SIMULATION CHAIN FOR METAL-CFRP SANDWICH MATERIALS IN THE DEVELOPMENT PROCESS OF AN AUTOMOTIVE FLOOR STRUCTURE

T. Schulte[1], S. Wiedemann[2], M. Gerkens[3], C. Schmal[3], C. Paul[4], L. Eckstein[1], F. Meissen[2] and G. Meschut[3]

[1]Institute for Automotive Engineering, RWTH Aachen University, Germany
Email: schulte@ika.rwth-aachen.de, Web Page: http://www.ika.rwth-aachen.de
[2]Innovationsgesellschaft für fortgeschrittene Produktionssysteme in der Fahrzeugindustrie mbH, Steinplatz 2, 10623 Berlin, Germany
Email: wiedemann@inpro.de, meissen@inpro.de, Web Page: http://www.inpro.de
[3]Laboratory for material and joining technology, University of Paderborn, Germany
Email: Gerson.Meschut@lwf.upb.de, Christopher.Schmal@lwf.upb.de, Michael.Gerkens@lwf.upb.de, Web Page: http://www.lwf.upb.de
[4]thyssenkrupp AG, TechCenter Carbon Composites, Frankenring 1, Kesselsdorf, Germany
Email: christian.paul4@thyssenkrupp.com, Web Page: http://www.thyssenkrupp.com

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Abstract

In this paper simulation models for novel steel-CFRP and magnesium-CFRP sandwich materials with thermoplastic matrix are being presented. The models cover the effect of cooling in the production of the materials, the forming, the joining and finally the crash simulations of a full vehicle model. By comparison of simulation results with a range of physical tests the models are being calibrated. The combination of the simulations is then used to develop a lightweight automotive floor structure made of metal-CFRP-sandwich materials fulfilling passenger and battery safety requirements. The current weight saving amounts to over 20 % compared to a lightweight steel counterpart.

1. Steel- and Magnesium-CFRP Sandwich Materials

The project LEIKA is funded by the German Federal Ministry of Education and Research (BMBF) and targets the production and application of innovative metal-carbon fibre reinforced thermoplastics sandwich materials in the automotive sector. One of the advantages of these sandwich materials, compared to other sandwich materials already known in other industries (e.g., aerospace), is the processing. The sandwich materials discussed are produced as semi-finished products which can, to some extent, be treated similar to conventional metal sheets in manufacturing steps e.g. forming and joining.

The manufacturing of the sandwich materials and the floor structure is discussed by Wollmann et al. in [1]. Although a large variety of material and stacking combinations is possible using the chosen production process, this paper is focussed on two sandwich materials. The first consists of steel with a thickness of 0.25 mm as cover layers and a 1.5 mm thick carbon fibre reinforced thermoplastic (CFRP) as core layer summing up to 2.0 mm material thickness. Polyamide 6 is used as matrix material. The second sandwich material consists of a thinner CFRP core layer with 0.7 mm. As cover layer magnesium sheets with a thickness of 1.0 mm are used.

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The lightweight potential and processability of the new materials are demonstrated via the development of an automotive floor structure within a reference vehicle with hybrid drive, see Figure 1. The centre tunnel and lower longitudinal members made of steel-CFRP sandwich are combined in one component and stiffened by glass fibre reinforced overmoulding (PA6-GF30). The steel sandwich material was also used in bulkhead plates not illustrated in the figure to prevent intrusions into the battery compartment. Magnesium-CFRP is applied in the seat cross members and an underbody panel. The frontal part of the tunnel is made out of CFRP-Magnesium-CFRP sandwich material.

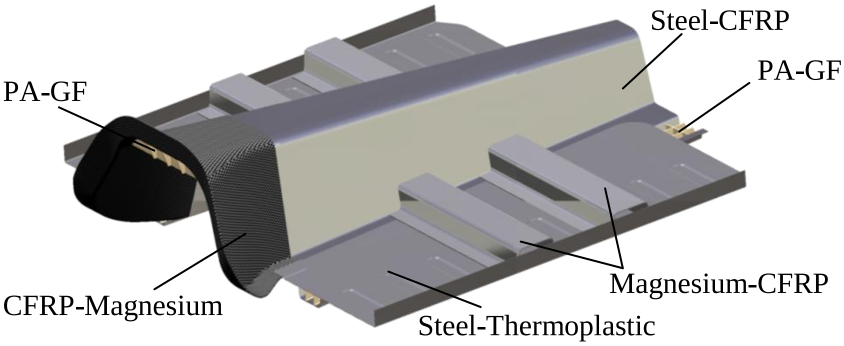

Figure 1. Automotive floor structure made out of several sandwich materials.

For the virtual safeguarding of structures made of the LEIKA materials, new simulation models for forming, the joint and crash behaviour are needed. Especially, the interaction between these disciplines is of interest as the production processes and joints highly influence the crash behaviour and structural properties of the discussed sandwich materials.

To cover these effects in the virtual dimensioning and design of the structural component a simulation chain is defined. The chain starts with the simulation of hot forming of the sandwich material sheets followed by a cooling simulation. The resulting residual stresses in metal and CFRP layers are simplified and included in the material models for the full vehicle crash simulation. Also simulation models for the joining technologies are added. The results of the crash simulations are used to derive design changes and altered joint positions to meet the safety requirements. However, these changes make it necessary to reevaluate the forming and cooling simulations and the joint concept.
The simulation methods for forming and cooling are covered in Chapter 2. Chapter 3 discusses the selection and simulation models of the joining techniques. In Chapter 4 crash simulation models are presented and the crash performance of the sandwich materials in an automotive floor structure is shown.

2. Forming and Cooling Simulation

The development of a simulation of the forming process is a necessary part of the numerical safeguarding of the manufacturing process for parts made of the metal-CFRP sandwich material. Furthermore, the prediction of the properties that are required for structural simulations is an important result of the forming simulation. The modeling of the forming process and the mapping of the results to structural simulations are developed at inpro.

A correct modelling of the forming process has to consider the different behaviour of the used materials. On the one hand, metals show plastic deformations allowing it to undergo large elongations. On the other hand, the in-plane shear deformation is the predominant mode of the continuous fibre

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reinforced core layer which only admits minor strains in fibre direction. Another difficulty is the stable contact modelling between all the layers and the tool.

For the simulation of the forming process, the explicit solver PAM-FORM is used since it allows the combination of traditional deep drawing, hot forming and draping of thermoplastic continuous fibre reinforced polymers. Especially, PAM-FORM provides a sophisticated homogenized material model for the CFRP and a stable contact algorithm.

Each layer (including the plies in the CFRP core) of the sandwich is represented by an individual shell mesh interacting with each other through a contact formulation (see Figure 2). The tangential movement of the layers is restricted by friction while an adhesive force in the normal direction prevents the layers from separating up to a certain separation stress.

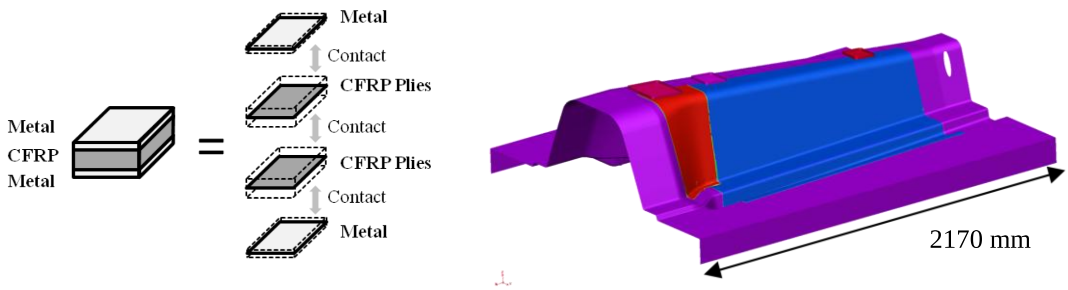

Figure 2. Modelling of the metal-CFRP sandwich material (left) and results of the forming simulation of the floor structure's central tunnel (right). The blue blank is a steel-CFRP and the red blank is a CFRP-magnesium-CFRP sandwich. Only the lower tool half (purple) and blank holders are depicted.

Another important aspect of the manufacturing process of metal-CFRP sandwich materials is the influence of the different thermal behaviour of the materials. The CFRP core layer does show a spring-forward at corners after cooling [2] whereas the metal layer does not. The metal layer rather has a spring-back effect after forming. Moreover, the materials have different coefficients of thermal expansion (CTE). These differences can result in thermally induced stresses which start to build up when the thermoplastic matrix in the core cools down below its crystallisation temperature. The stresses do influence not only the final shape of the manufactured parts but also their mechanical behaviour when they remain as residual stresses.

The simulation of the cooling after forming is modelled in Abaqus. The spring forward behaviour of the CFRP core is the result of different in-plane and out-of-plane CTEs. This behaviour is usually not included in standard shell models present in commercial finite element software. In order to model this behaviour a special material model for Abaqus has been developed at inpro.

The residual stresses from the forming simulation in the metal sheets are mapped from the PAM-FORM results to the cooling model. The stresses due to different CTEs are estimated by homo-genously cooling a whole part from crystallisation temperature to room temperature. This approach is also possible for the simulation of assemblies. In this case, the formed parts are initialized with the forming results within a model of the whole assembly. Next, only the parts that experience a thermal change after manufacturing, i.e., the sandwich material and injection molded parts, are cooled down within the assembly.

The influence of the manufacturing process on the mechanical behaviour of the material already becomes obvious for a simple tensile coupon test. The test specimen was cut out of the semi-finished laminate sheet. Due to the different CTEs, the cooling of the consolidated laminate results in residual

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stresses. Note, that no spring-forward effect is expected due to the flat geometry of the test specimen. The tensile tests were conducted at the Institute of Lightweight Engineering and Polymer Technology (ILK) of TU Dresden and are used to calibrate the modelling of the crash behaviour of the material.

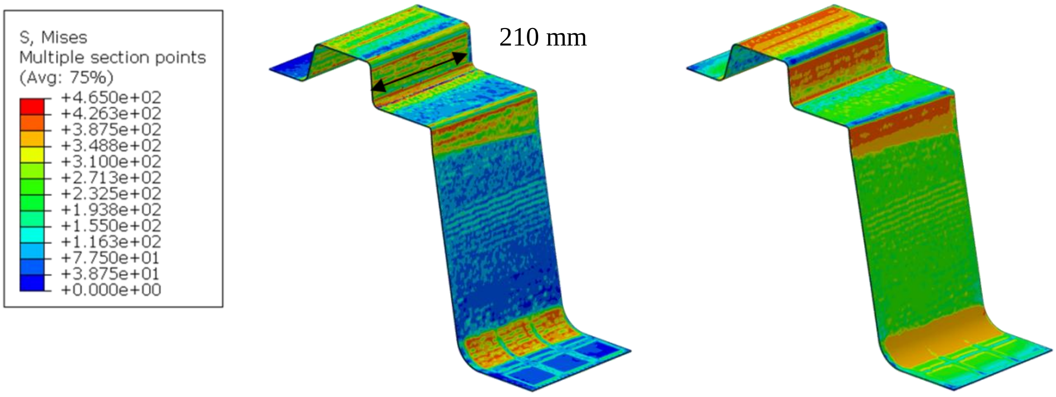

Figure 3. Initial residual stresses after forming (left) and after cooling (right) for a central tunnel test part manufactured at Kirchhoff Automotive using symmetric boundary conditions in the simulation.

Since no spring-forward must be modelled, the numerical simulation of the cooling process and the tensile test are both done in LS-DYNA and based on the crash simulation model. Thus, it is possible to directly use the results of the production simulation as initial values for the coupon test simulation. The material data of the components is based on already available data sheets and generic material constants. The simulation is closer to the experimental results when the production history is considered, see Figure 4.

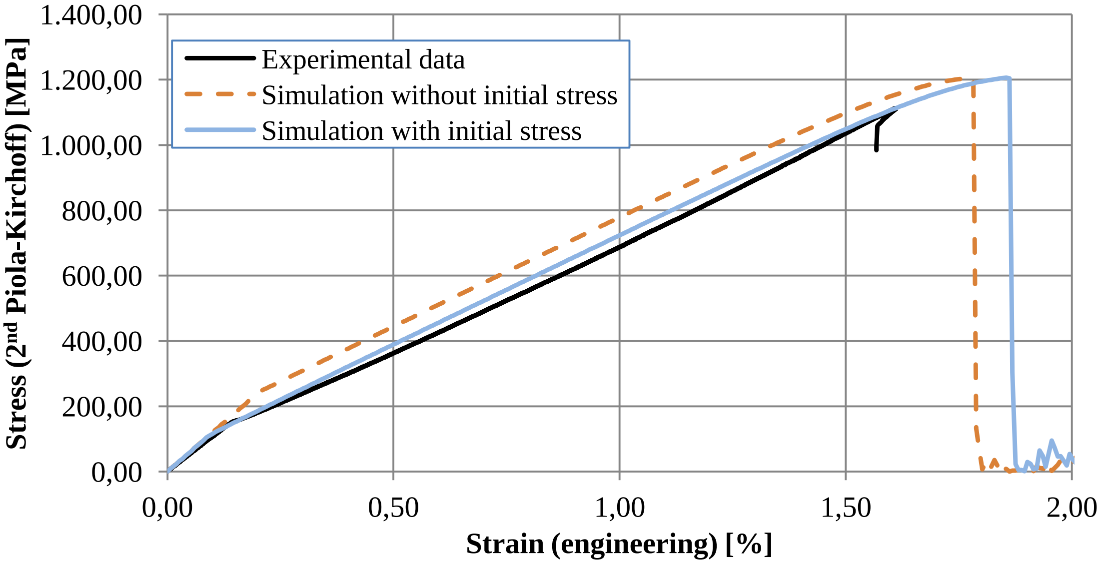

Figure 4. The plot shows the stress-vs.-strain curves for simulations with and without production history and the experimental data for a tensile test.

In a next step, it is planned to implement a mapping tool that enables the use of the residual stresses computed with the cooling simulation in Abaqus as initial values for the crash simulation of the floor structure in LS-DYNA.

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3. Adhesives and Mechanical Joining

The use of sandwich materials in the field of automotive mass production provides special technological and economic requirements on joining technologies. Modern body structures are joined by hybrid joining methods. In LEIKA, both, structural epoxy-adhesives and semi-structural polyurethane-adhesives are used. The fixing, which is necessary for the handling strength in the production process, is carried out through blind rivets within the floor structure and resistance element welding for the interface of the floor structure to the surrounding car structure (not nearer focused within this paper).

The analysis of materials and the analysis of the assembly sequence of the LEIKA floor structure (see Figure 1) leaded to very different joining tasks. Thus the sandwich materials with steel- and magnesium-cover layers must be joined with each other, with steels of different strength classes respectively with LITECOR®. Due to the risk of an exposure of the carbon fibres, a damage of the composite material and also the risk of a contaminated cataphoretic dip coating bath, the LEIKA sandwich materials with CFRP cores lead to high challenges concerning the joining technology.

The magnesium components must not be carried out together with the steel parts through the cataphoretic dip coating. This is an important constraint in manufacturing. Thus, the magnesium components are coated separately and are integrated into a “cold” structure. The analysis shows, that it must be assumed a large difference in thermal expansion in the steel and magnesium components, considering, in particular the fibre orientation. This Delta-Alpha ratios cause large expansions or relative displacements in the cataphoretic dip coating process (drying oven 180 °C). The resulting shear for the adhesive can be critical under certain circumstances, especially in high-modulus and high-strength epoxy adhesives with typical adhesive layer thicknesses in the range of 0.3 mm. A 2-K polyurethane adhesive applied with a layer thickness of 1.0 mm reduces the effective shear angle, helps to compensate tolerances between the components and thus represents a suitable compromise. In the LEIKA-floor structure, the compounds between the steel sandwich and the steel components, which are having the structural EP adhesive DOW Betamate 1496v, be used in a layer thickness of 0.3 mm. This is widely used in body construction, forms a stiff and high-strength compound and is also suitable for cataphoretic dip coating. With the joining tasks, involving the magnesium sandwiches, the semi-structural DOW BF 9050 is used with a layer thickness of 1.0 mm. The seat cross member is a structural component in the floor structure. Therefore, the bonded joint is to be interpreted regarding to static stiffness and crash behaviour. The selected PU adhesive BF 9050 (see Figure 5) has significantly higher stiffness and strength than conventional assembly adhesives (e.g., BF2850) and thus represents a good compromise between stiffness (e.g., BM2098 with much higher stiffness) and deformation capacity.

Regarding to handle stability strength during the production process, punctual fixings are required. Hence punctual fixings protect the adhesive bonding against unfavourable peeling stresses. Therefore, punctual fixations in form of mechanical joining methods are used in the body construction. In the LEIKA floor structure blind rivets are used, since these generate a very good clamping force (even in sandwich materials), hardly damage the laminate and also do not expose any carbon fibre.

For the simulation of the floor structure, the joining elements must be strictly considered. LS-DYNA will be used as simulation code. For the adhesives (see Figure 6) the new *MAT_TOUGHENED_ADHESIVE_POLYMER (TAPO/MAT252) model is used and for the blind rivets the simple analogous model *MAT_SPOTWELD_DAMAGE-FAILURE (MAT100).

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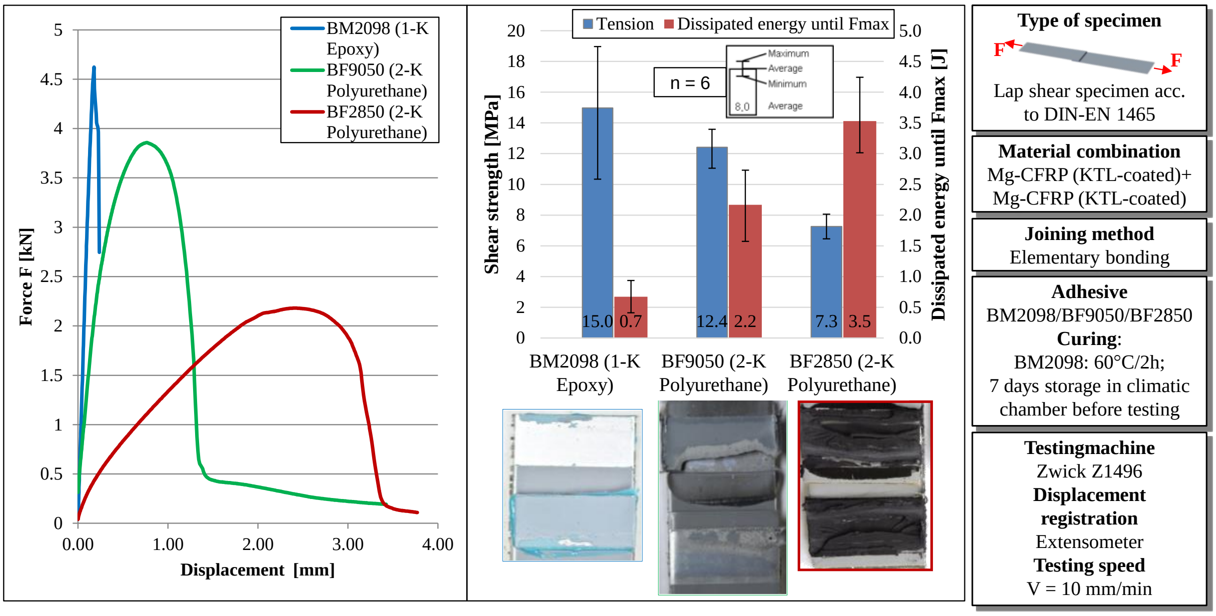

Figure 5. Force-displacement diagrams, shear strength and dissipated energy in the bar chart for lap shear tests bonded with epoxy (BF2098-blue, layer thickness: 0,3mm) and polyurethane (BF9050-green & BF2850-red, layer thicknesses: 1,0mm) adhesives under quasistatic testing speed

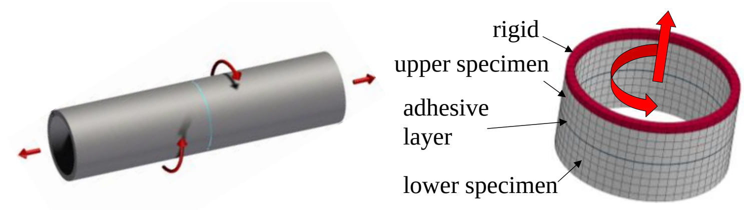

Figure 6. Parameter identification on standardised tube specimens with combined tensile and shear loading

The TAPO (Toughened Adhesive Polymer) model is an elasto-viscoplasticity material model for ductile modified high-strength adhesives, which has been developed at the Institute of Mechanics of the University of Kassel. It became available since LS-DYNA R7.1.1. and can be used with solid elements or with cohesive elements in combination with *MAT_ADD_COHESIVE. The theoretical structure is based on continuum and damage mechanics in order to predict the complex mechanical behaviour of crash optimized high-strength adhesives under combined shear and tensile loading. It comprises a yield function depending on the first invariant of the stress tensor and the second one of its deviator as well as a non-associated plastic flow rule. In addition, a nonlinear hardening enlarges the yield stress as a function of the effective plastic strain. The rate dependency and the damage evolution are in accordance with the Johnson-Cook Model. Consequently, the mechanical behaviour of structural adhesives is predicted sufficiently well, which is demonstrated by means of various simulations of specimens and components with adhesive joints under quasi-static and crash loading conditions [3-5].

Initially a very simplified failure criterion was chosen based on the maximum and shear or pull-out tension to take the blind rivets in the crash simulation of LEIKA-floor structure into account. Both load directions are combined via a quadratic approach in MAT100. That way critical flange sections can be identified in the simulation. The challenge in equivalent modelling of the blind rivet connections is the mode of failure. The joining element does not always fail, but rather an adherent failure occurs in certain types of loading and material combination. Thus, a custom equivalent model

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must be parameterized for each material combination in each direction. In the further course of the LEIKA project the semi-structural polyurethane adhesive is more extensively characterized and derived on an equivalent model based on the TAPO model. Furthermore, the blind rivets will be investigated with different material combinations, load directions and speeds. The results are used to parameterise equivalent models. The equivalent models of the adhesives and the blind rivets are used in crash simulation.

4. Crash Simulation and Development of Floor Structure

In general, layered materials can be modelled using a stacked solid, a stacked shell or a layered shell approach [6]. In the present project a stacked shell approach is being chosen to achieve a trade-off between computation time, meshing effort and necessary failure modes. Between three shell layers, each representing an individual material, cohesive zones are inserted to model the interface and possible delamination between metal and CFRP. The following simulations were carried out at Institute for Automotive Engineering of RWTH Aachen University (ika) in the finite element solver LS-DYNA R8.0 with Belytschko-Leviathan shell element formulation to include a physically based hourglass control [7]. For the cohesive elements material model 138 is being used which includes a bilinear traction-separation law for normal and shear loads. An average element size of 5 mm enables the usage of an identical mesh from coupon level to full vehicle crash simulations.

For the thin steel sheets a planar anisotropic material model is being selected based on the assumptions made by Hill (material model 122). Material model 124 is an appropriate representation for the magnesium sheets, since the difference in plastic behaviour on traction and compression loads supersedes the anisotropy. For the CFRP core layer material model 58 is being used. These models were calibrated using tension and bending tests on coupon level in various material directions. The same was done for the sandwich materials whereby the residual stress induced by the production process of the layered material had to be taken into account. Thus, the stiffness of the CFRP was reduced by approximately 20 % and the yield points of steel and magnesium were reduced by 5 %. For the next step in the sandwich material model calibration, omega shaped profiles were manufactured and tested under quasi-static and dynamic loads. The quasi-static bending and compression tests of the profiles were done at Kirchhoff Automotive Deutschland GmbH, the dynamic counterparts were carried out at the ILK of TU Dresden.

In Figure 7 (left) a comparison between test results and two simulation approaches of a steel-CFRP sandwich profile under quasi-static bending load is shown to illustrate the current quality of the simulation models. By using layered shells and thus neglecting the effect of relative dislocation of the individual layers, the structural strength is highly overestimated after an impactor displacement of 10 mm. However, the stacked shell approach is able to reproduce the reaction force qualitatively until an impactor displacement of 70 mm. Beyond that point the simulation is underestimating the material. This reveals the necessity of modelling the interface between the material by cohesive elements or similar techniques.

The same approach for modelling the fibre metal laminates was transferred to magnesium-CFRP. However, due to different adhesion properties between the materials, the cohesive zones have to be calibrated separately from the steel-sandwich. A comparison between a drop tower test done at ILK and the corresponding simulation is shown in Figure 7 (right). The impactor has a mass of 140.5 kg and impacted the sandwich profile with a velocity of 2.8 m/s. The profile has a length of 80 mm. During the first 7.5 mm of impactor displacement the reaction force in the simulation averages the peak forces in the test. The maximum displacement shows a sufficient consistency between simulation (23.8 mm) and test (23.1 mm).

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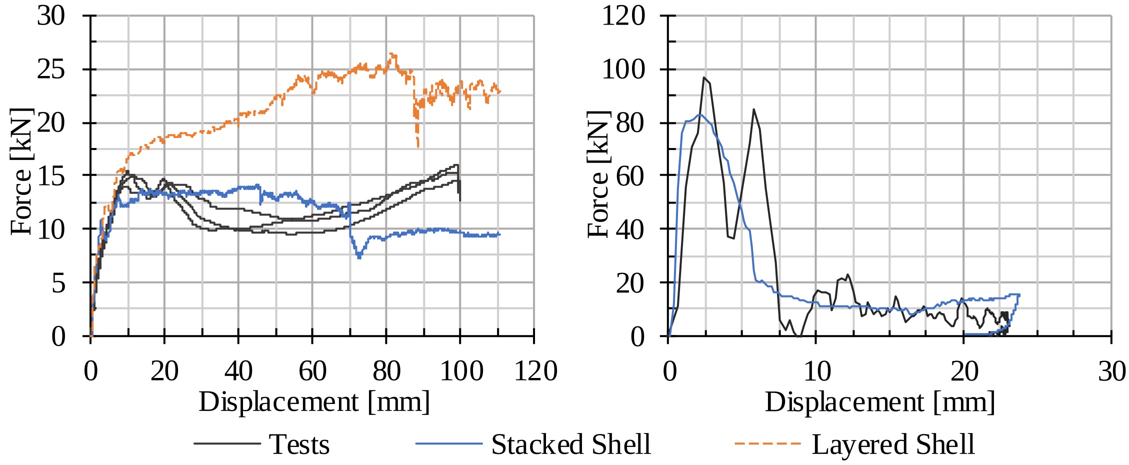

Figure 7. Quasi-static bending tests on steel-CFRP profiles (left) and dynamic compression test on magnesium-CFRP profile (right) in comparison to simulation results.

The material models explained above were used to design an automotive floor structure within a reference vehicle with hybrid drive. Development targets for the structure include consistent safety for passenger and battery in crash scenarios such as Euro NCAP Pole and Euro NCAP ODB in comparison to the reference as well as stiffness requirements. The floor structure was integrated into the simulation model of the reference vehicle taking into account the developed models for the adhesives and mechanical joining. Full vehicle crash simulations were conducted to verify the compliance with the safety requirements regarding maximum acceleration and intrusions. In Euro NCAP Pole the maximum dynamic intrusion is less than 290 mm into the passenger compartment, see Figure 8 left. Combined with a maximum acceleration of less than 25 g (filtered with CFC 60) in the tunnel area and a survival space of more than 350 mm the requirements are met. The same is true for the frontal crash scenario Euro NCAP ODB with an intrusion of less than 90 mm into the firewall (Figure 8 right) and a filtered acceleration of less than 35 g. In both crash cases also the targets regarding battery safety are fulfilled.

The mass distribution by material in the discussed automotive floor structure is as follows: 42 % steel, 22 % magnesium, 20 % CFRP, 14 % PA6-GF30 and 2 % non-reinforced thermoplastics. The developed structure using metal-CFRP sandwich materials is over 20 % lighter than the reference structure which consists of various high strength steel grades. The mass comparison already takes into account the different joining techniques and forming restrictions.

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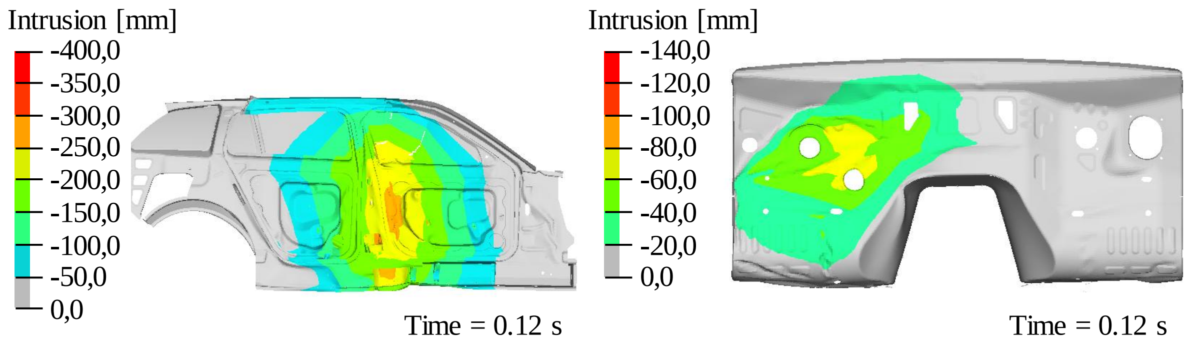

Figure 8. Intrusions into passenger cell in Euro NCAP Pole (left) and Euro NCAP ODB (right) load case simulations.

5. Conclusions

The presented simulation chain starts with the simulation of the forming of the novel metal-CFRP sandwich materials carried out in PAM-FORM. In the forming simulation every material layer was represented by an individual mesh and contact algorithms were used to distinguish between tangential and normal forces acting in the material. The effect of cooling to the material in form of residual stresses was investigated by a temperature-driven simulation in Abaqus on specimen and component level. To model the different in-plane and out-of-plane CTEs a special material model was developed.

The techniques available for joining the different sandwich materials were analysed and fitting Epoxy- and PU-based adhesives as well as rivets were selected. The mechanical properties of the joints were characterised and simulation models were calibrated using TAPO-model for adhesives.

Physical tests on coupon and component level were carried out to characterise the mechanical properties under quasi-static and dynamic loads of the novel sandwich materials. These results were used to calibrate simulation models for the dynamic crash simulation in LS-DYNA using a stacked shell approach. The metal and CFRP layer are represented by an individual shell layer connected by cohesive elements to model the interface and possible delamination. The comparison between the test results and simulations show satisfactory agreement.

The defined simulation chain was used to develop an automotive floor structure consisting of various metal-CFRP sandwich materials. Full vehicle crash simulations were carried out to verify the compliance with the safety requirements regarding maximum acceleration and intrusions into the passenger as well as battery compartment. The mass reduction in comparison with a lightweight steel floor structure amounts to more than 20 %.

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References

[1] T. Wollmann, C. Krbetschek, B. Poggel, O. Vogt, C. Paul, J. Jaschinski, N. Modler. Manufacturing of high performance metal carbon-fibre reinforced sandwich materials and their forming behaviour. *17th European Conference on Composite Materials ECCM-17, Munich, Germany,* June 26-30 2016

[2] D. W. Radford and T. S. Rennick. Separating Sources of Manufacturing Distortion in Laminated. *Journal of Reinforced Plastics and Composites Composite, 2000, 19: 621- 64*

[3] F. Burbulla, A. Matzenmiller, U. Kroll. Modelling of Adhesively Bonded Joints with *MAT252 and *MAT_ADD_COHESIVE for Practical Applications. *10th European LS-DYNA Conference 2015, Würzburg, Germany, 2015*

[4] A. Matzenmiller, S. Gerlach, M. Fiolka. A Critical Analysis of Interface Constitutive Models for the Simulation of Delamination in Composites and Failure of Adhesive Bonds. *Journal of Mechanics and Structures Vol. 5, No. 2, Pages 185-212, 2010*

[5] G. Schwarzkopf, M. Bobbert, D. Teutenberg, G. Meschut, A. Matzenmiller. Sensitivity Analysis of Manufacturing Parameters and Robust Evaluation of Structural Adhesive Bonding. Experimental and Numerical Investigations. *NAFEMS Seminar “Optimization and Robust Design”, Wiesbaden, Germany 23-24 March 2015*

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

[6] M. Maier, K. Schweizerhof, S. Schmeer, M. Magin and S. Mattern. *Statusbericht zur Berechnung von CFK-Strukturen im Automobilbau*. Forschungsvereinigung Automobiltechnik, 2007

[7] T. Belytschko, I. Leviathan. Physical stabilization of the 4-node shell element with one point quadrature, *Computer Methods in Applied Mechanics and Engineering*, 113:321-350, 1994

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