

Article

Expanded (Black) Cork for the Development of an Eco-Friendly Surfboard: Environmental Impact and Mechanical Properties

José M. D. Correia, Gabriel F. Serra , Ricardo J. Alves de Sousa * , António B. Pereira 
and Fábio A. O. Fernandes 

TEMA—Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, Campus de Santiago, University of Aveiro, 3810-193 Aveiro, Portugal; migueldiascorreia@ua.pt (J.M.D.C.); gfserra92@ua.pt (G.F.S.); abastos@ua.pt (A.B.P.); fabiofernandes@ua.pt (F.A.O.F.)

* Correspondence: rsousa@ua.pt

Abstract: Based on global needs for sustainable development, finding new sustainable materials that can replace oil-based ones for mass products is crucial nowadays. This paper focuses on employing an expanded cork-based composite to produce a surfboard. To evaluate the mechanical properties, uniaxial tensile and compression tests were performed on the skin and core materials, respectively. Bending tests were performed on the entire representative composite structure. Numerical models of the tests were arranged and validated from experimental results. From that, a surfboard prototype model was used to simulate some experimental conditions, permitting us to draw promising conclusions. An actual prototype was also produced. It was found that expanded cork performs very well when sandwiched between wood and polyester resin/glass fibre, being able to hold substantial loads and at the same time reduce weight and the environmental footprint of the composite by 62.8%. It can be concluded that expanded cork is an excellent candidate to replace oil-based foams in surfboard manufacturing. Despite a slight increase in weight, this sustainable material aligns with all the philosophies of surf practice worldwide.

Keywords: cork; composite; surfboard; sustainable; finite element



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1. Introduction

Over the last forty to fifty years, surfboards have evolved from mainly handcrafted to large-scale global industries. The essence of surfing remains the same, its essential instrument, which physically connects humans and nature. It is not only a piece of equipment but also carries cultural, social and emotional significance [1].

Following the surf industry's growth, the surfboard's design and function have undergone significant changes over the years. They have become shorter and lighter and have transitioned from longboards of up to five meters in length made out of solid wood to boards as short as one to two meters made out of mainly petrol-based polymers, such as expanded polystyrene (EPS), polyurethane foam (PU) and fibreglass. Regarding functionality, the addition of fins to the board's underside changed the dynamics of surfing by giving surfers more control when manoeuvring. The board shape evolved to have more angled noses with an upward curvature [2]. These changes have made the boards more hydrodynamic, enabling the creation of more lift and forward thrust as the water is steered along the base to the board's tail when on a wave. When the board flexes during the manoeuvre, it stores the energy released as an acceleration burst when returning to its standard shape after exiting the turn [3]. Therefore, the surfboard's composite material ability to go through this flexing with little fatigue and other factors such as weight, stiffness and the actual shape's design determines how dynamic a board will be.

However, despite the evolution in design and performance, this transition from a handcrafted to mass-produced item has brought many environmental issues and concerns.

Regarding the use of materials, the surfboard industry is heavily dependent on petroleum-based polymers that require high energy consumption, thus emitting more greenhouse gases (GHG) during manufacturing and impairing the boards' recyclability. Moreover, like many other mass-consumerist commodities, modern surfboards are not meant to last long. They have become disposable items with short life spans, considering that nowadays, a regular recreational surfer can go through up to three PU surfboards yearly [4]. Some other issues are related to the toxicity of petrochemicals and their impacts on health during the production process. Such types of non-eco-friendly oil-derived materials are not in line with the mindset of the surfer community.

To overcome these problems, some innovative solutions have emerged as ecologically sustainable alternatives. A few examples include a PU foam core blank made with 40% castor oil and a resin with more than 90% linseed oil [5]; the use of sugar beet oil instead of PU together with hemp cloth replacing some of the fibreglass [6]; and a study to implement honeycomb-structured 3d printed cores [7]. Furthermore, initiatives such as the ECOBOARD, introduced by a non-profit benchmarking agency, that aims to create a certification for boards that have been produced in a way that minimises environmental impacts to provide consumers with more transparent information, are helping reduce the effects caused by the industry [4]. Being an ancient and primordial material in surf history, wood attracts more fans nowadays due to its aesthetic look and reduced environmental impact. Wood is now a feasible option when buying a surfboard, although its weight can ultimately affect performance. An alternative is to add a thinner outer layer of wood to a Styrofoam core; however, production is more time intensive. Only a tiny portion of the surfboard is effectively sustainable.

Cork is the new revolutionary material in the surf industry. It is a 100% natural material possessing unusual properties such as low density and multi-functionality. Being a cellular material, it features an interconnected network of cells to fill the internal space, thereby optimising the load resistance with reduced density. It is referred to as the "green foam", and not only is this material an excellent shock absorber, but its softness also causes it to act as if it was an internal mattress for the surfer's heels [8]. Cork is also a damper, helping to reduce structural vibration and the slamming effect, an excellent surfboard property. The authors of [9] concluded that even the slightest use of cork (two curvilinear cork stringers embedded in an EPS core) can reduce the torsional stiffness and provide more damping than a traditional PU board with wooden skin. Finally, this remarkable material is also water-resistant and reflects the new ideology of Eco design and Eco efficiency in products.

Today, the most common way to manufacture a surfboard using cork is with cork skins. Some shapers also associate wood with it. Cork skin surfboards have a foam block as the core material for the structure, and the surface is covered with a thin layer of white cork agglomerate. Using this technology, the surfboard remains lightweight due to the low-density foam core and is more sustainable. By using a layer of white cork agglomerate, the surfboard does not need to be glassed. As cork will not rot in the presence of water, glass fibre can be avoided, thus reducing the environmental impact. Moreover, the cork's surface is a natural, non-abrasive and non-slippery surface [10].

To fill the research gap regarding surfboards made from sustainable materials, this work presents an innovative solution towards creating more sustainable surfboards by using expanded cork as the core material. Such an application reduces carbon emissions as well as increases recyclability and inclusion in a circular economy. This proposal of using expanded cork as a core material aims to fill the current gap in the surf industry concerning more sustainable alternatives by replacing fossil-based materials that are harmful to the very environment that the surfing culture values. Moreover, addressing some of the seventeen goals established by the United Nation's 2030 Agenda for sustainable development, [11] introduces a higher added-value application for a material mainly applied as an insulator.

2. Background

Expanded cork (EC) agglomerate, more known as black cork, is made from the expansion of virgin cork granulates that agglutinate between them. The virgin granulates come from the outer bark of oak tree branches due to their low commercial value and use. These tree branches have a higher resin (suberin) concentration than other kinds of cork, for example, from the stem [12]. After the pruning process, the bark is extracted from the branches and submitted to a grinding process to achieve a final granular size of 3 to 10 mm for acoustic insulation and 5 to 22 mm for thermal insulation purposes. The raw material used for EC manufacturing has high levels of impurity (e.g., wood fragments), which need to be excluded from the process. Such a procedure is conducted using densiometric separators, rotating drums or pneumatic sorting systems [13]. The granules are placed into autoclaves for the expansion and aggregation process, and pressure is applied to the granules by the hydraulic bottom (or top). This compression is used to control the final dimensions and density of the product, generally in the range of 110–150 kg/m³ (depending on the desired final density). The granules are bonded together by overheated steam at 300–370 °C and 40 kPa in a closed chamber [12]. They undergo a process of expansion due to the volume increase in the cork cells, resulting in the release of suberin, which is responsible for the granules' agglutination. This resin is what supports the agglomeration without the use of any synthetic binding agent [14]. The steam-baking process varies from 17 to 30 min, depending on the initial moisture levels [15]. The industrial process energy used to produce such a product comes essentially from biomass fuel. The burning of cork dust, a carbon-neutral energy source, corresponds to over 93% of the total necessary energy [16].

When the bark is extracted, the tree produces new bark, promoting more CO₂ fixation directly [17]. The 2.3 million ha of cork oak forests worldwide are seen as promoting the retention of about 14.4 million tons CO₂/year. It should also be noted that for each kg of cork extracted, 0.379 kg of CO₂ is emitted. However, it retains approximately 4.8 times that value (1.833 kg of CO₂) [12].

The expanded cork board (ECB) has a negative value of equivalent CO₂ emissions of −116.229 kg CO₂/m³, considering the embodied CO₂ in cork at the end of the production cycle. Compared to other insulation materials such as polyurethane (PU), Extruded polystyrene (XPS), Expanded polystyrene (EPS), lightweight clay aggregates (LECA) and stone wool (SW), EC is the only one with a negative carbon footprint [18]. In addition, the insulation of ECB has been reported to maintain essential properties for more than 40 years [17], meaning black cork can be re-used in several applications (building thermal insulation, etc.) during its lifetime. If it is not possible to keep using it in the same way due to contamination or damage, it could be ground for incineration or other potential applications.

EC is becoming a common choice for multiple applications. Its retail price is still expensive compared to other materials in the construction industry for insulation (3 to 4 times higher than conventional materials such as XPS and EPS, respectively). Nevertheless, its thermal conductivity is superior to these cheaper and non-sustainable options. EC is also being used in home furniture and wall interior covering for aesthetic reasons.

Cork is being also employed in sandwich structures. Cork sandwich structures have been used in the aircraft industry, where the mechanical properties of cork are considered essential to develop strong and lightweight components. The study of cork properties concluded that using cork agglomerates as a core material could bring many exciting features to the sandwich compound. Generally, sandwich structures with cork as the core material have higher flexural strength than conventional options. It is also an essential fact that cork decreases the possibility of crack propagation. Some studies compare the use of agglomerated cork in sandwich materials with insulation foam [19]. The samples with agglomerated cork or foam as the core material and were further laminated with glass fibre on the top and bottom. After the tests, the results showed that the high-density cork core displayed better strength parameters than the lower-density foam core. During the tests,

it was observed that the cork core materials returned to their original shape after being loaded. In contrast, the foam core material presented plastic deformation.

When exposed to a fatigue test, the sandwich samples had different responses, and as expected, foam core materials failed earlier. The cork core was shown to be the most resistant, presenting no catastrophic failure after 8000 cycles (see specification on [20]). Composites of low-density foam (Divinycell H60) were destroyed when exposed to 860 sinusoidal loading cycles. As mentioned before, the destruction mechanism in the samples was completely different. On the one hand, foam materials were destroyed by violent cracking. In contrast, cork core materials presented cracking in the glass-epoxy, but the core material returned to its original shape after the test.

A study analysing and combining multiple natural materials was conducted by [21]. Composites based on natural materials using cork's intrinsic characteristic of excellent recovery capacity and flax fibres as an outer layer of protection led to a material with good strength and a positive impact on the environment. However, the negative aspect of this new composite is the weight and price. The combination of two natural materials with bio-resins leads to an authentic, sustainable product. The use of wood is also a solution for an increase in the material's strength.

3. Materials and Methods

3.1. Materials

The challenge of developing a sustainable surfboard starts by selecting the raw materials that will be used. The desire to reduce the environmental impact of surfboards leads to decisions being passed in the search for more sustainable or bio-based materials. In terms of resins and fibre cloths, there are already many plant-based feasible options, but in terms of blocks, the possibilities are limited. White cork agglomerate has been used in surfboards but is limited due to its higher density ($\approx 165 \text{ kg/m}^3$ or more). Expanded cork, however, with a lower density ($\approx 110 \text{ kg/m}^3$), also has good energy-absorption capabilities and a negative carbon footprint [22]. This last feature is a significant source of motivation and makes this material stand out from the remaining conventional options. In addition, it was intended that this surfboard could be manufactured following the traditional surfboard's manufacturing processes. To be appropriately used as a core material, the expanded cork will need extra support once the granules' aggregation with suberin cannot withstand high bending and torsion loads during surf practice. For the surfboard here proposed, to grant it structural resistance, a top wooden layer is added as skin, giving mechanical resistance to bending and wear and creating an entirely natural composite (Figure 1). The thickness of the wooden layer was set to be around 3 to 4 mm, which aligned with the fibreglass to increase the whole structure's resistance. Since all of the athlete's weight is located on the feet, which could potentially cause local damage to the board, the presence of wood becomes essential to dissipate concentrated loads and energy transferred from the surfer's heel to the surfboard.



Figure 1. Virtual prototype of EC surfboard.

When it comes to aesthetics, it was essential to use fiberglass combined with a thin resin film in order to create a transparent and stiff layer so that the core material, the cork, would become visible to the customer. Moreover, the selection of noble materials was not only due to their addition of value to the overall product's aesthetics, but also because all their mechanical properties matched the needs of this project.

As the board's weight is always a concern, its volume was reduced to a minimum. The increase in a surfboard's volume makes surfing easier [23], but on the other hand, if its dimensions increase, so will the corresponding weight. The dimensions of the designed surfboard are 6'6" in length, 21.50" in width and 2.62" in thickness ($192 \times 54.61 \times 6.65$ cm). The total volume of the surfboard is 41.9 litres (0.0419 m^3), and the corresponding weight is 6.84 kg, composed of the components described in Table 1. Normal shortboards are 6'0" in length (180 cm) and 30 litres in volume (0.03 m^3), which creates a buoyancy force of 15.45 N (considering that it is 50% underwater). If the weight of the surfboard is increased in addition to the low volume, the necessary lift force will be greater. For the proposed surfboard design, the same boundary conditions are considered (50% volume underwater). The corresponding buoyancy force is approximately 21.6 N. By adding 20 cm in length and ≈ 12 litres in volume (0.012 m^3), the weight increases by 1.95 kg. Still, the buoyancy force is now 6.15 N. Low buoyancy is a common problem of small size surfboards, and that is why only expert surfers can manage to surf easily on them. Considering that the expanded cork surfboard will have extra weight, it is necessary to increase volume. Figure 2 shows the different forces acting on a surfboard in uniform water flow. The drag is higher on small surfboards because of the projected area perpendicular to the flow of water.

Table 1. Weight of the parts of EC surfboard. Values estimated with "Board Cad" software.

Part	Weight [kg]
Wood	0.50
Core	4.61
Glass Fiber	0.53
Resin	1.00
Plug and fins	0.20
Total	6.84

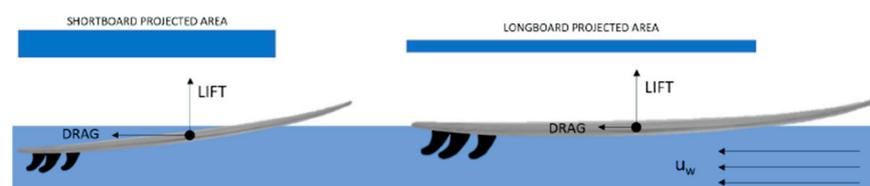


Figure 2. Acting forces on different types of surfboards for a constant water flow.

3.2. Mechanical Testing

In order to evaluate the performance of the developed laminated composites for surfboards, uniaxial tensile and compression tests were performed on the skin and core materials, respectively, and 3-point bending tests to the entire composite structure. Then, the complete surfboard structure was virtually tested through finite element analysis after previous validation of the mechanical tests.

3.2.1. Uniaxial Compression Tests of Core Material

The uniaxial quasi-static compression tests were performed in a SHIMADZU AGS-X 10 kN machine [24] at a low loading rate (10 mm/min). The $60 \times 60 \times 60$ mm samples (mass density $\approx 92 \text{ kg/m}^3$) were placed in the machine compression plates and then tested until the densification point was reached.

3.2.2. Uniaxial Tensile Test of Skin's Fibres

To determine Young's modulus and the ultimate tensile strength (UTS) of the external skin layers, four different types of samples were manufactured following ASTM D3039, which suggests that for polymer matrix composites, the samples should be rectangular with a gauge length (Lg) between 125 and 150 mm and a tab length (Lt) of 38 mm. The tests were performed in a Shimadzu AGx Plus 10 at a 10 mm/min strain rate. The composition of each of the samples is summarised in Table 2.

Table 2. Manufacturing parameters from different types of skin layers.

Sample	Description	Thickness [mm]	Resin	Density [g/m ²]
GL4	1 layer of 4oz GF	0.4	Polyester	371.11
GL6	2 layers of 6oz GF	1	Polyester	933.33
FL1	1 layer of FF	0.9	Polyester	760.00
FL2	2 layers of FF	1.2	Polyester	1353.33

Glass fibre (GL) is a widespread solution for surfboards. GL6 samples try to replicate them through two layers of 6 oz glass fibre cloth with polyester resin acting as the matrix. This is the conventional method used in surfboards shells and will be used as a reference point for comparison. Flax fibre (FL) is a common natural material used in the textile industry and has the potential to be used in many different applications, including surfboards. Ref. [25] proposed and produced a surfboard with flax fibres as the outer layer. However, the core remained a polyurethane foam. The fibre's natural origin and properties make it a potential suitable replacement for synthetic ones in terms of performance and sustainability. The fibre alignments are bidirectional, the same as glass fibre cloth. Therefore, they have all the characteristics to perform similarly. The produced samples are made from 1 and 2 layers of flax fibre reinforced with a PE resin acting as the matrix.

3.2.3. Bending Tests of Composite Laminates

Three-point bending experiments are helpful to determine the flexural modulus of the composite's structure. The tests (Figure 3) were carried out according to the ASTM C393 standard. A Shimadzu universal testing machine, equipped with a 50 kN load cell, was used, and the velocity was set to 10 mm/min. The supports and the loading tool have a diameter of 28 mm and 25 mm, respectively. Five samples were tested, SW1A and B with a heterogeneous core and SW1C, D and E with a homogeneous core. All the samples were visually analysed, checking the type and regions of failure. Although the ASTM C393 standard determines the mechanical properties, such as shear stress in the core and stress at the compression faces, this work solely focuses on studying the samples' bending stress behaviour. More specifically, the relation between load and displacement, when the sample fails and the cause.

To produce the intended sandwich-like composite, it was first necessary to cut 300 × 100 × 40 [mm] strips from an EC block and 300 × 100 × 3 [mm] from a wood panel. The latter was then glued on top of the EC using polyurethane glue. The fibre cloth was applied directly to the structure through dry "in situ" using polyester resin as the layer's binding agent. Samples were denoted as SW1A to SW1E.

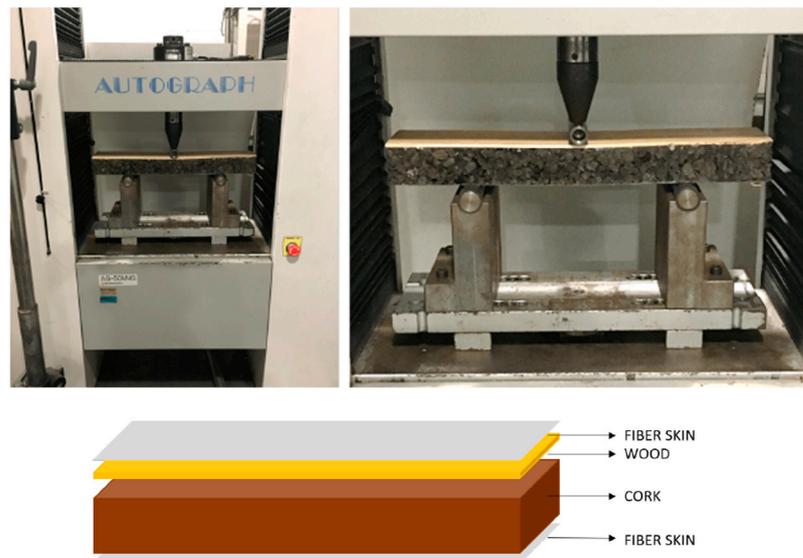


Figure 3. Three-point bending experimental setup and samples' schematics.

3.3. Virtual Tests

Finite Element Analysis (FEA) was employed to develop the surfboard's numerical model, to assess if the chosen design and materials could withstand all the loads and stress that originated during surf practice. Most of the studies with an engineering approach to surfboards focus on the fins [26–29] and make use of numerical simulation of the hydrodynamics—through computational fluid dynamics (CFD) software—to assess how their design, quantities and position affect the board's overall performance. To the best of the author's knowledge, no studies use FEA to simulate stresses and deformations on the surfboard's structure as a whole, only targeting the fins [30].

Before working on the entire model, one must validate the mechanical behaviour of the employed materials. To do that, the previous mechanical tests were replicated virtually. Uniaxial compression was simulated for EC, tensile tests for fibreglass and a 3-point bending test for the sandwich composite. The software used for the numerical simulation was Abaqus in its standard mode (implicit), and loads were considered quasi-static.

3.3.1. Uniaxial Compression of Core Material

To numerically validate the compression test, an apparatus that allowed us to simulate the compression of a cork block ($60 \times 60 \times 60$ mm) in between two rigid plates was designed on Abaqus. The plates were modelled as rigid shells, which makes them non-deformable. Therefore, the stresses and deformations only affect the cork block—a deformable 3D solid modelled using linear, fully integrated hexahedrons (C3D8). The upper plate displaces 55 mm towards the cork fixed on the bottom plate (fixed in all degrees of freedom) and compresses it, as seen in Figure 4.

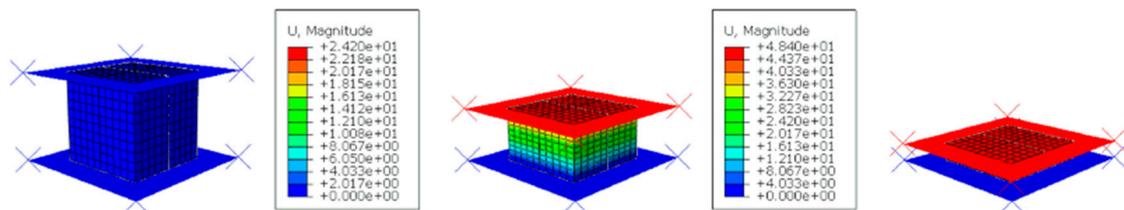


Figure 4. Simulation of EC compression.

Cork properties were defined based on experimental data using the crushable foam material model. This is the most accurate method to virtually replicate the behaviour of expanded cork.

3.3.2. Uniaxial Tensile Test of Skin's Fibres

After validating the core material, the model of the external layers was validated. These parts sized 200×20 mm were designed on Abaqus as a 3D deformable shell, given that their length is much bigger than their thickness. The boundary conditions of the experimental setup were easily replicated. The material's elastoplastic experimental behaviour was inserted via tabular data, and first-order 4-node shells (S4) were used (500 elements). Quasi-static implicit analysis was once again chosen.

3.3.3. Bending of Composite Laminates

For the 3-point bending validation, it was necessary to assemble the three constituent parts of the physical model, i.e., the two external layers and the core. To model the top layer, subjected to compression, only wood was considered since it is 7.5 times thicker than the fibreglass, withstanding all the compressive loads imposed. Wood behaviour was deemed to be of a linear elastic nature. The bottom layer was modelled using the elastoplastic model discussed above for the fibres. The final assembly structure was composed of the bottom shell layer, fibreglass with a section thickness of 1 mm (GL6), the 50-mm-thick EC core and the 3-mm-thick top layer of pine wood, also modelled as a shell.

The material properties of the fibreglass layer and EC were the ones validated before. As for the pinewood, 3 GPa was considered for its Young's modulus and isotropic behaviour to simplify the model as much as possible. The wood was designed as a 3D deformable shell with a section of 3 mm and meshed with 2000 S4 elements. The remaining parts of the sandwich composite, namely the core and the fibreglass layer, have, respectively, 20,000 C3D8 and 2000 S4 elements. The model constraints totalled just two. Tie constraints between the core and both the top and bottom layers were used to reproduce their genuine connection. To properly replicate the experimental test, three rolling cylinders with the exact same dimensions as the real ones were created and added to the assembly to represent the supports.

Regarding their boundary conditions, they were set to be free on their rotational axis degree of freedom. The contacts between the simulation parts were general surface-to-surface contacts with a defined friction interaction of 0.2. Finally, before running the simulation, a displacement of 30 mm was applied to the top roller towards the sandwich sample. The schematic of the simulation is presented in Figure 5.

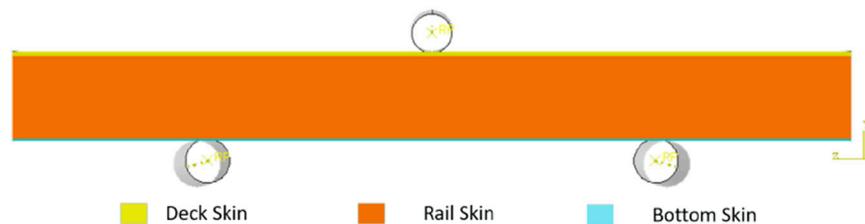


Figure 5. Section view of sandwich composite layers. Wood at yellow, EC at orange and fibreglass at blue.

3.3.4. Bending of the Surfboard Structure

Finally, to characterize the fully completed surfboard's structural model on Abaqus, it was necessary to import the CAD (IGES files) of the different parts, previously designed in Solidworks. The structural model is formed by three main components: The cork core, wooden top layer and fibreglass skin that covers the whole board. In Figure 6, it is possible to differentiate the cork core in white and the top wood layer in dark red. Using Abaqus' skin function, adding the extra fibreglass layer (in green) was then possible.

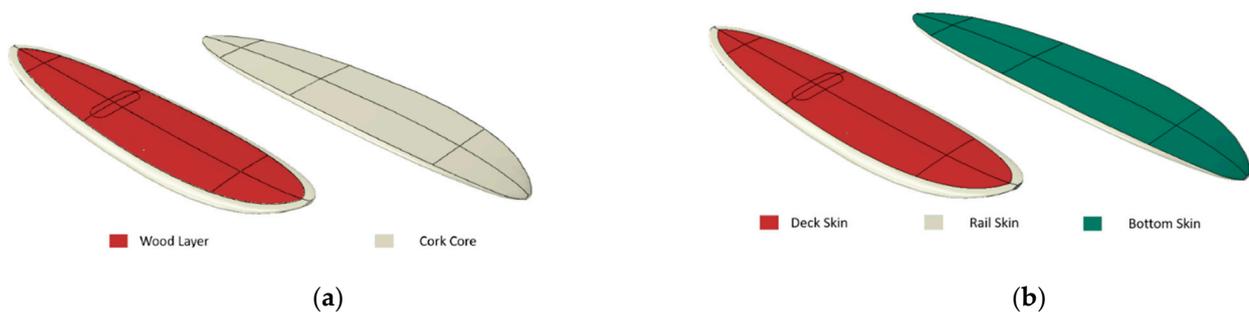


Figure 6. (a) Assembly of surfboard parts (core and wood layer); (b) different groups of skins defined on the model.

Material data were imported from the previous validations for each part of the surfboard. The interactions between the different materials were defined with tie constraints; the wood layer is “bonded” to the cork core, and the outer skins are necessarily attached to the parts they are offsetting. The parts were meshed independently with different types of meshes: The wood layer was discretised with 848 S4 elements, which are the most appropriate elements to simulate thin surfaces; the cork’s mesh is made of 8620 C3D10, i.e., 10-node second-order quadratic tetrahedron elements (free from locking issues). To impose boundary conditions and loads, one must remember that ocean conditions are highly unpredictable and hard to test outside of the natural environment. Multiple situations could be generated because the surfboard is basically a beam and the surfer is a mass point loaded on top of it. Nowadays, surfboard manufacturers do not follow a particular standard for surfboard resistance because most surfboards are not mass-produced. For some companies, though, a methodology can be defined. Torflex’s work [31] served as an inspiration to install some testing procedures to characterize the bending, torsional and vibrational frequencies of surfboards. The setup adapted to the Abaqus environment is depicted in Figure 7. After fixing the supports, the displacement of the loading tool was set to 50 mm.

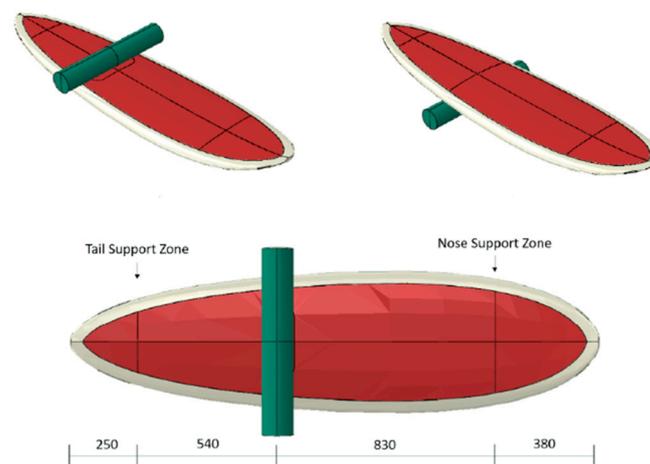


Figure 7. Simulation of 3-point bending on the surfboard.

3.3.5. Torsion Loading of the Surfboard Structure

Torsional shear stresses are also crucial for surf practice, especially during curves and fast direction changes. For the torsion test, the tail side of the surfboard was fixed, blocking all the DOF. Then the front support was rotated. A rotational value of 15 degrees was defined to simulate the torsion of the surfboard. In this situation, only part of the surfboard (tail) is in contact with the water, and the remaining (nose) is unsupported, as seen in Figure 8. The force created by the weight on the front foot of the surfer is represented as red in the figure, whereas the reaction force of the water on the tail of the surfboard is in yellow.

Considering that these two forces are acting in opposite directions and that the surfboard is at an angle (β) with the wave, momentum is created, and consequently, the surfboard will tend to twist. There are no reference values of torsion. Thus, 15 degrees was considered for the studies, although this value should be smaller in real scenarios.



Figure 8. Non-uniform force distribution on a surfboard that causes torsion.

3.4. Environmental Impact Study

After designing the product's virtual prototype, it is essential to evaluate the resulting impacts of the production. For the life cycle assessment (LCA) evaluation, the web-based software Ecolizer was used [32]. It was also necessary to analyse material extraction to the manufacturing processes and their energy consumption. This software uses Ecoinvent's database [33] and Simapro's calculation power [34]. There are some database limitations in terms of materials, such as resins and the desired types of foams for this study. To overcome this difficulty, various studies collected information about the different materials' contribution to global warming. From [18], the corresponding contributions of CO₂ equivalent for foams were derived, which are essential for future analysis. The comparison between glass and flax fibre is made in [35], where they concluded that the natural fibre has a much better environmental impact than glass fibres. Relative to resins, the authors of [36] performed a study where the global warming contribution of epoxy was considered to be lower than polyester resin.

The study only considered the direct influence of the material in the final product's impact. The transportation of raw materials and delivery from factory to retailer or client are not accounted for. The study's goal is to evaluate the different possible combinations of materials and the comparative CO₂ equivalent emissions. Regarding the surfboard's manufacturing processes, the majority is performed by hand and has no direct contribution. A deeper analysis would consider the amount of energy used to run the facilities (electricity, cleaning and maintenance of tools and equipment).

Moreover, this industry produces a lot of waste, such as the residual dust that originates from the process. Therefore, all the disposable protection gear needed—gloves, sticks and duct tape—should be considered more accurate. Surfboards are made of four essential parts: Core, skin cloth, resin and accessory parts. Figure 9 shows the different possibilities to produce conventional surfboards in each category. The present assessment only considers the three first columns. The environmental indicator of this analysis is based on the CO₂ equivalent, which has a consequential impact on global warming. Natural materials during their lifetime retain CO₂; consequently, if the processing steps do not add carbon to the final process, their contribution to sustainable products is essential. For core materials, the best option is expanded cork with retention of CO₂ due to the eco-friendly manufacturing process. Nowadays, the most used core is still PU, although surfers are

gaining some awareness and choosing EPS, which offers the same properties with reduced environmental impact. Even so, EPS is not eco-friendly when compared to cork.

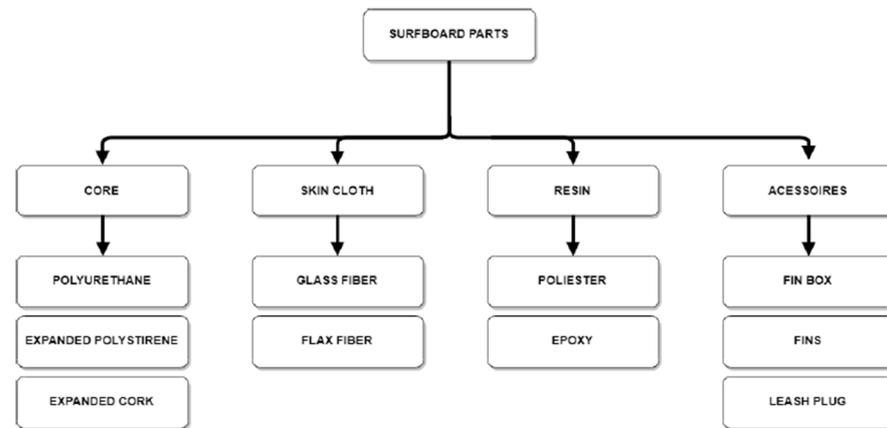


Figure 9. Surfboard parts.

Besides PU foam, resin is the raw material with the higher indicator per unit considered. For the resin, a practical assessment of the contribution of the manufacturing process of multi-part resins formulations was considered. The authors of [35] performed a multi-stage methodology that is more relevant to the batch processes used in manufacturing many structural systems. Again, the amount of material used is the same, and the consequent contribution is differentiated by the eco-indicator. The study produced up to 6.7 and 7.6 kg CO₂ when 1.5 kg of epoxy and unsaturated polyester resin were used, respectively.

4. Results

4.1. Mechanical Testing

4.1.1. Uniaxial Compression Tests of Core Material

The average results are shown in Figure 10 and Table 3. The denser white cork agglomerate presents a plateau with higher stress but earlier densification, yet absorbed more energy per unit volume.

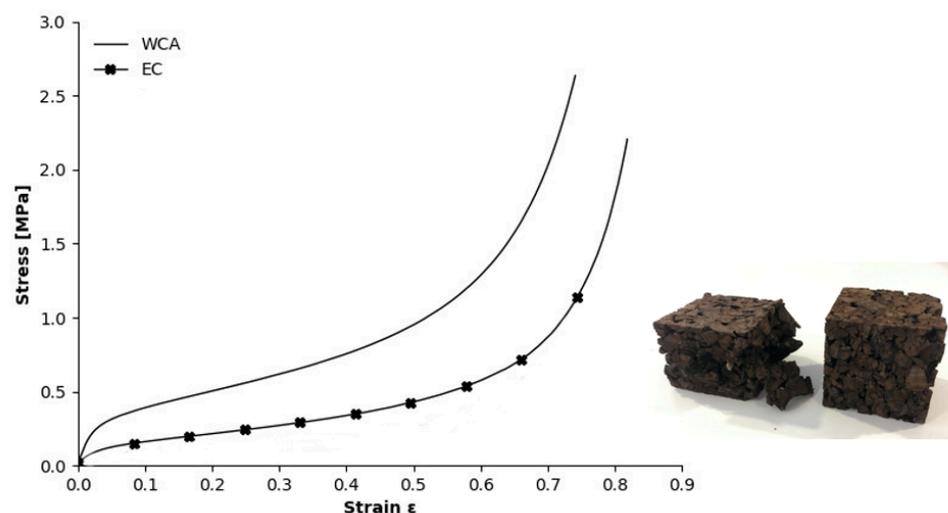


Figure 10. White Cork (WCA) vs. Black Cork agglomerates (EC) under quasi-static uniaxial compression.

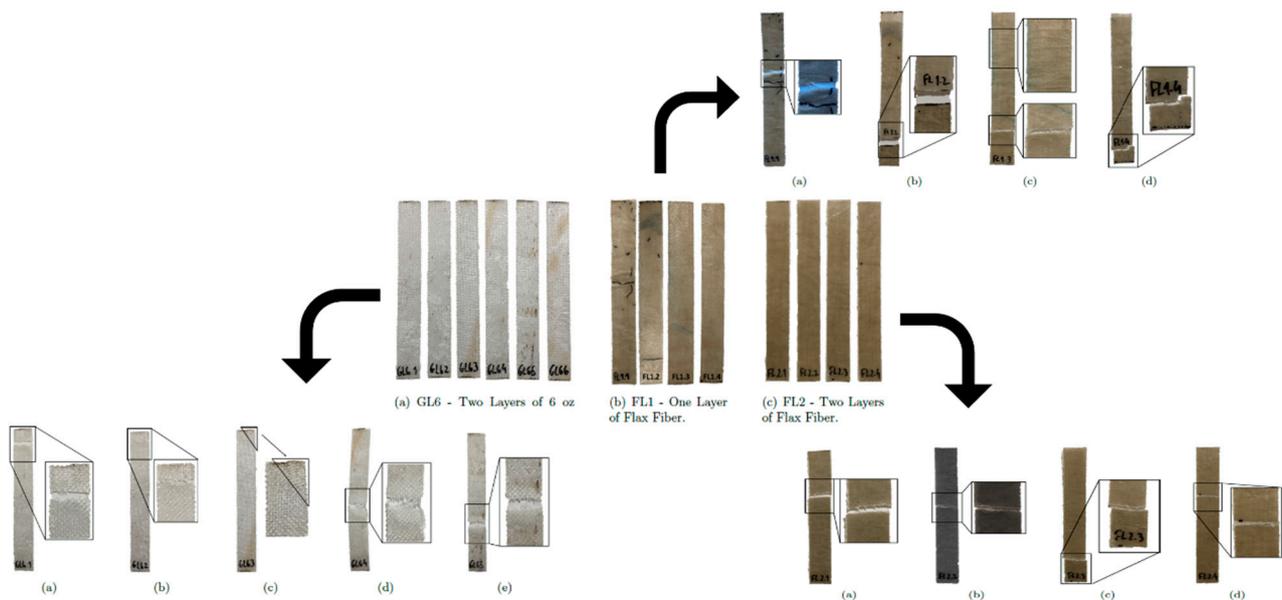
Table 3. White and black cork agglomerates test data.

	E [MPa]	ρ [kg/m ³]	Energy [kJ/m ³]
WCA	10.487	166.14	392
EC	3.113	92.304	173

During the tests, the EC samples lose integrity, Figure 10 (right), due to the low binding capacity of the suberin, the natural binder released during the expansion process to obtain this 100% natural material. Furthermore, in opposition to white cork agglomerates (that resort to PU-based thermosets), which contain air inside its cellular structure and show viscoelasticity, black cork offers a much more plastic behaviour, with permanent deformations, similar to the EPS material.

4.1.2. Uniaxial Tensile Test of Skin's Fibres

Figure 11 depicts the samples before the tensile test and the critical failure zones after testing. The glass fibre samples are brittle because of their intrinsic properties. Dozens of tests were performed, and only the stress and strain curves of samples showing regular rupture (not close to the grips) were considered for further analysis.

**Figure 11.** GL6, FL1 and FL2 samples before and after tensile test.

The samples were handcrafted, and for the FL1 group of samples, it was notorious that the textile wrinkled during the drying process, which ultimately led to some samples having non-conforming zones that would eventually interfere with the performance. On the other hand, FL2 samples were all homogeneous and had few imperfections.

FL1 showed more variability in stress–strain curves (Figure 12), contrary to those of FL2, with good repeatability. FL2.1 had an exceptional performance compared to the others and could withstand almost 60 MPa of stress before failure. FL2.3 and FL2.4 reached the limit of their deformation and broke close to a strain value of 0.081 and 40 MPa of stress. The rupture was always inside the gauge section on these samples, and the crack was always clean and transversal to the sample's length.

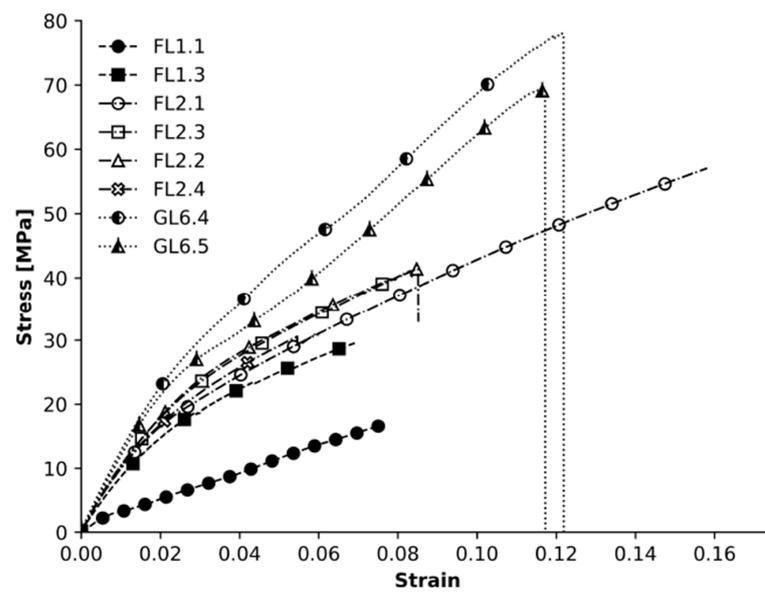


Figure 12. Stress and strain curves of skin layers tested.

These experiments may conclude that the variation in thickness and layer composition significantly impacts the laminate's performance. In Figure 12, it is possible to visualise that glass fibre laminates (GL6) perform better and withhold the highest stress levels. Based on the results of these experiments, the GL6 laminate type could be described as having Young's modulus of 1101.45 MPa, yield stress of 26.75 MPa and ultimate strength of 73.57 MPa. Natural fibres do not perform as well as GL6. However, their results proved to be more consistent and reliable. The two-layered laminate composite's stress-strain curve shows Young's modulus of 835.46 MPa, yield strength of 21.69 MPa and ultimate strength of 37.75 MPa (for FL2.1, the ultimate strength was not considered).

When working with bio-based materials, there is always a wide range of possible variations in the results, Table 4. For example, sample FL2.1 reached the highest value of failure strength, possibly because a particular region of fibres was thicker or more resistant. These variables are not easy to control in natural materials.

Table 4. Mechanical properties of different skins.

Sample	Young modulus [MPa]	Yield Strength [MPa]	Ult. Tensile Strength [MPa]
FL2.1	792.42	20.25	57.07
FL2.2	822.81	25.20	41.41
FL2.3	874.51	22.00	41.07
FL2.4	852.09	19.00	30.76
GL6.4	1079.2	30.00	78.02
GL6.5	1123.7	23.50	69.11

4.1.3. Bending Tests of Composites

In all samples, indentation occurred on the central area due to the concentrated load, but failure (delamination) happened on the core through the rupture of expanded cork particles (Figure 13). As already pointed out, suberin, the natural binder exuded during EC production, shows little aggregation force. Glass fibre and wood layers have shown no critical damage, neither on the points of support nor on the loading point. The glass fibre layer on the bottom was under tension, and there was no sign of failure in its middle part (critical zone). The core's EC particles cracked due to the spring-back forces acting on the part's extremities.

SW1A



SW1B



SW1C



SW1D



Figure 13. 3 Point bending test on SW1A, B, C, D samples.

From load–displacement curves in Figure 14, one may see the first two samples have a higher Young’s modulus and can withhold substantially more force. However, low shear strength often seems to be the cause of failure in composites where the expanded cork is the core material, as it has also been reported in a study from [37] where an EC, between two face sheets of glass fibre-reinforced epoxy resin, failed a three- and four-point bending test. Similarly, in [38], bending ended with failure by shear in the composite’s EC core. The external layers only had some marks left by the impactor and areas of support, therefore strongly suggesting that the difference in strength is related to the core. Moreover, the fact that there are no cracks alongside the glue line—only in the extremities (Figure 13—SW1A and SW1B)—demonstrates that the polyurethane glue used to bond the EC stripes together successfully acted as a reinforcement agent, increasing the sample’s resistance. The stress–strain curves and the sample’s points of failure conclude that adding a layer of glue in the core increases the material’s rigidity and, consequently, its bending resistance.

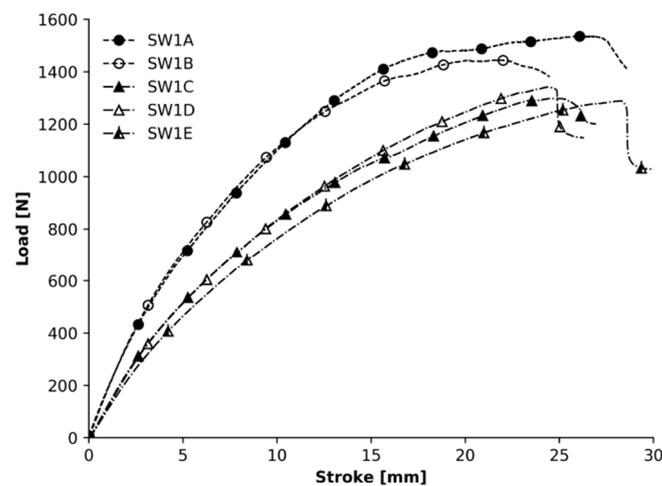


Figure 14. Three-point bending experimental test of a sandwich material with four layers: Expanded cork core, wood and different-thickness glass fibre layer on outer skins.

Performing mechanical tests allowed for the exploration of different material combinations and the analysis of their behaviour, both individually and as a whole. The data extracted from these tests can create the virtual model of the surfboard’s concept and validate its physical behaviour through computational simulation.

4.2. Virtual Tests

4.2.1. Uniaxial Compression of Core Material

Figure 15 depicts the compression of the 60 mm EC cube. Figure 16 shows the simulated stress–strain curve and its comparison to experiments, with good agreement. A deviation in the densification stage was found in the simulated version, which will have a slight influence on the results once it is not intended to subject the material to densification stages.

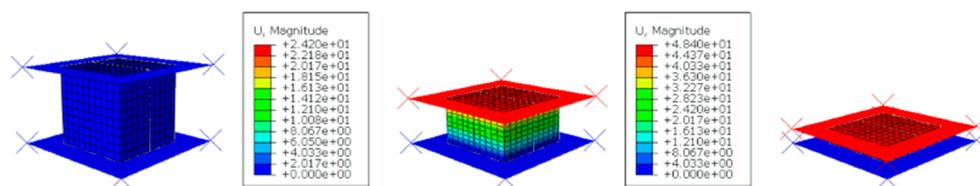


Figure 15. Simulation of EC compression.

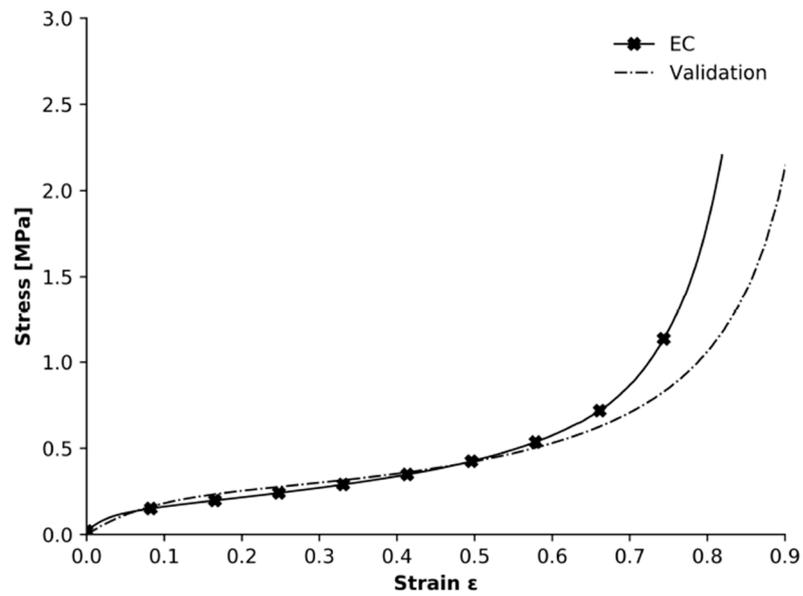


Figure 16. Experimental and simulated stress and strain curve of uniaxial compression test for EC.

4.2.2. Uniaxial Tensile Test of Skin’s Fibres

Figure 17 shows the evolution of the simulated sample over time, showing a good match with the experiments.

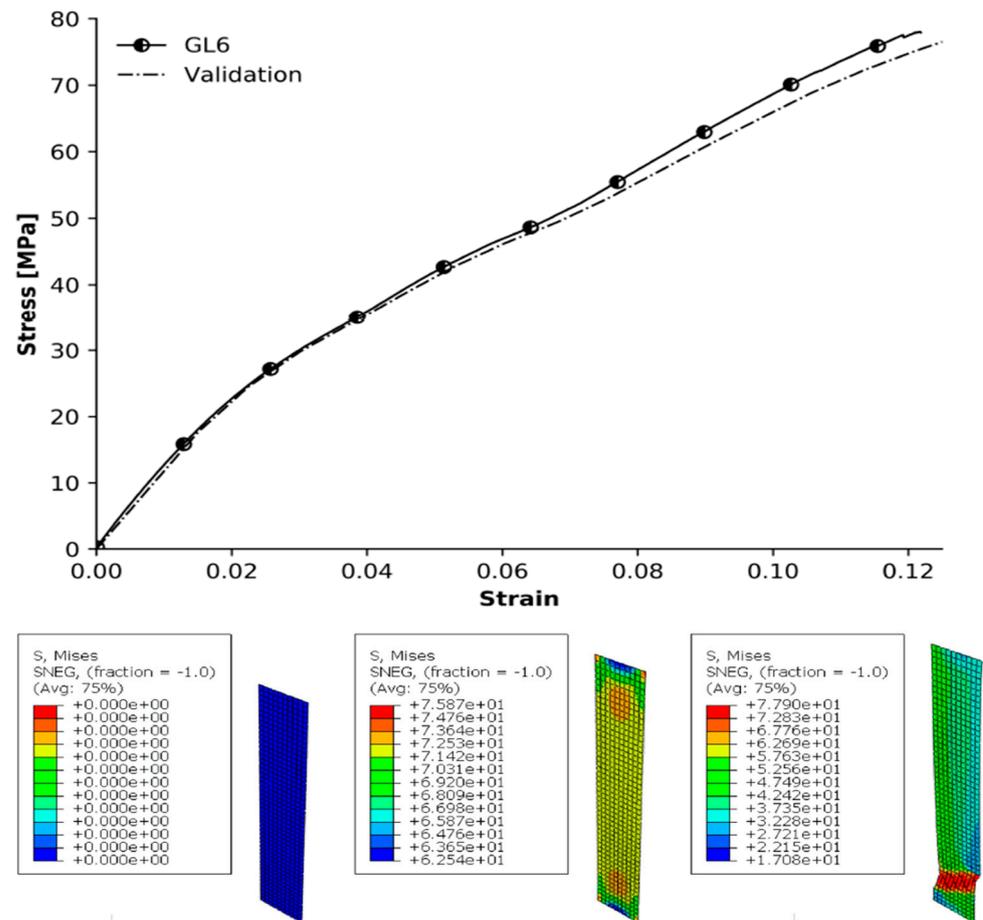


Figure 17. Experimental and simulated stress and strain curve of uniaxial tensile test for fibreglass.

4.2.3. Bending of Composite Laminates

The resulting force vs. displacement curve for the bending experiment is represented in Figure 18. The simulation was validated with matching results, and the three elements' behaviour was ready for the final model's complete simulation. It can be concluded that the sandwich structure can sustain at least a 1200 N compressive load. The first contact layer is the wood, which is essential for the outstanding mechanical performance obtained. The maximum equivalent von Mises stress sustained by the structure on the loading side is 115.4 MPa. In the experiments, neither the skin nor the wood layer reached failure, and the simulation's results suggest the same. As for the bottom layer, the maximum von Mises stress that fibreglass experienced was approximately 16 MPa. This value is not enough to lead to the failure of the external layer. From the local stress evaluation extracted from the software, it is possible to state that the skins would hold higher energy levels and bend further.

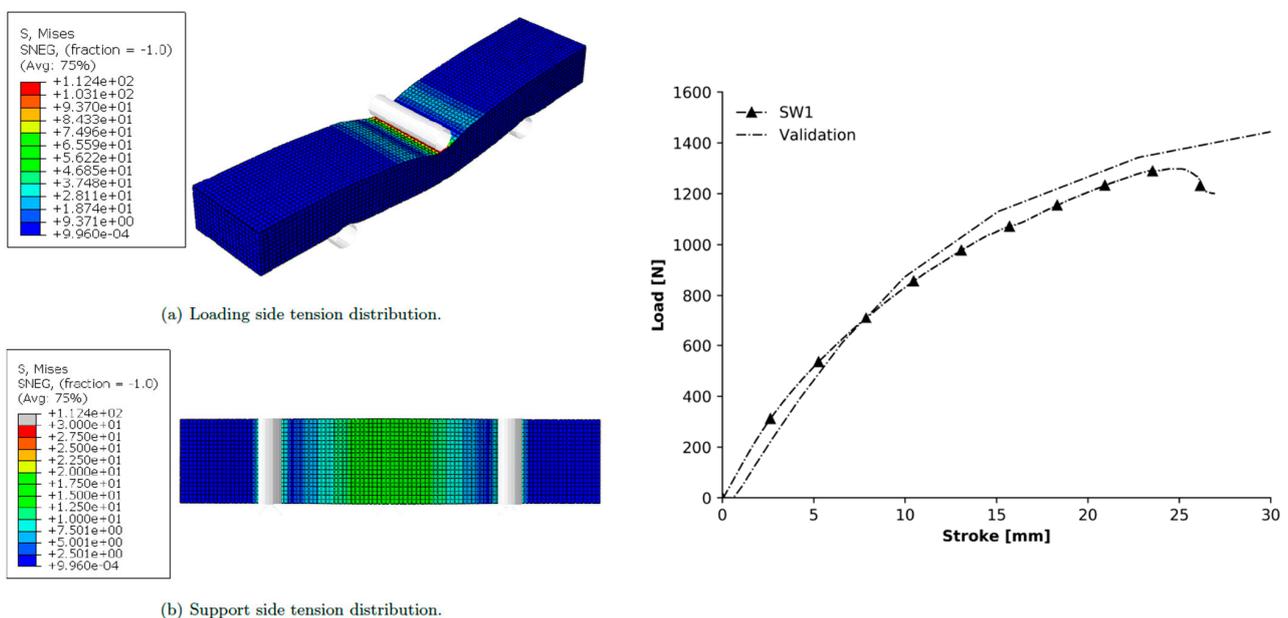


Figure 18. Experimental and simulated stress and strain curve of three-point bending on a sandwich structure.

4.2.4. Bending of the Surfboard Structure

The simulation made it possible to compute its reaction force, which reached a maximum of 1529 N, meaning that the surfboard can hold a body mass of approximately 156 kg with a 5 cm bending displacement. For a 637 N load, this value drops to 20 mm, as shown in Figure 19. These results give a reasonable margin of security even considering that dynamic loads during surf practice can be much more severe.

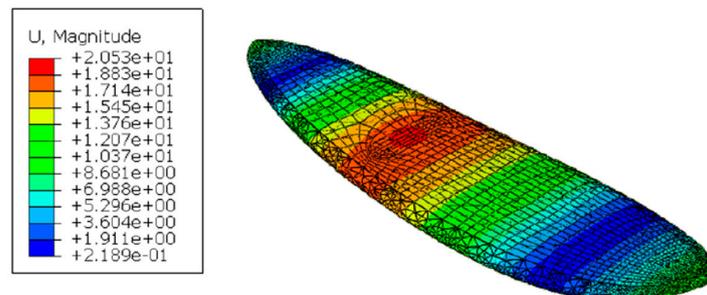
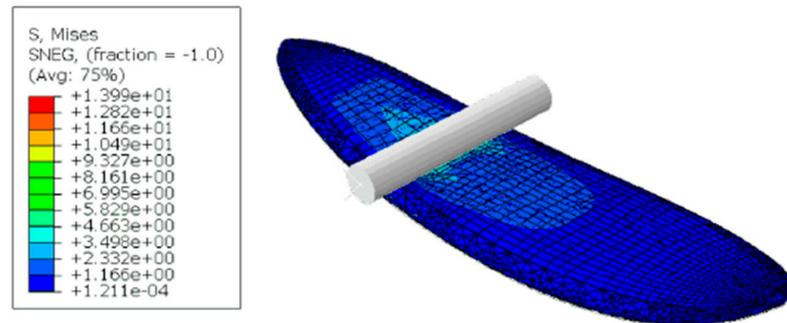
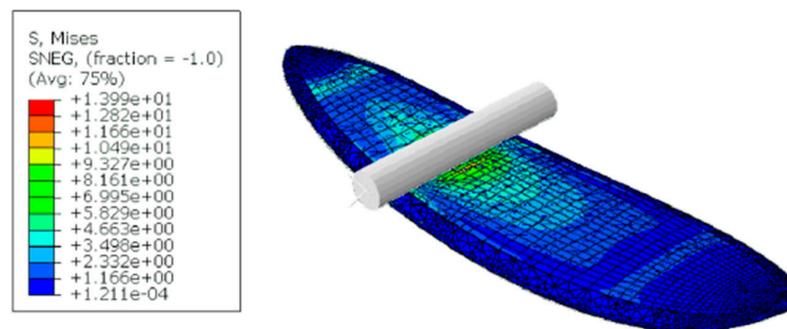


Figure 19. Surfboard displacement when a local load of 637 N (equivalent to 65 kg) is applied on the centre of the surfboard.

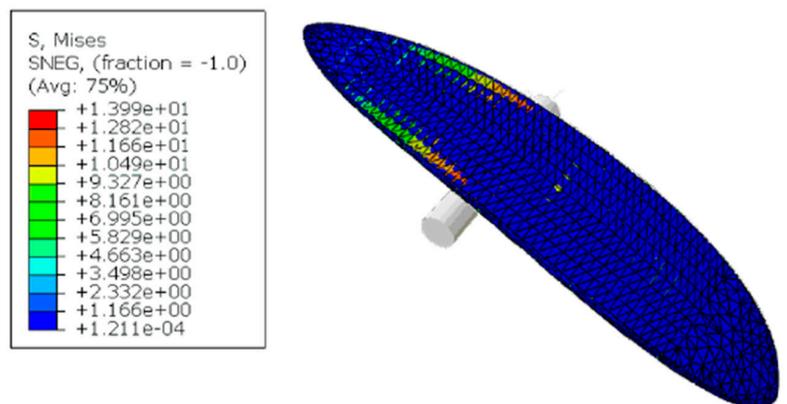
Regarding critical values of the von Mises stress, the highest value at the fibre layer is 13.99 MPa (Figure 20), which is lower than the yield strength of the tested fibreglass, keeping it in the elastic regime.



(a) Stress contour over top glass fiber layer.



(b) Stress contour over the wood layer.

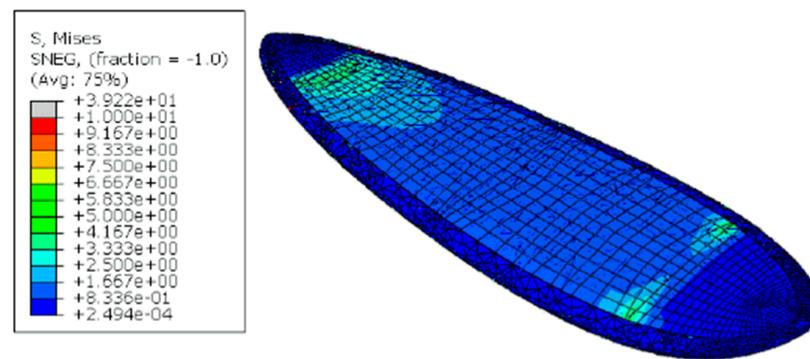


(c) Stress contour over bottom glass fiber layer.

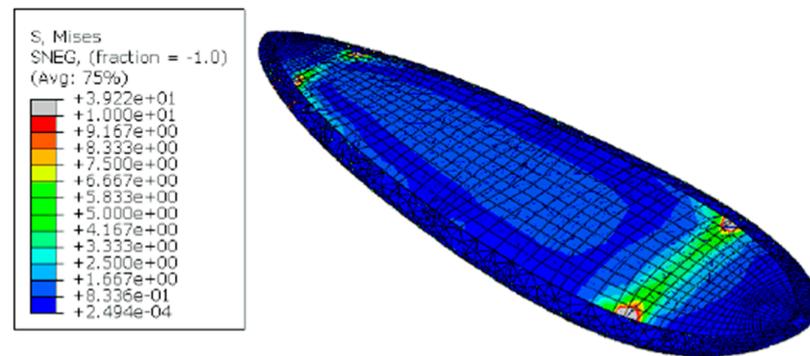
Figure 20. Stress distribution on the parts of the surfboard due to the three-point bending test.

4.2.5. Torsion Loading of the Surfboard Structure

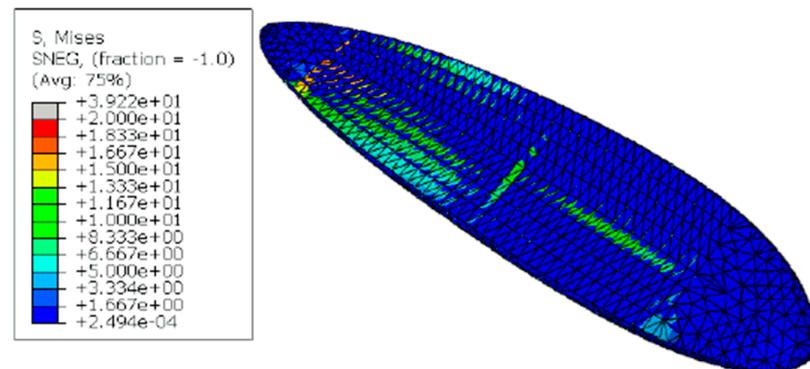
The simulated results in Figure 21 allow for the conclusion that for this amount of torsion, the skin layers and wood would not be damaged. Most critical stress values appear at the tail zone (due to the load imposed) and decrease towards the nose. Stresses are higher on the bottom glass fibre skin due to the thinner skin section than the wood and the top glass fibre altogether. If torsion was uniformly applied through the board, the stress distribution would be more uniform and less severe.



(a) Deck glass fiber stress diagram after torsion.



(b) Bottom stress diagram after torsion.



(c) Deck wood stress diagram after torsion.

Figure 21. Torsion of the surfboard simulated on Abaqus.

After carrying out this numerical analysis, it is essential to mention that the desegregation behaviour of the EC material is difficult to predict, and all the flexural, torsion and multiple impacts that the core will suffer could lead to the progressive degradation of the core. This kind of prediction is not easy to carry out, so fatigue tests and real-life scenario experiments should also be performed to understand how this material will behave after some intensive use.

4.3. Environmental Impact Study

Figure 22 shows the inventory of the different materials by category and the corresponding necessary quantities for manufacturing the surfboard and wasted material. Eco indicators are numbers that reflect the environmental burden of materials, processing methods, transportation, energy, recycling, and waste management. The higher the score, the more significant the environmental impact. The comparative unit for emissions is

kg of CO₂ equivalent emitted per part/process. Some eco-indicators were already in the desired unit. However, the ones from Ecolizer were expressed in milipoints. This is the unit system of the software where one milipoint corresponds to one millionth of the total annual environmental burden caused by an average European. The web article from Eurostat [39] states that during the year 2017, on average, one EU citizen produced an amount of CO₂ equivalent to 7.2 tons. From this value, it is possible to obtain the corresponding emission for the milipoint unit.

Part	Materials						Processing				Use	Recycling	Total Kg CO ₂ eq.					
	Type	Unity.	Quantity		Global warming indicator	Tot. Kg CO ₂ eq.	Process	Quantity	Global warming indicator	Tot. Kg CO ₂ eq.								
Core	EPS Core	1	volume (m ³)	0,0659	kg CO ₂ eq./m ³	59	3,88633	CNC (cm ³)	23982	(mpt/cm ³)	0,01	1,774668	Zero CO ₂ contribution from usage. Surfboards are not discarded after usage. They typically are reused (second hand) or stored at home.	5,661				
	PU Core	1				124,7	8,213989							9,9887				
	EC Core	1				-116,23	-7,65607							-5,881				
	Wood Stringer	1	massa (kg)	0,12	(mpt/Kg)	446	0,396048	Manual	1	0	0	0,396						
	Polyurethane Glue	1				0,15	452	0,50172	Manual	1	0	0		0,5017				
	Wood Skin	1				0,5	165	0,6105	Manual	1	0	0		0,6105				
Skin Cloth	Glass Fiber	1	mass (Kg)	0,54	kg CO ₂ eq./kg	2,65	1,431	Vaccum laminated. No information about equipment electrical consumption and necessary utensiles.					1,431					
	Flax Fiber	1				0,6069	-1,4						-0,85	-0,85				
Resin	Unsaturated Polyester	1	mass (Kg)	1,5	kg CO ₂ eq./kg	7,6	11,4											11,4
	Epoxy	1				6,7	10,05											10,05
Accessoires	Fin Box	3	Do not considered in the study.															
	Fin	3																
	Leash Plug	1																

Figure 22. Surfboard life cycle assessment. Global warming contribution of EPS, PU and EC extracted from [18], unsaturated polyester and epoxy resins from [36], glass fibre and flax fibre cloth from [35]. The remaining eco-indicators were extracted from Ecolizer software and are expressed in milipoints.

From Table 5, one may conclude that material selection for the production of a surfboard influences the resulting environmental impact. If the goal is to find the most ecological surfboard, the choices are easy, but that is not always the final customer’s desire. Weight, strength, and performance are interconnected when designing an optimum product. In this section, multiple scenarios of surfboard construction are created, from the conventional method to the most ecological amongst the available materials.

Table 5. Construction combinations.

	Core	Wood	Glue	Skin cloth	Resin	CO ₂ eq.[kg]
PU1	PU	Stringer	Polyurethane	Glass	Polyester	23.72
PU2	PU	Stringer	Polyurethane	Glass	Epoxy	22.37
PU13	PU	Stringer	Polyurethane	Flax	Polyester	21.44
PU4	PU	Stringer	Polyurethane	Flax	Epoxy	20.09
EPS1	EPS	Stringer	Polyurethane	Glass	Epoxy	18.04
EPS2	EPS	Stringer	Polyurethane	Flax	Epoxy	15.76
EC1	EC	Wood skin	Polyurethane	Glass	Polyester	8.06
EC2	EC	Wood skin	Polyurethane	Glass	Epoxy	6.71
EC3	EC	Wood skin	Polyurethane	Flax	Polyester	5.78
EC4	EC	Wood skin	Polyurethane	Flax	Epoxy	4.43

A conventional surfboard uses a foam core with a wooden stringer and an epoxy or polyester glass fibre lamination. If the foam block is from PU, the standard resin to be used is polyester. On the other hand, for foam blanks made of EPS, polystyrene resin will rust it, destroying the core. Natural materials have a negative global warming contribution, lowering the resulting CO₂ emissions, hence the use of flax fibre will also have a positive impact concerning the amount of greenhouse gas emissions. The most eco-friendly solution is a surfboard made with expanded cork, epoxy resin, and flax fibre cloth from the studied materials. The comparison between “poly” and “eco board” can be found in Figure 23. It is possible to see that a reduction of 24% in CO₂ emissions can be achieved through material selection.

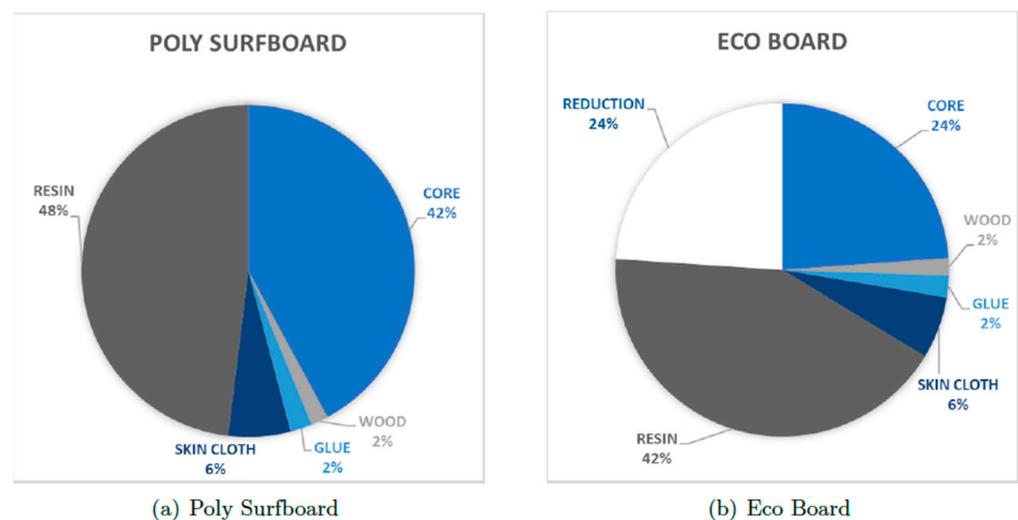


Figure 23. Percentage contribution of parts for CO₂ emissions.

Furthermore, by using the same remaining materials and changing from EPS to EC as a core material, the environmental impact would be reduced from 18.04 to 6.71 kg/m³. This change will increase the surfboard’s weight but will provide a reduction of 62,8% in emissions. Following the Ecoboard resource guide, this product could be accepted as an official Ecoboard. The main requirements for qualifying are the choice of materials, using a qualified resin (bio-based) and a qualified core with at least 50% recycled content of reclaimed and/or recycled wood. An entirely natural expanded cork, of which the manufacturing processes produce a carbon-negative material, fulfil all the requirements and could be a new opportunity to make boards even more eco-friendly. More about the project can be found on their website [40].

5. Discussion and Conclusions

The overarching objective of this study was to find an alternative solution to the traditional PU-based surfboards and combine environmental and structural advantages. Wooden surfboards may be less reliant on petrol-based materials; however, they have less manoeuvrability and more performance issues when compared to a composite fibre one [4]. Moreover, other more sustainable alternatives proved to have much lower mechanical properties when compared to the current surfboard’s standard materials—Bio-Foam presented a much lower compressive core shear strength when compared to PU and hemp cloth laminates are far less effective than fibreglass to protect cores [41].

This present study introduces an environmentally sustainable alternative (Figure 24) that does not compromise the board’s performance. The mechanical and numerical testing demonstrated that the combination of expanded cork, wood and fibreglass results in a very resistant composite that is able to withstand a great amount of force without failing. The investigation method has shown that numerical tools can effectively be used to speed up product development times and provide reliable structural analysis results once materials

and boundary conditions are carefully set. Besides a good mechanical performance, this combination also does well in terms of the environmental impact by reducing carbon emissions by almost 63%. Not only does it reduce the carbon footprint but also the toxicity in manufacturing processes, since PU blanks contain ingredients that are harmful to the long-term health of whoever is handling the material.



Figure 24. Final ready-to-surf prototype.

Nonetheless, this study also has some limitations. The composite developed herein is not yet fully optimised for the production of surfboards, so there is still room for improvements. The bending tests were only performed on the developed composite and not in a PU core, so there may not be a direct comparison between the proposed solution and the standard one. Due to the manufacturing process, this material is still too heavy compared to the current material on offer and has a weak connection between particles, needing extra structural strength. Because of this, further studies and development must be performed in the structural design of the surfboard to reduce the weight and increase the strength. Furthermore, the use of bio-based resin may have a massive impact on the product's life cycle assessment with similar mechanical performance.

Besides these limitations, this material has great potential as a blank material for surfing and other sports such as kayaking given its outstanding sustainability and excellent mechanical properties. Sustainability is an essential concern that society must have embedded in its core, and studies like this one are a small step towards winning the battle against climate change whilst raising awareness for the importance of reducing carbon emissions.

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