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Life Cycle Assessment and Experimental Mechanical Investigation of Test Samples for High-Performance Racing Boats

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Abstract: This paper investigates the environmental impact and mechanical performance of two composite sandwich structures, named Series 1 and Series 2, used in high-performance racing boats. Mechanical tests, including four-point bending and drop impact tests, were performed. It was found on a general basis that Series 2 has higher load-bearing capacity and limited deflection. Series 1, which has a higher density, was able to absorb more impact energy but was more susceptible to damage. A Life Cycle Assessment (LCA) was conducted to evaluate the environmental impact associated with the materials, considering also the testing phase, which plays an important role in the life cycle of materials and structures for advanced marine applications. In addition, two performance indexes were introduced to correlate the mechanical and environmental properties of the analyzed materials. This study emphasizes the importance of considering the testing phase in LCA, as the energy-intensive nature of mechanical testing contributes significantly to the overall environmental impact. The introduced indexes allow for a more comprehensive understanding of the balance between mechanical performance and environmental sustainability. The findings suggest a trade-off between mechanical performance and sustainability, calling for further research into recyclable composites and greener manufacturing processes to balance these competing priorities.

Keywords: impact testing; maritime safety; four-point bending test; life cycle assessment; high-speed vessel

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1. Introduction

The rising demand for high-performance materials across industries such as aerospace, automotive, and marine applications—where unique challenges, such as exposure to seawater, varying temperatures, and dynamic loading conditions exist—has intensified the reliance on advanced composites.

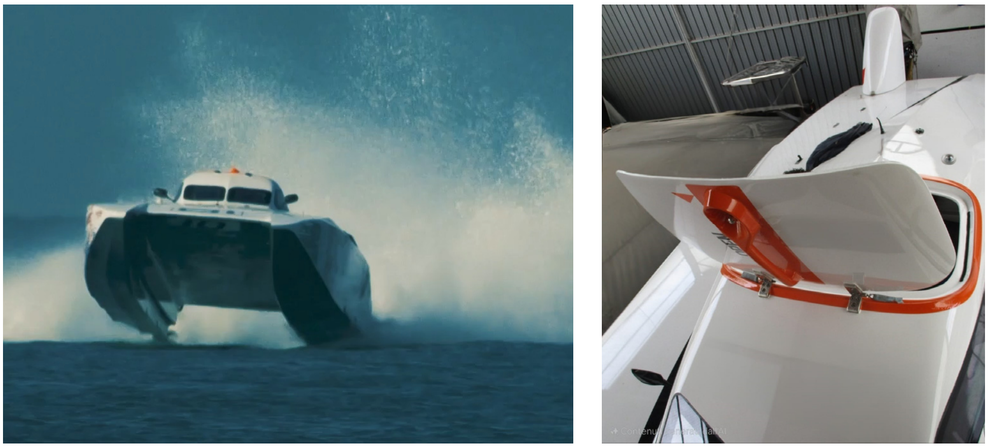
These materials are characterized by their high strength-to-weight ratio, durability, and resistance to harsh environmental conditions [1]. However, their use in extreme conditions should consider the effect of environmental degradation, deriving for instance from high temperatures, humidity, or UV, which can potentially compromise the structure's functionality [2].

Composite sandwich structures have become particularly attractive for boat manufacturing, notably for high-performance racing boats where weight savings, material properties, and the possibility to be molded into complex shapes are essential features to achieve superior performance. Hence, fiber-reinforced polymers (FRP) are popular in the marine industry to address challenges such as corrosion and weight reduction, with glass (GFRPs) and carbon fibers (CFRPs) being common reinforcements, followed by aramid fibers, while polymeric foams (e.g., polystyrene, PVC) and honeycomb structures commonly serve as core materials [3].

In the work by Gentili et al. [4], the study compared the environmental impact of two production processes for marine structures in carbon fiber-reinforced polymer (CFRP) laminates: a manual impregnation technique (Scenario 1) and a prepreg-based process (Scenario 2). The results showed a 32% reduction in CO_2 equivalent emissions with the use of prepreg (Scenario 2), totaling 228.22 kg of CO_2 eq compared to 335.75 kg of CO_2 eq for the manual process, due to the lower amount of carbon fiber required. The Life Cycle Assessment identified carbon fibers as the primary contributor to environmental impacts, suggesting that optimized design and fiber recycling could further improve the sustainability of advanced marine applications.

In the work by Rubino et al. [3], the authors compared the technologies of hand lay-up and vacuum infusion to produce fiber-reinforced composite materials in marine applications, highlighting differences in environmental impact and performance. The results showed that vacuum infusion had 30% lower CO_2 emissions compared to hand lay-up, due to greater efficiency in resin use and reduced waste. Structurally, composites produced by vacuum infusion demonstrated superior corrosion resistance and an improved strength-to-weight ratio, which reduces maintenance needs and associated costs. In contrast, hand lay-up resulted in greater waste and overall lower quality laminates, with a less homogeneous structure that makes them more susceptible to degradation in the marine environment. These findings suggest that vacuum infusion is a more sustainable and higher-performing choice for applications in harsh marine environments, where durability and resistance are essential requirements.

Figure 1a shows an XCAT boat, a typical example of the use of composite materials in the naval sports environment. These materials are chosen for their exceptional lightness and high mechanical performance, which are crucial for ensuring speed and maneuverability in extreme conditions.



(**a**) (**b**)

Figure 1. The use of lightweight composite materials in XCAT boats enhances performance and safety, as seen in the hull design (**a**) and the cockpit hatch (**b**).

In Figure 1b, the cockpit hatch detail exemplifies the strategic use of composites. This component, made of composite material, plays a crucial role not only for the pilots' access but also as an escape route in case of an accident. The hatch must be designed to withstand strong impacts and stresses that may occur during emergency situations or collisions without compromising the crew's safety. This highlights the importance of composites in combining lightness and structural strength in high-performance racing boats such as XCATs.

An essential phase in the real-world application of composite structures, especially when high-level performances are required, is represented by experimental analysis, which is crucial for understanding the behavior of composite structures. While numerical simulations or analytical models offer cost-effective initial assessments, experimental testing provides more accurate results for composite materials, especially under dynamic loading conditions, such as impact [5]. Therefore, experimental evaluation of complex composite properties, such as crashworthiness, is essential for validating models and failure theories developed to aid in composite design [6].

Manufacturing techniques for these composites range from hand lay-up to advanced methods offering higher quality, such as vacuum-assisted resin infusion [7], resin transfer molding [8], and 3D printing [9].

However, the environmental footprint of manufacturing advanced composites, such as carbon fiber-reinforced polymers and glass fiber-reinforced polymers, raises significant concerns. Indeed, the industry is shifting towards more sustainable materials and practices, exploring alternative fibers, matrix polymers, and sandwich cores to reduce environmental impact and improve end-of-life scenarios [10].

The composite manufacturing processes, while offering remarkable mechanical properties and design flexibility, often require energy-intensive production methods and the use of non-renewable resources. The synthesis of high-performance fibers and matrix materials, typically involving petrochemical feedstocks, contributes to greenhouse gas emissions, pollution, and high-energy consumption. Additionally, end-of-life disposal of composites presents challenges: the great majority of composites are destined for landfill or incineration [11], hence the recovery of materials is negligible and, what is more, energy-demanding processes are used.

As pointed out by Krauklis et al. [12], some recent key events—one of which is the ban in Germany on some materials used for landfilling, which affects composite—spotlighted the necessity to address composite recycling on a global scale. Such environmental concerns inevitably affect marine industry, which is increasingly facing pressures to reduce its ecological footprint, driven by regulatory shifts, customer demand for sustainable products, and global efforts to mitigate climate change.

In constructing boats and racing vessels, advanced composites are widely used to minimize weight while maximizing strength, leading to improvements in speed and fuel efficiency. However, the environmental trade-offs associated with these performance gains have yet to be fully addressed. As an illustration, despite weight reduction obtained with composite materials producing a so-called knock-on effect—involving lower fuel consumption, smaller fuel tanks, lower displacement, and lower loads on the structure [13]—composite waste management is still an open question, and significant research gaps exist, as suggested in Ref. [14].

A thorough understanding of the environmental impacts of composite manufacturing and end-of-life management in the marine sector is essential for developing more sustainable practices that align with broader environmental goals, such as reducing carbon emissions, minimizing resource consumption, promoting circularity through material reuse and recycling and supporting the introduction of cutting-edge strategies for performance improvements [15]. In this scenario, a Life Cycle Assessment (LCA) is crucial for evaluating and mitigating environmental impacts across the entire life cycle of ships and marine activities [16]. LCA helps identify key environmental issues, such as greenhouse gas emissions, climate change, and marine biodiversity loss [17]. It enables comparison of different fuels and technologies, supporting decision-making for more sustainable marine transportation.

This paper aims to analyze the environmental impact of some composite sandwich structures currently used for racing catamaran of the UIM XCAT World Championship, relating it to their mechanical behavior. The analysis also considers the experimental testing phase, a crucial step for high performance applications. The correlation between mechanical and environmental features, established through the definition of two indexes, is essential in the context of racing boats, where high performance and pilot safety are paramount.

By analyzing material production, energy consumption, waste generation, and the potential for recycling or reuse, this study will highlight key areas where more sustainable practices can be implemented. The ultimate goal is to provide insights into the path toward greener alternatives and manufacturing innovations that could reduce the environmental impact of composites without compromising their performance advantages in marine applications.

2. Materials and Methods

The wide use of composites and sandwich composite structure for XCAT boats is the result of their extreme operating conditions, involving high speeds and frequent impacts from interactions with waves, which require materials and structures with excellent impact resistance and high capacity for energy absorption. To verify that the sandwich panels used in XCAT boat hull construction comply with UIM standards and maintain their structural integrity, rigorous experimental testing is required.

In the current study, two types of sandwich composites, currently used for racing boats competing in the same offshore category of the UIM, were tested. The analyzed structures were selected among those used for the construction of cockpits in the same racing category; hence, they are designed to fulfill the same requirements from UIM rules and regulations. The performed tests enabled the evaluation of their mechanical performance and aided the identification of the best configurations for use in competitive boat manufacturing. Both types of sandwich structures were produced using the vacuum infusion technique.

The experimental analysis included four-point bending tests and low-velocity impact tests, specifically developed to replicate the actual conditions encountered during racing. The chosen energy levels for impact testing were designed to reflect the most critical conditions, as outlined by UIM standards, ensuring that the tests accurately represent the stresses experienced during competitions. These tests help confirm that the materials are capable of providing necessary reliability and safety in high-performance marine applications.

2.1. Tested Samples

The specimens used for the bending test measured 800 mm × 100 mm, with a total thickness varying according to the laminate stacking sequence, as specified by rule 508.03 of the 2017 UIM offshore regulations. For the drop impact tests, samples measured 100 mm × 100 mm. In the absence of a defined standard for the impact test parameters, ASTM D-7136 was adopted as the reference guideline.

The tested composite sandwich structures are grouped in the following categories:

- Series 1;
- Series 2.

The features of each sandwich structure type are summarized in Tables 1 and 2.

Table 1. Lamination layers of sandwich Series 1.

Ply	Material	Type	Weight (g/m^2)	Angle
Series 1_1	E-glass	Twill 2 × 2	400	0°/90°
Series 1_2	Carbon	Bi-axial	411	−45°/45°
Series 1_3	Carbon	Woven	416	0°/90°
Series 1_4	Carbon	Bi-axial	411	−45°/45°
Series 1_5	Carbon	Woven	416	0°/90°
Series 1_6	Carbon	Bi-axial	411	−45°/45°
Core	Gurit M130	Thickness 20 mm	140 (kg/m^3)	
Series 1_6	Carbon	Bi-axial	411	−45°/45°
Series 1_5	Carbon	Woven	416	0°/90°
Series 1_4	Carbon	Bi-axial	411	−45°/45°
Series 1_3	Carbon	Woven	416	0°/90°
Series 1_2	Carbon	Bi-axial	411	−45°/45°
Series 1_1	Aramid	Twill	175	0°/90°

Table 2. Lamination layers of sandwich Series 2.

Ply	Material	Type	Weight (g/m^2)	Angle
Series 2_1	Carbon	Bi-axial	300	−45°/45°
Series 2_2	Carbon	Woven	416	0°/90°
Series 2_3	Carbon	Woven	416	0°/90°
Series 2_4	Carbon	Bi-axial	300	−45°/45°
Series 2_5	Carbon	Woven	416	0°/90°
Series 2_6	Carbon	Woven	416	0°/90°
Core	PVC flexyfoam	Thickness 20 mm	90 (kg/m^3)	
Series 2_6	Carbon	Woven	416	0°/90°
Series 2_5	Carbon	Woven	416	0°/90°
Series 2_4	Carbon	Bi-axial	300	−45°/45°
Series 2_3	Carbon	Woven	416	0°/90°
Series 2_2	Carbon	Woven	416	0°/90°
Series 2_1	Carbon	Bi-axial	300	−45°/45°

2.2. Four-Point Bending Tests Setup

Four-point bending tests were conducted using an ITALSIGMA testing machine equipped with a load cell capable of a maximum load capacity of 25 kN. Tests followed the procedure required by UIM to authorize the use of sandwich structures for cockpit construction. The specimens were supported on steel cylinders with a diameter of 20 mm, and the load was applied using cylinders of the same dimensions, at a constant displacement rate of 0.4 mm/s. The experimental setup is displayed in Figure 2. To ensure the repeatability of the results, a minimum of three bending tests were performed for each type of specimen.

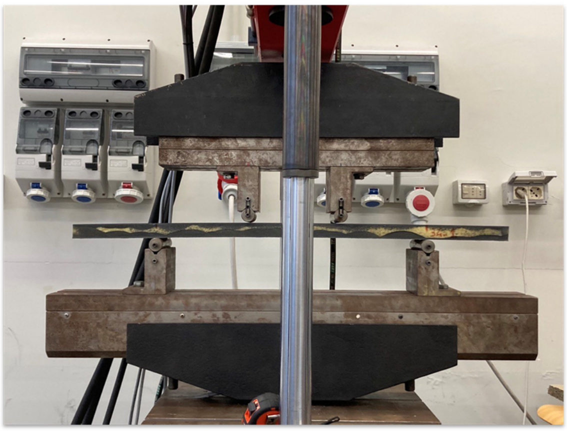


Figure 2. Four-point bending test setup.

According to UIM regulations, the samples must meet specific minimum load requirements depending on the competition class. For the XCAT class, the samples are required to withstand a minimum load of 3 kN without experiencing structural failure. This constraint ensures that the materials used in the construction of the boats possess sufficient strength to guarantee safety and maintain structural integrity during competitions.

2.3. Drop Impact Tests Setup

The impact resistance of composite sandwich structures for racing boats was evaluated by performing low-velocity impact tests with the drop-weight method already used on similar specimens from vessels competing in UIM Championships to assess the damage evolution [18] and the correlation between the imprinted volumes and the number of impacts [19]. Impact tests are useful to analyze critical conditions often encountered by sandwich structures on racing boats, such as impacts from interactions with waves or debris. The energy levels for the impacts were selected to ensure that the tests accurately represent the stresses experienced during competitions. A Fractovis Plus machine from CEAST S.r.l. (Pianezza, Italy), a commercially available device designed for low-velocity drop-weight impact testing, was used. The machine is equipped with a tower that incorporates an automatic system for positioning and releasing a striker, which impacts the sample, as well as a system for measuring impact velocity and a strain gauge to record the impact force $F(t)$ of the metal striker during the event. The test chamber, located at the base of the machine, enables observation of the impact through a protective window. The impact energy was adjusted by varying both the striker's mass and its impact velocity. A hemispherical striker with a diameter of 20 mm and a mass of 6.5 kg was employed. The experimental setup is displayed in Figure 3. Tests were conducted at five different energy levels, ranging from 20 J to 120 J. Each test was repeated three times to ensure the reliability of the results.

Figure 3. Drop impact test setup.

2.4. LCA

The LCA analysis was conducted using the OpenLCA software (GreenDelta, version 2.1.1), integrated with the Ecoinvent database (version 3.10, released in 2024) and IDEMAT (short for Industrial Design & Engineering MATerials database) data for aramid fibers [20]. In this analysis, the cut-off method was applied, meaning that the producer does not receive credit for using recycled materials. The recyclable materials used for the production of the composite samples, made of epoxy resin and carbon fiber, were sourced, when possible, from the Italian market, or alternatively from the European market. Consequently, these materials include all upstream environmental burdens, such as the average transportation within the geographical areas considered and the resources needed to compensate for losses during transport and trade.

To assess the environmental impacts associated with the life cycle of the composite samples, the Life Cycle Impact Assessment (LCIA) was performed using the Environmental Footprint (EF) 3.1 method, developed by the European Commission [21]. The EF 3.1 method introduces significant updates to characterization factors across various impact categories, aligning with the latest scientific knowledge and European environmental policies [22]. This method is distinguished by its ability to cover a wide range of impact categories, which are divided into four main areas of protection: Climate Change, Human Health, Resource Depletion, and Ecosystem Quality.

The LCA study adhered to standards defined by major international frameworks. Among these is the ISO 14040 series, which includes the ISO 14040 [23] and ISO 14044 [24] standards, first published by the International Organization for Standardization (ISO) in 1997. These standards provide a unified approach for the methods and procedures used in conducting LCA studies, ensuring a rigorous, shared methodological framework. The series was later updated and republished in 2006 [23,24], maintaining its relevance and rigor in the field of Life Cycle Assessments.

The LCA study was conducted following a 'cradle to grave' approach, covering all phases of the product's life cycle, from the production of raw materials to final disposal.

2.4.1. Goal and Scope Definition

The primary objective of this LCA study is to assess the environmental impact associated with the experimental testing of new sandwich specimens used in the construction of racing boats, such as those employed in XCAT competitions, as well as a broader range of sports vessels that utilize sandwich structures. For this analysis, the functional unit has been defined as a specimen of sandwich material. This choice allows for a fair and standardized analysis of the different scenarios and types of specimens involved in the tests, providing a clear benchmark for measuring the various environmental impacts throughout the material's life cycle.

The boundaries of this study encompass all phases of the life cycle of sandwich materials, extending from cradle to grave. Specifically, they include the extraction of raw materials necessary for the production of the specimens, their fabrication, subsequent transportation to the test site, and finally, the end-of-life phase, in which the specimens will be stored or disposed of at university facilities. Being a cradle-to-grave LCA analysis, we have considered all phases of the specimens' life cycle—from production to testing up to final disposal—to ensure an accurate representation of environmental impacts.

In the testing phase, which involved bending and impact machines, we primarily evaluated the energy impact. Other minor impacts, such as machine maintenance, the use of consumables (e.g., lubricants), and any indirect emissions, were included in the cut-off since they collectively represent less than 5% of the total impact. This allowed us to focus on the most relevant factors without compromising the accuracy of the analysis.

The ultimate goal is to provide reliable quantitative data on the environmental impact of an experimental testing campaign, not only to understand the effects of the testing process itself but also to develop potential scenarios for the disposal or recycling of the specimens at the end of their life. This contributes to a comprehensive assessment of the environmental sustainability of these new sandwich materials, considering the relevance that the testing phase has for high-performance applications such as racing boats.

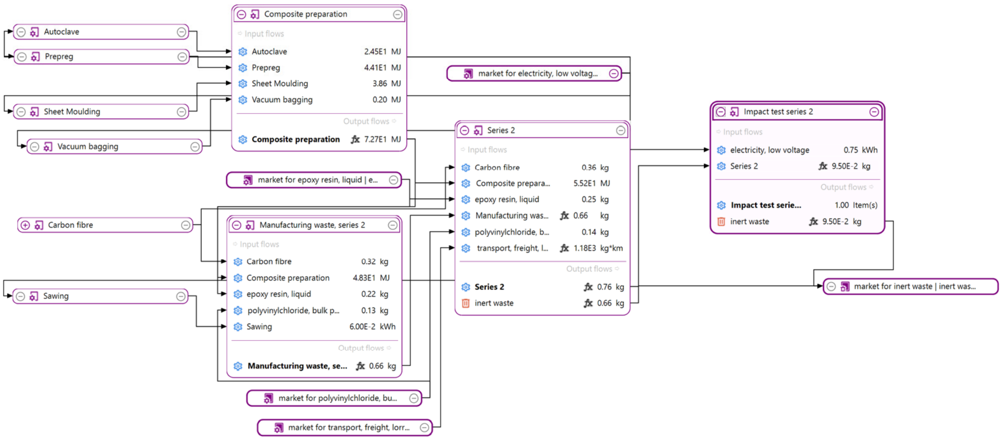
Figure 4 illustrates the complete process flow diagrams for the four-point bending test and the impact test on samples 1 and 2, starting from samples production to test execution, and concluding with their end-of-life disposal in a landfill.

2.4.2. Inventory Analysis

In the life cycle inventory phase, data related to the inputs and outputs associated with the experimental testing of two types of sandwich structures, named Series 1 and Series 2, are systematically collected and analyzed. This process includes quantifying the raw materials required, the energy consumed during production, and the emissions generated throughout the testing and manufacturing processes.

Table 3 presents the inventory data for both sandwich types analyzed in this study. The table lists the types and quantities of materials necessary for their production. The manufacturing process considered for the specimens is vacuum bagging. The production location is assumed to be in a generic Italian region, and transportation to the University of Messina has been modeled with average values. The energy consumption of the testing equipment, including four-point bending machines and impact test drop devices, has also been taken into account.

Figure 4. *Cont.*



(**d**)

Figure 4. The process in OpenLCA environment: Four-point bending test for Series 1 (**a**) and Series 2 (**b**), Impact test for Series 1 (**c**) and Series 2 (**d**).

Table 3. The inventory data relating to the two types of sandwich composites.

Material	Specimen Series 1 (kg)	Specimen Series 2 (kg)	Scraps Series 1 (kg)	Scraps Series 2 (kg)
Fiber Carbon	0.369	0.445	0.289	0.317
Fiber Glass	0.036	-	0.028	-
Fiber Aramidic	0.016	0.032	0.012	
Epoxy resin	0.330	0.334	0.259	0.222
Core	0.250	0.192	0.196	0.126

This inventory analysis provides a comprehensive basis for assessing the environmental impacts of each sandwich design, forming the foundation for the subsequent life cycle impact assessment phase. The comparison of material usage, energy consumption, and overall environmental footprint between Series 1 and Series 2 is clearly outlined to facilitate a thorough evaluation. All relevant data and processes are reported in the following sections.

For the modeling of material production, which included aramid fiber, glass fiber, epoxy resin, and the cores of the sandwich structures, the Ecoinvent database was used. However, for carbon fibers, a custom model was created based on the production process described by De Vegt and Haije [25].

The diagram in Figure 5 shows the production flow of a carbon fiber and epoxy resin sandwich composite using the vacuum bagging technique. The main phases include prepreg preparation, sheet molding, vacuum bagging, and autoclave curing. The reported energy values (44.1 MJ for prepreg preparation, 3.86 MJ for sheet molding, 0.2 MJ for vacuum bagging, and 24.5 MJ for the autoclave) are related to the production of 1 kg of composite sandwich and were taken from the by study Karthikeyan Ramachandran et al. [26] In the context of this LCA study, the process was scaled to the functional unit, which corresponds to a complete sandwich sample with dimensions of 800 mm × 100 mm.

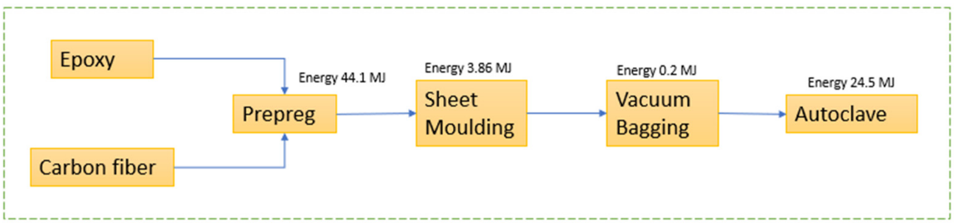


Figure 5. Production process of the carbon fiber and epoxy resin composite.

For the calculation of the transport impact, an average distance of 950 km was assumed, representing the transport of samples from shipyards in Rome and Venice to Messina. Specifically, the sample from Series 1 comes from a shipyard in Rome, while the sample from Series 2 comes from a shipyard in Venice. The distance from Rome to Messina is approximately 700 km, and from Venice to Messina is about 1200 km.

The transport was modeled using a Euro 4 van with a load capacity of 4.5 tons, corresponding to a typical vehicle used for medium-sized deliveries. Road distances were estimated based on these specific routes, reflecting typical transport scenarios from central and northern Italy to the destination. Furthermore, for landfill disposal operations, we used the Ecoinvent market dataset, which incorporates typical average transportation distances for this purpose, further reducing uncertainty in transportation assumptions.

A sandwich panel (Figure 6) with dimensions of 600 mm × 1000 mm was provided, from which 4 specimens measuring 800 mm × 100 mm were extracted.

Figure 6. Sandwich panel after cutting the specimens.

The time and energy required for cutting sandwich composite specimens were estimated using a 2 kW angle grinder. The specimens for the four-point bending test have dimensions of 800 mm × 100 mm and a thickness varying between 25 mm and 27 mm. For the impact test, the specimens have dimensions of 100 mm × 100 mm and are obtained by cutting a specimen of 800 mm × 100 mm, yielding a total of 8 specimens for the impact tests. The cutting speed was set at 1 m/min. The estimated energy for cutting is 60 Wh. The relatively low energy consumption is attributed to the short cutting duration and the efficiency of the tool, which is suitable for high-strength composite materials.

The operation of the machine for the four-point bending test is structured to apply a distributed load on a specimen to evaluate its bending resistance and mechanical properties (Figure 7); the main phases of the test procedure are summarized below:

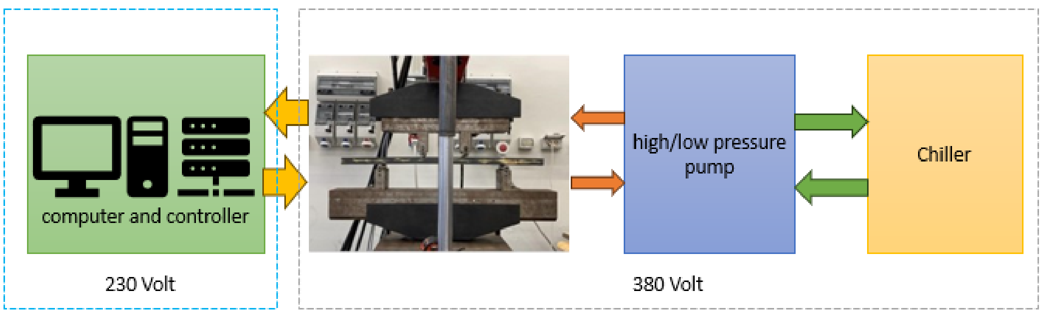


Figure 7. The operation of the machine for the four-point bending test.

- **Machine Operation**: The specimen is positioned on two lower supports, which act as fulcrum points. These supports define the bending span length. During testing, the machine applies a load at two upper points, pressing down on the specimen and creating a uniform bending force. This 4-point configuration (two lower supports and two upper load points) allows for an even distribution of the load, which is essential for assessing the material's resistance.
- **Hydraulic system and pumps**: The machine is equipped with a hydraulic system that uses both a low and a high-pressure pump to move the upper crossheads. The low-pressure pump is used to position the crossheads correctly before the test begins. Once positioned, the high-pressure pump is activated to exert the necessary force for the bending test, ensuring that the hydraulic pistons press on the specimen's upper points, generating the required deformation.
- **Chiller**: During the operation of the hydraulic system, it is essential to maintain a stable temperature of the hydraulic fluid to prevent overheating, which could affect the test results. This is achieved by the chiller, a cooling system that ensures thermal control during the test execution.
- **Computer and controller**: A computer and control system manage all machine operations, from regulating the applied force to collecting data during the test. This system ensures the test follows predefined parameters and allows real-time recording of results, continuously monitoring the applied force and the specimen's deformation.

Table 4 presents the power consumption, duration of the test of a single specimen, and the resulting energy consumption.

Table 4. Energy consumption four-point bending test.

Four-Point Bending Test	Power (kw)	Time (h)	Energy (kWh)
Hydraulic machine and high/low-pressure pump	7.5	0.03	0.25
Chiller	3.52	0.03	0.12
Computer and controller	0.5	0.03	0.02
Total			0.38

The impact test process (Figure 8) involves a series of preparatory and operational steps designed to ensure that the test is conducted accurately and safely. Here is a detailed explanation of the process:

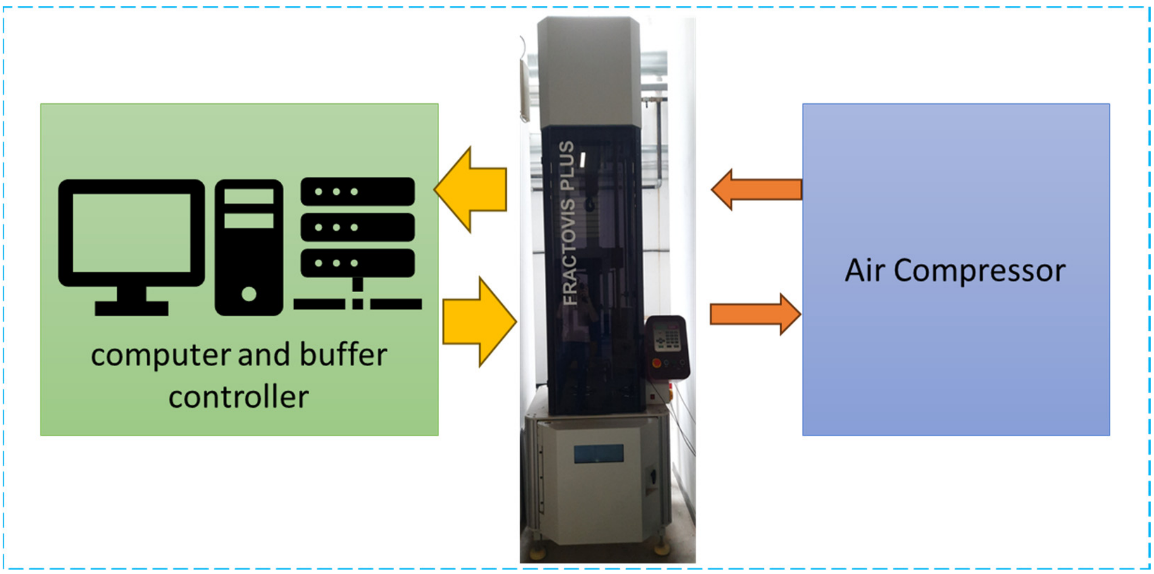


Figure 8. The impact test process.

- **Manual positioning of the specimen**: The test begins by manually placing the specimen in the designated impact area at the bottom of the machine. This area is carefully aligned to ensure the impactor will strike the intended spot on the specimen during the test.
- **Zeroing the machine**: Once the specimen is positioned, the machine needs to be "zeroed" by lowering the impactor until it contacts the top surface of the specimen, determining the "zero point". This reference point is crucial for ensuring that the impactor travels the correct distance and applies the expected force.
- **Adjusting the photocell distance**: Next, the position of the photocell (sensor) is adjusted to measure the impactor's velocity. The distance between the impactor and the photocell is critical, as it must be adjusted based on the thickness of the specimen. This adjustment ensures accurate speed measurement, which is essential for calculating the energy applied during the impact.
- **Lubrication of the impactor tip**: Before the machine is started, the tip of the impactor is lubricated to reduce friction during the test. This step helps in obtaining more reliable results by ensuring that the impactor moves smoothly, minimizing resistance that could affect the force of the impact.
- **Starting the machine**: After all the preparations are complete, the machine is started. The impactor is released and accelerates towards the specimen. The photocell records the velocity of the impactor as it approaches the specimen, and the machine measures the force of the impact as it strikes the specimen.
- **Activating the compressor**: The compressor (shown in the image as 1.5 HP) is responsible for propelling the impactor. It provides the necessary energy to accelerate the impactor and achieve the desired speed. The compressor stores air and releases it at the moment of impact, ensuring that the impactor hits the specimen with the predefined force.
- **Recording the results**: During the test, the buffer and controller collect data in real time. These components translate the impact speed and force into data that can be analyzed later. The controller manages the entire process, while the buffer stores the results.
- **Data analysis through the computer**: Once the test is completed, the recorded data are processed and analyzed by the computer, which provides a detailed assessment of the impact. This system allows for precise calculations of the energy transferred to the specimen and the resulting deformations.

Table 5 presents the resulting impact test energy consumption of a single specimen.

Table 5. Energy consumption impact test.

Impact Test	Power (kW)	Time (h)	Energy (kWh)
Impact machine	0.64	0.33	0.21
Air Compressor	3.52	0.33	0.4
Computer and buffer controller	0.4	0.33	0.13
Total			0.75

These data provide a detailed understanding of the energy requirements of the test, which is essential for the inventory analysis phase in the LCA. It offers the necessary information to assess the environmental impact resulting from the energy used during the experimental process. The energy consumption of each component is crucial for calculating the overall environmental footprint of the sandwich material testing campaign.

3. Results

3.1. Four-Point Bending Tests

Four-point bending test results are summarized in Tables 6 and 7 for sandwich structures Series 1 and 2, respectively. Figure 9 compares typical load-deflection curves of the two series. Figure 10 shows the results of a bending test on two of the tested samples.

Table 6. Four-point bending test results for sandwich Series 1.

Specimen N°	Thickness (mm)	Maximum Load Before Failure (kN)	Deflection at Max Load (mm)
1	27	5.64	20.99
2	27	5.36	18.81
3	27	5.58	19.28
Average		5.27	19.69
S.D.		0.14	1.15

Table 7. Four-point bending test results for sandwich Series 2.

Specimen N°	Thickness (mm)	Maximum Load Before Failure (kN)	Deflection at Max Load (mm)
1	25	14.79	10.99
2	25	14.36	10.38
3	25	12.90	8.35
Average		14.02	9.90
S.D.		0.99	1.43

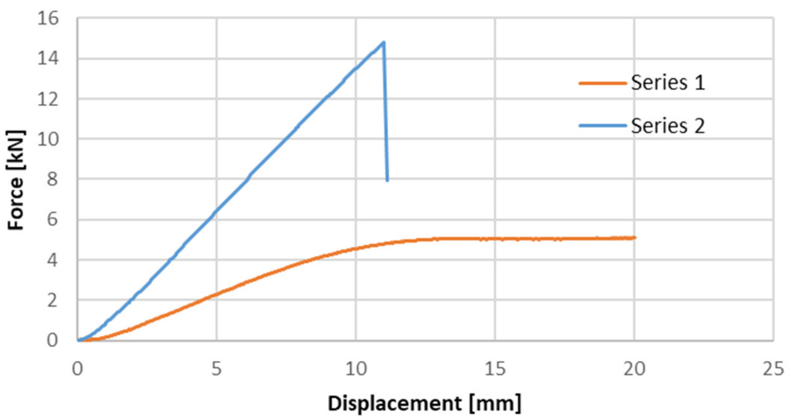


Figure 9. Load-displacement curves for both tested series under four-point bending.

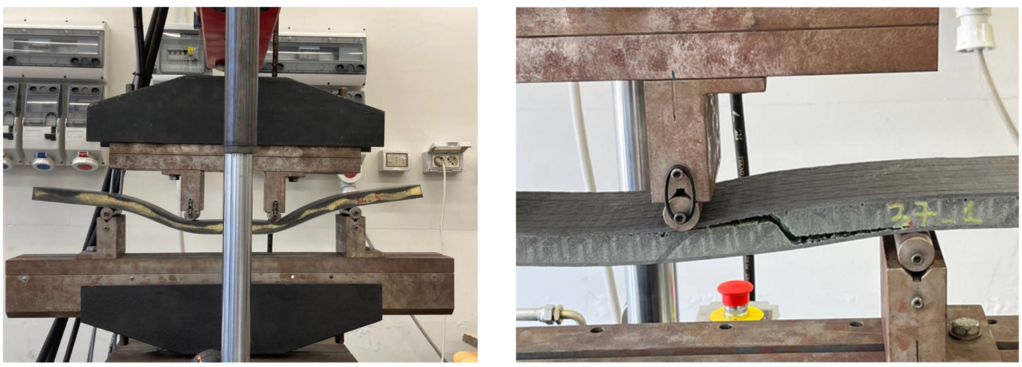


Figure 10. (**a**) Specimen from Series 1 where the characteristic shape of bending deformation is observed, and no delamination is visible; (**b**) Specimen of Series 2 subjected to four-point bending test, with visible shear fracture and delamination of the skins from the core.

All tested specimens were able to withstand a maximum load considerably higher than the 3 kN load limit imposed by UIM before experiencing critical structural damage.

The highest maximum load values were observed in Series 2 sandwich structures, which withstood load levels over twice those of Series 1, while also exhibiting minimal deflection at maximum load. As visible from the curves in Figure 9, the response of Series 1 shows a gradual increase in force with displacement, followed by a plateau phase where the force remains relatively constant. This plateau is indicative of a more ductile behavior. The absence of a sharp drop in force suggests that Series 1 does not experience catastrophic failure under these conditions, as confirmed by Figure 10a. Instead, the material enters a phase of progressive deformation, possibly due to local core crushing or a combination of different damage mechanisms that do not lead to immediate structural failure. Series 2 exhibits a more linear response initially, with a steeper slope compared to Series 1, reaching a peak force of about 14 kN. After the load peak, there is a sudden drop in force, which is indicative of brittle failure, as confirmed by Figure 10b. The steeper initial slope of Series 2 indicates that this sandwich structure is stiffer than Series 1, as it resists deformation more effectively up to the point of failure, hence has the capability to minimize the deformation, which could be a valuable property to improve hydrodynamic performance during competitions [27].

As seen in Figure 10a, Series 1 specimens in the four-point bending test, did not exhibit delamination, and showed a gradual and continuous deformation under the applied load. However, specimens from Series 1 sustained lower load and experienced higher deflections. For Series 2, Figure 10b shows that a visible fracture developed at an angle of approximately 45°, indicating a shear failure mechanism in the core. This type of fracture suggests that shear forces are acting in the plane of the sample under the bending load. Additionally, detachment between the skins and the sandwich core is observable. This provides valuable information about the mechanical properties of the material, including flexural strength and behavior under shear stress, both critical for evaluating its suitability for structural applications.

It is worth observing that both sandwich structure types conform to the established technical standards, as required by their high-performance application. However, there is a substantial discrepancy in their mechanical behavior. An explanation for this could lie in the different structural design and different balance between the constitutive parts of the sandwich structures. This also highlights the importance of performing an accurate experimental analysis, which enables detailed evaluation of failure mechanisms and structural performance.

3.2. Drop Impact Tests

The drop impact machine records the energy absorbed by the sample during the test, which at time t is calculated according to Equation (1):

$$E(t) = \int_t F(t)\, v(t)\, dt \tag{1}$$

When the time t corresponds to the end of the impact event, $E(t)$ represents the total energy absorbed by the sample, named Total Energy Absorption (TEA), according to Equation (2), where δ is deflection:

$$TEA = \int_0^{\delta_{max}} F\, d\delta \tag{2}$$

The ratio between the TEA and the specimen's mass m_t or the specimen's density ρ_t is defined as the specific energy absorption (SEA) related to these two quantities, as reported in Equations (3) and (4) [28]:

$$SEA_m = \frac{TEA}{m_t} \tag{3}$$

$$SEA_\rho = \frac{TEA}{\rho_t} \tag{4}$$

The SEA_ρ is a useful parameter to compare specimens with different volumes and geometries, which is the case for the current investigation.

Another parameter used for the analysis of impact results is the damage degree η [29], which quantifies damage degree a material undergoes after an impact by computing the effectiveness of energy absorption as a ratio between the dissipated energy (E_{dis}) and the total energy transformed during the impact, according to Equation (5):

$$\eta = \frac{E_{dis}}{E_{total}} \quad (5)$$

The dissipated energy corresponds to the energy lost through irreversible damage processes, including fractures and delamination, whereas E_{total} refers to the total energy converted. Values of η equal to or approaching 1 indicate a complete- or high-energy dissipation through damage, signifying substantial degradation of the material's structural and mechanical properties. This degradation reduces the material's ability to withstand further stresses or impacts. In contrast, a value of η less than 1 suggests that some energy has been stored as elastic deformation, which limits the amount of irreversible damage.

The results of impact tests, in terms of TEA, SEA_{ρ}, and η are summarized in Table 8, where for each impact energy the average values are reported.

Table 8. Summary of drop impact test results.

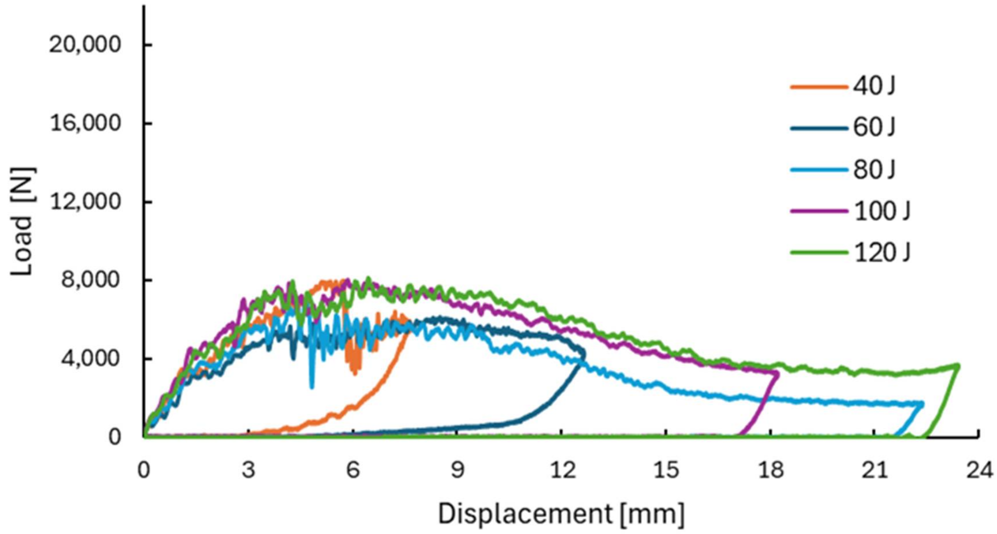
Sandwich Type	Impact Energy (J)	*TEA* (J)	SEA_{ρ} (J m^3/kg)	η
Series 1	40	33.5 (S.D. 0.8)	0.092 (S.D. 0.002)	0.838 (S.D. 0.020)
	60	56.9 (S.D. 2.1)	0.154 (S.D. 0.008)	0.949 (S.D. 0.035)
	80	79.1 (S.D. 0.2)	0.228 (S.D. 0.001)	0.989 (S.D. 0.002)
	100	96.8 (S.D. 0.7)	0.253 (S.D. 0.016)	0.968 (S.D. 0.007)
	120	118.4 (S.D. 0.4)	0.306 (S.D. 0.018)	0.987 (S.D. 0.004)
Series 2	40	29.7 (S.D. 1.6)	0.042 (S.D. 0.001)	0.742 (S.D. 0.040)
	60	41.4 (S.D. 7.5)	0.057 (S.D. 0.014)	0.689 (S.D. 0.125)
	80	62.7 (S.D. 7.2)	0.088 (S.D. 0.010)	0.784 (S.D. 0.091)
	100	90.6 (S.D. 2.3)	0.125 (S.D. 0.006	0.906 (S.D. 0.023)
	120	110.5 (S.D. 1.1)	0.150 (S.D. 0.002)	0.921 (S.D. 0.009)

The highest SEA_{ρ} values at each impact energy level are observed for the sandwich structures in Series 1. Nevertheless, for the same structure, the degree of damage increases markedly, approaching a value close to 1 for impact energies exceeding 60 J. This suggests that, while the material absorbs a substantial amount of energy, the majority is dissipated through damage mechanisms such as fractures or delamination, which severely compromise the material's structural integrity.

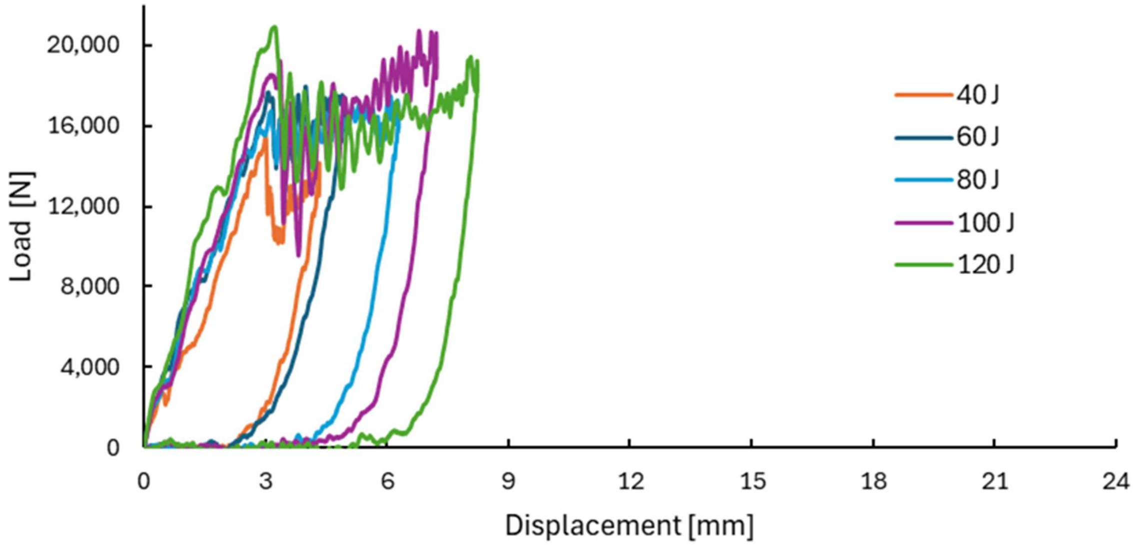
In contrast, specimens from Series 2 exhibit the lowest average degree of damage, yet they are responsible for the lowest SEA_{ρ}.

As suggested by Belingardi et al. [30], high energy absorption does not necessarily equate to optimal material performance. A high degree of damage suggests that the material has experienced substantial degradation, potentially compromising its structural integrity and its capacity to withstand subsequent impacts. Hence, a balance between high energy absorption capacity and structural damage minimization is desirable for materials destined for critical applications such as nautical competitions, where the safety of pilots relies on the cockpit capability to withstand impacts without failing.

Load-displacement curves for each sandwich type and for each impact energy are reported in Figure 11. Since an excellent repeatability of the tests was observed, the figures display only one out of the three repetitions performed.



(**a**)



(**b**)

Figure 11. Load-displacement curves obtained from impact tests for (**a**) Series 1, and (**b**) Series 2 sandwich structures.

For all specimens, the initial phase of load-displacement curves is characterized by an almost linear trend, which keeps the same slope at all impact energies, indicating this is an inherent material property.

As impact energy increases, the peak load generally rises, even if not significantly, indicating that the specimens withstand slightly higher forces before failure at higher impact energies. The curves for higher energies extend further along the *x*-axis, suggesting greater displacement before complete failure or rebound. The increase in load fluctuations for mid- to high-energy impacts indicates progressive failure mechanisms, such as micro-cracking, delamination, or fiber breakage.

Series 1 structures exhibit relatively smooth and stable load-displacement curves across all impact energies. Displacement grows with increasing energy levels, particularly at 100 J and 120 J, indicating that the specimens sustain larger deformations before failure. The gradual decline in post-peak load suggests a more ductile failure mechanism.

Series 2 demonstrates a different behavior compared to the other two series. The peak load for all impact energies is substantially higher, reaching over 20,000 N for the 120 J test. The load-displacement curves for this series are steeper, indicating a higher stiffness.

Displacement is significantly lower compared to the other two series. This suggests that Series 2 absorbs energy with less deformation.

Figure 12 shows specimens of the two types impacted at the highest energy level, displaying visible damage and deformation patterns.

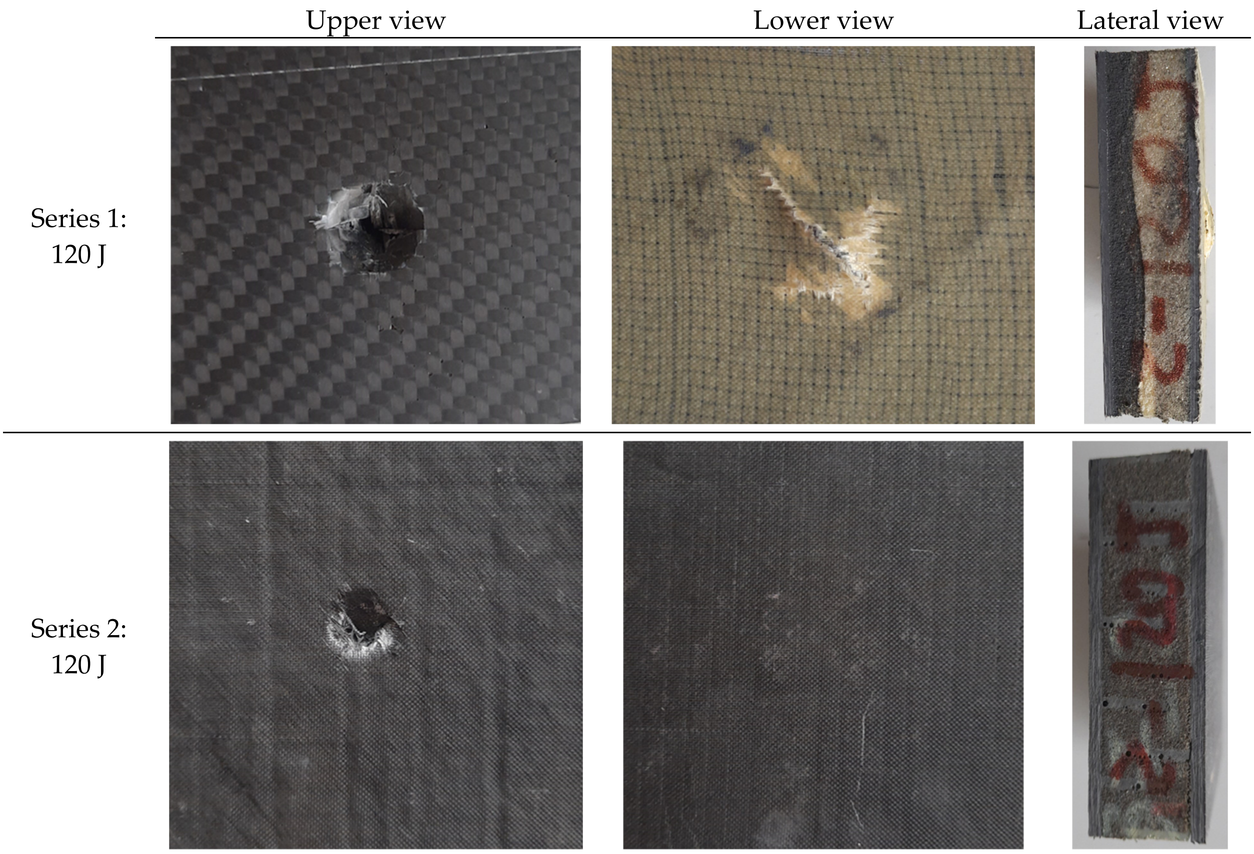


Figure 12. Upper, lower and later view of specimens impacted at the highest energy.

The upper surface of specimen from Series 1 exhibits relatively uniform damage, characterized by a well-defined circular pattern. The core of the sandwich structure is not exposed or visible upon visual inspection. On the lower side, cracks crossing the fiber in the region of impact are visible.

For Series 2 specimen hit at 120 J, the striker left an imprint on the surface, as clearly visible from the top view; in the bottom view the specimen is intact, suggesting that the impact was absorbed and caused no damage to the structure compared to the Series 1.

3.3. Impact Assessment and Interpretation

The main differences between samples 1 and 2, both in the four-point bending test and the impact test, are closely linked to the different material compositions. Sample 1 is heavier than sample 2 due to the core, which has a higher density, and the use of glass fibers, which are not present in sample 2. This contributes to a higher environmental impact for sample 1 in several categories.

In the four-point bending test, sample 1 shows higher impacts in the climate change category, with 23.5 kg CO_2-Eq compared to 20.6 kg CO_2-Eq for sample 2, and in the consumption of non-renewable energy resources (423 MJ versus 370 MJ for Series 2) (Tables 9 and 10). Additionally, freshwater ecotoxicity is higher for sample 1 (227 CTUe compared to 206 CTUe for sample 2), as is acidification (9.5×10^{-2} mol H^+-Eq for sample 1 versus 8.36×10^{-2} mol H^+-Eq for sample 2). However, regarding ozone depletion, sample 2 has a higher impact (7.31×10^{-7} kg CFC-11-Eq compared to 1.68×10^{-6} kg CFC-11-Eq for sample 1).

Table 9. LCIA of Four-Point Bending Test Series 1.

Impact Assessment of Four-Point Bending Test Series 1		
Impact Category Group	**Results**	**Unit**
Acidification	9.50×10^{-2}	mol H^{+}-Eq
Climate change	2.35×10	kg CO_2-Eq
Climate change: biogenic	6.07×10^{-2}	kg CO_2-Eq
Climate change: fossil	2.34×10	kg CO_2-Eq
Climate change: land use and land use change	6.64×10^{-3}	kg CO_2-Eq
Ecotoxicity: freshwater	2.27×10^{2}	CTUe
Ecotoxicity: freshwater, inorganics	1.35×10^{2}	CTUe
Ecotoxicity: freshwater, organics	9.22×10	CTUe
Energy resources: non-renewable	4.23×10^{2}	MJ, net calorific value
Eutrophication: freshwater	4.59×10^{-3}	kg P-Eq
Eutrophication: marine	2.24×10^{-2}	kg N-Eq
Eutrophication: terrestrial	1.96×10	mol N-Eq
Human toxicity: carcinogenic	1.02×10^{-7}	CTUh
Human toxicity: carcinogenic, inorganics	2.76×10^{-9}	CTUh
Human toxicity: carcinogenic, organics	9.91×10^{-8}	CTUh
Human toxicity: non-carcinogenic	2.42×10^{-7}	CTUh
Human toxicity: non-carcinogenic, inorganics	2.25×10^{-7}	CTUh
Human toxicity: non-carcinogenic, organics	1.68×10^{-8}	CTUh
Ionizing radiation: human health	1.90	kBq U235-Eq
Land use	9.94×10^{1}	dimensionless
Material resources: metals/minerals	2.41×10^{-4}	kg Sb-Eq
Ozone depletion	1.68×10^{-6}	kg CFC-11-Eq
Particulate matter formation	7.05×10^{-7}	disease incidence
Photochemical oxidant formation: human health	7.84×10^{-2}	kg NMVOC-Eq
Water use	1.15×10^{1}	m^3 world Eq deprived

Table 10. LCIA of Four-Point Bending Test Series 2.

Impact Assessment of Four-Point Bending Test Series 2		
Impact Category Group	**Results**	**Unit**
Acidification	8.36×10^{-2}	mol H^{+}-Eq
Climate change	2.06×10^{1}	kg CO_2-Eq
Climate change: biogenic	5.00×10^{-2}	kg CO_2-Eq
Climate change: fossil	2.05×10	kg CO_2-Eq
Climate change: land use and land use change	6.40×10^{-3}	kg CO_2-Eq
Ecotoxicity: freshwater	2.06×10^{2}	CTUe
Ecotoxicity: freshwater, inorganics	1.25×10^{2}	CTUe
Ecotoxicity: freshwater, organics	8.12×10^{1}	CTUe
Energy resources: non-renewable	3.70×10^{2}	MJ, net calorific value
Eutrophication: freshwater	4.21×10^{-3}	kg P-Eq
Eutrophication: marine	2.08×10^{-2}	kg N-Eq
Eutrophication: terrestrial	1.75×10^{-1}	mol N-Eq
Human toxicity: carcinogenic	9.48×10^{-8}	CTUh
Human toxicity: carcinogenic, inorganics	2.33×10^{-9}	CTUh
Human toxicity: carcinogenic, organics	9.25×10^{-8}	CTUh
Human toxicity: non-carcinogenic	2.12×10^{-7}	CTUh
Human toxicity: non-carcinogenic, inorganics	1.98×10^{-7}	CTUh
Human toxicity: non-carcinogenic, organics	1.47×10^{-8}	CTUh
Ionizing radiation: human health	1.69	kBq U235-Eq
Land use	8.90×10^{1}	dimensionless
Material resources: metals/minerals	2.06×10^{-4}	kg Sb-Eq
Ozone depletion	7.31×10^{-7}	kg CFC-11-Eq

Table 10. *Cont.*

Impact Assessment of Four-Point Bending Test Series 2		
Impact Category Group	**Results**	**Unit**
Particulate matter formation	6.11×10^{-7}	disease incidence
Photochemical oxidant formation: human health	6.95×10^{-2}	kg NMVOC-Eq
Water use	9.73	m^3 world Eq deprived

In the impact test, a similar trend is observed: sample 1 consistently shows higher impacts than sample 2. Climate change for sample 1 is 3.19 kg CO_2-Eq compared to 2.82 kg CO_2-Eq for sample 2, and the consumption of non-renewable energy is also higher (56.9 MJ versus 50.2 MJ) (Tables 11 and 12). In this case as well, freshwater ecotoxicity is higher for sample 1 (29.1 CTUe compared to 26.5 CTUe for sample 2). However, for ozone depletion, sample 2 has a higher impact (9.71×10^{-8} kg CFC-11-Eq compared to 2.15×10^{-7} kg CFC-11-Eq for sample 1).

Table 11. LCIA of Impact test Series 1.

Impact Assessment of Impact test Series 1		
Impact Category Group	**Results**	**Unit**
Acidification	1.29×10^{-2}	mol H^+-Eq
Climate change	3.19	kg CO_2-Eq
Climate change: biogenic	8.60×10^{-3}	kg CO_2-Eq
Climate change: fossil	3.18	kg CO_2-Eq
Climate change: land use and land use change	8.76×10^{-4}	kg CO_2-Eq
Ecotoxicity: freshwater	2.91×10^{1}	CTUe
Ecotoxicity: freshwater, inorganics	1.74×10^{1}	CTUe
Ecotoxicity: freshwater, organics	1.17×10^{1}	CTUe
Energy resources: non-renewable	5.69×10^{1}	MJ, net calorific value
Eutrophication: freshwater	6.29×10^{-4}	kg P-Eq
Eutrophication: marine	2.96×10^{-3}	kg N-Eq
Eutrophication: terrestrial	2.62×10^{-2}	mol N-Eq
Human toxicity: carcinogenic	1.34×10^{-8}	CTUh
Human toxicity: carcinogenic, inorganics	3.79×10^{-10}	CTUh
Human toxicity: carcinogenic, organics	1.30×10^{-8}	CTUh
Human toxicity: non-carcinogenic	3.34×10^{-8}	CTUh
Human toxicity: non-carcinogenic, inorganics	3.11×10^{-8}	CTUh
Human toxicity: non-carcinogenic, organics	2.29×10^{-9}	CTUh
Ionizing radiation: human health	2.66×10^{-1}	kBq U235-Eq
Land use	1.39×10^{1}	dimensionless
Material resources: metals/minerals	3.33×10^{-5}	kg Sb-Eq
Ozone depletion	2.15×10^{-7}	kg CFC-11-Eq
Particulate matter formation	9.33×10^{-8}	disease incidence
Photochemical oxidant formation: human health	1.05×10^{-2}	kg NMVOC-Eq
Water use	1.59	m^3 world Eq deprived

These differences indicate that the greater mass of sample 1, resulting from its higher-density core and the use of glass fibers, significantly affects its environmental impacts, especially in categories related to energy consumption and greenhouse gas emissions.

The results obtained for both testing scenarios are also reported in a graphical form in Figure 13 where the most relevant indicators for Series 1 and 2 are compared.

Table 12. LCIA of Impact test Series 2.

Impact Assessment of Impact test Series 2		
Impact Category Group	**Results**	**Unit**
Acidification	1.15×10^{-2}	mol H^+-Eq
Climate change	2.82	kg CO_2-Eq
Climate change: biogenic	7.26×10^{-3}	kg CO_2-Eq
Climate change: fossil	2.81	kg CO_2-Eq
Climate change: land use and land use change	8.48×10^{-4}	kg CO_2-Eq
Ecotoxicity: freshwater	2.65×10^{1}	CTUe
Ecotoxicity: freshwater, inorganics	1.61×10^{1}	CTUe
Ecotoxicity: freshwater, organics	1.04×10^{1}	CTUe
Energy resources: non-renewable	5.02×10^{1}	MJ, net calorific value
Eutrophication: freshwater	5.82×10^{-4}	kg P-Eq
Eutrophication: marine	2.76×10^{-3}	kg N-Eq
Eutrophication: terrestrial	2.36×10^{-2}	mol N-Eq
Human toxicity: carcinogenic	1.25×10^{-8}	CTUh
Human toxicity: carcinogenic, inorganics	3.25×10^{1}	CTUh
Human toxicity: carcinogenic, organics	1.22×10^{-8}	CTUh
Human toxicity: non-carcinogenic	2.97×10^{-8}	CTUh
Human toxicity: non-carcinogenic, inorganics	2.77×10^{-8}	CTUh
Human toxicity: non-carcinogenic, organics	2.02×10^{-9}	CTUh
Ionizing radiation: human health	2.40×10^{-1}	kBq U235-Eq
Land use	1.26×10^{1}	dimensionless
Material resources: metals/minerals	2.89×10^{-5}	kg Sb-Eq
Ozone depletion	9.71×10^{-8}	kg CFC-11-Eq
Particulate matter formation	8.15×10^{-8}	disease incidence
Photochemical oxidant formation: human health	9.41×10^{-3}	kg NMVOC-Eq
Water use	1.37	m^3 world Eq deprived

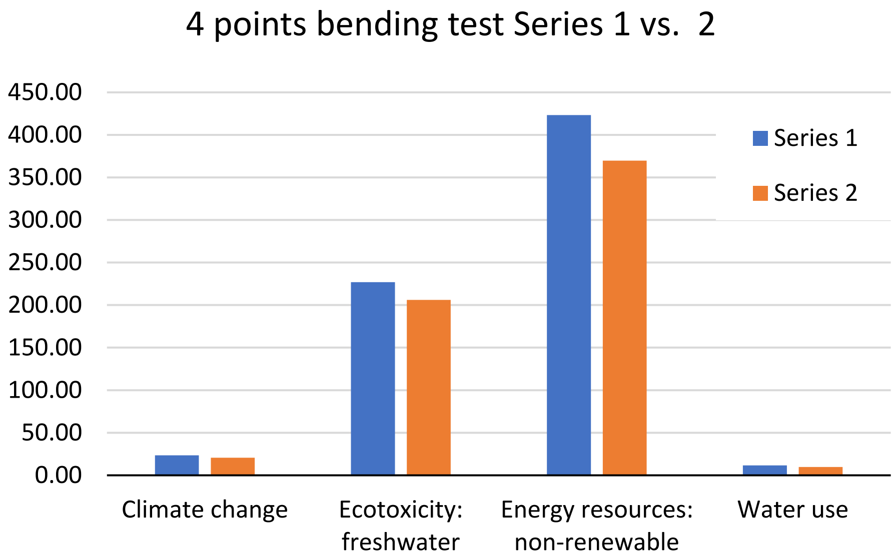
3.4. Correlation of Mechanical and Environmental Performance

In order to offer a novel way to link environmental performance with mechanical efficiency in the assessment of composite sandwich structures, two indexes were defined as follows:

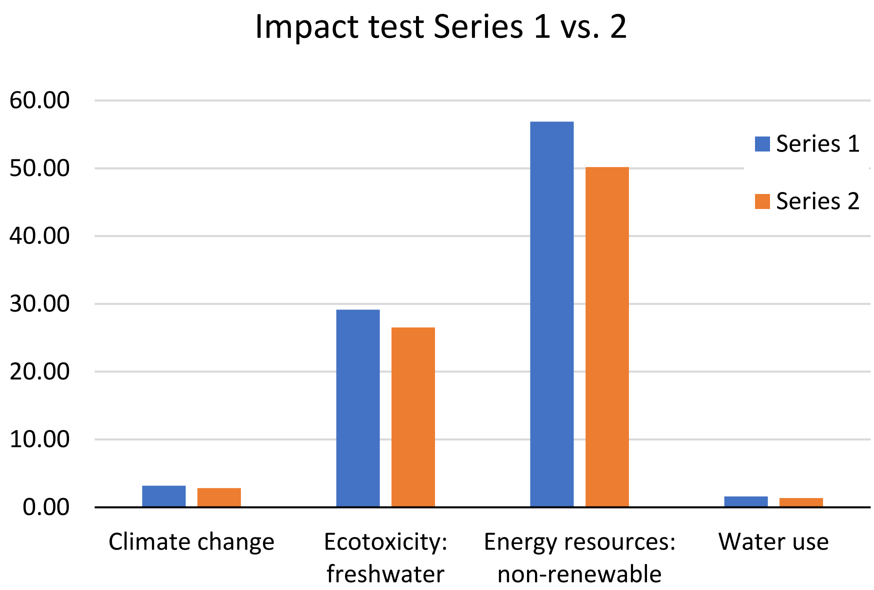
- One representing the ratio between climate change impact and flexural stress (CC/σ), where the flexural stress was calculated using the ABD matrix [31], which accounts for the stiffness properties of the laminate in terms of extension, bending, and their interactions;
- The other representing the ratio between climate change impact and Specific Energy Absorption (CC/SEA_ρ).

The results of the obtained values for both indexes and both sandwich structures are presented in Figure 14.

The first index quantifies the environmental cost associated with each unit of flexural stress that the material can withstand: In other words, this index reveals the environmental burden correlated with the strength of the material. Series 1 has a higher CC/σ ratio compared to Series 2, indicating that it is associated with higher environmental costs per unit of flexural stress. Thus, for every unit of strength provided, Series 1 contributes more to climate change. Series 2 structures perform better in this regard, with a significantly lower CC/σ value, suggesting that this composite sandwich offers higher mechanical performance with a reduced environmental footprint. This makes Series 2 a more eco-friendly choice for applications where flexural strength is critical.



(**a**)



(**b**)

Figure 13. Comparison of LCA results for Series 1 and 2 in (**a**) four-point bending and (**b**) impact test scenarios. Impact categories are expressed in the following units: Climate Change (kg CO_2-Eq), Ecotoxicity freshwater (CTUe), Energy Resources non-renewable (MJ, net calorific value), and Water Use (m^3 world Eq deprived).

With regard to the second index, Series 1 exhibits a lower CC/SEA_{ρ} ratio compared to Series 2. The higher CC/SEA_{ρ} for Series 2 implies that, while Series 2 materials may have lower flexural stress environmental costs, they perform worse in terms of energy absorption per environmental impact. This finding suggests that Series 2 materials might not be as environmentally efficient for impact-absorbing applications.

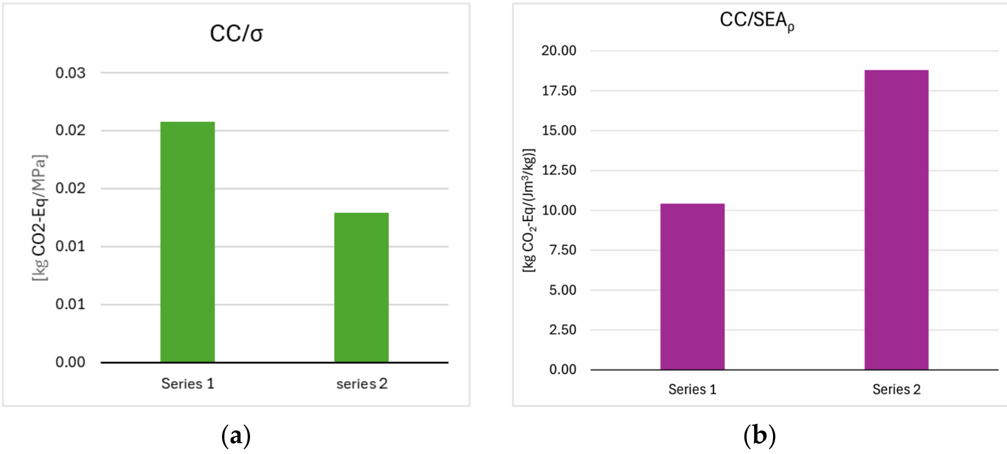


Figure 14. Results of indexes correlating the environmental and mechanical performance of the tested sandwich structures, with figure (**a**) showing the comparison between the environmental load index and the flexural strength of the material in the two sandwich structures, and figure (**b**) representing the environmental impact index in relation to the impact energy absorption of the material.

4. Discussion

The mechanical and environmental performance of composite sandwich structures, critical in marine racing applications, reveals a trade-off between structural integrity and environmental impact, with Series 2 showing overall superior mechanical properties while Series 1 incurs higher environmental costs due to its heavier construction.

The four-point bending tests demonstrated a clear distinction between the two series in terms of load-bearing capacity and deformation. Series 2 exhibited higher maximum load capacities and lower deflections, indicating superior stiffness and resistance to deformation under stress. This is crucial in racing applications, where minimal deformation under load can enhance hydrodynamic performance, leading to faster speeds and better handling in competitive environments. On the other hand, specimens from Series 1 were not subjected to delamination phenomena, keeping their structural functionality up until the end of the test. These results suggest that Series 2, with its carbon fiber and lower-density core, provides the necessary strength while maintaining a lightweight profile, a crucial factor for high-speed boats.

In terms of impact performance, the TEA and SEA results show that Series 1 absorbs more energy at higher impact energies, but this energy is largely dissipated through damage mechanisms such as fractures and delamination. This is evidenced by its damage degree, which approached a value of 1 at impact energies exceeding 60 J, indicating significant structural degradation. In addition, the apparently higher energy absorption capabilities of Series 1 structures come with the trade-off of increased weight, which could slightly reduce speed and maneuverability in competitions. Conversely, Series 2 exhibited a more controlled energy absorption with lower damage, maintaining structural integrity even at higher impact energies. This makes Series 2 a more reliable option for applications where repeated impacts are a concern, such as racing vessels encountering frequent wave-induced stresses.

The observed variability in mechanical behavior between Series 1 and 2 likely derives from differences in their structural design, which influence how loads and stresses are distributed across the composite layers. Variations in core-to-face sheet ratios or material properties may affect stiffness, strength, and energy absorption, leading to divergent mechanical responses. This balance between the constitutive parts dictates the load-bearing capacity and deformation patterns under applied stresses. Consequently, optimizing these parameters is crucial for achieving desired performance characteristics in composite sandwich structures.

The LCA results highlight the environmental costs associated with these materials. Series 1, due to its higher mass and use of glass fibers, had a significantly larger environmental impact across multiple categories, including climate change, energy consumption, and freshwater ecotoxicity. While Series 2 outperformed Series 1 in mechanical tests, its higher environmental impact in ozone depletion due to the use of carbon fibers raises concerns about the sustainability of advanced composite materials in marine applications. However, from a general perspective, Series 1 incurs a higher environmental cost due to its greater material consumption and energy use during production. Hence, the environmental impact results highlight the importance of saving weight.

Considering the newly introduced indexes to correlate environmental and mechanical performance, Series 2 materials are superior when flexural stress is the main design consideration, offering better environmental performance. Accordingly, where maximizing load-bearing capacity and minimizing deflection are predominant, Series 2 is the preferred option. As observed in Section 3.1, optimizing the mechanical design of sandwich structures by precisely balancing skin and core properties is essential for achieving high-performance outcomes tailored to specific applications. This balance not only enhances the mechanical integrity and functionality of these materials but also contributes to sustainability efforts, making efficient design a keystone in the development of greener solutions.

However, for impact-absorbing applications, Series 1 materials are more favorable in terms of minimizing environmental costs. The presence of aramid fibers and a higher density core in Series 1 samples may be partially responsible for better energy absorption characteristics, resulting in higher values of SEA_{ρ}, and consequently, lower values in the CC/SEA_{ρ} ratio. Hence, if the final application requires the minimization of environmental impact while keeping good energy absorption properties, Series 1 should be preferred. On the other hand, it is noteworthy that Series 2 exhibits a lower degree of damage than Series 1. Thus, Series 2 is recommended for applications in which preserving structural integrity following high-energy impacts or repeated impact events is essential, notwithstanding its greater environmental cost.

This indicates that the application context, whether the focus is on strength or energy absorption, should guide the selection of materials.

To the best of the authors' knowledge, the current literature addressing similar topics does not incorporate the testing phase within LCA boundaries. Although the contribution of experimental analysis to LCA outcomes in this study may initially appear minimal, it is important to emphasize that the functional unit has been defined as a single specimen. The experimental procedures included quasi-static bending and low-velocity impact tests, both of which are relatively time efficient. However, the significance of the experimental phase is likely to increase when a larger number of specimens is considered—a common practice in the design and qualification stages of composite structures for specific applications—as well as when more complex testing methods, such as fatigue testing, are required. Thus, the inclusion of the testing phase enhances the reliability and comprehensiveness of the LCA.

Efforts to reduce the environmental footprint of high-performance composites, such as recycling technologies for carbon fibers and exploring bio-based resins, are essential to balance the performance gains with sustainable practices. For instance, the development of recyclable composite materials and the use of natural fibers, as highlighted in recent research, could mitigate the environmental impact while maintaining the mechanical properties necessary for high-performance applications.

5. Conclusions

This study highlights the complex interplay between mechanical performance and environmental sustainability in the use of composite sandwich structures for marine racing applications. In the context of high-performance composite materials, particularly in marine applications, the testing phase plays a critical role in determining the overall environmental impact, which is often overlooked in traditional Life Cycle Assessments. Including the testing phase in LCA is essential to account for the possible energy-intensive nature of testing and for the material waste during testing. Therefore, it becomes possible to assess the full life cycle of the material, from raw material extraction to testing and eventual disposal. This allows for a more holistic evaluation of a material's environmental impact and ensures that the environmental trade-offs of achieving high mechanical performance are transparently documented, providing a clearer understanding of the material's true environmental cost.

In the current study, the combination of both mechanical testing and LCA was applied to two sandwich structures, named Series 1 and Series 2, typically used for high-performance racing boats. Series 2 outperforms Series 1 in terms of mechanical properties, including higher load-bearing capacity, superior stiffness, and lower deflection, making it a more suitable option for applications requiring high structural integrity and minimal deformation. Series 1, while absorbing more energy during impact tests, demonstrated higher susceptibility to damage and delamination, compromising its long-term reliability under dynamic loads. The performed tested also showed that experimental testing plays a crucial role in validating the effectiveness of the design process and in assessing the mechanical behavior and failure modes of a structure under operational conditions. The experimental testing not only confirms the adequacy of the design but also helps to identify potential discrepancies between predicted and actual performance, allowing for further refinement and optimization.

The LCA highlights the significant environmental footprint of both materials, with Series 1 exhibiting a larger impact due to its heavier construction and higher energy consumption during production. However, Series 2 contributes more to ozone depletion due to the use of carbon fibers, underscoring the environmental trade-offs involved in selecting materials for high-performance applications.

The introduction of two indexes (CC/σ and CC/SEA_ρ) into the analysis has proven to be an effective method for quantifying and comparing the environmental impacts relative to mechanical performance. Series 2 specimens generally offer superior environmental performance in relation to their flexural strength (CC/σ), making them an attractive option for applications where mechanical strength is the primary concern. However, when specific energy absorption (SEA) is considered, Series 1 demonstrates lower environmental impacts (CC/SEA_ρ), suggesting it may be more suitable for applications where energy dissipation is crucial, such as in crashworthiness or impact-resistance scenarios, and where the environmental impact needs to be limited. However, Series 2 exhibits a lower degree of damage than Series 1, making it more suitable for applications requiring better structural reliability after high-energy impacts or repeated impact events, despite its greater environmental cost.

These findings underscore the need for a balanced approach that considers both performance and sustainability in high-performance marine industries. It was observed that a well-balanced mechanical design of sandwich structures is critical not only for optimizing structural performance but also for minimizing environmental impact. By achieving an optimal balance between the mechanical properties of sandwich constituents, material efficiency can be maximized, reducing the overall weight and resource consumption of the structure. This, in turn, leads to reduced energy requirements during manufacturing and transport, as well as improved material longevity and recyclability. Thus, the integration of environmental considerations into the design process is essential to advance both the performance and sustainability of sandwich structures in engineering applications.

A detailed LCA that accounts for the testing phase is also crucial to provide a more comprehensive view of the overall environmental impact and enable engineers and designers to make more informed decisions when selecting materials, therefore supporting further research into eco-friendly materials and recycling technologies which will be essential to reconcile different competing priorities.

Future research should focus on the development of eco-friendly composites and recyclable materials that meet the demanding mechanical and environmental requirements of high-performance marine applications. Key areas for investigation include bio-based resins and natural fiber reinforcements, which could offer lower environmental footprints while maintaining strength and durability. Additionally, advances in carbon fiber recycling technologies and the creation of modular composite structures designed for easier disassembly and reuse could significantly reduce the environmental impact of composite materials over their life cycle. These innovations could contribute to a more sustainable marine industry by enabling high-performance, low-impact materials optimized for end-of-life recovery and reuse.

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