intrusion protection at the minimum possible weight penalty, was followed.

3.2.2 Door intrusion- Redesign

For the redesigned passive safety configuration, two design principles were considered:

- Utilization of both hinges as structural connections of the crash element to the inner and outer door shells.
- Use of a larger contact surface area between the loading apparatus and the crash element.

This has led to the design of a new steel crash element which is depicted in Figure 6, along with its assembly inside the door. The thickness of the new bar was set to 1mm, in order to retain added weight penalty to a minimum. Two design iterations were analyzed: One with the old lamination sequence and the redesigned crash element (A1), and one exploiting both the redesigned crash element and a new laminate sequence, namely a [0 45 45 90] (A2).

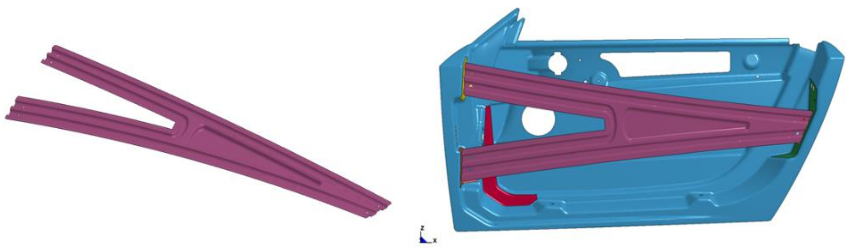

Figure 6: Door redesign

Figure 7, presents the force vs intrusion profile for the new designs in comparison to the old ones.

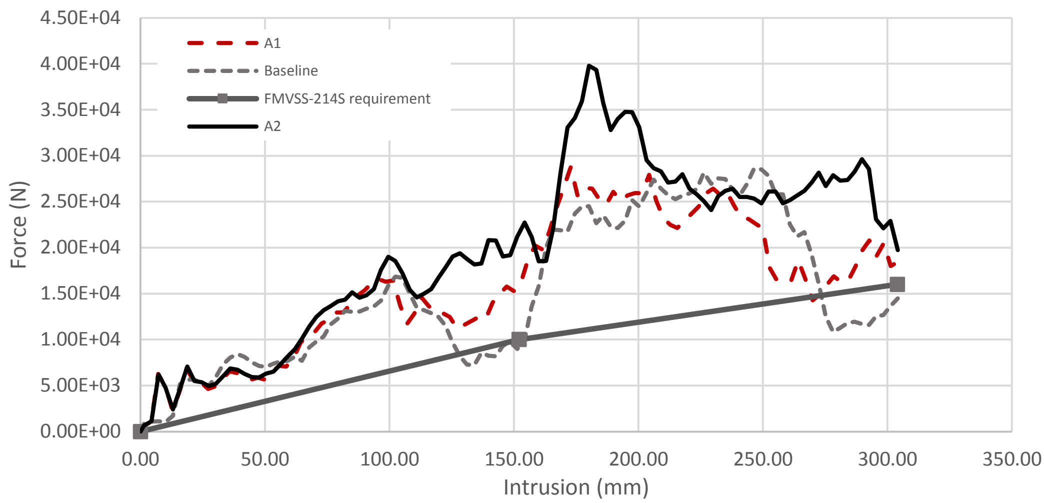

Figure 7: Force intrusion profile

As it can be seen, both new designs surpass the requirements set by FMVSS214S. Forces at the requirements intrusion levels are reported in Figure 8.

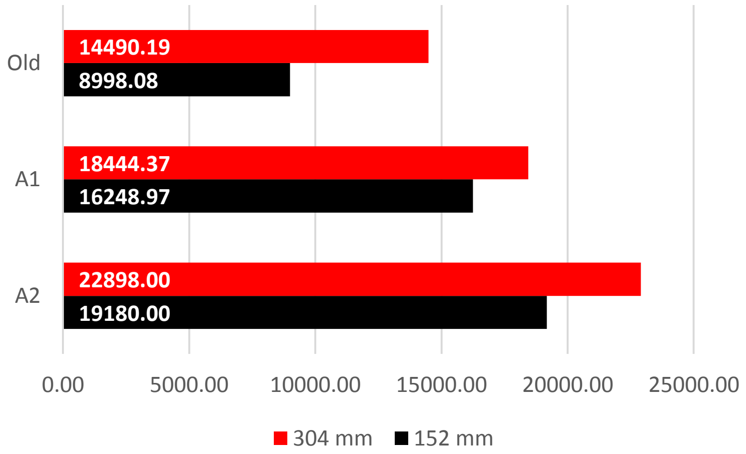

Figure 8: Maximum Forces at 152 and 304 mm intrusion

The use of a more compliant laminate plays a positive role in the intrusion resistance of the door. This is due to the fact that the outer shell laminate of A2, permits higher deflections before failure in comparison to boththe baseline's and design option's A1. This essentially allows for the adhesive of the two shells to fail more extensively before the laminate itself fails (keeping in mind that Loctite® UK 2015 is a high strength and high elongation adhesive with a 100% failure strain, especially designed for multimaterial and composites bonding). Figure 9, outlines the deleted elements for all three cases on the two shells of the door.

Excerpt from ISBN 978-3-00-053387-7

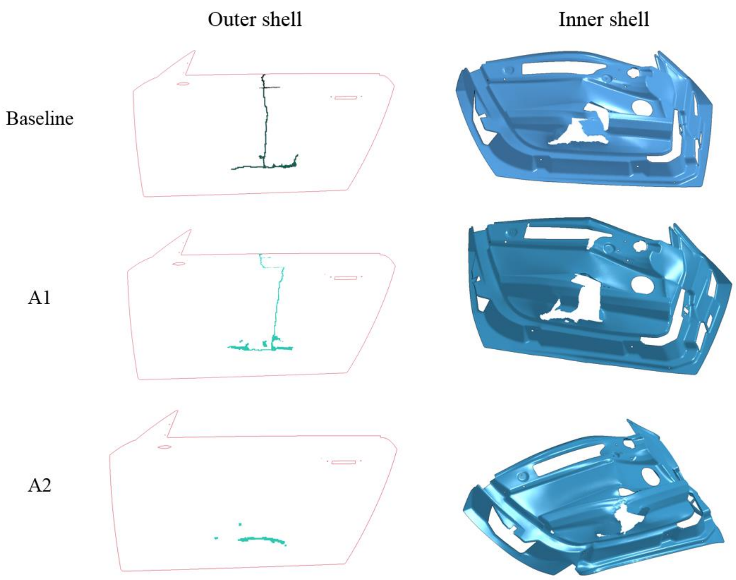

Figure 9: Inner and outer shell of design cases

The deleted elements from the outer shell in the case of A2 are reserved near the lower edge of the cylinder, while in the other two cases, a tear occurs in the middle of the outer shell, along the line of contact between intrusion device and door. In case A2, the laminate is more compliant, and as such it can exhibit higher relative displacements in relation to the inner shell. This leads to essentially debonding failure between the two shells (inner and outer) and the warpage of the outer shell around the cylinder. Due to this reason, it becomes significantly more difficult to break open the outer shell, which continues to transmit forces more uniformly to the crash element, delaying even further damage (in the form of plastic deformation/erosion) to the components that structurally interface the crash element to the inner shell. This is significantly made apparent in the case of the latch structural connection, as presented in Figure 9, where with teal color, the failed elements are presented at an intrusion depth of 304 mm.

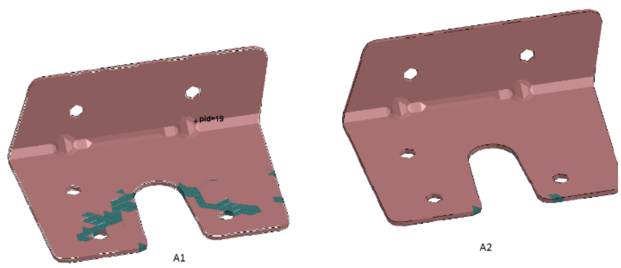

Figure 10: Latch reinforcement at 304 mm intrusion. Teal elements are the failed ones

The weight associated with each design option is presented in Table 2. As it can be seen, the total weight penalty, is just 320gr for a significant intrusion protection capability increase. As only the lamination sequence changes between A1&A2, and the shells are identical with the baseline case, the only mass increase occurs due to the change of interfaces and crash element.

Excerpt from ISBN 978-3-00-053387-7

Table 2: Mass balance of design options

	Baseline	A1&A2
Crash element (Kg)	1.15	1.94
Adaptors (Kg)	0.40	0.42
Hinge Reinforcement (Kg)	0.49	-
Total (Kg)	**2.04**	**2.36**

4. Conclusions

The present paper outlines -within the confines of available space – part of the optimization work conducted for the crash structure of an already lightweight composite automotive door. The FMVSS214S static intrusion test was used as the load case for judging designs, since it permits separate optimization of the door crash structure. As expected, it has been shown that the design of the laminate, along with the design of the crash structure, can provide significant improvements to the intrusion behavior of the door at minimal weight penalties. Even on an established design, significant optimisations can take place by simply tailoring composite properties at minimal or zero weight penalties.

In general, during the culture shift that is occurring towards composites and material-agnostic design thinking for the automotive industry, the presence of engineering capability can prove crucial in the reduction of costs and the quick proliferation of composites within the sector.

References

[1] Swentek, B. Beck, T. Potyra, V. Ugresic, F. Henning, Impact of HP-RTM process parameters on mechanical properties using epoxy and polyurethane, Proceeding of the 2015 Society of Plastics Engineers, Automotive composites and Conference Exhibition

[2] T.L. Teng, K.C. Chang and T.H. Nguyen, Crashworthiness Evaluation of Side-Door Beam of vehicle, Technische Mechanik, 28, 3-4,268-278, 2007.

[3] Jianguang Fanga, Yunkai Gao, Guangyong Sun, , Qing Li, Multiobjective reliability-based optimization for design of a vehicle door, Finite Elements in Analysis and Design Volume 67, May 2013, Pages 13–21

[4] Wu, C., Liang, C., and Lee, J., Optimization of Side Impact Bar for Crashworthiness," SAE Technical Paper 2006-01-0245, 2006.

[5] J. Ji, G. Belingardi, Crashworthiness evaluation of composite vehicle side door based on dummy response, 43th Convegno Nazionale, Bologna, September 9-12 2014.

[6] *LSTC.* "LS-DYNA Keyword User's Manual, Volume 2" *(PDF). Livermore Software Technology Corporation (LSTC).*

[7] C. Derdas, M. Jevons, Impact validation and simulation of composite aerofoil structures, Proceedings of the 16th European Conference for Composite Materials, Seville, June, 22-26 2014

[8] NHTSA, National Highway Traffic Safety Administration laboratory test procedure for FMVSS 214s (static), Side Impact Protection, 1992, Retrieved from *www.nhtsa.gov*

Excerpt from ISBN 978-3-00-053387-7