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COMPOSITES MEET SUSTAINABILITY

Vol 5 – Applications and Structures

Editors : Anastasios P. Vassilopoulos, Véronique Michaud

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Editorial

This collection gathers all the articles that were submitted and presented at the 20th European Conference on Composite Materials (ECCM20) which took place in Lausanne, Switzerland, June 26-30, 2022.

ECCM20 is the 20th edition of a conference series having its roots back in time, organized each two years by members of the European Society of Composite Materials (ESCM).

The ECCM20 event was organized by the Composite Construction laboratory (CCLab) and the Laboratory for Processing of Advanced Composites (LPAC) of the Ecole Polytechnique Fédérale de Lausanne (EPFL).

The Conference Theme this year was “Composites meet Sustainability”. As a result, even if all topics related to composite processing, properties and applications have been covered, sustainability aspects were highlighted with specific lectures, roundtables and sessions on a range of topics, from bio-based composites to energy efficiency in materials production and use phases, as well as end-of-life scenarios and recycling.

More than 1000 participants shared their recent research results and participated to fruitful discussions during the five conference days, while they contributed more than 850 papers which form the six volumes of the conference proceedings. Each volume gathers contributions on specific topics:

Vol 1 – Materials

Vol 2 – Manufacturing

Vol 3 – Characterization

Vol 4 – Modeling and Prediction

Vol 5 – Applications and Structures

Vol 6 – Life Cycle Assessment

We enjoyed the event; we had the chance to meet each other in person again, shake hands, hold friendly talks and maintain our long-lasting collaborations. We appreciated the high level of the research presented at the conference and the quality of the submissions that are now collected in these six volumes. We hope that everyone interested in the status of the European Composites’ research in 2022 will be fascinated by this publication.

The Conference Chairs

Anastasios P. Vassilopoulos, Véronique Michaud

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And all those who helped, colleagues who reviewed abstracts and chaired sessions, and CCLab and LPAC students and collaborators who worked hard to make this conference a success.

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OPTIMISED COMPOSITE CRASH STRUCTURE DEVELOPMENT WITH FOCUS OF LIFE CYCLE ANALYSIS FOR A FUEL CELL ELECTRIC VEHICLE

Nithin Jayasree[a], Sadik Omairey[a], Vasiliki Loukodimou[a], Aidan Bradbury[b] Mark Lidgett[b], Roger Elliott[c], Lucy Bull[c], Chris Page[d], Sofia Sampethai[d], Stuart Lewis[d], Kieran Dennington[e], Richard Coltart[e], MJ Bull[e], Mihalis Kazilas[a]

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Abstract: *Low-speed accidents see a year-on-year increase. To improve crash performance in these accidents, a crash box is attached between the vehicle bumper structure and the side rail. The determination of the crash box material and geometry is critical to absorb the impact energy to result in safer vehicles and minimised repair costs. As the automotive industry transitions to more sustainable platforms, it is seeking to use lightweight materials including in the crash structure. This study develops an innovative crash box with optimal impact energy-absorption capabilities for a fuel cell electric vehicle. The concept is based on topology optimisation considering the composite structure and crash energy dissipation. In further work, the results from the life cycle analysis are utilised, and a comparative study between carbon fibre reinforced polymers and biocomposites in crash structures is performed. The latter includes an extensive characterisation campaign under static and dynamic conditions.*

Keywords: Composites; crash box; crashworthiness; lightweight; life cycle analysis

1. Introduction

Low-speed (20mph) accidents see a year-on-year increase of 31% [1]; injury increase is broken down as fatal (+79%), serious (+47%), and slight (+42%). A crash box is a thin-walled structure attached between the vehicle bumper structure and the side rail part of the vehicle and aims to improve crash performance in low-speed accidents. Frontal crashes are responsible for more deaths and serious accidents than any other type [2]. The identification of the material and geometry of the crash box plays a key role in the absorbance and dissipation of the impact energy. Hence, having effective crash boxes will result in safer roads and vehicles, along with minimised repair costs.

Conventional crash boxes are manufactured from steel or aluminium. These exhibit high peak force and have no way of controlling the deceleration rate following a crash. However, as the automotive industry is shifting to more sustainable platforms such as fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs), weight reduction is essential in designing these vehicles. Hence, there is a shift towards utilising advanced lightweight materials in crash box applications beyond the body in white (BIW). Composite alternatives are excellent candidates for these applications; however, they are limited in use due to unpredictable failure. Multi-material crash boxes' light-weighting, high-specific stiffness and strength, and improved crashworthiness have led to their use in high-end vehicles.

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PROTECT project (Modular multi-material crash-box for tailored impact energy absorption during low-speed collision) [3] aims to produce an innovative crash box with improved impact energy absorption capabilities enabling minimal damage to road users, vehicles, vehicle-occupants in low-speed collisions. The challenge lies in designing and developing a multi-material crash-box system that enables tailoring energy absorption and functionality in every millimetre along the component length and smooth energy transition from crash-box to longitudinal. For this purpose, a novel mix of multi-materials (aluminium and carbon fibre reinforced polymers) is utilised, allowing for inter material properties that enable better energy absorption.

The following sections of this paper include a description of the end-user requirements, the architecture of the crash zone, concepts development, and the concept selection process.

2. End-user requirements

To ensure ultimate use and deployment of crash structures being developed in this study, a set of end-user requirements and specifications are defined. These criteria are aligned with the vehicle architectures and business model. This not only assesses the feasibility of the designed solutions but highlights the areas that require further development. Some of the key functional requirements set by the end-user Riversimple [4] are presented in Table 1

Table 1. Examples of End-user's key requirements.

Operating Environment	• Withstand ambient air temperatures from -20°C to +70°C and be able to pass the mandatory crash requirements at those temperature extremes. • Use chemicals and materials within the structure that are chemically unreactive with typical automotive glycol-based coolant. • Withstand direct UV exposure over a period of 20 years and be able to pass the mandatory crash requirements after exposure. • Withstand exposure to water without failing/the structure breaking down. Recommended that the structure meets standards to pass the cyclic damp heat test. • Withstand relative air humidity ranges from 20% to 95% for extended periods of time and be able to pass the mandatory crash requirements after exposure. • The crash structure will be subjected to mechanical vibration and repeated shocks during normal use of the vehicle and must not fail due to this.
Mass	• It is a target that the crash structure developed from this project has a mass of 10.0kg or lower. • Be a bolt-on structure. • Fit within the boundary volume • Target of sitting 50mm or greater below the A-surface of the bonnet for pedestrian impact.
Functional	• Crush in a controlled and predictable manner so that the occupant's head never exceeds 80G for more than 3ms in all mandatory crash tests. • Target peak acceleration to be less than 35G for the European Type Approval test (56km/h frontal impact). • Contain a structural threaded section for a towing eye. This must be able to withstand a force of half the vehicle's mass in the x-direction without plastic deformation occurring (SAE Vehicle Co-ordinate System).

	• Towing eye fastening must be of a design that allows it to be attached and removed without removing any of the vehicle's bodywork and without the use of tools. Crash simulations will be conducted without the towing eye fitted.
Crash Tests Scenarios	• Very Low-Speed Impact: 5km/h full-frontal, rigid barrier. Target of no crush of the crash structure. • Low Speed Impact: 32km/h (20mph), recommended to look at full frontal and offset barriers to satisfy the initial project brief. • Medium Speed: 56km/h, offset deformable structure, 40% overlap as per ECE Reg 94 (European type approval regulations).
Performance	• The crash structure must still be able to pass the initial crash performance requirements after 20 years of service on a vehicle. This can be simulated through standard automotive accelerated life testing.
Safety	• Materials used in construction are recommended to not be hazardous to health or the environment. It's advised that the toxicity of the materials chosen is investigated and materials chosen minimise the impact to the environment in the event of an accident.
Sustainability	• Must be designed with a roadmap for recycling in mind at the end of the component's life with a line of sight to closed-loop recycling.
Manufacturing	• Be able to be scaled up to 5000 units manufactured per annum from one set of tooling. • Target of using low energy manufacturing processes where possible.

3. Crash zone architecture and design space

The architecture of Riversimple [4] Rasa vehicle offers a narrow design space for the bumper beam and limited possibility for support above or below it across vehicle's centreline due to packaging constraints created by the cooling system, see Figure 1. As a result, a well-optimised and compact solution is required.

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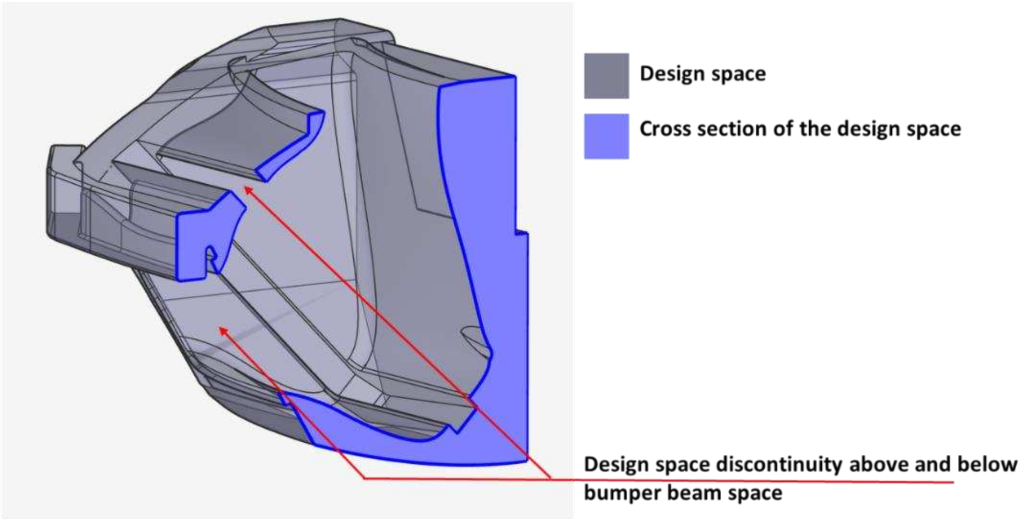


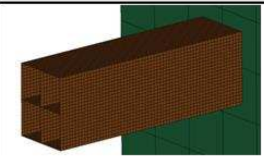
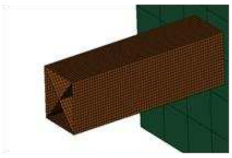
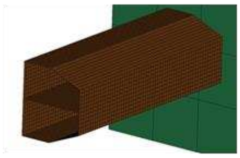
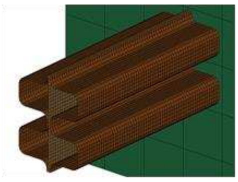
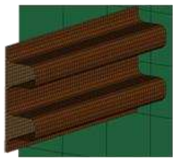
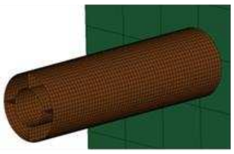
Figure 1. Design space surrounding the bumper beam area.

4. Concepts development and initial crash tests

Following multiple topology optimisation where the surfaces of the cross section were assigned parameters in ANSA which was coupled to LS-OPT [5] where the parameters became design variables. A Design of Experiments (DOE) was created with 50 designs with design variables chosen using the Latin Hypercube Point selection.

Among the 50 initially proposed concepts, a few were shortlisted based on the manufacturability assessment. A quick summary of the shortlisted concepts for further analysis is exhibited in Table 2. The peak force, peak acceleration, mass, absorbed energy and average force were measured. The Specific Energy Absorption (SEA) was measured using the crush mass and the crush tube's displacement. The current study is focused on further shortlisting the concepts based on the crash simulations and the experimental trials. Multiple FE material cards are being generated as part of the project to understand the usability of flax composites, GFRP and CFRP. This was done by performing an extensive static characterisation campaign. Dynamic characterisation was done specifically for the CFRP on multiple strain rates as this material would be the primary candidate for crash structures. The FE material card was written in MAT 58 in LsDyna [6].

Table 2 Sample crash box concepts

Concept		Peak force (N)	SEA (KJ/kg)
Plus box		≈ 1E+06	≈70
Crossbox		≈ 1E+06	≈50
D-section		≈7E+05	≈48
Mirrored W section		≈1E+06	≈60
W section		≈9E+05	≈32
Bio inspired [7]		≈ 1E+06	≈90

The structures investigated had the SEA varying from 30KJ/Kg from the mirrored W section to 90 KJ/Kg for the bio inspired [7]. The ideal geometry was expected to have a progressive crush failure mode enabling efficient energy absorption, instead of having a buckling failure mode. The addition of trigger mechanism through the indentation of the geometry was found to reduce the peak force and increase the SEA of the crush tubes. For some concepts that were showing buckling failures, the addition of an indented trigger mechanism has initiated a progressive crush failure, which thereby increased the energy absorption. The most critical consideration is the manufacturability of the concepts which is been explored currently. The best performing concepts will be redesigned for manufacture with composite materials. Based on an initial design for manufacture, some of the concepts are deemed too complex and expensive to be manufactured with composite laminates. The final concept will be selected by CAE that shows the most efficient crush performance.

5. Concepts selection

Similar to any product development process, several concepts are being developed in this study. At the end of the development phase, a single concept should be selected to proceed with.

However, given that the crash structure has several performance requirements with different importance levels, selecting and optimising concepts can be challenging. To address this, a concept selection process is developed to select the optimum concept through achieving the following four key objectives: a) End-user performance requirements indicators are defined along with their relative importance. b) Solution elements are defined in line with what the project aims to achieve and end-user's performance requirements. c) Concepts are developed and optimised to included solutions based on their weighting against end-user performance requirements. d) basing optimum concept selection on measurable indicator that reflects concepts performance against all of the performance requirements set by the end-user. These objectives are implemented in two steps; first using Quality Function Deployment (QFD) to identify and prioritise end-user's expectations quickly and effectively. And second, using Pugh chart to compare design concepts against end-user's criteria to select the final concept. These steps processes are illustrated in Figure 2 and the sections below:

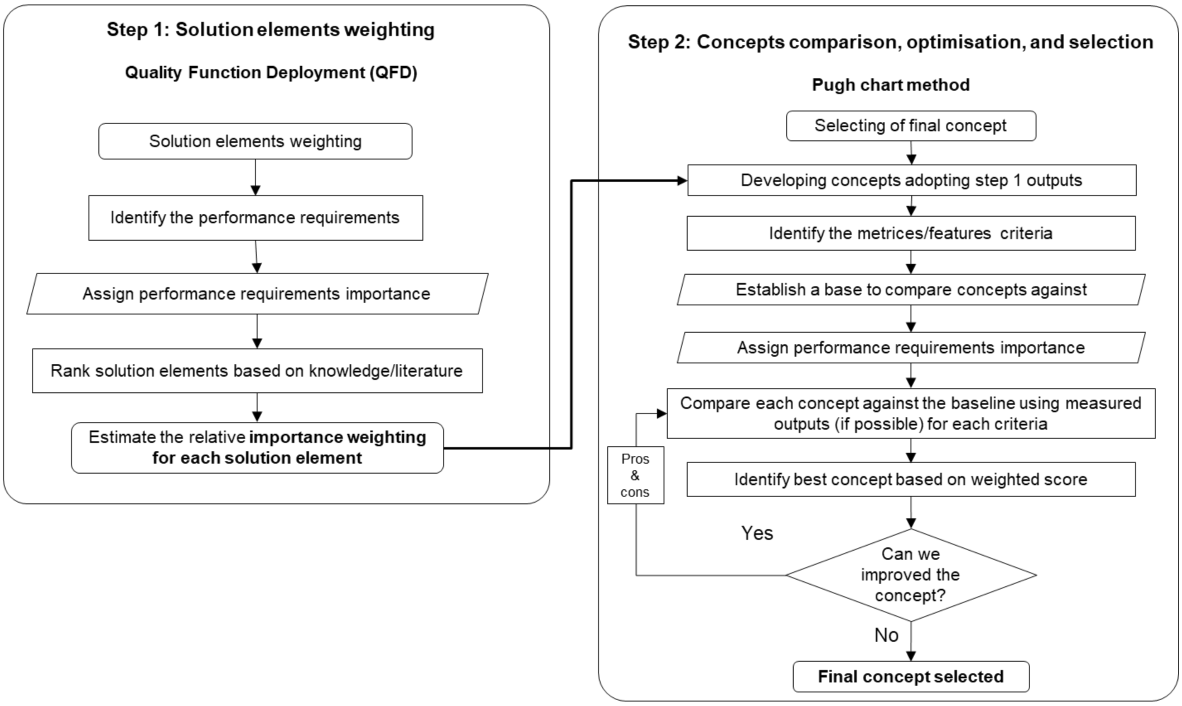


Figure 2. Solution elements weighting and concepts selection process.

4.1 End-user performance requirements indicators

The crash system to be developed in this project aims to offer tailored crash performance, reduce weight, and offer recyclability options. In addition to this, several functional requirements are equally important and should be met, such as cost, modularity, and production rate. Equally important to defining these indicators is their relative importance. Table 3 lists the identified indicators and their significance.

Table 3. End-user performance requirements indicators and their importance (5 very important, 1 less important).

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Performance requirements	Description	Relative importance
Sustainability	The indicative contribution of the solutions and concepts towards sustainability in QFD and Pugh chart, respectively.	5
Component Cost	The indicative manufacturing cost for implementing the proposed solution and the overall indirective cost for each concept in QFD and Pugh chart, respectively.	2
Lifetime Cost	Indicates the operational cost associated with implementing a specific solution or the concept in QFD and Pugh chart, respectively.	4
Cycle Time	Indicates the influence of a specific solution or the overall concept on the production rate in QFD and Pugh chart, respectively.	2
Modularity	Indicates the opportunity to have a modular crash structure for a specific solution or the overall concept in QFD and Pugh chart, respectively.	2
Performance	Indicates the effect of solutions on performance in QFD matrix or the overall crash performance of the concept in Pugh chart.	5
Weight	Indicates the influence of solutions on weight in QFD matrix or the overall importance of the concept in Pugh chart.	4

4.2 Solution elements

To meet project's goals, there is an array of solutions that can be employed during concepts development stages such as the use different materials and design philosophies. However, there is a need to link these solutions with end-user performance requirements to produce a satisfactory design that meets end-user's requirements and expectations. Hence, these solutions are listed and defined in Table 4 for use in the QFD matrix to provide the design team with a measurable indicator of which solution(s) have higher relative importance based on their influence on end-user performance requirements indicators (see section 4.1), so that it/they can be implemented in concepts development and optimisation iterations.

Table 4. Proposed key design solutions considered as part of concepts development stage.

Solution elements	Description
Use of biomaterials	The use of biomaterials increases sustainability and can decrease cost compared with the use of carbon fibre. However, the mechanical performance will decrease.
Use of thermoset materials	Manufacturing thermoset composites is a well-established method. Compared with the thermoplastic process, it requires less start-up capital and allows the manufacturing of complex shapes. However, it can be labour intensive, have a limited scaling possibility, and reduce recycling opportunities.
Use of thermoplastic materials	Thermoplastic composites offer higher sustainability compared with thermosets as they can be recycled. However, their overall cost is higher than thermosets. Hence, their use can be limited to smaller sections.
Use of metallic materials	Although metallic materials offer a high level of recyclability, fast production rate, and modularity, their performance to density is lower than composites.
Single-piece solution	Integrated crash concepts, which consist of single-piece attachable, can offer the lowest possible weight and improve the assembly process. However, such solutions can be cost-intensive in manufacturing and operation due to high replacement/repair costs if damaged, hence high insurance costs.
Multi-piece solution	Multi-piece or modular solutions offer less operational cost as they should be repaired or replaced at a lower cost compared with single-piece solutions. However, they generally will have a higher weight due to the number of joints and fasteners needed.

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6. Conclusion and future work

Multiple concepts of crash structures have been developed as part of the project through topology optimisation, material homogenisation and manufacturability. These concepts were explored as sampled in Table 2, as the ideal geometry of the crashboxes were further evolved to more manufacturable shapes, and is currently being shortlisted for impact, drop and crash testing scenarios. Based on the initial assessment, the best performing geometry with the best SEA and energy dissipation was the bio-inspired [5], However, this concept was not easily manufacturable based. On the other hand, the addition of a trigger mechanism was investigated, and it was found that the peak force was reduced, and the energy absorption was increased by initiating progressive crushing. This ongoing project is focused on finalising a manufacturable crash box concept, with the ideal material and trigger mechanism to optimise the energy release while considering the lifecycle aspects. Upon defining the final concept, a detailed life cycle analysing study will be conducted to assess the sustainability of the developed crash box.

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