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Angaben zur Veröffentlichung / Publication details:

Trauth, Anna, and Kay A. Weidenmann. 2016. "Mechanical properties of continuously-discontinuously fiber reinforced hybrid sheet molding compounds." In *2. Internationale Konferenz Euro Hybrid - Materials and Structure, 20.-21. April 2016, Kaiserslautern: Proceedings*, edited by Joachim M. Hausmann and Marc Siebert, 57–62. Sankt Augustin: Deutsche Gesellschaft für Materialkunde (DGM).

MECHANICAL PROPERTIES OF CONTINUOUSLY-DISCONTINUOUSLY FIBER REINFORCED HYBRID SHEET MOLDING COMPOUNDS

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ABSTRACT: Chopped glass fiber Sheet Molding Compounds (SMC) offer a high design freedom for complex part geometries featuring high surface quality combined with low material and processing costs. A new approach focuses on the combination of discontinuously reinforced structures based on SMC with unidirectional carbon fiber prepregs. The integration of such prepregs manufactured by an adopted SMC process featuring continuous reinforcements aims to obtain better load-bearing capacities at highly loaded areas. As a first step, continuously-discontinuously (CoDiCo) fiber reinforced laminate sheets have been processed by combining layers of chopped glass fiber and unidirectional carbon fiber prepregs during molding.
This work aims to contribute significantly to a fundamental understanding of the structural behavior of different CoDiCo structures by determining macroscopic material properties. Mechanical characterization included quasi-static tension, compression and bending. Impact tests were also performed to assess the dynamic properties.
The results indicate that compared to solely discontinuously reinforced Sheet Molding Compounds, the CoDiCo laminates show increased global strength and stiffness, with the mechanical properties expectedly depending on layer architecture. In general, laminates showed also a higher damage tolerance in comparison to discontinuously reinforced SMC.

KEYWORDS: Sheet Molding Compound, glass fiber, carbon fiber, prepreg, mechanical characterization, material properties

1 INTRODUCTION

The growing demand for fuel efficient and hence light vehicles and aircrafts led to a remarkable development of fiber-reinforced polymeric composite manufacturing methods in the past few years. Sheet Molding Compound (SMC) technology offers the possibility to manufacture structures at a very high productivity combined with good part reproducibility, cost efficiency, surface quality and the possibility to manufacture parts with complex geometries. Sheet Molding Compounds are based on flat semi-finished product of cross-linkable resins with or without filler and additives reinforced by glass or carbon fibers processed to the final geometry using compression molding. Chopped glass fibers are the most common type of reinforcement found in SMC industry. This discontinuous fiber reinforcement offers a high bulk material flow capability, which leads to a high design freedom. Due to the short fiber length and depending on process parameters, which lead to more or less pronounced anisotropic fiber distribution, discontinuously glass fiber reinforced SMC offer only low stiffness and strength. Better mechanical properties can be obtained in general by using carbon fibers as reinforcement component. Since these fibers are more expensive than glass fibers and causing higher cycle times [1], approaches to combine glass and carbon fiber reinforcements for SMC structures appear more suitable for industrial applications. The first technical application of a hybrid tailored chopped carbon – chopped glass fiber SMC was demonstrated by the 2003 Viper. With this material composition mass reduction and stiffness improvement could be achieved for different structural automotive parts such as the fender support system, windshield surrounding structure and inner door panels [2].

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Cabrera-Rios et al. [3] also studied the relative improvement in physical properties of SMC structures consisting of a combination of chopped glass and chopped carbon fibers in a per ply basis with different ply arrangements. Measurements of tensile and bending properties showed that not only the position of the plies with different fiber types but also the variation of mixture affected the mechanical properties [3].

In contrast to chopped fibers, continuously fiber reinforced structures have a significantly higher load-bearing capacity. With an optimized composition of continuously and discontinuously fiber reinforced structures parts with complex geometries combined with high stiffness and strength could be obtained. This represents a novel material class in the field of fiber reinforced polymers based on the integration of unidirectional continuous carbon fiber placement in the SMC molding process.

First trials to combine chopped glass fiber SMC with unidirectional carbon fibers were done by Gortner et al. [4]. This group placed dry textile preforms together with the SMC semi-finished product in a mold for a standardized SMC process. The chopped glass fiber SMC based on an unsaturated polyester resin. Reinforcement elements were ±45° non-crimp fabrics of glass or carbon fibers and a one and two side reinforcement with the two different structures were investigated. Mechanical characterization showed that a local textile reinforcement could improve tensile and bending properties compared to pure glass fiber reinforced SMC.

Wulfsberg et al. [5] combined chopped glass or carbon fiber SMC, also based on unsaturated polyester resins, with prepreg compression molding in a one-shot compression molding and curing process. Mechanical characterization highlighted that different material combinations of chopped and unidirectional fibers lead to an increase of tensile and bending properties.

2 FABRICATION OF CoDiCo SHEET MOLDING COMPOUNDS

In contrast to the approach of Wulfsberg et al. the unidirectional carbon fiber prepregs for this study are themselves manufactured in a modified continuous SMC process with both the matrices of continuous and discontinuous matched each other.

This offers the opportunity to process prepregs in an easier and cheaper way than usual prepreg materials. Additionally, a specific hybrid resin system is used which ensures fiber position and alignment of continuous reinforcement structures while compression molding with (flowable) chopped glass fiber SMC. It offers not only a high viscosity during molding but also increases productivity as there is no more need for maturing. High grammage carbon fibers can easily be manufactured with this resin system to meet best economical needs of the industry. Realizing combined continuous and discontinuous reinforced structures within one part following this processing route leads to a noticeable improvement of loading path orientated high volume manufacturing.

The International Research Training Group of Integrated Engineering of Continuous-Discontinuous Long Fiber Reinforced Polymer Structures (GRK 2078) aims to contribute significantly to a fundamental understanding of combined discontinuously and continuously SMC structures. This study is a first step to investigate the mechanical properties of laminates based on a combination of sheets out of continuously carbon fiber as well as discontinuously glass fiber (CoDiCo) with different ply arrangement during compression molding.

To manufacture CoDiCo laminates chopped glass fiber SMC and unidirectional carbon fiber SMC were manufactured on two different impregnation lines. Individually manufactured unidirectional carbon fiber SMC sheets were combined with chopped glass fiber SMC during compression molding to create hybrid continuously discontinuously (CoDiCo) laminates.

The discontinuous glass fiber SMC is based on a vinyl ester (type Atlac XP810X by Aliancys). To optimize structural properties no fillers were added. The semi-finished products were manufactured using a flat conveyor plant type HM-LB-800 by Schmidt & Heinzmann and matured for seven days at 30°C. The weight content of the reinforcing glass fiber (type Multistar 272 by Johns Manville) is set to 41 wt.-% which equals 23 vol %).

The unidirectional carbon fiber SMC sheets were manufactured with a labor-scale impregnation line, built at the Fraunhofer Institute for Chemical Technology. In contrast to the described standard SMC manufacturing line, this process based on carbon fiber fabrics (type Panex35 by Zoltek) and a hybrid unsaturated polyester - polyurethane resin system (type Daron 41 by Aliancys). Additionally the labor-scale impregnation line is equipped with a heatable table which allows for heating up of the impregnated fabric to achieve the B-stage precuring. To prevent any further chemical reaction and to achieve the full B-stage the semi-finished sheets are subsequently cooled down to room temperature [6].

For this study unidirectional carbon fiber SMC semi-finished sheets with a fiber weight content of 62 wt.-% (50 vol. - %) were manufactured. After maturation the DiCo and Co sheets were cut into plies, stacked and compression molded. To investigate mechanical properties of CoDiCo SMC, two different laminates architectures were realized. These differ in arrangement of the continuous and discontinuous reinforced plies. All laminates consist of three layers. Type A (GCG) has two discontinuously glass fiber reinforced outer layers with an inner layer of unidirectional carbon fiber SMC. The plates had a thickness of 3.3 mm. Type B (CGC) consists of two outer layers reinforced with unidirectional carbon fibers and one discontinuously glass fiber reinforced sheet in the middle (thickness: 3 mm). Besides that purely glass fiber reinforced sheets (G) were manufactured. They had a thickness of 2.3 mm.

For all plates a mold coverage of 100 % was realized so that flow phenomena can be neglected.

After molding for each laminate samples in 0° and 90° with regard to the orientation of the unidirectional carbon fibers were cut by water-jet cutting.

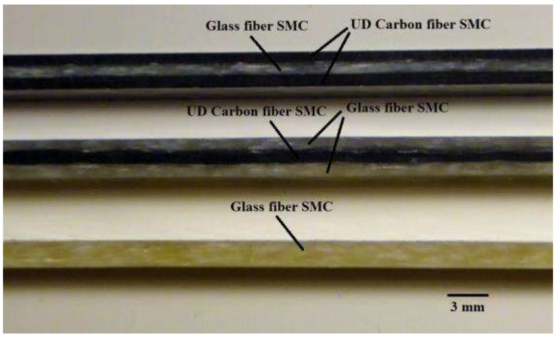

Fig. 1 *CoDiCo Laminates: CGC (top), GCG (middle) and G (bottom)*

3 CHARACTERIZATION

To understand the effect of continuously reinforced chopped glass fiber SMC and especially to evaluate the influence of ply arrangement on the mechanical properties of CoDiCo fiber reinforced structures tensile, bending, compression and impact tests were performed. Results of the characterization for both laminate types were compared to mechanical properties of purely discontinuously reinforced glass fiber SMC. All tests were carried out at room temperature.

3.1 TENSILE TEST

The quasi-static tensile tests were performed with a ZwickRoell ZMART.PRO universal testing machine equipped with a maximum capacity of 200kN. For laminate type A and B rectangular specimen with length x width x thickness = 230 mm x 25 mm x 3.3 mm for Type A, respectively 3 mm for Type B were used for testing. Additionally, Type B laminates were provided with cap strips. The tensile properties of glass fiber reinforced SMC were determined with dog-bone like specimen with a rectangular measurement section of 60 mm x 20 mm x 2.3 mm (Fig.3). Clamping distance was 150 mm for each sample type and longitudinal strains were measured with an extensometer with a gauge length of 100 mm for the rectangular and 60 mm for the dog-bone like specimen. Testing velocity was 2 mm/min. For each specimen type 5 samples in 0° and 90° were considered for testing. Elastic modulus was calculated by linear regression between ε_1=0.05 % and ε_2=0.25 %.

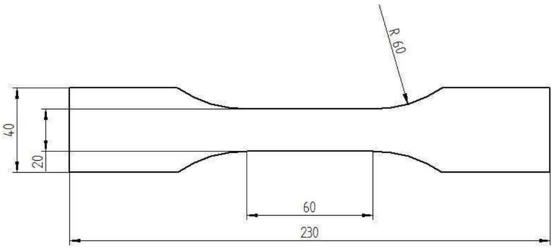

Fig. 2 *Dog-bone like specimen used for tensile testing of purely glass fiber reinforced SMC*

3.2 BENDING TEST

Three-point bending tests were performed on a ZwickRoell Z2.5 testing machine with a 2.5kN load cell. The rectangular specimen had a width of 15 mm and a thickness to span ration of 1:32. The testing velocity was calculated according to DIN EN ISO 14125 to guarantee a strain rate of 0.01 1/min for all sample types. Bending stresses and bending strains were also calculated according to DIN EN ISO 14125 and taking into account a corrected formula if measured deformations were > 0.1 x span length. For each specimen type 5 samples in 0° and 90° were considered for testing. Flexural modulus E_B was calculated via linear regression with stresses measured at ε_1=0.05 % and ε_2=0.25 %.

3.3 COMPRESSION TEST

Compression tests were performed on a ZMART.PRO 100kN universal testing machine equipped with a HCCF clamping unit. Measurement length was 12 mm and deformations were detected by two clip-on sensors, one at each side of the specimen to control bending of the specimen. For each specimen type 5 samples in 0° and 90° were considered for testing. Testing velocity was 1mm/min and compression modulus E_C was calculated via linear regression between ε_1= 0.05 % and ε_2 = 0.25 %.

3.4 IMPACT TEST

To determine impact properties, dynamic tests were performed with an Instron dynatup 9250HV drop tower. A wedge shape indenter was dropped on rectangular specimen with a constant thickness to span ratio of 1:15. The impact velocity was calculated for the three specimen types to obtain a strain rate of $1*10^3$ in each case. For each specimen type at least 3 samples in 0° and 90° were considered for testing. Impact strength was calculated as quotient of maximum energy measured during impact and cross section of the sample.

4 RESULTS

Regarding the elastic properties, the implementation of unidirectional reinforcements in the investigated laminates leads to an increase of modulus for both ply arrangements and for all considered loading cases, if loading direction was parallel to the fibers. For tensile, bending as well as compression the increase of elastic modulus was more distinct for laminate type B with two carbon reinforced outer layers, whereas the biggest increase was reached for bending. For laminate type A flexural modulus is 150% of the elastic modulus of pure glass fiber SMC. With unidirectional carbon fiber reinforced outer layers the modulus was with 70.7 GPa and hence more than ten times (increase of 1090%) the value for glass fiber SMC (6.5 GPa) (Fig. 3).

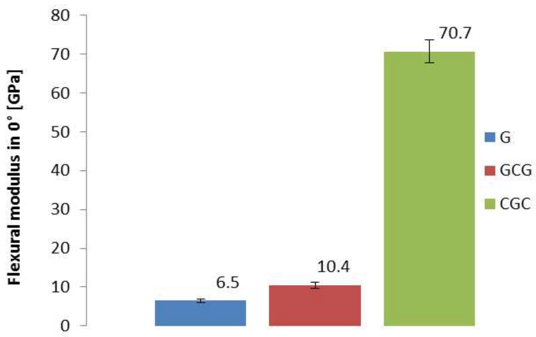

Fig. 3 *Flexural modulus for glass fiber SMC (G), laminate type A (GCG) and B (CGC) in 0°*

The increase of the elastic modulus for tensile load is also significant for both laminate types. The modulus is 4 times higher for laminate type A and 7.5 times higher for laminate type B compared to the purely glass fiber reinforced SMC (Fig. 4).

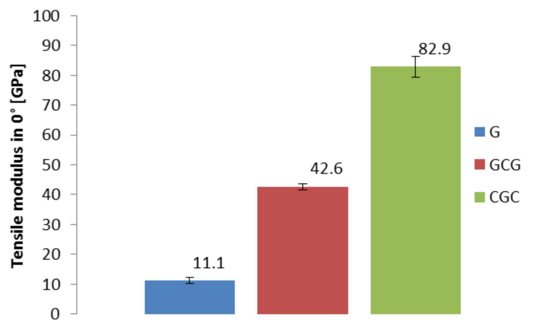

Fig. 4 *Tensile modulus for glass fiber SMC (G), laminate type A (GCG) and B (CGC) in 0°*

Considering compression load, the modulus increases from 8.6 GPa for pure glass fiber reinforced SMC to 29 GPa (+340%) for laminate type A and 67 GPa (+780%) for type B (Fig. 5).

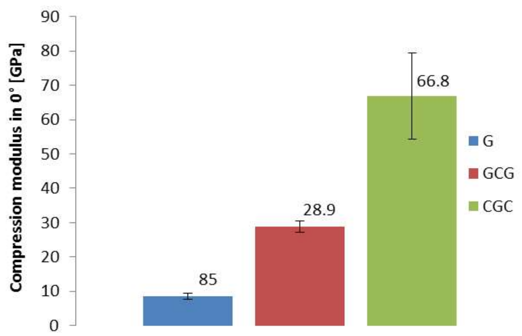

Fig. 5 *Compression modulus for glass fiber SMC (G), laminate type A (GCG) and B (CGC) in 0°*

If loading direction was perpendicular to the unidirectional fibers, no significant difference between the three considered materials were observed for tensile and compression loadings. For bending loadings, laminate type A showed the highest modulus perpendicular to fiber direction, which was 1.3 times higher than for pure glass fiber SMC. Unidirectional carbon outer layers even weakened mechanical performance by 35 %.
Regarding at compression and bending strength, laminate type B shows the biggest increase compared to purely glass fiber reinforced SMC. There was an increase of 500 % (Fig. 6) considering flexural strength and 280 % for compression loads (Fig. 7) in fiber direction.

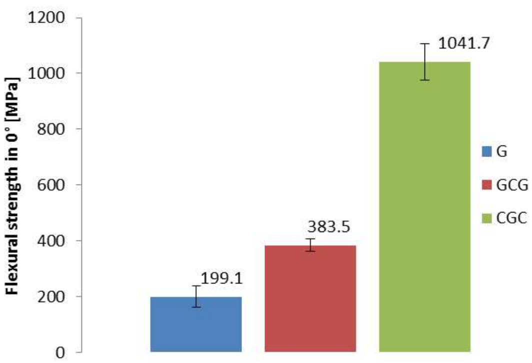

Fig. 6 *Flexural strength for glass fiber SMC (G), laminate type A (GCG) and B (CGC) in 0°*

For dynamic loads, as for quasi-static loadings, especially the outer layer of the laminate determines mechanical properties. With laminate type A an 80% increase of impact strength in fiber direction was observed. For type B impact strength is even more than twice as high as for purely glass fiber reinforced SMC (Fig. 8).
Considering samples tested perpendicular to fiber direction, for laminate type A as well as for type B impact performance decreases compared to purely glass fiber reinforced SMC from 57 J/m^2 to 35 J/m^2 respectively 42 J/m^2 (Fig. 9).

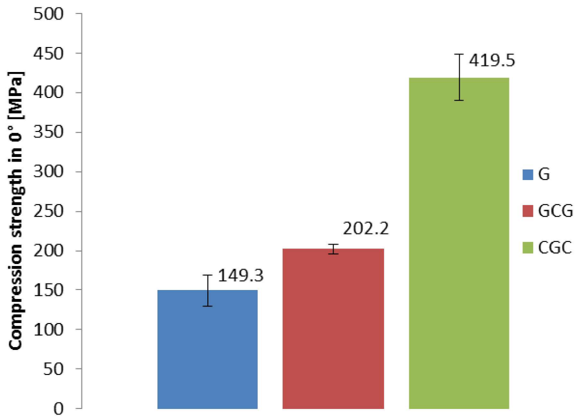

Fig. 7 *Compression strength for glass fiber SMC (G), laminate type A (GCG) and B (CGC) in 0°*

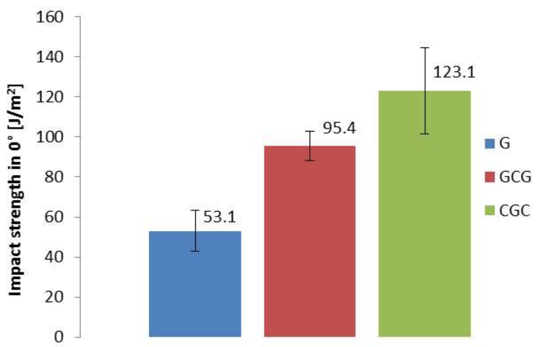

Fig. 8 *Impact strength for glass fiber SMC (G), laminate type A (GCG) and B (CGC) in 0°*

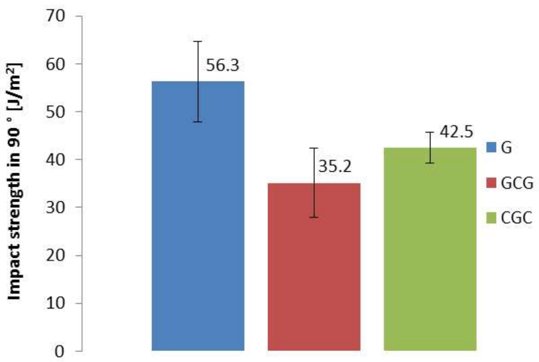

Fig. 9 *Impact strength for glass fiber SMC (G), laminate type A (GCG) and B (CGC) in 90°*

5 DISCUSSION

This paper proved the possibility to reinforce chopped glass fiber SMC with unidirectional carbon fiber SMC in an one shot- compression molding process. Different laminate architectures were realized which showed an increase in mechanical properties considered quasi-static and dynamic loadings. For all tested loading cases the reinforcement effect was most important for laminates with two unidirectional carbon fiber SMC outer layers. The biggest increase in modulus and strength was observed for bending. If loads are applied perpendicular to fiber direction, there was no reinforcement observed. In this case, matrix characteristics are decisive for mechanical properties. Especially for compression loadings a high standard deviation was observed evaluating the compression modulus. The inhomogeneity of the laminates caused a slight curvature in the elastic region of the stress-strain curve. This complicated the definition of an evaluation region to determine the compression modulus, which was valid for all tested samples. To evaluate the effect of unidirectional reinforcement and the lightweight potential of obtained laminates a comparison based on resultant laminates' density would be appropriate in general. As the material compositions in this study were adapted to obtain components with the same density, the price was taken into account for an evaluation of the reinforcement effect. For a first theoretical comparison Young's moduli for laminate type B with different ply thicknesses were calculated with the material selection software CES EduPack [7]. Calculation based on measured elastic properties for pure chopped glass fiber and pure unidirectional carbon fiber SMC. As the described manufacturing process was realized on a laboratory scale no manufacturing prices are known for the described material system. Nevertheless, to get an estimation of laminates' prices depending on plies' thicknesses, the prices for thermoset based glass fiber SMC and epoxy based unidirectional carbon fiber laminates were taken into consideration (Fig. 10).

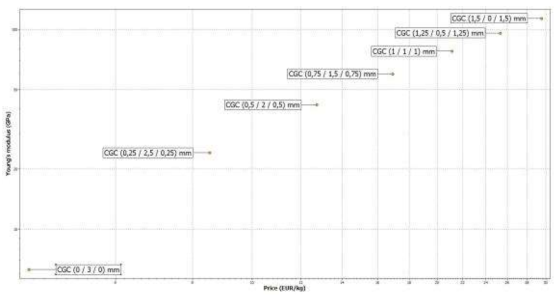

Fig. 10 *Price vs. theoretical Young's modulus for different ply thicknesses for laminate type B (CGC) [7]*

The theoretical modulus for a laminate architecture with two 1 mm thick carbon fiber reinforced outer layers and a 1 mm glass fiber reinforced SMC sheet in the middle is 79.4 GPa according to the material selection software. With an experimentally measured value of 83 GPa it could be proven that theoretically calculated values can be obtained with the described manufacturing process.
Flexural moduli for different ply thicknesses for laminate type A (GCG) and B (CGC) were also calculated based on measured values for pure glass

fiber respectively unidirectional carbon fiber SMC and plotted again versus the prices obtained by the CES EduPack (Fig.11). Theoretical values for laminates with a ply thickness of 1 mm are 8.9 GPa for type A (GCG) and 69.9 GPa for laminate type B. These calculated values fit once again very well with measured moduli (type A: 10.4 GPa and type B: 70.7 GPa). The theoretical estimation underlines the potential of the described approach to combine unidirectional carbon fiber SMC with chopped glass fiber Sheet Molding Compounds in an integrated process.

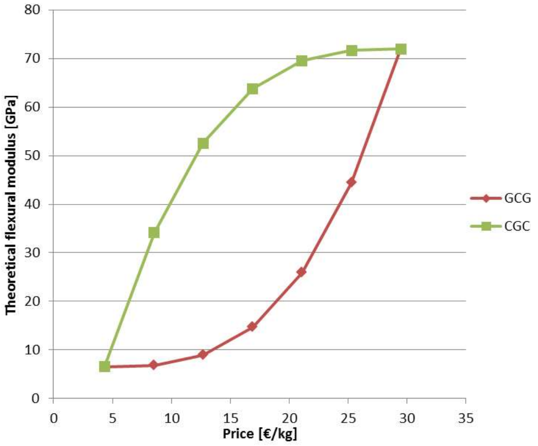

Fig. 11 *Price vs. theoretical flexural modulus for different ply thicknesses for laminate type A (GCG) and B (CGC)*

The integration of dry carbon fiber ±45° non-crimp fabrics, realized by Gortner et al. [4], increased tensile modulus by 220 %. This study proves that a combination of two different SMC semi-finished components with unidirectional carbon fiber reinforcement and based on a one-shot manufacturing process could increase the elastic modulus by 750 %. The difference is also more severe if bending loads are considered. With an increase of approximately 1000 % due to the hybrid compression molding technique this methods is once again superior to the integration of dry ±45° non-crimp fabrics, with an increase was only 125 % compared to pure glass fiber SMC. The approach presented by Wulfsberg et al. [5] considered unidirectional carbon fiber prepgres as middle ply of a three-layered laminate. This combination tripled tensile modulus and strength. Bending modulus was also doubled whereas there was no difference in bending strength compared to pure glass fiber SMC. The results of this study show, that independent of ply arrangement and also with glass fiber reinforced outer layers the increase of mechanical properties was more important than described by Wulfsberg et al. With the integration of unidirectional carbon fibers in the outer layers the increase of mechanical properties was even more distinctive.

6 ACKNOWLEDGEMENT

The research documented in this manuscript has been funded by the German Research Foundation (DFG) within the International Research Training Group “Integrated engineering of continuous-discontinuous long fiber reinforced polymer structures“(GRK 2078). The support by the German Research Foundation (DFG) is gratefully acknowledged. The authors also kindly acknowledge the Fraunhofer ICT in Pfinztal, Germany for manufacturing the SMC sheets and laminates with a special thanks to D. Bücheler (Institute of Vehicle System Technology, Karlsruhe Institute of Technology).

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