CARBON FIBER MEETS POLYPROPYLENE – NEW OPPORTUNITIES WITH CF FOR THERMOPLASTIC COMPOSITES

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Abstract

Thermoplastic matrices for composite solutions are becoming increasingly popular in various markets, especially materials with carbon fibers (CFRTP) based on polar matrices like PA6 have been well developed, whereas non-polar polyolefin based CFRTP (e.g. with PP matrix) still have issues on interfacial surface between fiber and matrix, resulting in low durability and low mechanical properties. However, CFRTP based on PP have a huge potential to contribute to manufacture an economical, high performance lightweight composite as CF-PP could offer lower densities and higher rigidity combined with a high weight reduction, higher workability as well as outstanding resistance to water absorption and hydrolysis. With regards to the mentioned challenge, a recent composite development of Mitsui Chemicals is focusing on unidirectional tapes based on carbon fibre and polypropylene (**TAFNEX™ CF-PP UD**). In this study, the material and UD tape development will be described in order to show the improved bonding and compatibility of the combination PP and CF. In conclusion, the CF-PP UD tapes have been used in hybrid solutions (e.g. with injection molding compounds or GF-based organosheets) to enable a cost-effective solution for semi-structural applications. A simulation approach has been developed together with our subsidiary ARRK Engineering using the tapes to predict the crash behavior and improve the lay-up of the tapes in the part.

Background

With the ongoing trend to lightweight construction, the automotive industry is increasingly an innovation driver behind new developments and alternative solution approaches in composite materials. The requirements of individual OEM's are as varied as the composite materials themselves, making the practiced handling of these materials a key qualification for series maturity. The combination of individual, integration-oriented product engineering, the construction of well-designed tools and flexible small-series production brings high added value in the use of composite materials. The automotive industry has many requirements for the strategic use of these materials: complex geometries, high strength, stiffness, and low component weight. Mitsui Chemicals and ARRK as part of the Mitsui Chemicals Group work together on the development, manufacture and elaboration of applications of these materials for the automotive industry. With extensive knowledge on the starting materials and long experience in the product development process, the two companies pool their expertise for the optimum use of thermoplastic composites in vehicles.

Material Development

From the early development stage Mitsui Chemicals developed a special PP-compatible sizing for carbon fibers to improve the fiber matrix adhesion. Exemplary SEM image (see Figure 1 left) after specimen fracture shows PP residues still on the carbon fibers, what is a good indicator for the improved bonding. In addition, an own modified PP compound as matrix is used, so that the bonding is further increased, and mechanical properties could be also improved. Therefore, a comparison between standard epoxy sizing and own developed sizing for CF as well as the influence of the PP modification have been conducted. Interfacial strength based on single fiber testing as well as interlaminar strength based on laminate testing have been improved significantly. Based on the material development, CF-PP UD Tapes (TAFNEX™) are produced on a full-scale production line and are ready to be used in different widths (see Figure 1 right).

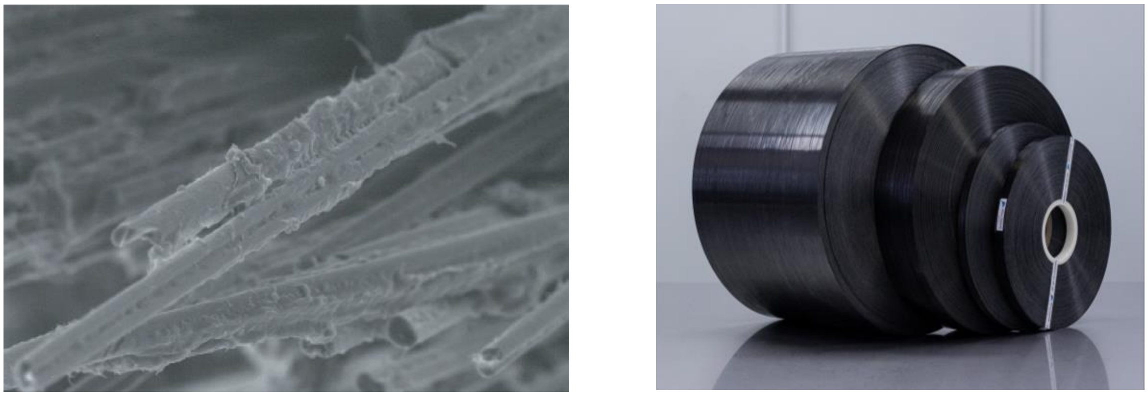

Figure 1: SEM image of fracture surface of UD laminate test piece (left) and mother coils from TAFNEX™ CF-PP UD with different post-slitted widths (right)

A comparison study using tensile tests (DIN ISO 527-5) and bending tests (DIN EN ISO 14125 A) at three different temperature conditions (-30°C, 23°C, 80°C) is shown in Figure 2 (left). The tensile properties at low and high temperatures drop only by 10 % compared to room temperature. The flexural properties are changed depend on temperature because kink susceptibility is affected by polymer hardness. In summary, the use of TAFNEX™ CF-PP UD in lower and higher temperatures is possible, especially when stiffness-driven requirements are required. The effect of higher application temperature with the combination of PP and CF is also shown in Figure 2 (right), presenting the load deflection curve (HDT 1.8 MPa, referred to JIS K7191-3) for three different types of PP based materials: Block PP, PP-GF30 and TAFNEX™ CF-PP UD. It can be shown that with fibre reinforcement the deflection starts at higher temperatures, resulting with TAFNEX™ with CF into a much higher temperature range in which the deformation point occurred (~150 °C).

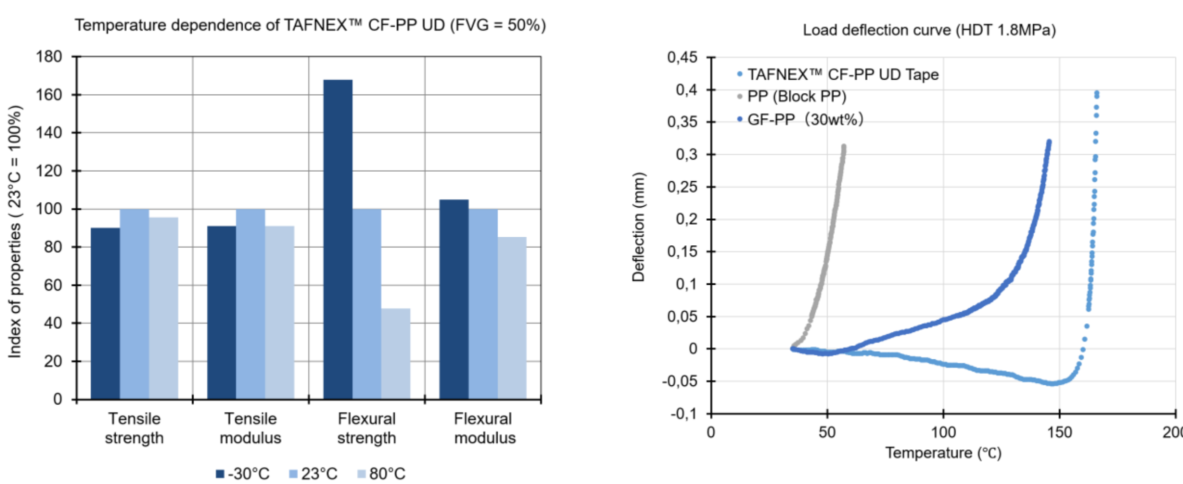

Figure 2: Temperature dependence study (left) load deflection analysis (right)

In addition to the studies on the temperature behavior of TAFNEX™ CF-PP UD, dynamic properties as well as lifetime prediction is also part of the latest material investigations. In [1] the statistical life prediction of UD tapes under creep tension load have been investigated in cooperation with the Kanazawa Institute of Technology, Japan, in which correlations were found to predict the statistical lifetime.

Application Development

As already mentioned, the investigation and development of possible applications based on novel materials like thermoplastic composites in the automotive industry is very important. UD tapes, like TAFNEX™ can be utilized in a broad application field (Figure 3), in dependence of their further processing. One possibility is to produce sheets based on UD tapes, like cross plies, woven structures (both in full carbon or in hybrid layout possible), random sheets with chopped UD tapes or even customizing existing conventional organosheets. Using those sheets as semi-finished products, they can be used in back-injection molding processes in combination with compounds, in sandwich parts with PP foam core or PP honeycombs, in thermoforming processes or also in visible carbon parts based on the random UD chip structure.

Figure 3: Processability of TAFNEX™ CF-PP UD

Another direction with UD tapes, and especially for those based on carbon fibers like TAFNEX™, is the use of narrow slitted tapes for tape placement or tape winding. For both processes, the in-situ consolidation from layer by layer can be ensured by laser heat source. With tape placement, complex structures can be layed-up for stand-alone parts or can be used as inserts for e.g. in a back-injection molding process. Also, single tape layers as patches can be used in the local reinforcement of other PP based structures. The application of single layers or patches is possible both before (e.g. fixation in the injection mold) or after component production (tape placement). Finally, narrow tapes can be used also in tape winding processes in order to produce tubes with very flexible laying angles. In addition, those tubes can be processed further, e.g. by over molding the tube structure with compound material or bending the tube after consolidation.

In the following section some of the above-mentioned processing methods will be utilized in order to present use cases with TAFNEX™.

Sheet hybridization with TAFNEX™ CF-PP UD and GF based on PP

Figure 4 shows a study, in which a long glass fiber reinforced PP (GF-PP) with 20 wt% glass fibers was compared to those that were reinforced with TAFNEX™ CF-PP UD (one side and both sides). It can be seen, that the mechanical properties can be increased significantly, especially the modulus by 545 %, at nearly same density. Thus, the combination of GF-PP injected molded materials with unidirectional materials based on CF enables many new application possibilities on PP basis.

MECHANICAL PROPERTIES	METHOD	UNIT	VALUES		
			GFPP 20wt%	GFPP + UD TAPE ONE SIDE	GFPP + UD TAPE BOTH SIDES
DENSITY	-	g/cm³	1,03	1,06	1.07 (+3,8%)
TENSILE STRENGTH	ASTM D3039	MPa	72	161	245 (+240%)
TENSILE MODULUS	ASTM D3039	MPa	3440	5680	7350 (+113%)
FLEXURAL STRENGTH	ASTM D790	MPa	98	254	235 (+140%)
FLEXURAL MODULUS	ASTM D790	MPa	4260	8900	27480 (+545%)

Figure 4: Partial Reinforcement on Basic GF-PP Compound

Considering combining GF based UD tapes with CF based materials, Figure 5 shows the comparison study between conventional organosheets and those sheets which have been produced by weaving the UD tapes into a hybrid sheet. Thus, the CF ration was increased in this study (from one CF woven layer each side to full CF woven layers). The results of three-point bending tests (DIN EN ISO 14125) show that even with one CF woven layer the stiffness could be increased by 83 %. As expected, the full CF woven parts show an increase of about 200 %. In general, due to the low undulation UD based fabrics have higher mechanical properties than roving based fabrics.

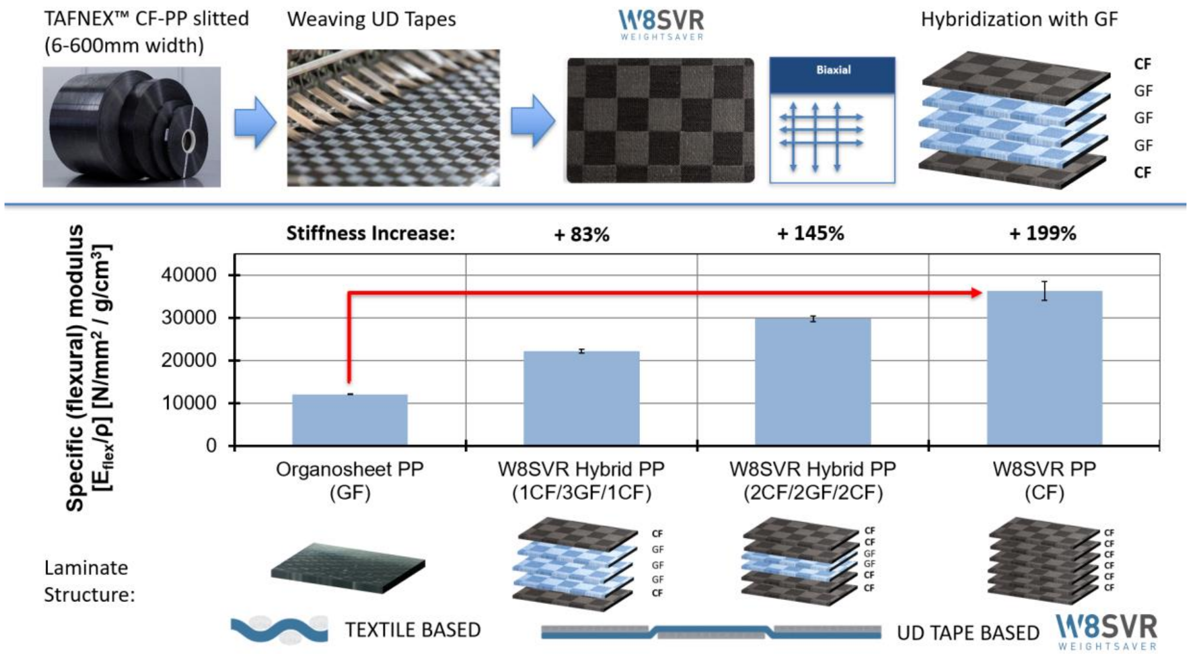

Figure 5: Hybrid sheets based on woven UD tapes

Local reinforcement of GF-PP based parts with TAFNEX™ CF-PP UD

As mentioned above, one possibility to reinforce a part locally is to apply the tapes in a post processing method like tape placement. Usually a local placement of UD patches enables lower wall thicknesses while maintaining the same mechanical properties. This can be shown in the following bumper fascia study (Figure 6). Two layers of UD tapes lead to a reduction of 40 % of the bumper fascia thickness considering the same deflection requirement.

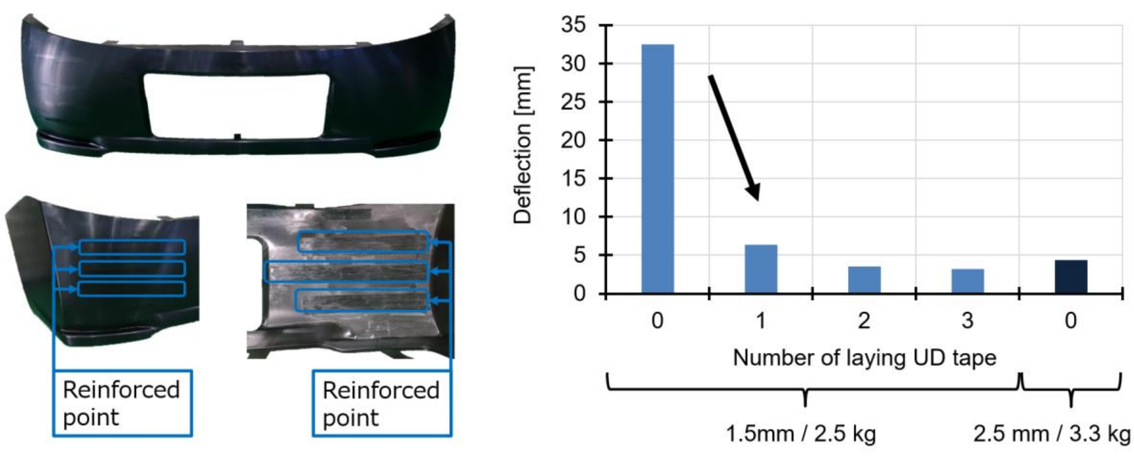

Figure 6: Post processing reinforcement by tape placement

A model (window frame part) of an automotive back door has been molded to investigate the effect of local reinforcement with TAFNEX™ CF-PP UD by using injection molding technology (Figure 7). One method to investigate the influence of the local reinforcement is to measure the displacement degree. The back door is fixed by three points whereas at the fourth point a load is applied. Afterwards the effect of local reinforcement with UD tape at the stress concentration is calculated and verified by practical tests. The results of the displacement measuring for a neat PP based backdoor and a glass fiber reinforced backdoor is also shown in Figure 7 (right). It could be confirmed that the displacement is reduced by 15 % for both variants with the use of TAFNEX™ CF-PP UD tapes as local reinforcement. Thus, one layer of UD-tape (18g) increased the stiffness by 12-24%. Also, in further investigations it could be found out, that rib structures are not necessary if using five layers of UD tapes

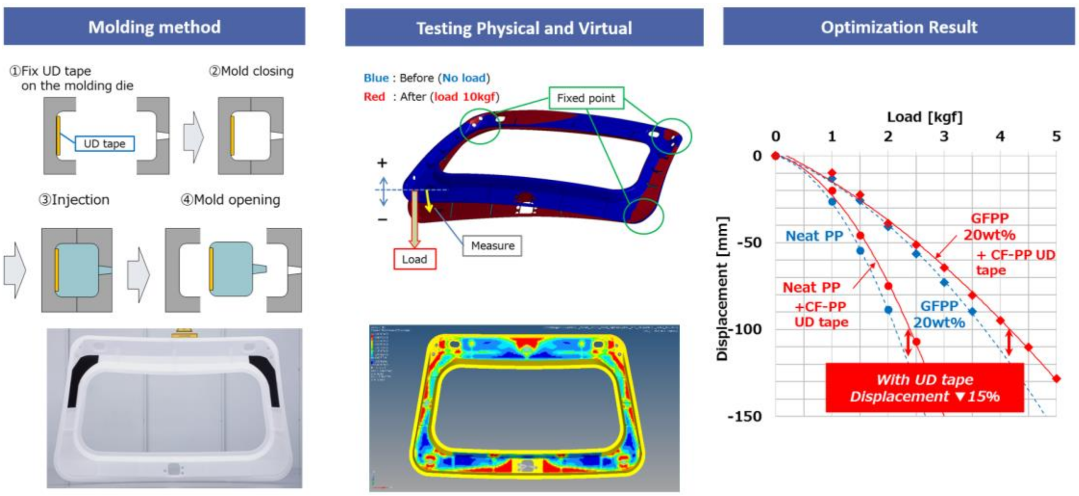

Figure 7: Local Reinforcement study of a tailgate

Simulation approach for composite delamination prediction using TAFNEX™ CF-PP UD

Accurate prediction of delamination in composite materials is a challenge and often limits the application of lightweight materials in safety relevant components, as it may reduce the available strength significantly. In order to correctly evaluate delamination of composites while retaining a good runtime performance, a new modeling approach in LS-DYNA® was studied by ARRK Engineering using a full thermoplastic front bumper beam as demonstrator to perform a virtual vehicle evaluation. The front bumper beam was made with the FiberForm technology from Krauss Maffei using a composite sheet made of TAFNEX™ CF-PP UD and back injection molded with a long glass fiber reinforced polypropylene (EDX4030) also from Mitsui Chemicals.

After performing detail testing of TAFNEX™ CF-PP UD at ARRK Engineering testing facility with different load applications, two digital material cards for in-plane and out-of-plane properties were generated in order to predict damage, failure and delamination in static and dynamic simulations. The front bumper beam was used for component validation (dynamic and quasi-static 3-point bending). Results from simulation and test correlate well, showing a high prognostic property of the material card (Figure 8, [2]).

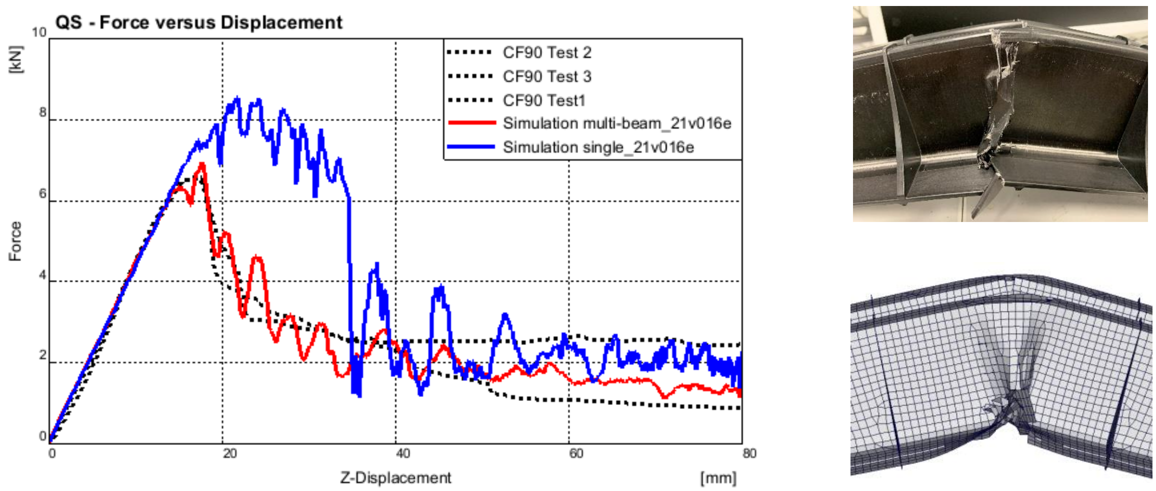

Figure 8: Correlation of load levels and failure mechanism (blue line: simulation without delamination, red line: simulation with delamination, dot line: testing)

Afterwards, the front bumper beam was evaluated virtually in a full vehicle setup according to FMVSS-US Part 581 regulation, initially showing insufficient energy absorption, resulting in significant damage of the cooler. Based on the energy target from full vehicle simulation a parametric study was performed in order to clarify the correlation between stiffness and absorbed energy. The results of this study were used to define a stiffness target and a layup to achieve this. Therefore, a new batch of front bumper beams with improved layup was produced and tested. Load level and stiffness were improved according to prediction (Figure 9).

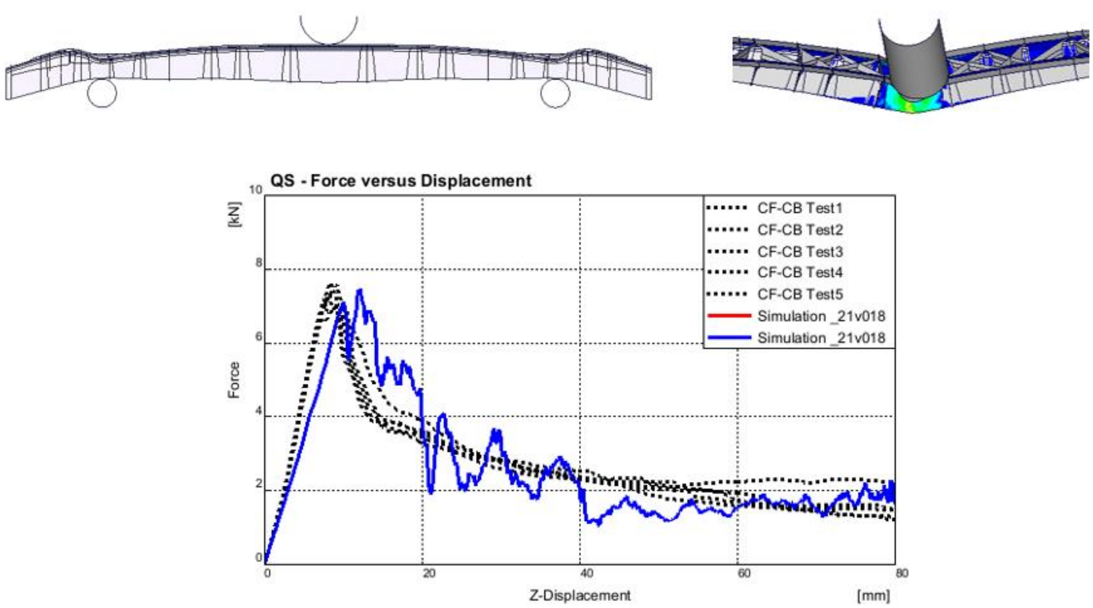

Figure 9: Component re-evaluation for improved lay-up (top: simulation plot, bottom: comparison of load level between tests [dotted] and simulation [blue]). Stiffness nonlinearity as observed in this test is not included in this modelling.

The optimized layup was re-evaluated in the full vehicle. Contact force and absorbed energy were doubled with less failure occurring and a major decrease in intrusion. By using CAE to evaluate material performance early in the development, unnecessary but costly tooling, prototyping and testing can be reduced (Figure 10).

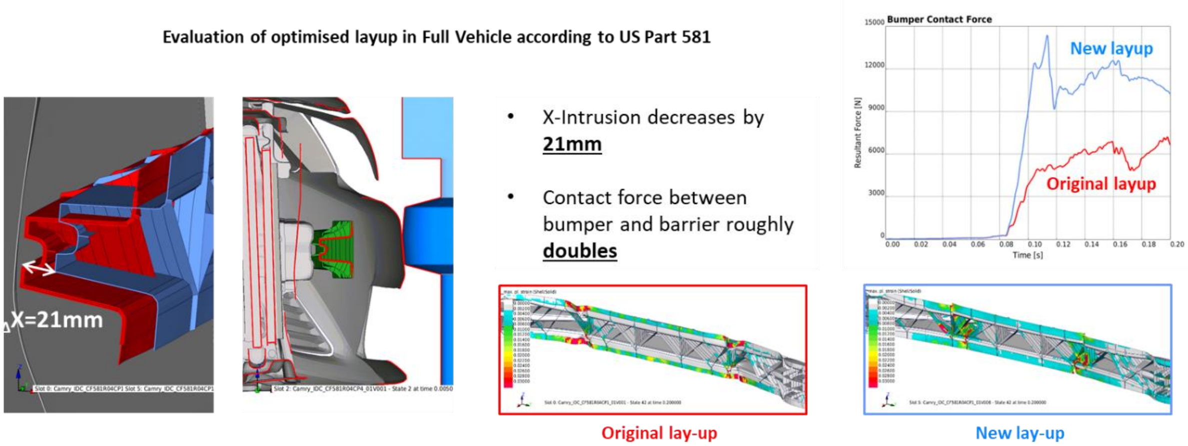

Figure 10: Evaluation of optimized layup in Full Vehicle according to US Part 581

Summary and Next Steps

TAFNEX™ CF-PP UD material is distinguished by a specially own developed bonding solution for carbon fibers what results to good fiber matrix adhesion and high mechanical properties. A modified PP compound as matrix is used what could increase the bonding further and higher application temperatures are possible. By evaluating TAFNEX™ CF-PP UD for different applications the combination of long glass fiber reinforced PP compounds and the CF-PP UD tapes could show a high potential for composite solutions.

Regarding the simulation approach, the new stacked shell modeling from ARRK Engineering has shown promising results at coupon and component level with TAFNEX™ CF-PP UD. At the full-vehicle simulation scale, the new modeling approach has presented robust delamination prediction capability while still retaining high run time performance. Thus, the approach can be adopted in full-vehicle crash in order to evaluate composite delamination.

Mitsui Chemicals and ARRK Engineering are looking forward to new opportunities and component evaluation using TAFNEX™ CF-PP UD.

Bibliography

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