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Research Article

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Reusable fibre composite crash boxes for sustainable and resource-efficient mobility

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Abstract: In this study, a carbon fibre-reinforced polyamide 6 crash box was designed, manufactured, and crash-tested as part of a novel automotive front-end structure, developed in the EU-Project SALIENT. The crash box concept, design, and manufacturing process were based on previous investigations reported. This prior research enabled the efficient definition of key design parameters, including inner diameter (D_i), wall thickness (t), trigger design, and an optimized fibre lay-up. The crash box features an innovative combination of thermoplastic composite material and an advanced manufacturing method – laser-assisted tape winding – to enable precise, automated production of reusable structures. It was tested under crushing conditions to explore further applications for the inversion mechanism, as described in the literature, to enhance crash performance and improve energy absorption. The use of a thermoplastic matrix (PA6) helped to minimize dust and particle generation, contributing to improved health and environmental safety. Additionally, the use of this material enhances recyclability, and the long service life of the composite allows for potential reuse of the structure at the End of Life in future vehicle generations.

Keywords: crash, CFRP, lightweight construction, reuse, circular economy

1 Introduction

The automotive industry is currently facing significant challenges related to safety, environmental protection, and sustainability [3]. With increasing demands for reducing emissions and conserving natural resources, the development of innovative lightweight and safety technologies is becoming more critical [4]. In this context, advanced composite materials are playing a vital role, particularly in the design of new passive safety components like crash boxes.

Crash boxes are essential for protecting vehicle occupants during collisions by absorbing and dissipating impact energy. Traditionally, these structures have been made from metals such as steel or aluminium [5,6]. However, in recent years, the use of fibre-reinforced plastics (FRPs) has gained momentum due to their higher specific energy absorption (SEA) and superior compression efficiency compared to metals [7,8]. Furthermore, the use of thermoplastic materials like polyamide 6 (PA6), when compared to thermosetting materials, offers additional environmental and crashworthiness benefits, including improved recyclability and a reduction in harmful or dangerous fragments during a crash, as reported in previous research [2,9]. It is crucial to adopt a reuse-friendly design for FRP crash boxes from the very beginning, including joining techniques for easy installation and removal from the vehicle, to align with circular economy principles and contribute to greater sustainability in the automotive sector.

2 Goal and concept

This work addresses the designing, manufacturing, and testing of a carbon fibre-reinforced polyamide 6 (CFPA6) crash box for use in the front-end structure (FES) of vehicles. The FES is designed to absorb and dissipate energy in the event of a collision, protecting occupants by minimizing deformation of the passenger compartment. It includes crumple zones that deform during an impact, reducing the forces transmitted to the occupants (cf. Figure 1).

This work focuses on the low-speed impact zone (Zone 2 in Figure 1), where a novel CFPA6 crash box is to be installed to achieve a specific average force level ($F_{\mathrm{AV\,G}}$). The structure needs to absorb sufficient energy to minimize damage during low-speed impacts (10–15 km/h) [10]. Zone 2 is part of a crash management system subdivided into four functional zones, each tailored to different crash

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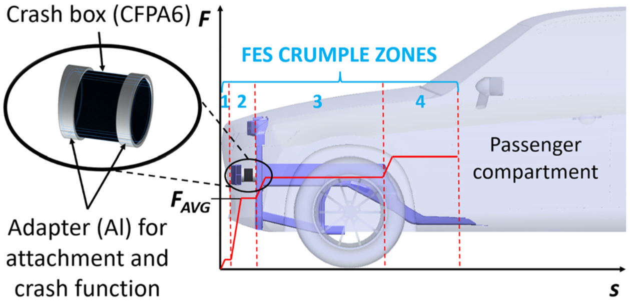

Figure 1: FES with new kind of CFPA6 crash box subdivided into crumple zones based on the impact energy absorbed; Zone 1: Energy absorption for pedestrian protection; Zone 2: Energy absorption during low-speed crashes; Zone 3: Energy absorption during high-speed crashes; Zone 4: Load distribution elements.

scenarios: Zone 1 is designed for pedestrian protection during minor collisions, Zone 2 addresses low-speed impacts with the aim of limiting repair costs and preventing damage to the longitudinal rails, Zone 3 is responsible for managing energy in high-speed crashes to protect occupants, and Zone 4 contains load distribution elements that help manage the overall force transmission through the structure. Within this system, Zone 2 plays a crucial role in bridging the gap between pedestrian safety and high-speed crash protection, ensuring that minor collisions do not compromise the vehicle's structural integrity or lead to disproportionately high repair costs.

Furthermore, given the statistical rarity of accidents, the innovative crash boxes should be designed for modularity and adaptability, allowing reintegration into future vehicle generations (reuse). The innovation lies in the use of CFPA6, a thermoplastic material that combines high durability and corrosion resistance to recyclability. In addition, the crash box features an optimized geometry for controlled energy absorption and is manufactured using laser-assisted tape winding (LATW), an advanced and highly precise process enabling automated, reproducible fabrication of complex, fibre-reinforced structures. This approach offers significant ecological and economic advantages by eliminating emissions and costs associated with new production, as existing components can be reused rather than manufactured anew [2,11,12].

In crash box technology, there are differences in how various materials absorb energy and the failure mechanisms that occur during a collapse. The folding and buckling as a deformation principle, most commonly used in metallic crash boxes, does not require triggers for collapse [13]. On the other hand, crash boxes made of composite materials must be able to absorb a large amount of energy in a stable manner. To avoid catastrophic failure of the fibre composite crash box during the compression test and to ensure a stable fracture process, a predetermined breaking point (trigger) is always required on the FRP crash box to initiate this progressive fracture process [14]. The biggest challenge lies in understanding the dynamic behaviour of these structures. For composites with a thermosetting matrix, energy absorption occurs through fragmentation. Compared to the plastic deformation of metals, these processes have a higher SEA and higher crushing efficiency, resulting in a constant collapse load.

Both for metallic energy-absorbing components and composite structures, the geometry can be varied according to the preferences of the designers. The elongated shape is a key factor, and options include a constant thickness, a conical shape, a conical–cylindrical configuration, or a complex geometry, as seen in energy absorption components for race cars or aircraft [15]. Tanlak's and Sonmez study [16] focuses on the selection of cross-sectional geometry for tubes under axial loading with an emphasis on crash safety. Over the years, simple circular and square cross sections have been primarily analysed, as they are particularly well suited for the lamination process due to their ease of manufacturing. Thornton and Edwards [17] reported that square and rectangular tube cross sections are generally less effective at absorbing energy than circular ones. Their research suggests that the corners act as stress concentrators, leading to the formation of splitting cracks. This often results in an unstable collapse with lower energy absorption. Consequently, this work is focused exclusively on cylindrical crash structures with round cross-sections (crash tubes).

3 Material specifications

As part of the SALIENT Project, a continuous carbon fibre-reinforced polyamide 6 (CFPA6) was developed. The carbon fibres are optimally embedded in the polymer matrix through the direct impregnation process, which endows the material with exceptionally high strength and stiffness in the fibre direction. The direct impregnation process, as developed by thermoPre ENGINEERING GmbH [18], represents an especially efficient method for the manufacture of semi-finished unidirectional (UD) products. This is due to the fact that a semi-finished product can be produced in a closed process by melting the thermoplastic granulate and then impregnating the carbon fibres. Consequently, damage to the plastic caused by repeated melting can be circumvented, thereby achieving a high degree of cost efficiency. The result is a semi-finished product with high performance characteristics, exhibiting an even distribution of fibres and homogeneous impregnation of the matrix.

The developed material has a tensile strength of up to 1,800 MPa, a modulus of elasticity of approximately 105 GPa in the fibre direction, a fibre volume content of approximately 45%, and a density of 1.43 g/cm^3. The selection of material and preliminary evaluations of its mechanical properties were based on findings reported in Deliverable D3.3 of the SALIENT project [19]. The CFPA6 exhibits superior load-bearing capacity and rigidity compared to conventional materials such as aluminium. Concurrently, the PA6 matrix exhibits high impact strength, enabling the material to withstand dynamic loads and to have a long service life. These mechanical properties render CFPA6 an optimal material for demanding applications, including those in the automotive industry, aviation, and mechanical engineering.

The material exhibits high thermal stability, with a determined glass transition temperature of approximately 49 °C and a melting temperature of 220 °C. It also demonstrates dimensional stability even at elevated temperatures and can be employed in typical automotive processes, including the cathodic dip painting process. In chemical terms, CFPA6 is distinguished by its high resistance to oils, lubricants, bases, and alcohols [20,21], while its resistance to acids (*e.g.* H_2SO_4) is limited [22,23]. The PA6 matrix also exhibits considerable resistance to moisture, although a degree of water absorption is inevitable due to the nature of the material. These chemical properties render the material particularly well-suited to utilisation in corrosive environments or under conditions of adverse environmental influence [23].

The most significant benefit of CFPA6 is its capacity to combine high performance with versatility. The material is notably lightweight yet exhibits specific strength and stiffness that exceed those of many conventional materials. This enables substantial weight savings, which is especially crucial in lightweight construction and electromobility. In comparison to metals, CFPA6 is resistant to corrosion and therefore requires less maintenance, which ultimately reduces operating costs. Furthermore, the material's thermoplastic matrix allows for a high degree of design freedom, as complex geometries can be produced in a single manufacturing step. Another crucial consideration is the recyclability of CFPA6. As a thermoplastic composite material, the PA6 matrix can be reused by melting. To this end, unmixed components can be shredded and the material processed into a long fibre-reinforced compound in a compounding process [24]. Advanced processes such as depolymerisation make it possible to recover the polyamide monomers, while the carbon fibres can be reused in many cases. While the economic and technical efficiency of these processes still requires further development and large-scale facilities, CFPA6 offers a promising basis for a sustainable circular economy [25].

Although the material costs of CFPA6 are higher than those of conventional materials such as aluminium or glass FRPs, it offers significant potential for use in automotive applications due to its lightweight construction, energy savings over the product life cycle and high performance. It combines superior mechanical, thermal and chemical properties with a high degree of recyclability, making it a key material for innovative and sustainable industrial applications.

4 CFRP crash box computation and design

To determine the appropriate design for the crash boxes, the extrapolation method from the study by Nossol [2] was applied for dimensioning. This is an analytics-based sizing tool for CFRP crash tubes, which has been experimentally and numerically verified. It provides a three-dimensional design surface – spanned by tube diameter, wall thickness, and average force level – which allows a suitable combination of parameters to be selected to meet the desired crash performance. The surface was generated based on analytical estimations, and subsequently validated using experimental data and numerical simulations [2]. The tool assumes a preferred winding angle of ±30 ° and a fibre volume content of approximately 54%.

A safety factor of 1.3 was selected to account for variations in fibre volume content, which can significantly affect material properties. It also compensates for potential material imperfections, such as fibre breaks, microcracks, or shrinkage voids in the matrix, as well as manufacturing-related deviations, like variations in the winding angle or pressure. This ensures reliable and safe performance.

Initially, the diameter of the crash box was determined based on an existing winding mandrel with a diameter of 63.5 mm (see also Section 5), considering the installation space available within the design constraints of the EU research project SALIENT. Along with the required average force level of 50–60 kN for the newly developed crash box and the defined safety factor, a wall thickness of 2.5 mm was derived using the sizing tool (Figure 2). In this way, the main dimensions of the crash boxes were determined efficiently and purposefully.

A long bevel trigger was defined to ensure its easy manufacturability through turning or milling, keeping production costs low, which was successfully tested in the

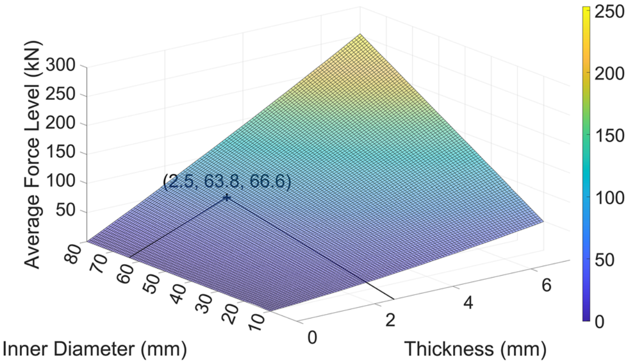

Figure 2: Determination of the required crash box wall thickness with the sizing tool for CFRP crash tubes according to the study by Nossol [2].

study of Nossol and Saleem [9]. It was intentionally designed longer with a chamfer angle of 10° to allow for a further connection with the vehicle surroundings using bolts or riveting and bonding (Figure 10 in Section 8). The final design for manufacturing is shown in Figure 3.

5 LATW manufacturing

LATW technology is vastly used to produce axisymmetric composite parts with fibre reinforced thermoplastics. In this production technology, fibre reinforced thermoplastic tapes are heated with a laser source, winded on a rotating mandrel and then pressed by a consolidation roller (Figure 4).

In general, tape winding technology is suitable for large series production because of its high process speed, made possible by the quick and accurate heating from the laser. The localized and controlled heating ensures minimal thermal stress, which leads to high-quality bonding between the tapes and enhances the mechanical properties of the final product. The precision of the laser allows for even temperature distribution, minimizing the need for further finishing steps, thereby saving time and costs.

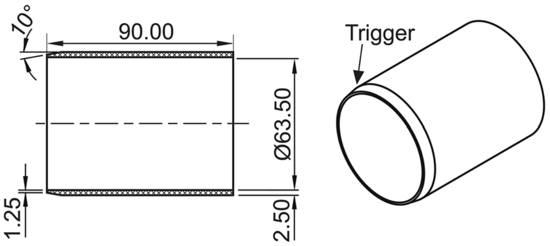

Figure 3: CFRP crash box design with main dimensions.

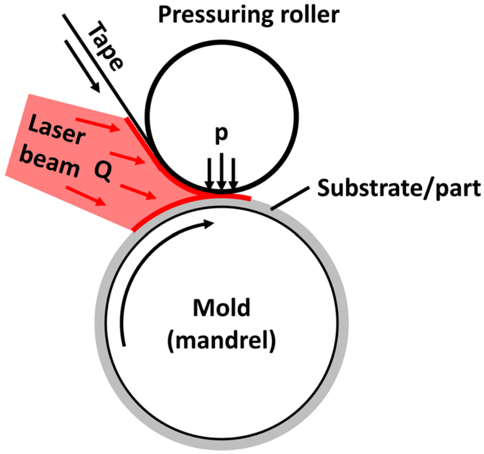

Figure 4: Schematic representation of Laser-assisted Tape Winding (LATW) according to the study of Weiler [26].

LATW provides the possibility of manufacturing tubular components with a uniform layer structure in the circumferential direction, as it is crucial for the CFRP crash box profiles (Figure 5).

First, a longer tube (approximately 1,139 mm) was manufactured using the LATW process. The layer structure consisting of 18 layers of UD-Tape (CFPA6) was based on the investigations done in the study by Nossol [2] and as follows:

$$[+30^\circ/-30^\circ]_2/[0^\circ]_{10}/[+30^\circ/-30^\circ]_2.$$

The CFPA6 tapes were draped over a winding core with a diameter of 63.5 mm. Layers oriented at 0° were applied with a precise tolerance of ±0.01°. In contrast, for layers at the planned 30° angles, the deviation was within the range of 30.33° to 33.21°. The tapes were laid down at a speed of 11.5 m/min ±0.3 m/min. The temperature varied between 279 and 302 °C. The temperatures for the inner layers, which were draped first, were within the lower

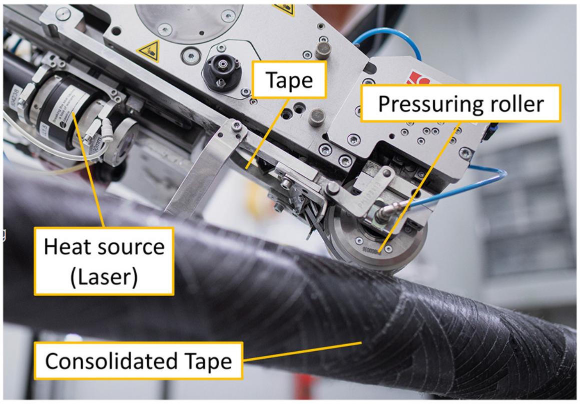

Figure 5: LATW of CFRP tubes (image source: [27]).

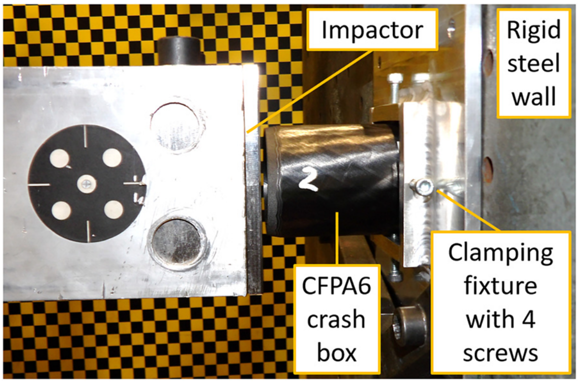

Figure 6: General view of the horizontal impactor device.

part of this range. As more layers were added, temperature increased and became more stable, due to reduced heat dissipation to the winding core.

After removing the core, the tube was divided into the desired section lengths by cutting. A total of three crash box specimens were prepared from this tube and labelled as samples 02, 03, and 04. For each of them, a bevel trigger was manufactured by turning on a lathe. These three specimens were subsequently tested in the experimental campaign described in Sections 6–7. The resulting crash box elements were measured to document the as-manufactured dimensions. The geometric boundary conditions diameter and wall thickness were measured both near the trigger and on the opposite flat side. The diameter and thickness were determined at two and four circumferential positions, respectively. The average values for the samples are summarized in Table 1.

6 Methodology and definition of test setup

The crash boxes were tested in a horizontal impactor device (Figure 6). In this device, a steel beam of determined mass is launched at a certain speed towards the crash box, causing its collapse. The beam has a rectangular cross-section and a flat impacting surface. Ballast can be added to increase the mass of the impacting beam, and the speed can also be adjusted, so that the desired amount of energy is put in place. In this setup, the crash box is fixed to a rigid steel wall by means of a tooling manufactured to this end. The tooling consists of a plate counting with a cavity in which the crash box is inserted, centring its position thanks to four screws located around the cavity.

Table 1: Dimensions of the manufactured crash boxes, including the average (AVG) and corresponding standard deviation (SD)

Crash box no.	**02**	**03**	**04**	**AVG**	**SD**
Flat side in mm					
D (AVG 2 Pos.)	68.78	68.71	68.73	68.74	0.29
t (AVG 4 Pos.)	2.51	2.46	2.48	2.48	0.13
Trigger side in mm					
D (AVG 2 Pos.)	68.87	68.63	68.69	68.73	0.09
t (AVG 4 Pos.)	2.50	2.48	2.51	2.50	0.01
Length in mm	89.92	89.95	89.91	89.93	0.02

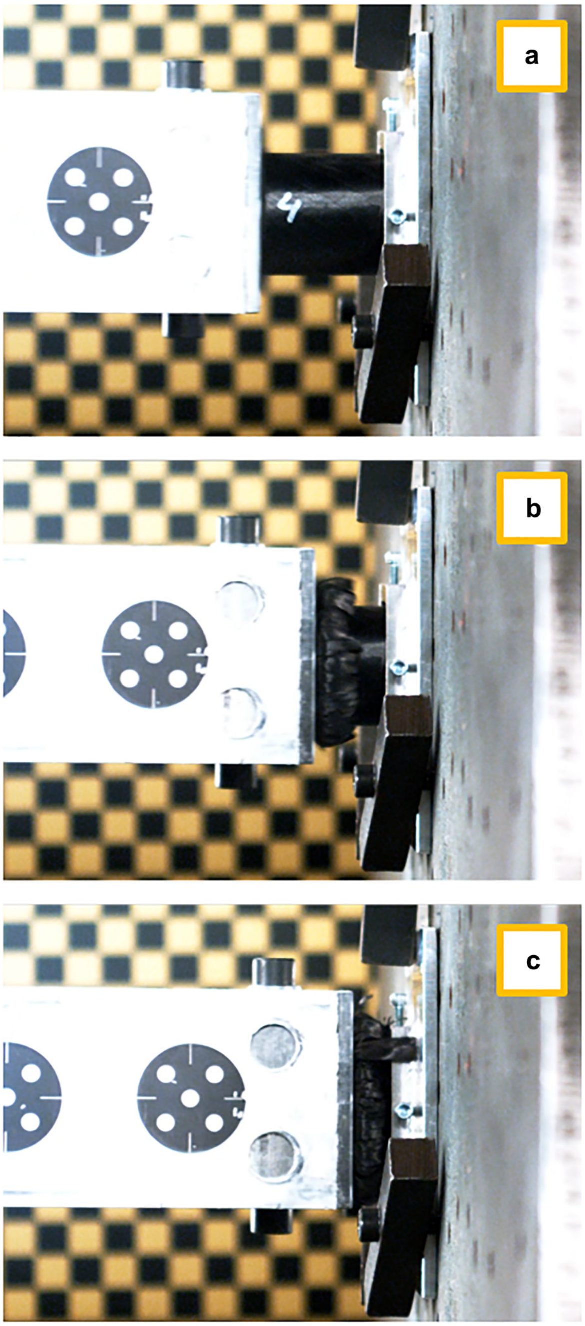

Figure 7: Evolution of the collapse (A–C) of crash box No. 04 at 40 km/h.

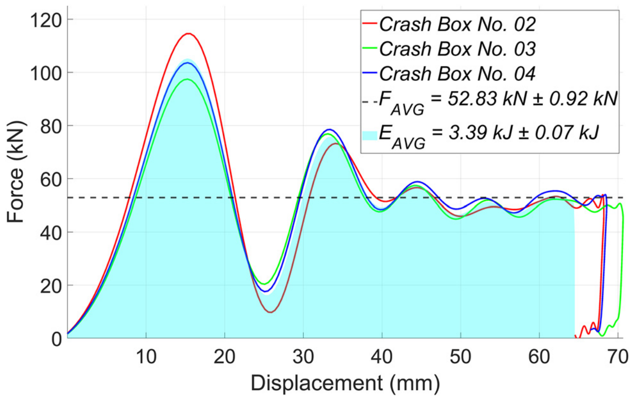

Figure 8: Measured force displacement curves for the tested CFPA6 crash boxes at 40 km/h; Based on the measurement data calculated average force level (F_{AVG}) and averege absorbed energy (E_{AVG}).

The tooling is made of aluminium to avoid steel steel contact in case the setup or the testing object does not work as expected.

In the SALIENT project, full vehicle finite element simulations including the original, all-steel full FES were carried out to determine the performance targets for the individual components of the FES, considering the spatial limitations of the intended application (Fiat Panda Cross vehicle) to ensure representativeness. In this context, it was found that for the Euro NCAP FWRB (Full Width Rigid Barrier) test, the expected energy absorption of the crash boxes is in the range 3–4 kJ. Exact values depend on the position of the crash box (in the upper or lower bumper, or on the right or left side of the FES, as the real structure is not completely symmetric). Hence, this range was targeted in the component test design.

For the CFPA6 crash box testing, an impactor beam mass of 60 kg and a speed of 40 km/h were selected, resulting in a total energy of 3.7 kJ. The main variables recorded during the tests were acceleration and displacement. Accelerations were measured by means of two accelerometers (ENDEVCO 7264B-2000T) located symmetrically onto the beam. Displacement was measured with a magnetic displacement sensor (ASM PMIS3-50-125-50-TTL-S). The acceleration signals, after averaging and filtering using the CFC-180 filter as indicated in SAE J211, were integrated to obtain force and energy absorption values.

The samples were conditioned at 70 °C for 24 h. Although considered sufficient, this procedure may deviate from ISO 1110, as humidity control and weight monitoring to confirm that moisture equilibrium was not ensured.

The tests were also recorded with a high-speed video camera (VISION RESEARCH VEO-440S) at 2,000 fps. The recording allowed tracking the collapse of the crash boxes, as well as validating the effectiveness of the trigger mechanism (Figure 7). The duration of the collapse is 8 ms on average.

7 Evaluation

The analytical preliminary design of the crash box (Figures 2 and 3) shows a good match with the measured values on the manufactured crash boxes (Table 1). Specifically, thanks to the high-speed tests (Figure 7), it was possible to demonstrate that the average force level (F_{AVG} = 52.83 kN) matches the required target of 50–60 kN (Figure 8). With an average absorbed energy E_{AVG} = 3.39 kJ (calculated for an intrusion of 65 mm) and a standard deviation of ±0.07 kJ, the results demonstrate high reproducibility. The CFPA6 crash box has an average mass of 61 g, resulting in an SEA of 81 kJ/kg. In comparison, the SEA of a typical aluminium crash box (made from a crash-relevant alloy like AW6060 T66) is around 28 kJ/kg [2,9]. This results in 2.9 times higher energy absorption for CFPA6 compared with aluminium. A high lightweight factor emerges, which can also be understood as an

Figure 9: Example fracture images of crash box No. 04: Trigger side (left); Flat side (right).

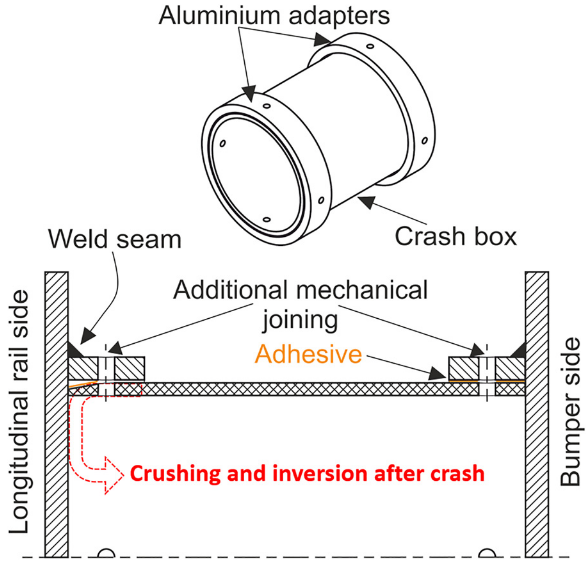

Figure 10: Concept of a CFRP crash box assembly with two aluminium adapters for a new lightweight FES design (top); Longitudinal section of a CFRP crash box in metal (aluminium) surroundings with crash mechanism principle (bottom).

ecological factor, as it allows for resource savings and, through the possibility of reuse, provides significant benefits for environmental protection by eliminating emissions from production like shown in [11].

The CFPA6 crash box also exhibits an inversion, in which the cohesion of the material is largely preserved. The resulting wedge splits the inner part of the tube wall inwards and the outer part outwards, creating a kind of triple-walled tube. The section of the tube wall that is inverted displays noticeable folds due to the diameter reduction (Figure 9). The newly formed outer wall slides along the undamaged outer tube wall until the inverted sections meet the lower compression plate. Only occasional cracks form in this process. As the inverted layers meet the lower compression plate, further deformation occurs, but the tube maintains its overall integrity, with only minimal material fractures observed. This structure demonstrates a stable transition zone between the inward and outward inverted areas (0 °-layers), contributing to the formation of a reinforced, layered tube configuration.

8 Conclusions and outlook

The conducted investigations show numerous advantages of using fibre-reinforced crash boxes in novel FES. These advantages include the precise adjustability of the required force level and a high SEA. For example, the SEA of the tested CFPA6 crash boxes reached values of up to 81 kJ/kg, which is nearly three times higher than typical values of aluminium crash profiles (approx. 28 kJ/kg).

Moreover, the results of the three tested samples (IDs 02, 03, and 04) showed an average force level of 52.83 kN with a remarkably low standard deviation of only ±0.92 kN (≈1.7%), confirming the high reproducibility and reliability of the manufacturing and performance.

Thanks to the chosen thermoplastic composite material, the crash boxes exhibit long-term durability and robustness, making them particularly suitable for reuse-oriented and scalable design strategies.

A key innovation of this study lies in the use of a thermoplastic-based CFPA6 material in combination with the LATW process. This combination enables the automated manufacturing of robust and recyclable crash boxes, while allowing the fibre architecture to be tailored to the required crash performance.

In terms of structural integrity, the CFPA6 crash boxes offer significant advantages during impact, especially due to minimized dust and particle generation. This contributes to improved health and environmental safety. Moreover, the crash boxes demonstrate a benign failure behaviour: even under severe loading, the structure does not shatter, which significantly reduces the risk of injury from debris for vehicle occupants and pedestrians.

Additional potential for resource savings arises from the recycling or remanufacturing (*e.g.* cut to size after partial damage) and reuse of the CFRP crash tubes from End-of-Life (EoL) vehicles. The investigations conducted with an inclination of up to 10 ° in the study by Nossol [2] also show great potential for using the designed crash box in oblique impact scenarios.

As part of future investigations, it is crucial to consider the impact of varying moisture contents and temperature conditions on the mechanical and crash performance of CFPA6. In this study, the material was conditioned at 70 ° C for 24 h. However, the procedure did not fully comply with ISO 1110, as neither humidity was controlled nor was moisture equilibrium verified by regular weighing. Therefore, variations in moisture levels – such as those occurring under seasonal environmental conditions – were not explicitly evaluated. Future work will aim to quantify these effects to provide a more comprehensive understanding of how environmental factors influence the material's behaviour and its overall performance in automotive applications.

For application in vehicles, however, crash boxes must be attached to the car's FES as part of a functional assembly. The immediate peripheral components needed for joining the crash box with the rest of the structure might affect its crushing behaviour. Thus, joining technologies and interface components play a major role in the performance of the crash box itself. To guarantee the desired crush behaviour (crushing, inversion), adapters can be used as an attachment aid and for load transmission. The required adapters also serve as a connection and positioning element for the corresponding peripherals in vehicle construction. A mounting concept for the innovative crash box is shown in Figure 10. This measure can eliminate the risk of any undesired local damage and could enable the correct triggering of the crushing mode.

Adhesives can be used as a primary joining technology between the CFRP crash box and adapters. For higher structural integrity, additional mechanical joining such as bolts or riveting can be used. Furthermore, such joining technologies are also partially or fully removable (*e.g.* releasable adhesives). Thus, the potential reuse of undamaged CFRP crash boxes from EoL vehicles can contribute towards sustainability.

As part of on-going research within the EU project SALIENT, the integration of the crash box into an aluminium-based vehicle environment is currently being investigated. The mounting concept described above has already been developed and visualised. The experimental evaluation of the complete crash box system, including realistic boundary conditions and joining elements, is part of the next development phase and will be presented in a subsequent publication. This work will also enable a deeper understanding of how structural interfaces and mounting configurations influence the global crash behaviour and reuse potential of thermoplastic CFRP crash components.

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Author contributions: All authors have taken responsibility for the content of the manuscript, agreed to its submission, reviewed all results, and approved the final version of the manuscript. PN, AS, and RM from Fraunhofer IWU (Germany) were involved in the development of the general crash box concept, including solutions for integration into a novel type of FES, as well as computation, design, manufacturing technology, and evaluation. Their contributions are reflected in Chapters 1–2, 4–5, and 7–8. SI from thermoPre ENGINEERING (Germany) was responsible for the development of the material as part of the publicly funded SALIENT project, significantly contributing to Chapter 3. MI and JV from CIDAUT (Spain) defined the testing setup, conducted prototype testing, analysed the resulting data, and contributed to the writing of Chapters 6 and 7.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The datasets generated and analyzed during the current study are not publicly available due to the sensitive nature of the data and privacy regulations. However, de-identified data may be shared upon reasonable request, subject to approval by the corresponding author and compliance with applicable ethical and legal requirements. Researchers interested in accessing the data may contact Patryk Nossol at patryk.nossol@iwu-fraunhofer.de. Requests will be evaluated on a case-by-case basis to ensure adherence to privacy and confidentiality agreements.

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