Use of recycled carbon staple fibers in an advanced thermoforming process and analysis of its crash performance

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ABSTRACT
Carbon fiber reinforced polymer composites (CFRPC) are one of the promising lightweight materials in car production and show excellent energy absorption potential. In this paper, crash absorbers made of recycled carbon staple fibers (rCSF) and polyamide 6 are manufactured by an advanced thermoforming process in a multi-segment mold. The innovative wave design is meant to prevent the crash absorber from unintended crushing effects like bending or buckling and easy to manufacture by the investigated process. The formed crash absorbers were tested in a horizontal test rig by using a crash sled with an impact energy of 1925 J. The rCSF based crash absorbers feature a specific energy absorption (SEA) of 58.12 ± 0.58 J/g. Also, the standard deviation of the rCSF crash absorbers is remarkably low (1.0%). Thus, rCSF based crash absorbers represent a viable alternative to crash absorbers made of virgin fibers.

GRAPHICAL ABSTRACT

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Introduction
Carbon fiber reinforced polymer composites (CFRPC) are one of the promising lightweight materials in car production but the production of carbon fibers requires much energy in combination with high production costs. A promising alternative is using recycled carbon staple fibers (rCSF) with a thermoplastic matrix for manufacturing parts, e.g. crash absorbers, in a fast and cost-effective thermoforming process. The advantage is not only the reuse of the carbon fibers but also the recyclability and an improved processability of the composite [1, 2], which allows faster cycle times and tooling with a reduced complexity in production. Besides a high specific (density-related) strength and stiffness, fiber reinforced polymer composites (FRPC) offer a high potential for energy absorption. These properties in combination with significant light weight capability are driving their use in many industry sectors. One example of a future application is the use of FRPC for crash absorbers in the automotive industry. These components absorb energy in the event of a vehicle crash to protect the vehicle occupants and are mounted in the engine compartment. Through the use of carbon fiber reinforced polymer composites (CFRPC), a high safety level in case of a front crash can be achieved. In addition, the vehicle weight and as a consequence the environmental impact can be reduced. Therefore, this paper investigates the mechanical potential of crash absorbers out of a recycled carbon staple fiber organic sheet (rCSF-OS) by employing an advanced thermoforming process for the manufacturing of an undulated crash absorber geometry (cf. Figure 1).

State of the art
In a thermoforming process components are manufactured out of organic sheet materials. This process can be divided into several steps: At first the organic
sheet material is heated up over its matrix’s melting temperature by using infrared radiators or convection ovens. Afterwards the melted material is transferred, mounted and positioned in a press with a transport system considering the cooling of the organic sheet while handling. Is the processing temperature of the material reached, the press closes and forms the resulting component. Thereby, the tooling in the press is temperate to a lower temperature than the melting temperature of the organic sheet material. After a material specific hold time of pressing, the material is demolded and trimmed to final dimensions [3].

With a thermoforming process short cycle times can be realized which makes it highly attractive for industrial applications (e.g. in the automobile industry). In this context a few examples of use (e.g. brake pedal, component carriers) can be already quoted [4–6].

The central characteristic value for measuring the crash performance of a material is the specific energy absorption (SEA). It is given in literature in J/g, and is calculated by the division of the absorbed energy $E_{\text{abs}}$ of the crash specimen with the crushed specimen mass $m_{\text{crush}}$ as follows (e.g. according to [7]):

$$\text{SEA} = \frac{E_{\text{abs}}}{m_{\text{crush}}} = \frac{\int_{0}^{s_{\text{crush}}} F(s) \, ds}{m_{\text{crush}}} \quad (1)$$

Crushing means in this case the (intended) destruction process of the crash absorber without its bending and buckling. The absorbed energy $E_{\text{abs}}$ of the crash specimen is obtained by integrating the force-displacement (F-s) curve of the crash test (cf. Figure 2) [7].

Another characteristic value for the assessment of the energy absorption behavior of crash absorbers is the crush force efficiency (CFE). It results from the quotient of the average force $F_{\text{avg}}$ (arithmetic mean value of all force values until the maximum displacement $s_{\text{crush}}$ is reached, cf. Figure 2) and the maximum force $F_{\text{max}}$ (cf. Figure 2) of the crash test. The CFE is calculated as follows:

$$\text{CFE} = \frac{F_{\text{avg}}}{F_{\text{max}}} \quad \text{(for constant cross sections)} \quad (2)$$

This value characterizes the force peak of the crash. For crash absorbers, high peaks mean high energy absorption with comparatively low displacement and have to be avoided because of the adverse effect on the vehicle occupants. Therefore, the CFE for an ideal crash absorber has the value 1 and indicates an even energy absorption over the complete crash displacement.

Research on crash absorbers can be subdivided on the basis of the matrix systems investigated. An overview of the state of research on thermoset crash absorbers (with focus on hybrid materials) is given by Supian et al. [8]. Hybrid crash absorbers, often made of steel or aluminum and an FRP coating, show better SEA values by using an FRP reinforcement [9–11]. Crash absorber made of steel show comparable SEA values to absorbers made of aluminum, usually in the range of 15–30 J/g [12, 13]. Crash absorbers with thermoplastic matrix were investigated with regard to the influences of the fiber type [14] fiber orientation [15, 16], failure mechanisms [17] and the thermoplastic type on the SEA value [18, 19]. The literature shows that especially for carbon fiber reinforced thermoplastics the SEA values are up to six times higher than the values of aluminum or steel.

It should be noted that the geometry of the crash absorber also affects the SEA value [20]. Most geometries used for crash testing and crash value determination are tubes and feature a constant cross section in crash direction. Because of their constant curvature they show high buckling stability [21]. Unfortunately manufacturing of tubes based on...
Compression molding is not possible using simple tooling. Also, open and closed rectangle profiles were deeply investigated [22, 23]. Due to their flat areas without any curvature, they tend more to local bending and buckling, which leads to a lower energy absorption of the specimens. To prevent this failure mode undulated specimens formed by sinus-wave or semicircular geometry (e.g., omega profile) can be used [24, 25].

With the finite element method (FEM) the crash behavior of crash absorbers can be modeled and predicted [26, 27]. The basis for the simulation and validation of the models is built by crash properties measured in experimental testing with specimens that show robust and reproducible results as well as a valid failure without buckling or bending of the specimen.

Materials

For the investigations in this paper, undulated crash absorbers were manufactured. The crash absorber consists of staple fiber organic sheet (SFOS) material made of recycled carbon staple fibers (rCSF) and polyamide 6 (PA6) staple fibers. The recycled carbon staple fibers were recovered from waste coils of Torayca T700GC-24k carbon fibers, produced by Toray Carbon Fibers America Inc. The new PA6 staple fibers (type Grilon P300) were manufactured by EMS-CHEMIE AG. Both fibers, rCSF, and PA6 are spun into hybrid staple fiber yarns, which are then used to manufacture non-crimp fabrics (NCF). The NCF features 400 tex weft yarns and 800 tex warp yarns. Due to the thread count of weft yarns being 4 threads/cm compared to 2 threads/cm for warp yarns, the NCF shows a balanced fiber distribution in 0° and 90°. A basic laminate of 1 mm thickness has been used, which had been produced at the IVW in a larger quantity by using a Continuous Compression Molding machine [28].

Due to the crash absorber thermoforming tool’s cavity of 2 mm, two layers of the basic laminate were co-consolidated by an autoclave, using the process parameters shown in Figure 3.

The final SFOS laminate architecture thus contains eight layers of NCF with warp yarns facing each other in order to facilitate nesting effects, cf. Figure 4.

The resulting SFOS provides a fiber volume content of 45% and shows comparable tensile and bending properties like conventional organic sheets (cf. Table 1).

Methodology

The specimen used for crash testing shown in Figure 5 has an innovative wave design. The undulation is implemented orthogonal to the crash direction (warp direction of fibers) of the specimen, preventing bending and buckling during crash testing, and consists of three wave crests and 2 wave troughs. The specimen has a dimension of \( l = 230 \text{ mm} \) in length and \( w = 75 \text{ mm} \) in width.

For increasing stability while crushing it has a tapered design in width: The amplitude of the waves increases from 5.5 mm to 8 mm in longitudinal crash direction of the specimen, with a constant curve period of 25 mm. Due to the tapered design the cross-sectional area of the specimen increases by 21.5% linear over the specimen’s length. The idea of this geometry is the easy manufacturing in combination with the efficient generation of comparable crash values that can be used for validating crash simulation models in FEM.

The manufacturing of this crash absorber geometry can be divided into four steps, as shown in Figure 6. At first, the plate materials were cut into square shape with a dimension of \( 275 \times 275 \text{ mm}^2 \) and dried for 24 h at 80°C. For heating and forming, each square plate was mounted in a movable frame using springs on each corner to ensure the movability of the plate’s edges in the molding process. The heating was performed between two infrared heater panels warming the plate from the upper
and bottom side. To track the temperature a thermocouple was attached to the upper surface of each SFOS. In addition, the mounting was shielded with an aluminum foil to ensure the fixation of the plate in the frame during the heating and forming process.

After reaching $T_{\text{heating}}$ in the infrared heating the specimen molding followed in the next manufacturing step. Process parameters of the thermoforming process are given in Table 2 and are visualized in Figure 7. Therefore, the frame together with the organic sheet was transferred via a short slide path through the heating and forming cycle.

![Figure 4: Build-up of eight-layered rCSF organic sheet material.](image)

**Table 1.** Mechanical properties of SFOS base laminate (mean value and standard deviation [SD]) [28].

| Unit  | Tensile strength | SD   | Tensile modulus | SD   | Bending strength | SD   | Bending modulus | SD   |
|-------|------------------|------|-----------------|------|-----------------|------|-----------------|------|
| Warp  | 805.0            | 66.9 | 52.3            | 3.8  | 585.4           | 37.1 | 38.8            | 3.1  |
| Weft  | 551.0            | 46.7 | 46.3            | 1.7  | 688.1           | 53.1 | 43.0            | 4.0  |

![Figure 5: Undulated crash absorber specimen.](image)

![Figure 6: Specimen manufacturing of the undulated crash absorber in 4 steps.](image)

**Table 2.** Process parameters of thermoforming process.

| $T_{\text{heating}}$ | $T_{\text{forming}}$ | $T_{\text{press tool}}$ | Hold time | Molding pressure $p$ | Conditioning |
|-----------------------|-----------------------|--------------------------|-----------|----------------------|-------------|
| $^\circ C$            | $^\circ C$            | $^\circ C$               | s         | bar                  |             |
| 270                   | 230                   | 130                      | 60        | 25                   | Drying 24 h at 80 $^\circ C$ |
to a hydraulic press. During the time of frame moving the organic sheet cooled down to the forming temperature $T_{\text{forming}}$ (cf. Table 2 and Figure 7). The sheets were positioned between an upper and bottom press tool; both heated to a nominal constant temperature $T_{\text{press tool}}$ (cf. Table 2 and Figure 7).

While the bottom tooling had a solid form, the upper tooling consisted of three spring-loaded advancing slides (as shown in Figure 8) helping to form the undulated specimen geometry. The spring-loading is performed using three springs in parallel with an equal spring rate $D_{\text{spring}} = 1.852 \text{ N/mm}$ in the middle as well as in the front and back end of each advancing slide. This results in an overall spring rate of $D_{\text{adv.slide}} = 3 \times D_{\text{spring}} = 5.556 \text{ N/mm}$. When closing the hydraulic press, the organic sheet comes in contact with three deformation sensitive (spring-loaded) advancing slides (cf. Figure 8, Step 1). By further closing of the press the middle advancing slides stays ahead of the ones on the right and left side until the first contact with the bottom tooling (cf. Figure 8, Step 2), because the organic sheet is still over the matrix’s melting temperature and mounted in the frame, resulting in a bending of the sheet material. Despite the same spring rate of all springs it is chosen to be capable of adjusting to the bending of the material. When contacting the bottom tooling, the middle advancing slide begins to move backward faster than the neighboring ones until it reaches the same level. In this case, the left and right advancing slide contact the bottom tooling as well.

Because of the advancing slides’ movement, the tooling represents a self-adjusting forming process until the press is closed and the springs of the advancing slides are fully compressed. This forming process is complete in around 2 s (cf. Figure 7, “Closing mold”).

After closing the tooling completely (as shown in Figure 8, Step 3), a molding pressure of $p = 25\text{ bar}$ was applied for 60 s. The molded rCSF-specimens had a thickness of 1.8 mm corresponding to the initial organic sheet thickness.

In the third step of manufacturing the molded organic sheets were tailored to the final dimensions. The edges in width direction were cut because they do not contribute to a desired crushing failure of the crash specimen. In the last step, the impact edges of the specimens were provided with 45° chamfers on both sides to trigger a crushing failure and to ensure the first contact with the crash sled in the median plane of the specimens.

The test set-up for crash testing is shown in Figure 9. The crash specimen was clamped vertically to the test stand wall. The test was performed by a crash sled which was mounted on rails and onto the specimen drives in longitudinal direction of the specimen. The impact energy is defined according to formula 3 by the weight of the sled $m$ and the nominal sled velocity $v$ at which it comes in contact with the specimen.

$$E = 0.5 \times m \times v^2$$  \hspace{1cm} (3)

All the tests were carried out with a sled mass of 60.15 kg and a nominal sled velocity of 8 m/s,
resulting in a nominal crash energy $E$ of 1925 J. The impact on the specimen was filmed by a high-speed camera for qualitative evaluation of the specimens’ failure mode. During the crash test, a load cell mounted behind the clamping measured the force progression. A laser-Doppler vibrometer was used to record the associated displacement signal of the sled for the output of a force-displacement diagram. With this diagram, the energy absorption of the specimen and the SEA value (according to formula 1 and 2) were measured. In this study 3 rCSF crash specimens were tested.

**Results**

All specimens could be successfully manufactured using the thermoforming process explained above. The reason for this lies not only in the application of advancing slides in the tooling but also in the ability of the rCSF to slide past each other while the matrix material is in a flexible state.

Focusing the laminate quality, microsections in warp and weft direction of the rCSF organic sheet base material as well as cross sections of the tested specimens’ wave geometry were investigated. Exemplary microsections of the base material and a crash specimen (rCSF-PA6-1) are visualized in direction of the warp yarns (crash direction) in Figure 10. In these microsections, all fibers are fully covered with matrix material and no delamination of the laminate layers are visible indicating a good consolidation quality, especially of the thermoformed crash specimen. In addition, no voids are visible in the microsections. Typical water or air inclusions could be prevented by pre-drying the PA6 material before manufacturing of the base material and thermoforming of the specimens. All in all, the good laminate quality of the crash specimens in comparison to the base material indicates the potential of the thermoforming process using rCSF organic sheet material.

The force-displacement and energy-displacement curves (CFC-300 filtered) of the tested rCSF crash specimens are shown in Figure 11. The progression and reproducibility of the rCSF-curves are almost ideal. After the impact on the specimen, the force initially increases and the first force peak is reached directly. After this peak, the force is slightly rising during the crushing of the specimen due to its conical geometry and increasing cross-sectional area as mentioned before.

For calculating a comparable CFE value the force values have to be normalized by a geometry function of the undulated specimen. Therefore, the geometry function $P_{\text{area}}(x)$ is implemented, which is a linear function of the normalized specimen’s
cross-section area increase depending on the specimen length $x$ given in formula 4:

$$ P_{\text{area}}(x) = (9.3266 \times 10^{-4}) \times x + 1 \quad (4) $$

To normalize the force curves of the specimens, they were first cut before their first and after their last force peaks. The resulting force progressions were then divided by the geometry function according to formula 4.

The geometry-normalized force-displacement curves and average force values of the rCSF material are visualized in Figure 12. The mean CFE value based on the normalized force data is $0.87 \pm 0.05$ (according to formula 2). An overview of all relevant testing values of the rCSF-crash specimens is given in Table 3.

In order to classify the specific energy absorption of the investigated material, Figure 13 shows a comparison to the reference material and literature values for similar fiber-matrix combinations and a selection of metals. If the literature indicated several SAE values (e.g. by alternating fiber orientations, fiber volume contents, etc.) the highest value was chosen. All SEA values of glass fiber reinforced test
specimens in Figure 13 are exceeded by up to 141% by the rCSF organic sheet. With a value of 58.12 ± 0.58 J/g the rCSF material shows a comparable value to other CF-PA6 specimens in literature. The significant higher value of 66 J/g according to [19] can be attributed to the fiber orientation of the tested material (2/3 of the fibers in crash direction), since the second value of 59 J/g was determined identically. The only difference is a divergent layup (equals ±45°/C14 and 0°/C14-layers in crash direction).

The comparison of the different SEA values should only be used as an orientation since the values are partly based on different fiber orientations, fiber volume contents, specimen geometries, test methods, and other factors. The comparability is therefore limited. However, it can be stated that rCSF organic sheets have a comparable crash performance to CF-PA6 organic sheets.

**Summary and conclusion**

In this paper, crash absorbers made of recycled carbon staple fibers (rCSF) and polyamide 6 (PA6) were manufactured by a multi-segment mold in an advanced thermoforming process. By using advancing slides and the ability of rCSF to slide past each other during forming, the manufacturing of undulated crash absorbers out of rCSF organic sheets (rCSF-OS) has been proven. Moreover, it can be stated that the rCSF-OS material can be conventionally processed like OS materials out of virgin fibers.

The manufactured crash absorbers were tested in a horizontal test rig by using a crash sled with an impact energy of 1925 J. The rCSF based SFOS crash absorbers feature a specific energy absorption (SEA) of 58.12 ± 0.58 J/g and show a high CFE value of 0.87 ± 0.05.

The wave design was intended to prevent the crash absorber from crushing effects like bending or buckling. This has been proven by rCSF crash absorbers.

It is remarkable that the rCSF-PA6 organic sheets show a comparable crash performance to CF-PA6 organic sheets and a very low standard deviation of 1.0% for the SEA value. This low standard deviation could be related to the specific staple fiber architecture of the used SFOS and should be a topic of future research.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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