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COMPONENT TESTING OF CONTINUOUSLY AND DISCONTINUOUSLY REINFORCED HYBRID SHEET MOLDING COMPOUNDS (CODICOSMC)

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ABSTRACT: In order to simultaneously achieve cost savings in addition to the known positive lightweight effect of fiber reinforced plastics, attempts are made to combine continuous and discontinuous fiber reinforcement to achieve a targeted increase of the rigidity of components. Within the scope of this contribution, a four-point bending test on hybrid continuous-discontinuous SMC components was performed to characterize the effect of hybridization on mechanical properties. The components made from a discontinuous fiber sheet molding compound (SMC) featured a locally introduced continuous carbon fiber reinforcement. The matrices of both the continuous and the discontinuous component are based on a novel unsaturated polyester-polyurethane two-step curing resin system which ensures the chemical compatibility of the two constituents. As reference, SMC components of the same resin system with exclusively discontinuous glass fiber reinforcement were considered. The components were subjected to cyclic bending loads to measure the damage-related stiffness reduction. It has been demonstrated that the continuous carbon fiber reinforcement has a positive effect on the stiffness as well as the damage evolution of the reference structures without increasing the weight of the components.

KEYWORDS: bending testing, GFRP, CFRP, component testing, damage evolution

1 INTRODUCTION

Sheet Molding Compounds were first used in the 1960s. One of the biggest buyers is the automotive industry. In 1999 alone, 66 000 tons were considered for vehicle construction, which accounts for around 35% of total SMC consumption [1]. One of the main reasons for the widespread use of SMC is its excellent design freedom combined with an outstanding surface quality which is well suited for painting. The SMC itself can also be colored. These aspects are an important factor for high surface quality components (so-called Class A components). The development of SMC has been directly designed for high automation, which brings an economic advantage. Compared to steel sheet forming, tools are up to 40% less expensive [2, 3].

Another advantage of SMC is its lightweight potential. The resin system can be modified in a way that it can be adapted to virtually any application [4]. Unsaturated polyester resins are most commonly used as they are inexpensive and cure quickly [2]. But other resins systems, for example vinyl ester resins or epoxy resins can be considered as well [3]. In general, discontinuous glass or carbon fibers are used as reinforcement with glass fibers being the most widespread. However, carbon fibers have been used more and more frequently lately, and also natural fibers are increasingly being considered for SMC [3]. Typical fiber contents are 15% by weight to 30% by weight. In the case of the so-called structural SMC or Advanced SMC, however, the fiber contents are more than 50% by weight. The fiber length can vary between 0.5 and 2 inches [5].

Regarding the generation of hybrid SMC, Cabrera-Ríos and Castro [6] carried out an experiment in which carbon and glass fibers were mixed as discontinuous fibers in the material. This mixing can be achieved by two different methods of preparation: On the one hand, the fibers can already be mixed during the production of the SMC semi-finished sheets or, on the other hand, can be mixed during molding, in which carbon fiber and glass fiber reinforced semi-finished products are inserted in layers. It could be shown by the "layer by layer" method that not only the respective proportion of fiber is important, but also how the stack is arranged during molding. It could be confirmed that the variation of the fiber composition and arrangement has an influence on the tensile strength, Young's modulus and bending strength. Another approach is to combine discontinuously reinforced SMC with pre-impregnated continuous carbon fibers, as demonstrated by Wulfsberg et al. [7] to develop hybrid SMC material mainly for the aircraft industry .The experiment shows that by adding the continuous fiber reinforcement the flexural modulus as well as the tensile modulus can be increased. The integration of unidirectional carbon fiber layers increases the tensile strength twice compared to the SMC without continuous reinforcement. Another finding is that the impact strength is particularly positively influenced by a combination of discontinuous glass fibers and a woven carbon fiber fabric. However, no improvement can be observed when using discontinuous carbon fibers. According to Wulfsberg et al. this may be due to the poor interlaminar shear strength between carbon fibers and the HUP 27 resin considered within this study. Even SMC with 50% discontinuous carbon fiber in combination with carbon fiber fabric, deterioration of impact resistance is observed. In addition, partial delamination occurred. This proves that in the hybridization of SMC, the resin systems of the continuous and discontinuous phase must be compatible with each other. The International Research Training group on the "Integrated engineering of continuous-discontinuous long fiber reinforced polymer structures" (GRK 2078) focus on the development of a structural hybrid continuous-discontinuous SMC (CoDiCoSMC), whereas the use of a novel UPPH resin system for both the discontinuous SMC and the continuous fiber reinforcement considered within this study offers the possibility to be hybridized in a one shot compression molding process [8].

2 MATERIAL AND METHODS

2.1 MATERIAL

SMC consists essentially of two components, the resin system and the fibers. A detailed description if the individual components of the resin system of the one-inch fiber length discontinuous glass fiber reinforced SMC and the continuous carbon fiber prepreg used for the local reinforcement are listed in Table 1. The individual components are first mixed under vacuum and then further processed on a conventional SMC conveyor belt plant by Schmitt&Heinzmann (Bruchsal, Germany) at the Fraunhofer ICT (Pfinztal German). Next, the glass fiber reinforced semi-finished product was stored to matured for several days at approximately 30 °C. The nominal fiber content was set to 41 wt.%. The carbon fiber-based prepregs featuring a nominal fiber content of 60 wt.% were produced on the same conveyor belt. Both components were automatically cut to size on a cutting table. The continuous fiber inserts were cut directly to the final geometry, the SMC semi-finished product was cut to 249 x 280 mm².

Table 1: Individual resin components and fiber type of investigated glass and carbon fiber SMC

Component		Discontinuous glass fiber SMC	Continuous carbon fiber SMC	Supplier
Resin		Daron ZW 14141	Daron 41	Aliancys
Additives	Release agent	BYK 9085	BYK 9085	BYK
	Inhibitor	pBQ	pBQ	Fraunhofer ICT
	De-airing	BYK A 530		BYK
	Impregnation additive		BYK 9076	BYK
Peroxide		Trigonox 117	Trigonox 117	Akzonobel
Thickener	Isocyanate	Lupranat M20R	Lupranat M20R	BASF
Styrol			Mono Styrol	BASF
Accelerator			BorchiKat0243	Borchers
Fiber		MultiStar 272		Johns Manville
			PX3505098T-13	Zoltek

The molding steps for the manufacturing of components made from CoDiCoSMC is depicted in Fig. 1.
Since the carbon fiber inserts should stay in place during molding, they are directly put at its final position in the mold. This position is located on the longitudinal slopes of the reference structure. The glass fiber reinforced SMC semi-finished sheets are placed on the insert. To be able to achieve the same flow conditions, the SMC discontinuous semi-finished sheets are also placed in the same position for the non-locally reinforced structures.
SMC plaques with a section of 800 mm × 250 mm, featuring the component in the middle, were molded in a press type: COMPRESS PLUS DCP-G 3600/3200 AS by Dieffenbacher (Eppingen, Germany) at 125 bar at

approximately 150 °C and 112s mold closing time. The reference structure was then extracted from the molded plaque by milling. Figure 2 shows the final parts with and without local reinforcements.

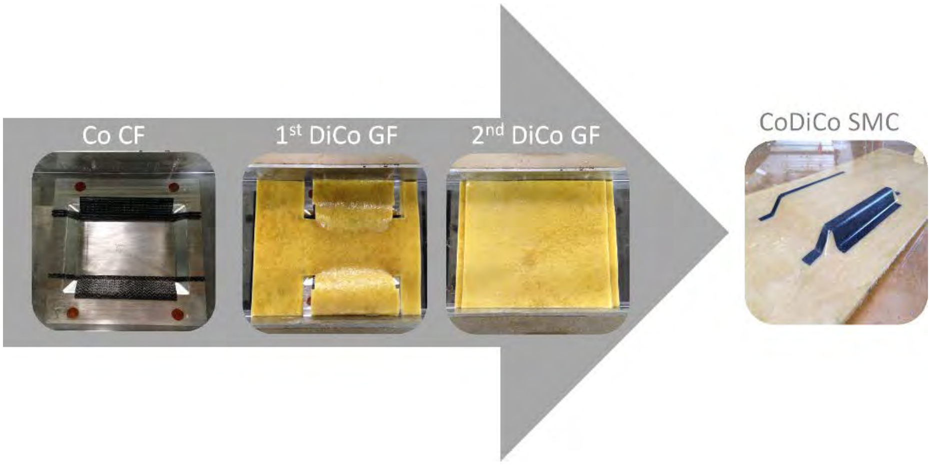


Fig. 1 *Molding steps to manufacture hybrid continuous-discontinuous SMC reference structure*

a) b) c)

Fig. 2 *SMC reference structure considered for testing. Discontinuous glass fiber SMC specimen (a), locally reinforced specimen (b) and schematic CAD sketch (c)*

2.2 METHODS

2.2.1 EXPERIMENTAL

The component test was performed on a Zwick Roell Universal testing machine with 500 kN load capacity. As shown in Fig. 3, the specimens were placed on two lower supports, which were aligned at a distance of 120 mm. The supports themselves were mounted on a cage made of aluminium extrusions to be able to measure the deflection directly below the sample with a tactile transducer. The specimens were loaded by two upper supports, having a distance of 40 mm (Fig. 3). The testing machine was controlled by the testXpert II software, which also performed the cyclic test sequence described below (Fig. 4). In addition to the load cell of the testing machine, displacement of the specimens was measured by means of a stereo digital image correlation (DIC) system (GOM 4M). With the aid the software ARAMIS resulting strains at each point in the measuring range could be calculated. After reaching a preload of 100 N, the DIC system was started and images were captured with a frame rate of 1 HZ up to final fracture. The 4-point bending test was carried out cyclically with a constant nominal crosshead speed of 2 mm/min. Each cycle consisted of a maximum deflection (Table 2) and four subsequent stages of descent from 30% to 70% of this previous maximum value. Between different cycles, a force of 100 N was maintained for 90 seconds. After eight cycles, the deflection has been increased until fracture of the specimen.

Fig. 3 *Setup of four- point bending test with DIC measurement.*

Table 2: *Cycle number and maximum deflection*

Cycle	1	2	3	4	5	6	7	8
Max. deflection in mm	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0

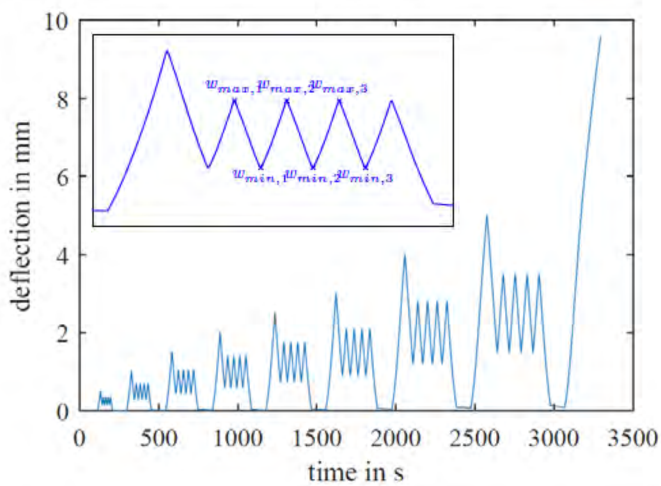


Fig. 4 *Cyclic deflection-time evolution of four-point bending tests.*

The global stiffness S of the specimen is calculated from the load F and the deflection w as follows:

$$S = \frac{F_{max,i} - F_{min,i}}{w_{max,i} - w_{min,i}} \quad (1)$$

with $i \in \{1, 2, 3\}$

Locations of w_{max} and w_{min} for a cycle are depicted in Fig. 4. They refer to the maximum and minimum deflection reached within the 30%-70% cycle after the maximum deflection of the cycle. $F_{max,\mathrm{min}}$ is the force at this point. The stiffness was calculated over the unloading phases and the arithmetic mean value of the three calculated stiffness values considered for one cycle was evaluated for the specimens with and without local reinforcement.

The decrease in stiffness can furthermore be represented as damage D, with D equal to:

$$D = 1 - \frac{S}{S_0} \quad (2)$$

and $D \in [0,1]$.
$D = 0$ means that there is no damage ($S = S_0$) and $D = 1$ means that the stiffness has dropped to $S = 0$ and thus there is complete damage of the structure. The stiffness from the first cycle is defined as S_0

3 RESULTS

3.1 BENDING TESTS

As explained in sub-chapter 2.2, the load data from the load cell, strain data from the digital image correlation and deflection data measured via a tactile transducer were recorded. These data are presented and evaluated in the following. Since the test was carried out deflection-controlled, the deflection data of the specimens are among themselves identical, except for the maximum deflection at breakage. The measured force, however, differed and will be discussed in the following.

In Fig. 5, the force values at the maximum deflection per cycle for reference structures solely made of discontinuous glass fiber SMC (DiCo GF) and specimens featuring an additional local reinforcement (DiCo GF with Co CF reinforcement) are compared with each other. It is clearly visible, that for components with local reinforcement the load increase over deflection is higher, i.e. the stiffness of the parts significantly increases due to the incorporation of a local reinforcement. At the last loading stage (8), the specimens with continuous carbon fiber reinforcements carry an average load surplus of 946 N in comparison to specimens without local reinforcement. That corresponds to an increase in strength of 32 %. Looking at the fracture strength at failure, the specimens with local reinforcement averaged 739 N higher than those without local reinforcements. That corresponds to approx. 17 %. Additionally, the deflection of specimens with local reinforcement at fracture is 15 % less compared to pure SMC parts. The scatter of the fracture strength is significantly reduced for parts featuring a local reinforcement. This is a first hint regarding the fact that the local reinforcement has an impact on the damage evolution.

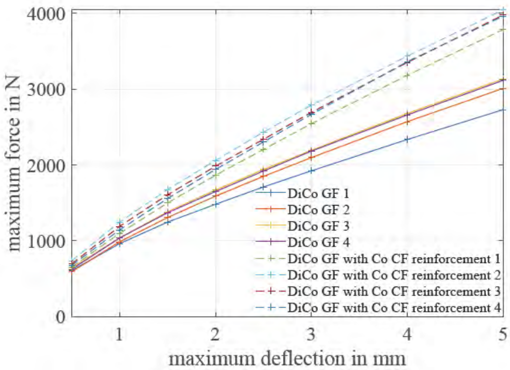


Fig. 5 *Evolution of maximum force during cyclic four-point bending test evaluated at maximum deflection of each cycle*

Figure 6 summarizes the corresponding stiffness of the two different specimens calculated from eq. 1. It is obvious, that the stiffness is significantly increased (approximately 250 to 300 N/mm) by the local reinforcement for every cycle.

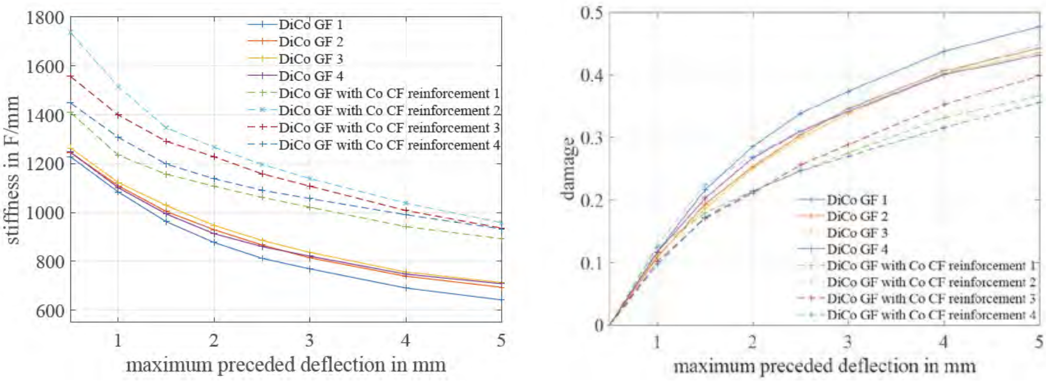
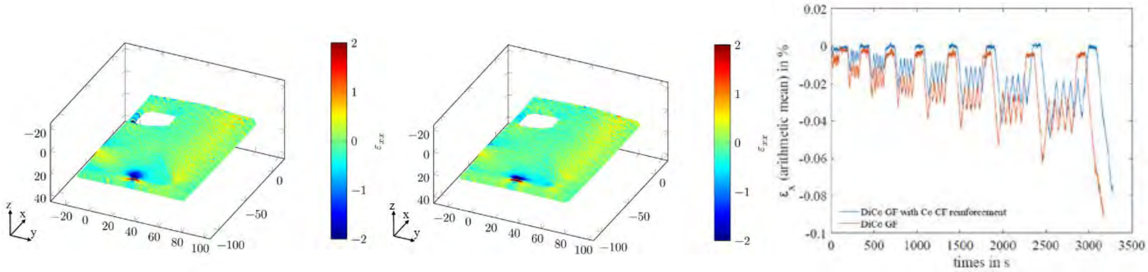


Fig. 6 *Stiffness and damage evolution due to cyclic four-point bending.*

Regarding the quantitative damage evolution, no significant difference can be expected. This assumption is proven by Fig. 5, which shows, that the stiffness loss for both configurations is comparable, whereas a certain tendency to lower damage parameters at equal stages for the reinforced parts is visible.

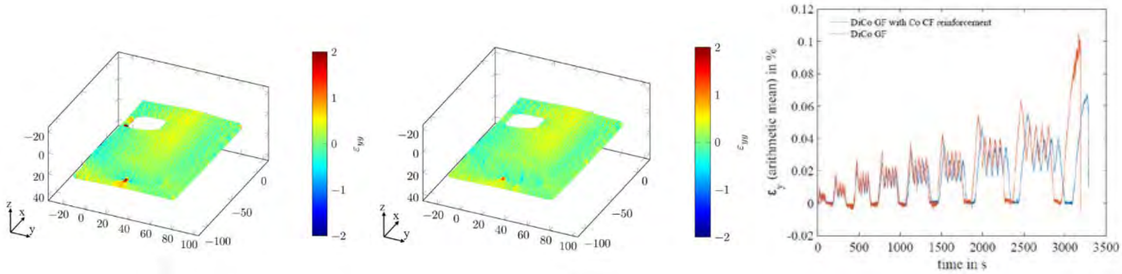
To analyze the data from the DIC system, a surface element was defined on the specimen via the software ARAMIS, which can be seen in Fig. 7 and Fig. 8. The surface element is the same for all specimens and the following results always refer to this surface element.



a) b) c)

Fig. 7 *Resulting strain field ε_{xx} (in %) corresponding to maximum deflection of cycle number 8 for reference structure (DiCo GF) (a) and reference structure with local reinforcement (DiCo GF with Co CF reinforcement) (b). Evolution of ε_{xx} during cyclic four-point bending test (c).*

Figure 7a and Fig. 7b shows the strain fields evaluated by ARAMIS for two exemplary specimens with and without local reinforcement. For both configurations the strain in the x direction at load stage 8 is shown. The large strain in the region of the supports is remarkable. At this point, significant differences between the two specimen types can be seen. In this respect, the reference part features a much larger area around the support with higher strain than the specimen with a continuous carbon fiber reinforcement. There are no significant differences on the remaining area. For these two specimen types, the arithmetic mean value of the strain is plotted for the entire test procedure (Fig. 7c). It can be seen that the part with reinforcement evolves lower average strain on the entire defined area in the x-direction than the reference specimen (DiCo GF). For the same specimen configuration, the strain on the same area in the y-direction is shown in Fig. 8a and Fig. 8b. Here, the higher strain in the region of he supports for the reference part extends to a larger area, too. Additionally, high strains stretching to the edge are visible, while for the specimen with reinforcements, the region with higher strains is localized to region of the lower support. The strain field on the remaining surface, however, hardly differs from each other. The averages over the whole region of interest show that the component with reinforcement elongates less than those without reinforcement, despite the same displacement (Figure 8c)



a) b) c)

Fig. 8 *Resulting strain field ε_{yy} (in %) corresponding to maximum deflection of cycle number 8 for reference structure (DiCo GF) (a) and reference structure with local reinforcement (DiCo GF with Co CF reinforcement) (b). Evolution of ε_{yy} during cyclic four-point bending test (c).*

3.2 DAMAGE BEHAVIOUR

The damage evolution for the specimen with local reinforcement does not differ significantly from those without local reinforcement. Both specimen types show a starting crack near an upper support point which propagates along the edge. This is shown in Fig. 9. Instable crack propagation after the last loading stage at very high deflection explain the sudden failure in the end of the testing sequence. Although the part is not symmetrical, no tendency for one certain side regarding the crack occurrence could be observed. In general, the cracks did not start at the same support point.

Nevertheless, taking a detailed view, it can be seen, that delamination occurs at the support points. For the locally reinforced part, this delamination is also occurring and even leads to a delamination of the continuous reinforcement from the surrounding matrix. This indicates that the interface between the continuously and the discontinuously parts of the component may be a weakest link although the chemical composition of the matrix is identical.

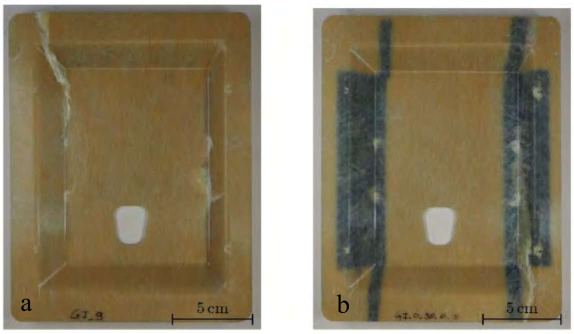


Fig. 9 *Damaged reference structures: discontinuously reinforced reference structure (DiCo GF) (a) and locally reinforced reference structure (DiCo GF with Co CF reinforcement) (b).*

4 DISCUSSION

The components with local continuous carbon fiber reinforcement feature superior mechanical performance both regarding the component stiffness and the stiffness decrease due to damage. However, there is a certain scatter in the initial value of the stiffness in comparison to pure discontinuous SMC parts. This may be a process-induced difference based on a misalignment of the local reinforcement. Of course, the relatively low number of investigated specimens has also to be taken into account. Looking at the average strains, it is noticeable that hardly any differences between the specimen types can be observed. Nevertheless, regarding the local strain evolution around the support, there is a certain difference between the locally reinforced structure and the pure DiCo GF SMC component. The heterogeneous strain field around the support is limited to a smaller region for parts featuring a local reinforcement. Consequently, the damage evolution for both configurations is also comparable except the fact, that samples with local reinforcement may show a delamination of the reinforcement from the surrounding matrix. Unfortunately, a direct comparison of the results presented here with the experiments carried out by Wulfsberg et al. [7] is not possible, as this preset contribution focused on a structural specimen instead of coupon specimens. However, it can be proven, that it is feasible to reinforce SMC parts regarding the overall stiffness with local reinforcements based on continuous carbon fibers in a one shot process.

5 SUMMARY AND CONCLUSIONS

The aim of this contribution was to determine the influence of continuous carbon fibers (Co CF), which were introduced as local reinforcement on a discontinuous glass fiber SMC component, on the stiffness and damage behaviour of the final component. It was shown, that components with local Co CF reinforcement offer significant advantages. The parts are stiffer without sacrificing the benefits of discontinuously reinforced SMC regarding the design freedom. Additionally, the material and manufacturing costs are lower in comparison to components manufactured solely from continuous fibers. As SMC is already widely used, this hybridization option enlarges the area of application of these components. In order to further characterize the material, other load cases must also be investigated in future. The shape of the specimen was designed for a bending load, but in reality often combinations of different types of stress occur. Further investigations with regard to realistic loads can show how the component geometry and shape of local reinforcement, or its position, can still be optimized for practical use.

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