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Design and manufacture of long-lasting lightweight structures for sustainable mobility

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Keywords

Circular Economy, Crash, Fiber Reinforced Plastics, Pultrusion, Reuse

Abstract

The focus in this paper is on the latest results of the crash, reuse and remanufacturing design concepts for a durable sill structure for a modular vehicle platform architecture. Like the entire vehicle platform the sill structure is also designed modular, with the possibility to replace damaged or to reuse intact components. The innovative sill structure consists mainly of durable carbon fiber reinforced composite plastic (CFRP) crash absorbers in the form of tubes and a C-profile manufactured by a cost effective serial process – pultrusion. Those crash tubes were designed using experimental and numerical knowledge based on internal studies. A special layup was chosen to achieve the highest energy absorption in case of a crash. Therefore, the mechanism of crushing and inversion are targeted. The innovative alignment of the crash tubes consider protection against oblique impact according to the latest NCAP standards. For a smooth transmission of the incoming force into the tubes, an auxetic-structured buffer element is placed between the outer C-profile and the crash tubes. In case of a crash or a vehicle design change, intact crash tubes can be reused or remanufactured thanks to the high durability and detachable connections, which corresponds to a cycle concept.

1 Introduction

The automotive production as a very energy and resource consuming economy is an important point to rethink the state of the art structures with the aim of generating a more eco-friendly future for example by means of circular economy. One step ahead in this direction could be a vehicle platform, which is long-lasting in the use. This is the basic idea of the project “KOSEL” [1]. The project is funded within the funding measure “Resource-efficient Circular Economy – Innovative Product Cycles (ReziProK)“. „ReziProK“ is part of the research concept “Resource-efficient Circular Economy“ of the Federal Ministry of Education and Research (BMBF).

The entire platform is designed with the focus on component durability and interchangeability. This is intended to reduce maintenance costs and achieve a longer life for the vehicle, especially the platform. The service life of the platform is decisive for the overall service life of the vehicle. This has been set at a minimum of 1,000,000 km, which is equivalent to five times that of a current vehicle. The service life of the components is correspondingly up to 30 years. Individual service lives must be determined for the respective add-on parts, as some of them are wearing components. Further specifics and requirements can be found on the official website [1]. This work is mainly focused on the development of the side crash protection for this novel platform and a reuse friendly design.

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2 Development of a concept for lightweight and durable crash protection

2.1 Relevant crash cases for the modular vehicle platform

First, the relevant crash load cases for the e-vehicle platform were selected and analyzed. As basis served the EURO NCAP standards (2020) as well as others, like IIHS and e-CFR *Table 1* and *Figure 1* show the final selected standards adapted to the 3.5 t vehicle class. Since the pole impact is significantly more critical in terms of battery protection (shortest intrusion path approx. 218 mm) than the selected frontal and rear impacts, it was considered first.

Table 1: Principal information on the considered crash standards for the design [2],[3],[4]

	Frontal impact (I)	**Oblique pole side impact (II)**	**Rear impact (III)**
Standard	EURO NCAP	EURO NCAP	e-CFR (49 CFR)
Overlap	40 % ± 20 mm	100 %	70 %
Direction of impact	0°	75° ± 3°	0°
Velocity	V_{VF} = 64 km/h ± 1 km/h (vehicle)	V_{VS} = 32 km/h ± 0.5 km/h (vehicle)	V_{BR} = 80 km/h ± 1 km/h (barrier)

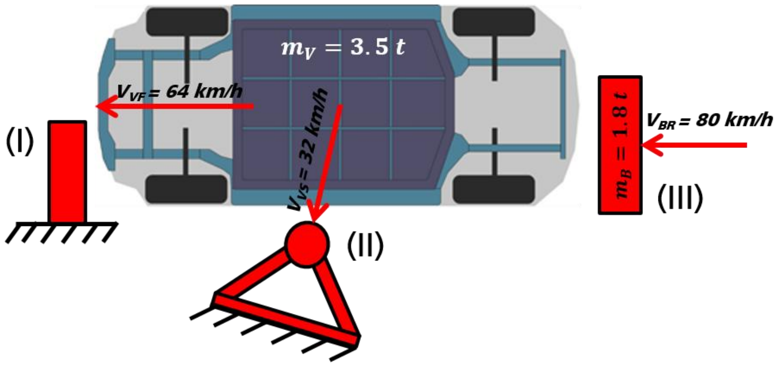

Figure 1: Load cases to be considered for the development of a crash protection for the vehicle platform

2.2 Conception of a durable fiber composite crash absorber

First concepts for FRP crash absorbers for crumple zones were derived from an internal study [5]. Selected and project-relevant concepts are shown in *Figure 2*. The focus was on the development of variants of crash tubes and C-profiles or sandwiches for crush-collapsible zones.

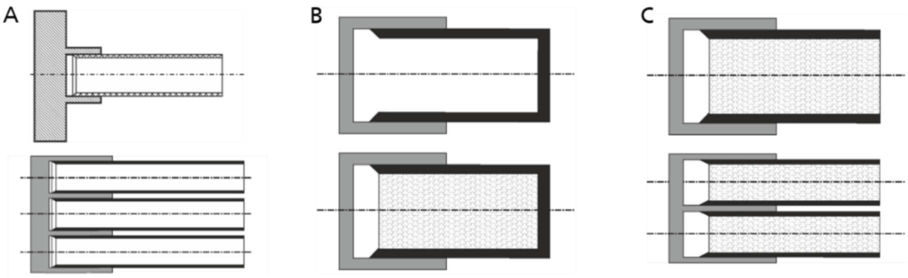

Figure 2: FRP tubes as crash elements, tubes arranged in several rows (A); FRP C-profile, foam core stabilizes walls during crash (B); Sandwich with FRP cover layers and foam core, foam core stabilizes cover layers during crash (C) [5]

Further development for the crash absorbers was based on previous investigations published in [5] and [6] and some other internal studies, which included the following project-relevant input:

- highly dynamic tests (8.9 m/s i. e. 32 km/h) with crash tubes and C-profiles made of CFRP,
- test of different crash mechanism principles suitable for FRP,
- measured force-displacement characteristics to derive empirical design factors,
- simulation models for CFRP tubes and C-profiles
- trigger design,
- favored ply design: $[\pm30°x/0°y]_S$, x/y=0.25,
- force introduction elements (auxetic structure),
- oblique impact tests with crash tubes up to 10° skew.

Furthermore, the following advantages from a circular economy point of view resulted for the use of the CFRP crash tubes and C-profiles in the KOSEL project:

- local replacement of crash tubes is possible (reuse of intact tubes),
- high durability of the CFRP material (long-lasting, predestined for circular economy),
- simple and cost-effective production by pultrusion process (continuous production for series),
- pultruded structures can be easily adapted in length (remanufacturing possible by cutting).

Previous experimental tests showed a good performance of the CFRP crash tubes up to 10° skew as shown in *Figure 3.* Additionally, an additive manufactured force introduction element has been designed and used to level force peaks, as shown in *Figure 4*. By the auxetic design of the structure the force introduction element contracts with the incoming force resulting in a more homogenous introduction of the force into the crash tubes, even in oblique test. This is important to avoid shock peak loads and high G-forces.

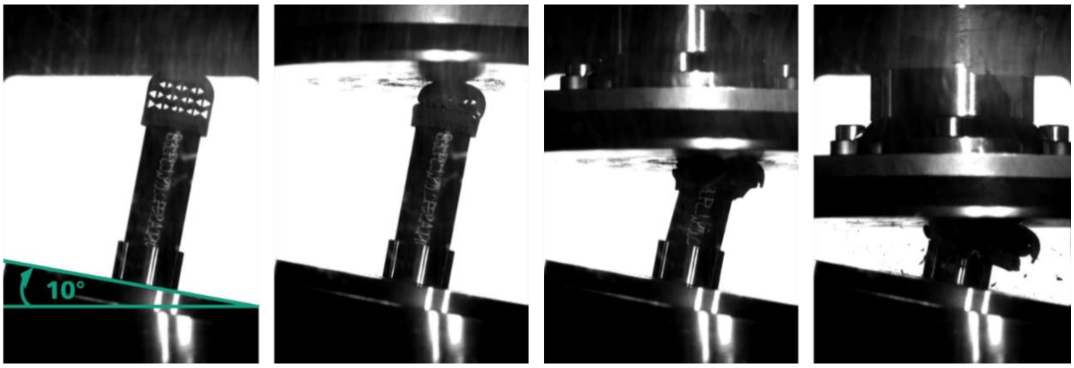

Figure 3: High-speed oblique test (8.9 m/s) with CFRP crash tube and auxetic force introduction element

Due to the increase in energy absorption of approx. 30-50 % by applying the inversion principle compared to simple crushing (see [6]), the inversion crash mechanism was chosen for frontal, side and rear crash absorbers. For this purpose, the internal study provided proof of function on individual crash tubes.

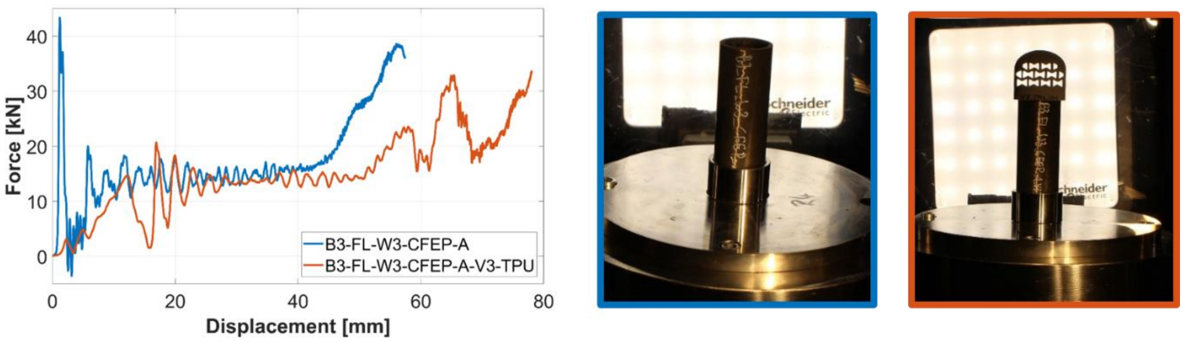

Figure 4: Influence of the auxetic force introduction element on the force-displacement curves

2.3 Long-lasting sill structure concept for circular economy

Based on the previous ideas and investigations, a concept-design for a long-lasting sill with CFRP components could be developed. To comply with the current EURO NCAP standards (side-pole impact with up to ±15° skew), a corresponding alignment of the CFRP tubes with ±5° angular position in relation to the Y-vehicle axis was set for the sill design (see *Figure 5*). This is realized by special mounts for the crash tubes with the defined angle of inclination. Furthermore the mounts enable the inversion crash mechanism, secure fastening, dismantling, and replacement. To achieve a smoother force transmission an auxetic structure in the form of an elongated buffer element is placed between the outer C-profile and the crash tubes (see sectional view in *Figure 7*, chapter 3). This should have a long service life (≈30 years) and rubber elasticity under normal environmental conditions. Therefore a durable thermoplastic elastomer (TPU) or elastomer (EPDM rubber) is recommended here [7].

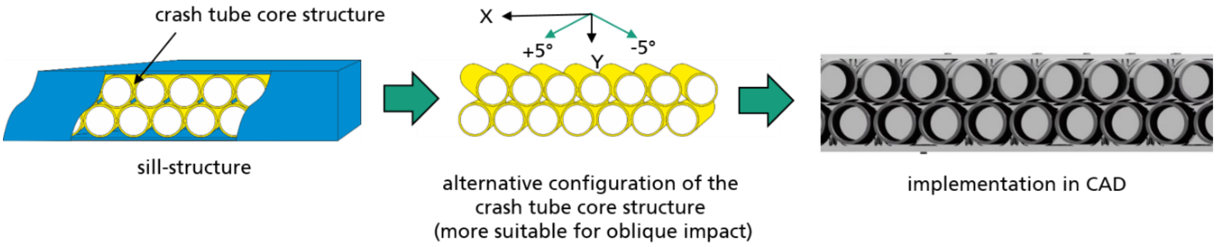

Figure 5: Concept for the alignment of the crash tubes in the sill structure

The main goal of the project is to design a vehicle platform that allows the reuse of durable components. This primarily applies to the CFRP crash tubes and C-profiles, which can be used again (reused) in a next vehicle model or new car generation, if it is still intact. The basic reuse and cycling idea is shown in *Figure 6*. Through this approach a long-lasting sill structure for sustainable mobility is to be designed and manufactured.

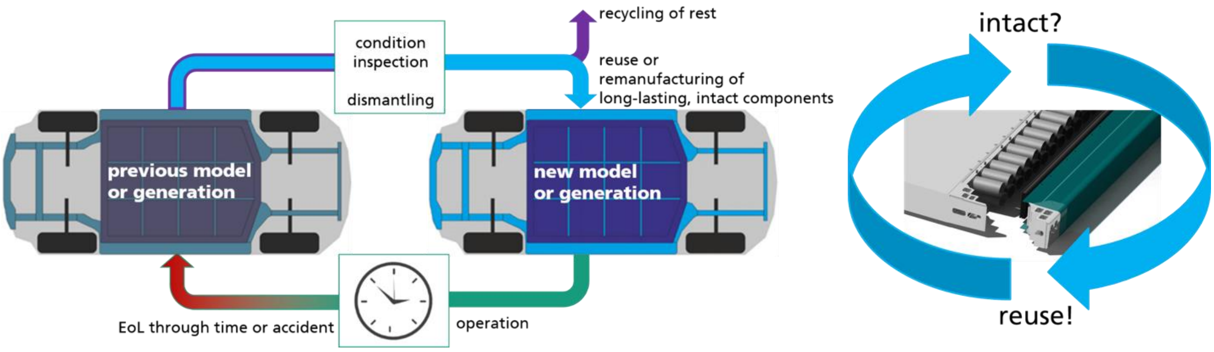

Figure 6: Schematic reuse and cycling representation of long-lasting, intact components for sustainable mobility

3 Empirical and numerical dimensioning of the crash protection

3.1 Upscaling and optimization of the CFRP crash absorbers

In the first step, the pole side impact was considered, which represents the most critical load case for both the occupants and the battery. Based on the investigations done in [6] and several numerical simulations, empirical factors could be determined for the upscaling and optimization of the CFRP crash tubes and the cover C-profile to get the final design for the sill structure. *Table 2* shows this procedure in some representative steps for crash absorbers. The available design space allowed a max. outer diameter of 77 mm for two rows of crash tubes (as shown in concept in *Figure 5*). As a result, the crash tubes for the side impact protection have a weight of 0.28 kg each. The final design (Ø = 77 mm, t = 5.66 mm) is a universal design for front (L_F = 500 mm) side and rear (L_S = L_R = 150 mm) crash protection which enables interchangeability within a model or reusability for a new model if the crash tubes remain intact.

Table 2: Extract from the optimization of the wall thicknesses of the CFRP crash tubes (fiber volume content min. 50 %, Ø77 mm, Intrusion way set to 115 mm for the absorber) in case of oblique impact

Design change	**Energy absorption**	**Wall thickness (nr. of layers)**	**Notes and assumptions**
Only the row of tubes pointing to impact direction absorbs energy $[\pm 90°/0°_4]_S$	start setup	16 mm (96)	Upscaled experimental data for the lay-up $[\pm 90°/0°_4]_S$ (W10° and B3-R0) [6]
1st optimization of the lay-up $[\pm 90°/0°_4]_S \rightarrow [\pm 30°_6]_S$	+ 19 %	13.5 mm (81)	Transfer from the axial test (B3-R0) [6]
The tube row pointing away to impact direction also absorbs energy	+ 35 %	9.2 mm (55)	Factor from the simulation
2nd optimization of the lay-up $[\pm 30°_6]_S \rightarrow [\pm 30°_x/0°_y]_S$ (consideration of the 0° layer)	+ 16 %	8.7 mm (52)	Factor from the simulation
Cover C-profile $[\pm 30°_x/0°_y]_S$, t = 2 mm also absorbs energy	+ 10 %	7.8 mm (47)	Experimental data for C-profile
Cover C-profile $[\pm 30°_x/0°_y]_S$, t = 4 mm also absorbs energy	+ 20 %	7.2 mm (43)	Upscaled with C-profile simulation
Consideration of the remaining car structure	× 60 %	4.3 mm (26)	Assumption: the remaining car structure absorbs 40 % of impact energy → sill 60 %
Consideration of modularity and compatibility for front and rear impact (replacement, reuse)	× 133 %	5.7 mm (34)	Grater frontal and rear impact forces

3.2 Numerical validation

For the validation of the crashworthiness of the new sill structure concept (section 2.3), a numerical model was created based on the dimensioning (section 3.1) and the CAD data of the vehicle platform (chapter 4). To reduce computation time and model size, only one side of the battery box with the sill structure was modeled. The components that were not considered by the FE-mesh (structures of the front and rear car, the vehicle body and remaining parts, as well as 9 people with luggage) were idealized into one mass point with its global inertia properties. It was connected to specific nodes of the platform representing the A-, B-, C-pillars by RBE3-Elements (see Figure 7). The battery cells in the battery modules have been geometrically and materially simplified and modeled in a reduced way.

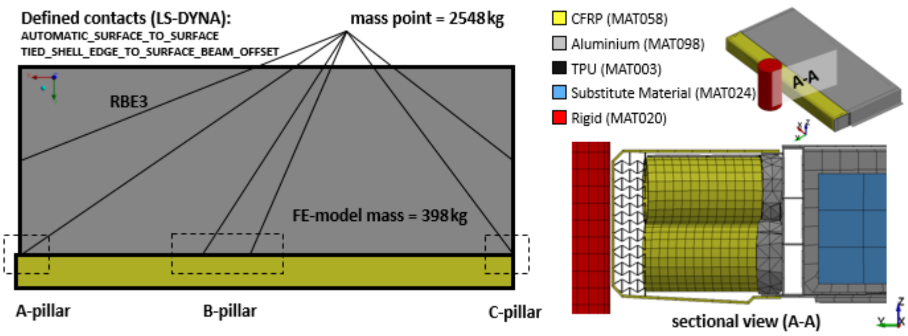

Figure 7: Considered geometry, mass, and material models in the simulation

The simulated load cases C1-C3 correspond to a "car-to-pole" scenario, in which the structure collides with a rigid and unmovable pole at a speed of 32 km/h according to EURO NCAP “oblique pole side impact” guideline (see *Figure 8*).

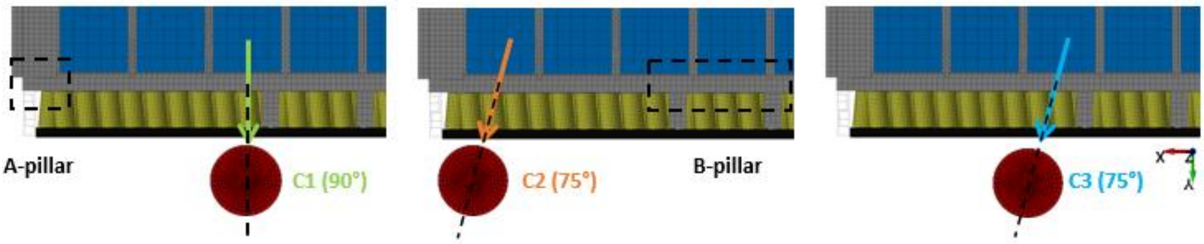

Figure 8: Defined load cases based on EURO NCAP

As shown in *Figure 9*, the restriction for the max. intrusion of 218 mm was fulfilled with the new sill concept for all three load cases (C1-C3). The decreasing intrusion at C2 is due to a global rotation of the vehicle around the pole.

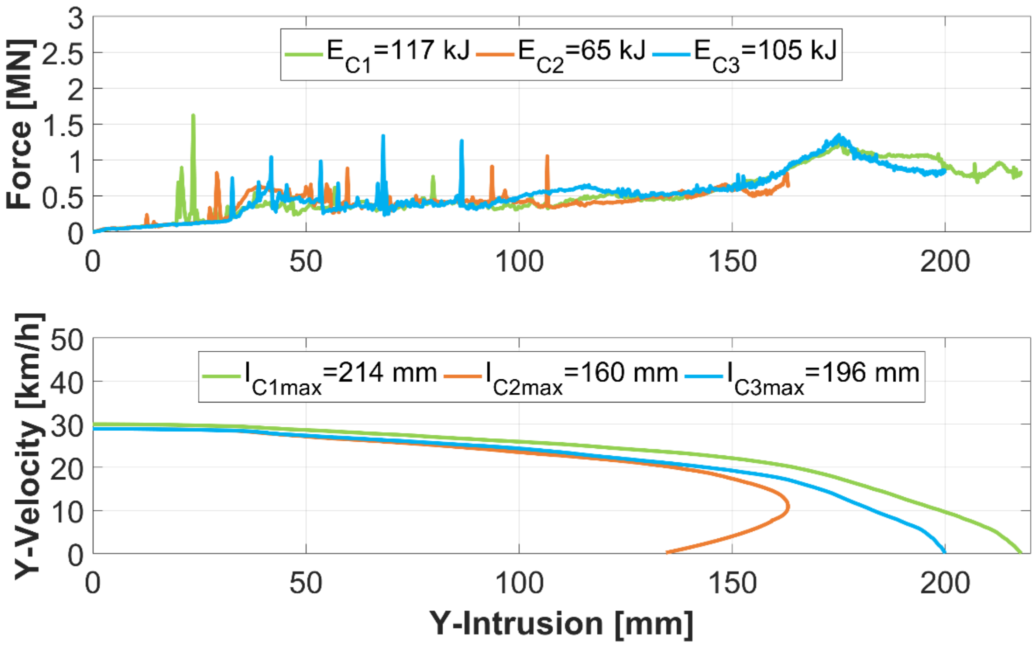

Figure 9: Numerical results: force-displacement diagram with the absorbed Energy values (top), velocity-displacement diagram with the max. intrusion values in global Y-direction (bottom); LS-DYNA solver version: R10.1, with the preset: message passing parallel (mpp_d_R101)

4 Design implementation into CAD according to manufacturing restrictions

Based on a first design space model defined for the project, initial concepts for the sill structure were developed, which are gradually being designed. The requirements include:

- low parts diversity,
- crash performance,
- ease of assembly,
- manufacturing,
- disassembly capabilities to allow reuse of even smaller subassemblies,
- low component mass (lightweight design).

According to the calculations and FEM-analysis described in chapter 3. Crash tubes and mounts for these were designed. Chosen was the concept where always 3 tubes are mounted in one fixture, compare section 2.3 and *Figure 10*.

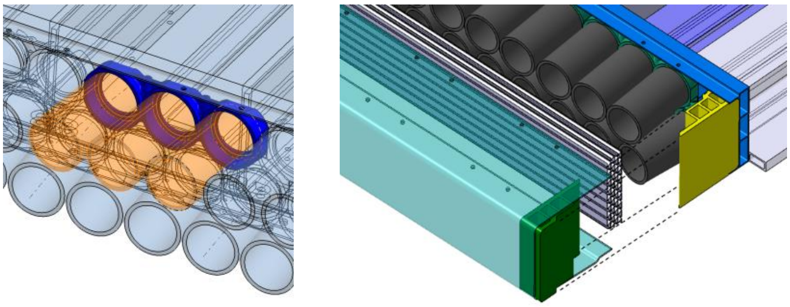

Figure 10: Left: crash tube mount, right: auxetic buffer element (grey), detachable two part node (green, yellow)

5 Manufacturing – pultrusion of crash tubes

The crash tubes are designed with an outer diameter of 77 mm and an inner diameter of 66 mm. This manufacturing process is very economical for high volumes, the tube is produced continuously and cut to the desired length at the end of the line. This also allows the same die to be used for tubes of different lengths.

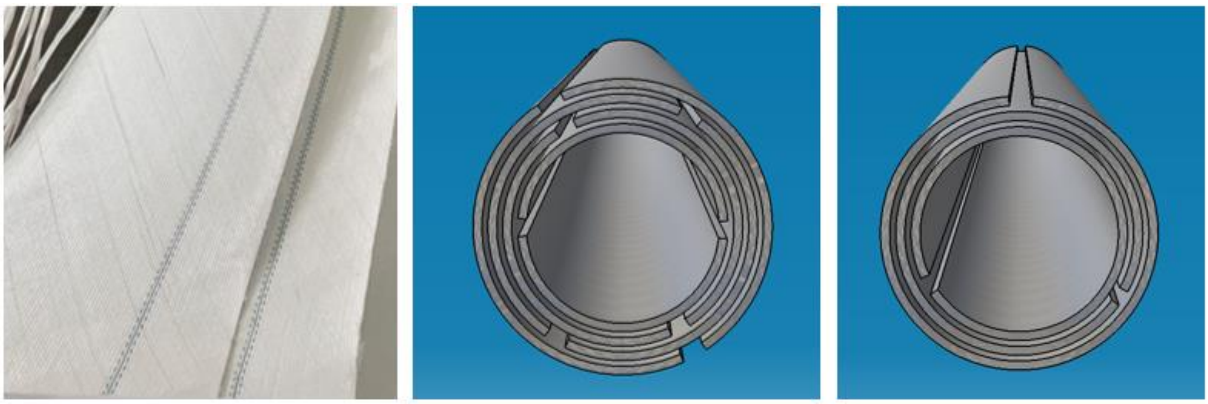

Figure 11: Example of complex fabric (left), possible lay-ups of the fabric to complete the tubes (right)

Mostly straight rovings are used for the pultrusion. These are for example led through a resin bath for impregnation and afterwards pulled through a die, where the curing under heat takes place. For the crash tubes, a more complex layup of the reinforcement fibers is needed (see calculations in chapter 3). To realize the desired 30° direction of the reinforcing fibers, semi-finished products can be used.

These ensure that the calculated layup can be pultruded with less deviation. To avoid an angular displacement of the fibers in the fabric by the pulling forces in the process a layer of straight rovings is added at the contact surfaces to the die and the core. The challenge lies in the realization of the preferred layup as tube. Two possibilities were discussed (*Figure 11*, right):

- Per layer 2 semi-shells around the core
- Per layer only 1 complete shell

Option 2 with only one semi-finished product was chosen, so the number of the seams could be minimized, knowing that this option would be harder to realize in the process. Due to the low purchase quantity it was only possible to get glass fiber fabrics with the wanted angles. The challenges are similar to CRFP and the experiences can be transferred from GFRP pultrusion of the tubes to CRFP. Expected problems include wrinkles in the semi-finished product layers, especially amplified by the gravity and very complex guiding panels. Therefore an iterative process was used, in the first pultrusion not enough fabrics and fibers could be fed into the die. Due to a fiber content which was too low, the surface of the tube had a bad quality. A redesign of the layup and the guiding panels was done. Tubes could be successfully manufactured. Due to the "floating core" and use of the fabrics, an alignment of the core is a challenge. A tube with a varying wall thickness of about 0.5 mm was pultruded.

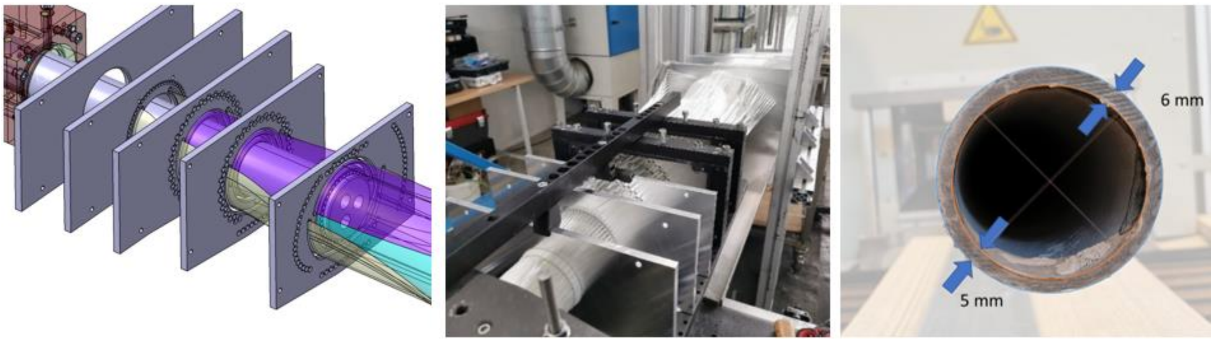

Figure 12: Pultrusion in the preparation, guiding panels, pultruded profile (left to right)

6 Discussion and conclusion

In this work, a development path for a long-lasting sill structure with the focus on the impact protection elements and a reuse friendly design was shown from the basic idea till manufacturing. The main crash protection consists of individual crash tube absorbers made of FRP with a specific layup by pultrusion. The manufacturing was successful, more experiments and stiffer bearing panels for the core are necessary to improve the layup quality (wrinkles, concentricity). The function of similar CFRP crash tubes has been previously proven in studies with scaled experimental tests up to an inclination of 10°. Due to the special arrangement of the tubes in the sill, compliance with the latest NCAP is expected. Corresponding buffer elements were also designed. These are intended to level high peak forces and thus protect the occupants and the on-board equipment. A numerical evaluation shows high protection in case of the oblique pole side impact with optimization potential regarding further mass reduction for the battery box. This should be followed by future investigations regarding the risk of short circuits in the battery modules. The modular and long-lasting sill design makes it easy to reuse the crash protection elements, which is in line with a circular concept.

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