CRASHWORTHINESS CHARACTERISTICS OF CARBON-FLAX COMPOSITE TUBES FOR AEROSPACE APPLICATIONS

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Abstract

The specific energy absorbing capabilities of composite tubes with woven flax and carbon layers were analyzed and evaluated using quasi-static and dropping-weight compression tests. Four different lay-ups were manufactured, each made of eight woven layers of either flax, carbon or both with fiber orientations of 0°. The quality of the tubes was analyzed using microscopic imaging. The hybrid tubes showed a high fiber volume fraction, which lead to a lower weight than expected and was explained by a denser volumetric packing of the fibers in their interface-area. For crashworthiness analysis, the specimens were first loaded under quasi-static pressure, then with an $8\,\mathrm{m/s}$ impact load. The stacking order showed an influence on the crushing mode of the tubes, while the common crushing mode was splaying, the $[C_2/F_2]_S$-tubes crushed in fragmentation mode. Dynamically tested, the pure carbon tubes also showed the fragmentation mode. The dynamic analysis of CF-stacked hybrid tubes resulted in good specific energy absorption, which means only 15% less than the respective pure carbon fiber reinforced tubes, with a 24% bio-based mass fraction. Also, the hybrid tubes were not as sensitive to the testing speed as the carbon tubes, which could be beneficial for a wide range of crashworthiness applications.

1. Introduction

The demand of sustainable materials evolved with the environmental awareness, leading to political and scientific interest in bio-based materials such as flax. Bio-based materials can reduce the environmental footprint of structural parts due to the a lower energy consumption of the production process [6]. Another promising factor is the lightweight potential, as flax fibers have a lower density than conventional fibers, such as carbon and glass [21] ($\rho_{Flax} = 1.4 - 1.5\,\mathrm{g/cm^3}$, $\rho_{Glass} = 2.5 - 2.6\,\mathrm{g/cm^3}$, $\rho_{Carbon} = 1.7 - 1.8\,\mathrm{g/cm^3}$). Also, the energy dissipating properties are emphasized in different sources, including very good vibrational damping, crash absorbing and impact resistance properties [14, 1, 18, 15, 12].
The aim of crashworthiness in helicopter applications is to reduce the peak loads that injure the occupants,

keep the integrity of the cabin, reduce the hardware damage and minimize the risk of post-crash dangers, such as fire [10, 9]. Representative crash scenarios of helicopters show, that the 95^{th}-percentile velocity of survivable accidents in longitudinal direction is $15.24\,\mathrm{m/s}$ and in vertical direction $7.92\,\mathrm{m/s}$ respectively [5]. The survivability of the occupants can be evaluated using Eiband-curves [7] which show human tolerances of loads over time.

Crashworthiness applications require, in order to serve the survivability of occupants, a low initial peak force and a steady state force with low scatter, while dynamic energy is absorbed. In this manner, the most energy can be absorbed without endangering occupants.

In this work tube geometries were chosen, as they are commonly used in seat crashworthy structures. The goal of this research is to find out about the potential of flax and carbon woven hybrid laminates for crashworthiness structures. A high potential of specific energy absorption (SEA), crush force efficiency (CFE) and stroke efficiency is expected by the low density accompanying high energy absorbing properties of the flax-laminates [2, 13]. On the other hand the (compression) strength of flax is significantly lower than the strength of carbon [4] ($\sigma_{c,ult,Flax}$ =119 MPa [3], $\sigma_{c,ult,Carbon} > 1000\,\mathrm{MPa}$ [11]).

2. Specimens and Laminates

The flax material for this work was received by Lineo, with the identification: FlaxPly BL 150, the carbon weave (identification: CW200-TW2/2-E503-45%) was produced by the SGL Group.

The flax material was a 2/2-twill weave of $150\,\mathrm{g/m^2}$ and the carbon material was a 2/2-twill weave of $200\,\mathrm{g/m^2}$. Both were chosen due to same thicknesses and comparable meshing sizes. Additionally, in prior studies the $150\,\mathrm{g/m^2}$ showed better mechanical behavior than the $200\,\mathrm{g/m^2}$ flax material [16]. All specimen tubes were produced with eight woven layers and fiber orientations of 0°/90°regarding the cylinder axis.

The tubes were made using prepreg materials and autoclave curing with the following parameters: $-0.95\,\mathrm{bar}$ (vacuum), $5\,\mathrm{bar}$ (external pressure) and 140 °C for 2 hours, with heating and cooling rates of 2 °C/min. All tubes have a cylindrical shape with both a hight and an outer surface diameter of $50\,\mathrm{mm}$. The wall thickness is approximately $2\,\mathrm{mm}$ for each tube and a 45° chamfer is applied for crack initiation at the top of each tube. In Figure 1 the geometrical dimensions are shown, including precision values as well as stack-up.

The high thickness range of 1.1-$4.1\,\mathrm{mm}$ results from folds in the cured specimens, which appeared due to the inner mold core for the production. Nevertheless the quality was considered feasible for the planned crash tests and the folds should have a neglectable influence on the crashworthiness parameters compared to the different materials of investigation.

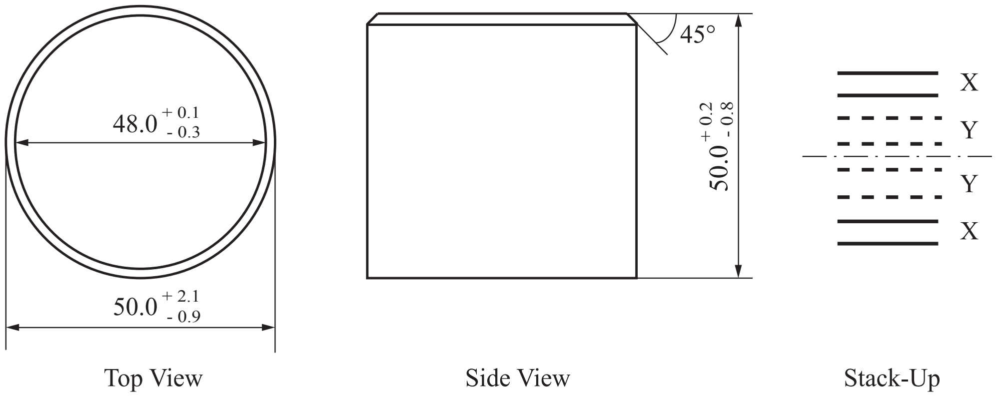


Figure 1. Dimensions of Test Specimens and Stack-Up

Four different configurations were investigated, stacked-up in the forms $[C]_8$, $[C_2/F_2]_S$, $[F_2/C_2]_S$ and $[F]_8$. In Figure 1, X and Y label the layer materials. In tables and explanations, the specimen indication is written in the form XYi, where X names the outer and inner layers and Y the material of middle layers, with C for carbon and F for flax. i indicates the number of the specific specimen, e.g. "CF2".
As flax fibers are not endless, they need to be spun into a yarn for the weave fabrication, the diameter of a yarn is about 5 to 10 times the diameter of a fiber, which can be seen in Figure 2. The resulting large bundles lead to a large spacing in the weave between the yarns, as well as a high void content inside each bundle. Some yarns seem to be hollow, which can be seen in the longitudinally cut fiber bundles in the microscopic pictures of FF and FC in 4-20x magnifications. Nevertheless, the fiber-matrix bonding also showed good results in the higher magnifications of 50x where the cross-section is perpendicular to the fiber yarns, Figure 2.

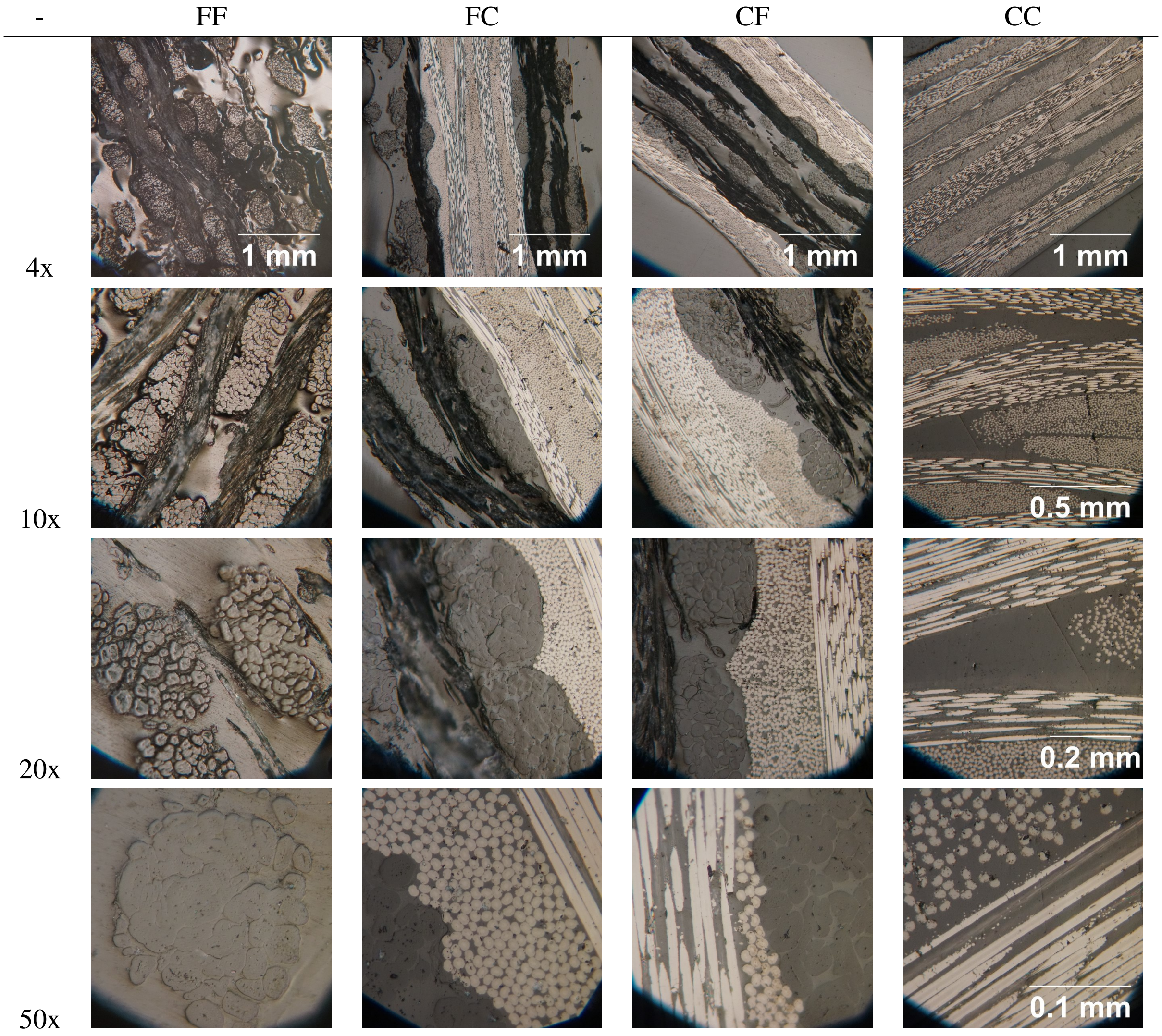


Figure 2. Microscopic Inspection with Different Magnifications, all Specimen

The volume content was calculated by equation (1) (next page) using weight and size measurements with data of the respective Technical Data Sheet. The sums over i and j are iterating the used materials. The specimens weights and the fiber volume fractions with respective standard deviations, are shown in Table 1.

Significantly, the masses of the hybrid tubes do not order linearly between the weights of pure carbon and pure flax tubes. The expected mass of the hybrid tubes was about 19 g instead of the measured values at around 17.6 g. The lower weight resulted in the assumption of a higher fiber mass and volume fraction within the hybrid laminates than within the pure laminates. In order to verify this statement, the microscopic inspection was analyzed in the contact area of both laminates. It was observed, that a more compact packing due to different fiber diameters of flax and carbon was a possible explanation. Both laminates were pressed in between each other (Figure 2 CF and FC columns, where carbon fibers appear light colored and flax fibers dark). Still, the standard deviations of the measured data was high, and this statement needs further verification.

For analysis of the environmental benefit, the bio-based mass content was calculated as well. With a non-bio-based matrix, only the flax-content was considered bio-based. The results are listed in Table 1 as well.

In order to obtain equal testing conditions, the tubes were conditioned at 23°C and 40% rel. humidity before testing at laboratory conditions.

Table 1. Average Masses, Fiber Mass and Volume Contents and Bio-Based Mass Fractions with respective standard deviations of each Lay-Up Configuration

Configuration unit	Mass [g]	s [g]	Fiber Volume [vol.-%]	s [vol.-%]	Fiber Mass [mass.-%]	s [mass.-%]	Bio-Based Mass [mass.-%]
CC	21.4	1.62	46.2	4.05	56.8	4.02	0.0
CF	17.6	0.76	50.4	2.56	58.6	2.47	24.2
FC	17.7	0.86	50.0	2.72	58.2	2.66	24.0
FF	16.6	1.13	46.3	3.73	51.5	3.74	51.5

3. Methodology and Test

The energy absorbing capabilities of hybrid layered tubes with woven flax and carbon layers should be evaluated within this project. Therefore specimen will be crashed under a static pressure test with a speed of $5\,\mathrm{mm/min}$ and afterwards dynamically with a dropping weight at an aimed speed of $8\,\mathrm{m/s}$.

In order to analyze the crushing behavior on the basis of the different force-displacement curves, the equations (2)-(8) were used. x_1 indicates the stroke at the first force minimum after the first peak force and was set to 5 for all specimen, see Figure 4. a is set to 29 for all specimens, as this was the lowest crushing length appearing, to make comparison between the results easier. The results of the different specimens are listed in Table 2 for the static and dynamic tests.

$$\varphi_f = \sum_i \frac{\frac{m_{f,i}}{\rho_{f,i}}}{\sum_j \frac{m_{f,j}}{\rho_{f,j}} + \frac{m-\sum_j m_{f,j}}{\rho_m}} \qquad (1)$$

$$E_{abs} = \int_0^a F(s)\,\mathrm{d}s \qquad (2)$$

$$E_{spec} = \frac{\int_0^a F(s)\,\mathrm{d}s}{m_{destroyed}} \qquad (3)$$

$$E_{dens} = \frac{\int_0^a F(s)\,\mathrm{d}s}{V_{destroyed}} \qquad (4)$$

$$F_{mean,s} = \frac{\int_{x_1}^a F(s)\,\mathrm{d}s}{s_{max}} \qquad (5)$$

$$\sigma_{mean} = \frac{F_{mean,s}}{A} \qquad (6)$$

$$F_{peak} = max(F(s)) \qquad (7)$$

$$\eta_{eff} = \frac{F_{mean,s}}{F_{peak}} * 100 \qquad (8)$$

First, one specimen of each configuration was tested in a static compression test. The testing machine was a hydraulic press, in combination with a $100\,\mathrm{kN}$ (noise $s_{Force} = 0.82\,\mathrm{N}$) load cell. The test results were used to calculate the energy levels for the dynamic test setup. Figure 3 shows the quasi-static test in four different states of compression and the two hybrid specimen layups, recorded by a conventional video camera. A difference in the crushing mode can be seen, which will be addressed in the "Results and Discussion" section.

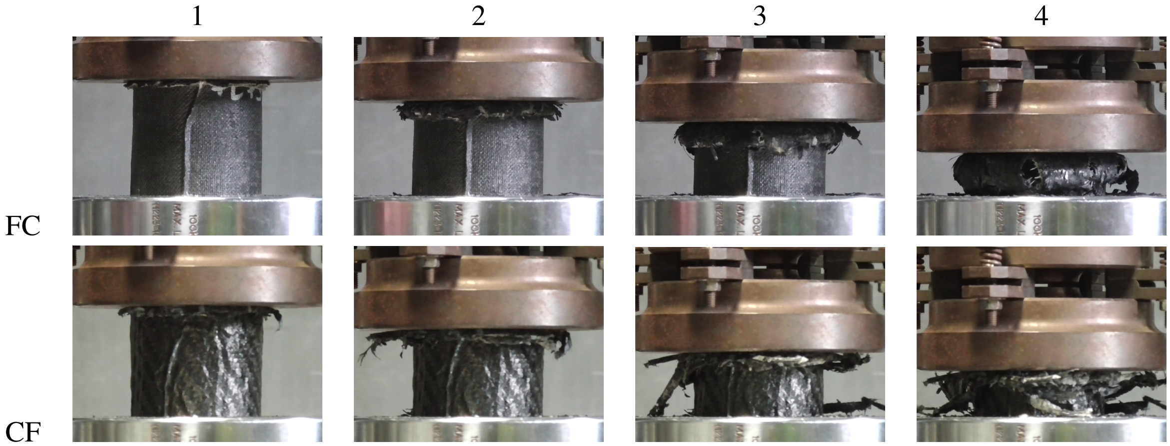


Figure 3. Splaying and Fragmentation Mode of the FC1 and CF1 Specimen during the Quasi-Static Compression Test

The dynamic tests were performed in cooperation with the Institute of Composite Materials in Kaiserslautern, Germany. A drop weight tower was used with a $400\,\mathrm{kN}$ (noise $s_{Force} = 94.4\,\mathrm{N}$) load cell, a laser-displacement sensor and a high-speed camera for recording the crashing behavior itself. The noise of the load cell signal results for the weakest probes in an measurement error of 1.9 %.

The target velocity of $8\,\mathrm{m/s}$ was fulfilled within a range of 7.53-$8.04\,\mathrm{m/s}$ with a median of $7.91\,\mathrm{m/s}$, which is very close to the vertical crash requirement as defined in MIL-STD-1209A ($7.9\,\mathrm{m/s}$) [9]. The resulting weights and heights were calculated with conservation of energy rules, aiming 85% of the static absorbed energy (AE) over a crushing length of $35\,\mathrm{mm}$. 85% is a typical ratio of dynamic and quasi-static energy absorption of conventional composites, according to references [9, 17].

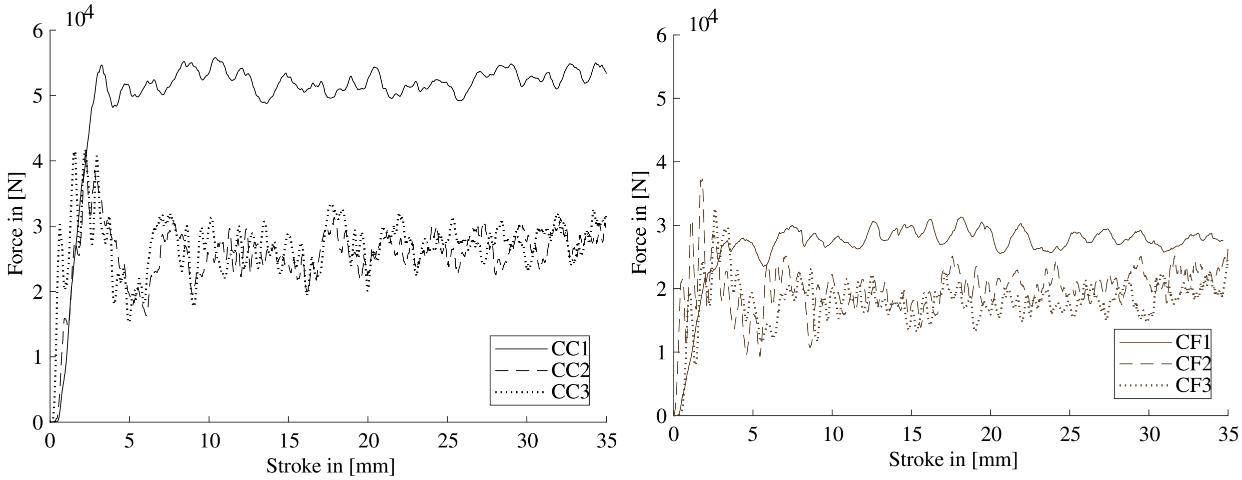
4. Results and Discussion

The results of the quasi-static and dynamic test analyses are listed in Table 2. Also, the force-displacement curves, grouped by each configuration, are plotted in Figure 4. All specimens showed lower energy absorption under dynamic loading, than under the quasi-static compression, which is a typical phenomenon in crash-testing [17].

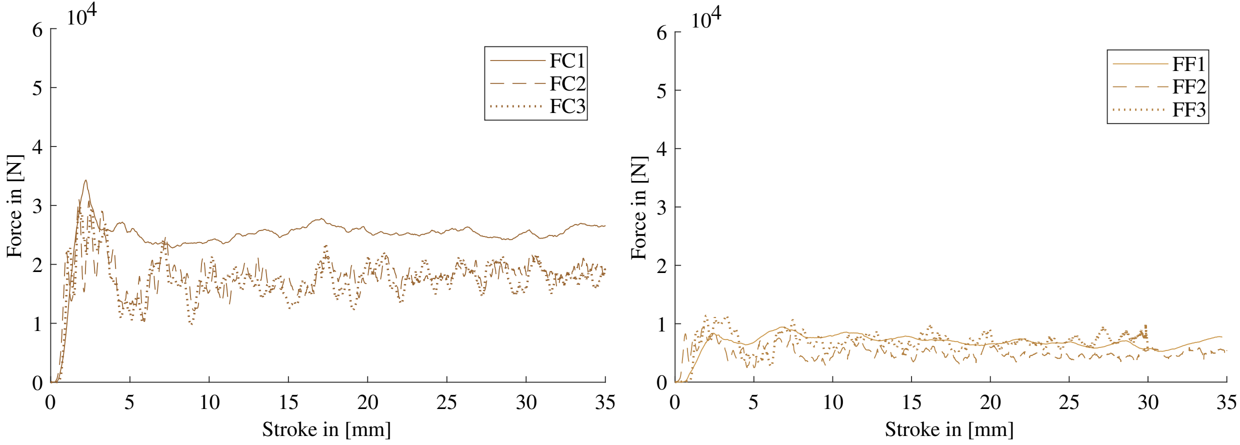
The peak force was comparable in static and dynamic tests, for all flax-including tubes, for the pure carbon tubes, dynamically tested specimens showed significantly lower peak forces. Also, the CC and CF specimens in static tests show a higher scatter around the mean force while the FF and FC specimen show a rather smooth quasi-static force-displacement curve. Generally, the dynamic tests showed a higher scatter than the quasi-static tests, in all configurations.

Table 2. Summary of Results from Quasi-Static and Dynamic Compression Tests of All Specimens

Specimen	E_{abs}	E_{spec}	E_{dens}	F_{mean}	σ_{mean}	F_{peak}	η_{eff}	Mode
unit	[J]	[J/g]	[J/cm^3]	[kN]	[MPa]	[kN]	[%]	-
equation	(2)	(3)	(4)	(5)	(6)	(7)	(8)	-
CC1-s	1420.2	103.6	79.5	52.0	84.4	55.81	93	Splay.
CC2	732.5	62.0	41.02	25.6	41.5	41.42	62	Frag.
CC3	775.2	62.3	43.4	26.8	43.6	41.69	64	Frag.
CF1-s	768.2	71.2	47.9	28.0	50.7	31.30	90	Frag.
CF2	566.6	53.9	35.3	19.7	35.6	37.31	53	Frag.
CF3	515.1	52.9	32.1	17.8	32.2	32.61	55	Frag.
FC1-s	710.0	63.5	41.9	25.1	43.0	34.31	73	Splay.
FC2	511.6	48.3	30.2	17.7	30.4	31.13	57	Splay.
FC3	498.8	49.7	29.4	17.5	30.0	29.75	59	Splay.
FF1-s	200.8	19.3	11.2	7.3	11.8	9.43	77	Splay.
FF2	145.2	16.0	8.1	4.9	7.9	9.39	52	Splay.
FF3	197.8	19.9	11.1	7.1	11.5	11.38	62	Splay.



a) CC b) CF



c) FC d) FF

Figure 4. Force over Stroke in the Quasi-Static and Dynamic Test ordered by Configurations

The 45°chamfer seems to fulfill its purpose to trigger the crushing in order to reduce the peak to mean load ratio (Crush Force Efficiency - η_{eff}) [19], nevertheless, within results of the hybrid specimens this effect is less apparent, than with the pure specimens. And generally, the dynamic tests show lower η_{eff}-values, than the quasi-static results. Pure carbon tubes showed the strongest decrease of total absorbed energy between quasi-static and dynamic tests, with the total and specific absorbed energy being reduced by almost half. The hybrid and pure flax specimens showed a lower reduction of these parameters, only about 30%. It appears, as if the flax material is less sensitive to changes in the impact velocity. Regarding the low batch sizes and strong variations in parameters, this statement needs further verification. As only one tube of a kind was analyzed in quasi-static testing, and the carbon tube showed a high specific energy absorbed, compared to other research results [17], this discrepancy could be due to an statistical outlier. The pure flax tubes ordered well in between respective research results [13, 19].

In terms of energy dissipation as well as mean force and mean stress, the CF specimens were slightly better than the FC specimens, considering the same materials, the stacking order seems to influence the results. Additionally, mean force and mean stress levels of the hybrid tubes do not order linearly between the pure carbon and flax tubes. This emphasizes the potential of the hybridization.

Comparing the different stack-ups, the hybrid tubes showed good performance, with down to 13% lower specific energy absorption than the pure carbon tubes, while using 24% bio-based material. The energy dissipation density E_{dens} shows similar ratios.

In terms of crushing modes, there were two modes observed: splaying and fragmentation mode, where the splaying mode is the more common mode [18, 19, 20, 17], see Figure 5.

In the splaying mode the main failure mechanism is delamination in axial direction, where some layers curve to the outside and others to the inside of the tube, forming curvatures around the tangential axes of the cylinder. The fragmentation mode is different, the main failure mechanism is shear failure, which makes circular parts rip off the cylinder in radial direction and form small fragments around the tube.

The FF and FC tubes always crushed in splaying mode, which can be seen in Figure 5 c) and d), while the CF specimens always crushed in fragmentation mode, Figure 5 b). Significantly, the CC-specimens showed a splaying mode in quasi-static testing, while crushing in fragments when tested dynamically.


a) CC b) CF c) FC d) FF

Figure 5. Crushing Modes, Photographs after Quasi-Static Compression of all Configurations

In [8] the effect of the different failure modes is explained by the friction coefficient between the tool and the specimen surface. In the quasi-static test, the fragmentation mode only occured on the CF specimen, the friction coefficient might be higher, with the flax layers in between the carbon layers having a less smooth fracture surface. The strong carbon layers hold them upright, with the fracture surface being grated by the tool.

Another explanation is, that the flax composite is more ductile, compared to the brittle carbon composite. The outer layers, either brittle oder ductile, dominate the crushing behavior and define the crushing mode, especially in dynamic tests.

5. Conclusion

The crushing behavior of hybrid carbon and flax tubes was experimentally investigated using a quasi-static testing speed and a dynamic test with an impact velocity of about $8\,\mathrm{m/s}$. To compare the results all tests were also performed with pure carbon and pure flax tubes. Generally, the hybrid epoxies linked well and a dense volumetric packing could be observed within microscopic inspections of the hybrid tubes. The differently sized fibers and yarns showed compact interspaces with bundles of each in between the others.
Hybrid specimens showed better values than expected, in terms of mass, energy absorption, mean crushing force and stress. The values did not order linearly between the values of pure material specimens, but were shifted in a positive way. Thereby the potential of the hybridization could be emphasized. The CF specimens showed good potential in terms of specific energy absorption, with about $53\,\mathrm{J/g}$ being only 15% lower than the values of the pure carbon specimens. Additionally, the hybrid and pure flax specimens showed crushing behaviors less sensitive to the crushing speed than pure carbon specimens.
In general, the outer layers of the tubes were dominating the behavior. Either in terms of crushing modes, as outer carbon layers were rather showing the fragmentation mode and flax always the splaying mode, as in terms of mass, energy absorption and loads, where the CF-specimens' results were closer to the ones of pure carbon and the FC specimens showed results closer to the FF-specimens.
All in all, a first insight was given on hybrid carbon and flax tubes' crushing behavior and the potential of the CF-stacked tubes could be emphasized. Nevertheless, the sample size was small, with only three specimens per configuration and the manufacturing quality varied, therefore the results and assumptions need further verification. Additionally, different stack-ups and a variation of fiber angles could be an interesting matter of investigation.

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