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Research article

Investigation of high-performance recycled carbon fibre reinforced aluminium core sandwich structures

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Abstract. This study examines the performance of hybrid sandwich composites with a recycled aluminium foam (AlF) core and a recycled carbon-reinforced polymer skin layer. Three composite skin configurations were examined: (i) unidirectional (UD) carbon/epoxy sheets representing aligned virgin fibre reinforcement, (ii) randomly oriented recycled carbon fibre (rCF) mats consolidated by hand layup with epoxy, and (iii) randomly oriented rCF/epoxy sheets consolidated by hot pressing. The AlF core structure analysis revealed a low density and uniform open-cell structure ideal for lightweight cores. Comprehensive testing revealed significant performance differences between skin types and manufacturing methods, underscoring the critical role of processing – particularly hot pressing – in enhancing fibre compaction, matrix consolidation and interfacial bonding between the core and facesheets. Unidirectional carbon fibre skins achieved the highest flexural stiffness. In contrast, hot-pressed rCF mats provided the most balanced properties, combining high compression, damage resistance, and flexural strength, due to improved consolidation and reduced porosity in the face sheets. Thus, hybrid sandwich structures fabricated from recycled AlF core and rCF represent a viable, environmentally responsible alternative for aerospace, automotive, and protective applications requiring lightweight, high-strength, and damage-resistant materials.

Keywords: *composite, sandwich structure, recycled carbon fibre, aluminium foam core, impact testing*

1. Introduction

1.1. Composite sandwich structures

In the design of large-scale technical structures, the issue of sustainability is becoming increasingly prominent. However, meeting sustainability goals should be achieved without compromising the load-bearing capacity of structures. The development of composite materials is driven by two primary objectives: weight reduction and the combination of tailored properties. These materials possess exceptional specific mechanical properties, which have led to their widespread application in numerous industrial sectors. Figure 1. depicts a general composite sandwich structure comprising a core and a reinforcing shell.

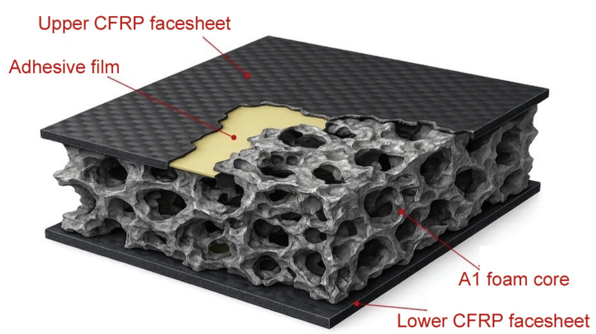

Figure 1. Schematic of a composite sandwich structure with an Al foam core.

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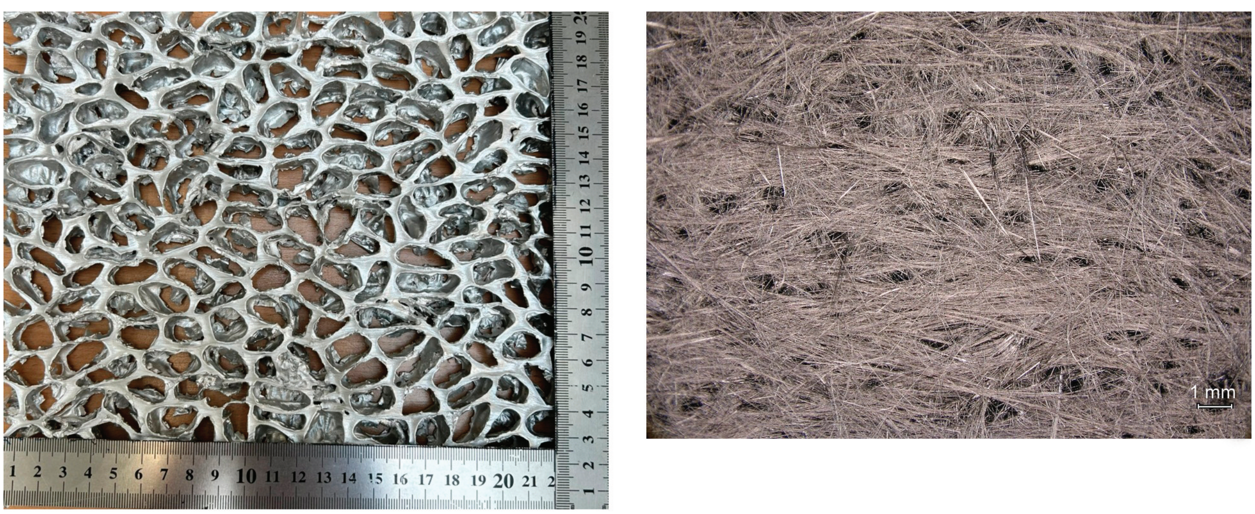
The design of composite sandwich structures offers high specific flexural stiffness and strength, which is essential in bending load cases. The sandwich structure comprises two or more layers of a high-strength, flat or moderately curved surface, which are interconnected by the core material, forming a single mechanical unit. Overall performance is driven by the material properties of the sheet and core materials, the thickness of the core, and the connection between the two subcomponents. Sandwich structures combine the advantages of the subcomponents, resulting in exceptional bending stiffness-to-weight, good corrosion resistance, low thermal and acoustic conductivity and other multifunctional properties [1], enabling application in the transportation industry.

Polymer-based hybrid composite sandwich structures are a particular family of structural materials where polymer composites are combined with other materials, such as metals. An excellent example of this could be a sandwich panel made of a metal core material and polymer composite shells. Aluminium honeycombs are generally used in sandwich structures, offering lightweight and high compressive strength. The main challenge of aluminium honeycombs is creating a proper connection between the core and the shells. The honeycomb structure is produced from thin aluminium plates/foils, resulting in a small contact surface for glueing. Due to recent developments, core material can also be made from a foam-like structure, which can be produced cost-effectively at competitive prices, mainly from aluminium (Figure 2). Aluminium foams (AlF) have a different pore structure and higher cell wall thickness, which is ideal for bonding and possesses full recyclability.

Currently, most high-performance polymer composites contain carbon fibre reinforcement, which is challenging to manage at the end of life. The rapid growth in the use of CFRP (carbon fibre reinforced plastic) started decades ago, but the service life of the products is usually 20–30 years. As a result of these past applications and the continued expansion of production, a significant amount of CFRP waste is expected to be generated in the coming years. According to some estimates [2], approximately 20 000 t of CFRC waste is generated annually in the US and Europe, and 6000–8000 commercial aircraft are expected to reach end-of-life by 2030. Therefore, technologies and systems must be developed to manage waste from manufacturing processes and end-of-life products [3]. Pakdel *et al.* [4] classified carbon fibre waste into three main categories: the first is carbon fibre residues from manufacturing, which have mechanical properties similar to virgin carbon fibres; the second is residues from pre-production; and the third is semi-finished products and recoverable fibres from carbon fibre composites. There are three main ways of dealing with CFRC waste: disposal (landfilling), energy recovery (incineration), and recycling. Landfilling is cheap but not environmentally friendly. Incineration can recover energy from the polymer matrix, but leaves CF as residual char and releases significant amounts of pollutants into the environment. Recycling allows fibres to be recovered from the polymer matrix and reused in production



a) b)

Figure 2. Structure of used materials: a) aluminium-based open cell metal foam, b) recycled carbon fibre nonwoven needle punched mat.

[5]. However, this process depends on the matrix type: while a thermoplastic matrix can be melted and reused, the recycling of a crosslinked matrix is more complex.

Due to the increased demand for carbon fibre, a large amount of CFRP waste will be generated in the coming years, and recycling will become an important issue. One of the main

The drawback of virgin CF production is its high cost, which is further increased by the energy demand to produce it. CF production requires about 250 MJ/kg of energy, significantly higher than the energy needed to make glass fibre. In addition, the production process generates by-products such as hydrogen cyanide, ammonia, carbon monoxide, carbon dioxide, nitrogen oxides, and other volatile organic compounds that harm the environment. In contrast, recycling CF requires a fraction of the energy. In reclamation, the properties of CF recovered from the polymer matrix highly depend on the type of matrix, reclamation processes, and parameters. Mechanical, thermal, and chemical recycling are three methods for recovering carbon fibres [6]. Mechanical recycling is a commonly used, efficient method for processing composite waste. Its advantages include rapid processing and easy distribution by size. However, it has the disadvantage of breaking the length of the CFs and leaving resin residues on the fibre surface, which reduces their secondary application. Processing can be done in several ways: chopping, crushing, grinding, or milling the composite parts. Size reduction takes place in several stages. First, the shredders cut the waste into 50–100 mm pieces using multi-axis shredders. The distance between blades, rotational speed, and the hardness of the CFRP waste determine the final granulate size. This process helps to remove metal parts and reduces transport costs by reducing volume.

The scrap is then further shredded, usually to a size between 0.05 and 10 mm, and separated into different fractions using sieves and cyclones. The final products are divided into fine fibres, fine powder, and coarse recyclate. Mechanically recycled fibres are most commonly used in composites, concrete, asphalt, or coatings [7–10]. Thermal processes generally facilitate the partial recovery of energy stored in matrix materials through heat. However, specific thermal methods enable the recovery of both energy and material. For crosslinked matrix composites, combustion is a commonly employed method for energy recovery, but its efficiency is relatively low. This inefficiency primarily arises from inorganic components such as glass fibres, fillers, and flame retardants. Moreover, combustion generates substantial solid residue, presenting additional disposal challenges.

Fluidised bed technology provides a more targeted method for recovering composite materials. This process introduces chopped composites into a fluidised bed containing quartz particles. The matrix material evaporates from 400 to 650 °C, thereby recovering reinforcing fibres. Afterwards, the pretreated composites are transferred to a separator, where the evaporated resin is extracted, and the solid fillers and fibres are separated. The released gases can be captured and used as energy in thermal power plants, while the recovered fibres can be repurposed [11]. The main goal of this process is to recover reinforcing fibres due to their significantly higher cost than other composite components. However, the commercial feasibility of fluidised bed technology remains limited, as it is only economically viable when processing at least 9000 t of composite material annually [12].

In pyrolysis, the polymer matrix of the composite waste is thermally degraded in an inert environment (typically nitrogen) at controlled temperatures (350–1000 °C) and atmospheric pressure within a pyrolysis reactor [13, 14]. During this process, the composite waste is decomposed into solid (reinforcement and filler materials), liquid (pyro-oils), and gas (pyrogases) components [15]. The gases produced during pyrolysis can serve as secondary fuels to sustain the process due to their high calorific value. A secondary oxidation heat treatment is necessary to eliminate the pyrolytic soot formed on the surface of the recovered fibres. Still, there is a risk that oxidation of the fibres may result in a 10–15% reduction in their mechanical properties. This effect can be minimised by properly selecting parameters while the fibre surface is cleaned [16–18].

Chemical recycling employs solvents to separate the matrix from fibres, preserving their length and mechanical properties. However, it is only feasible in laboratory settings, resulting in high costs. A specific type, solvolysis, uses supercritical solvents to degrade the polymer matrix, yielding purified fibres, inorganic fillers, depolymerised matrices, and monomers. Different solvolysis types include hydrolysis (water), alcoholysis (alcohols), glycolysis (glycols), and acidolysis (acids) [13, 19]. High pressure, temperature, or alkaline catalysts enhance these reactions, although removing alkaline salts can be challenging. Supercritical fluids, with properties between gases and liquids, offer efficient degradation and partial oxidation of polymers. Water and alcohols are adequate for crosslinked polymers, with water being low-cost, recyclable, and reusable. Supercritical water's low viscosity and high diffusion enable quick penetration into CFRC microcavities, aiding epoxy resin degradation. Its dielectric constant resembles non-polar solvents, ensuring miscibility with organic compounds. subcritical and near-critical water is also adequate, inexpensive, non-toxic, and eco-friendly. Near-critical water features a high diffusion coefficient and low density. Supercritical alcohols are low-cost, non-toxic, recyclable, and dissolve organic and inorganic compounds, yielding high-quality recycled fibres while producing hydrogen to assist decomposition reactions [20].

Recycled carbon fibre is available in various structures, one of the most promising of which is carded/needle-punched fabric (Figure 2b), but it lags behind oriented structures in terms of mechanical properties.

1.2. Methods for the production of metal foams

A metal foam is a material or structure composed of a solid metal with a significant portion of its volume consisting of gas-filled pores. Metal foams are characterised by high porosity, with only 5–25% of their volume comprising metallic base material. These materials retain specific physical properties of their base material. For instance, if constructed from a non-combustible substance, the metal foam remains non-combustible and can typically be utilised as a recyclable raw material. Metal foams possess excellent energy-absorbing properties due to their cellular structure. They also serve as good thermal and sound insulators because of the gases trapped within their structure. Two primary categories of foams can be identified: open-cell and closed-cell foams. These two types differ significantly in both structure and application.

Several methods for producing metal foams can be categorised into three main types: melt fabrication, powder metallurgy, and coating techniques [21]. The technology employed significantly influences the material properties of the metal foam, including its structure and relative density. Aluminium is the most commonly used metal in the foaming process. One prevalent technique is the gas injection method, called bubble foaming, which forms closed-cell metal foams. The metal is heated to a molten state in this process, and viscosity-enhancing agents are added to make the melt more manageable. Subsequently, gas (air, nitrogen, or argon) or water is introduced into the melt, and a stirrer creates bubbles that ensure uniform distribution. This results in a more ordered structure for the metal foam, enhancing its mechanical properties [22]. The metal melt containing the bubbles rises to the top of the crucible due to the density difference, from where a conveyor belt can extract it. As the temperature decreases, the metal solidifies into a metal foam. This technology enables continuous production, and theoretically, infinite lengths of metal foam can be manufactured. The foam's thickness is typically around 10 cm, while its width is determined by the width of the conveyor belt.

Another standard method for producing metal foam involves using a foaming agent. The first aluminium foams were created by this process by Elliott in 1951 [23]. Since then, the technology has been continuously enhanced, and foams with uniform distribution can now be produced. The foaming method consists of adding a blowing agent to a metal melt in a foaming mould, which, when heated, decomposes into gases and forms bubbles. This initiates the material's expansion, gradually filling the mould. As the temperature decreases and the material reaches a state below the melting point, solid aluminium foam is formed, which can then be removed from the mould. Initially, controlling the cell structure of metal foam produced through foaming was challenging, as the pore size and distribution varied. Larger bubbles formed in the centre of the mould, while smaller and fewer bubbles appeared at the edges, resulting in higher material density at the edges. High-speed mixing at 10 000 rpm successfully addressed this issue, preventing large bubbles and promoting a more homogeneous cell structure. It was noted that a more uniform structure results in better final material quality. One of the key parameters in the process is the viscosity of the melt; higher viscosity materials release the generated gases more slowly, causing bubbles to move more slowly in the melt. Viscosity enhancers are frequently used to manage this. This process is a drawback because it is currently applicable only in a batch plant, limiting productivity and making metal foam production costly.

Figure 3. Aluminium foam made by the granular method.

Another technology is the granular method (Figure 3). In this case, soluble granules that remain stable at the melting point of the metal are used.
For example, aluminium foams can be produced relatively cheaply and easily using granules based on sodium chloride (NaCl). During the process, the granules undergo heat treatment to reduce their porosity, after which uniformly sized particles are sorted and placed in a mould. The molten metal is poured onto the granules, allowing it to flow between them and fill the mould. The bottom of the mould must be equipped with air vents to let excess air escape. The process may be aided by using overpressure or vacuum. After the metal-granule mixture cools and solidifies, the granules are dissolved away, such as with salt or running water, to obtain an open-cell aluminium foam. The main advantage of granule production is that it uses a very common, easily obtainable, and inexpensive material for creating metal foams. In a specific variant of this method, gas-filled metal spheres are employed as granules, with their shell becoming part of the metal foam during production, eliminating the need for a solvent. This allows for the production of high-quality foams with uniform cell sizes. However, producing metal spheres is more challenging than using simple granules. Orbulov *et al*. [24] present a novel, low-cost composite metal foam (CMF) made by infiltrating AlSi9MgMn alloy with 60 vol% lightweight expanded clay particles (LECPs) using low-pressure liquid infiltration. The resulting CMFs demonstrate uniform structure, strong interfacial bonding due to chemical interactions, and tunable mechanical performance – particularly compressive strength and energy absorption – based on LECP size and standardised three-step high temperature (T_6) heat treatment. A key finding is establishing an exponential decay relationship between LECP diameter and mechanical properties, highlighting the material's suitability for energy-absorbing automotive applications. The study by Szlancsik *et al*. [25] systematically evaluates the effects of different filler materials – ceramic hollow spheres (CHSs), metallic hollow spheres (MHSs), and lightweight expanded clay particles (LECAPs) – on the mechanical and economic performance of metal matrix syntactic foams (MMSFs). Results show that CHSs provide the highest structural strength, MHSs are optimal for energy absorption, and LECAPs offer a cost-effective alternative with competitive performance for large-volume applications. These findings underscore the importance of filler selection in tailoring MMSFs for specific functional and economic requirements. The study by Taherishargh *et al*. [26] on low-density expanded perlite–aluminium syntactic foam presents an innovative composite material combining expanded perlite (EP) and A356 aluminium via counter-gravity infiltration, achieving ultra-low density (~1.05 g/cm^3) and high porosity (~61%). Despite EP's limited structural strength, the foam displayed excellent compressive behaviour, with a plateau stress of 30.8 MPa and high energy absorption efficiency (~88%), due to uniform particle distribution and stable microstructure. These results highlight expanded perlite as a cost-effective, chemically inert filler suitable for lightweight, energy-absorbing applications. Pados *et al*. [27] investigated the bending behaviour of *ex situ* functional metal foams, demonstrating that foam-filled tubes with adhesive bonding show greater flexural strength and energy absorption than non-adhesive or bare syntactic foams. The study highlights the role of gap and adhesive bonding in enhancing mechanical performance under bending. The research by Marx *et al*. [28] on composite metal foam (CMF) armours demonstrates their Exceptional energy absorption capabilities, with steel–steel CMF (SS-CMF) absorbing up to 83% of a projectile's kinetic energy while achieving a mass efficiency ratio of 1.5 compared to conventional rolled homogeneous armour (RHA). Among the three tested armour designs, the optimal configuration combined a thin RHA faceplate, a single ceramic layer, a CMF core, and an aluminium backplate, effectively balancing fragmentation and energy dissipation. The study concludes that CMF armours provide superior ballistic protection and weight savings, and offer added benefits such as thermal insulation and radiation shielding, highlighting their potential for next-generation lightweight military vehicle armour. The review by Castanié *et al*. [29] comprehensively traces the evolution of composite sandwich structures in

aeronautics, emphasising their mechanical design complexities, manufacturing challenges, and role in lightweighting aircraft. It distinguishes between symmetrical and asymmetrical sandwich types, highlighting that metal foam cores have been investigated particularly for the latter, where their plastic failure behaviour under clamped conditions is interesting. Moreover, metal foam cores are identified among the innovative core materials – alongside folded, kagome, and lattice geometries – being explored for enhanced multifunctional performance and potential substitution of traditional honeycomb cores in future aerospace applications. Sun *et al*. [30]'s study investigates interfacial toughness enhancement in carbon-fibre/aluminium foam sandwich structures using short aramid fibre interleaves. Results demonstrate that inserting 6 mm long aramid fibres at the interface significantly improves the critical energy release rate – up to 80% compared to non-toughened samples – by promoting effective crack bridging and energy dissipation within the foam surface cavities. This low-cost, lightweight toughening method shows strong potential for improving sandwich composites' durability and structural integrity in aerospace applications. Styles *et al*. [31] reveal that core thickness critically affects failure mechanisms, strain distribution, and flexural strength. Thinner cores tend to fail via skin wrinkling and fibre fracture, while thicker cores fail predominantly through core indentation and crushing. Strain patterns vary accordingly, with thicker cores reflecting foam cell morphology. Flexural analysis shows that although maximum core stress decreases with thickness, core shear stress remains constant, and facing stress reduces due to dominant core failure. Moreover, increasing skin thickness on thick-core panels shifts failure from indentation to shear cracking, significantly enhancing load capacity. The study emphasises size effects and calls for further mechanical characterisation to support constitutive modelling.

In summary, while composite sandwich structures with AlF cores and polymer-based composites have shown excellent potential in lightweight and multifunctional applications, their sustainable integration is still hindered by challenges in bonding performance, recyclability, and reliable characterisation of mechanical behaviour. Although significant progress has been made in developing recycling technologies for CFRP and in producing cost-effective metal foams, there remains a knowledge gap in understanding how rCF reinforcements interact with metallic foam cores in hybrid sandwich configurations, particularly regarding their damage resistance and load-bearing capacity. Therefore, the present study aims to address this gap by experimentally investigating the structural performance of AlF–rCFRP sandwich composites, with specific attention to their flexural behaviour and damage resistance.

2. Materials and methods

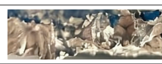
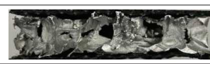
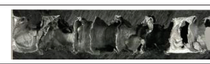
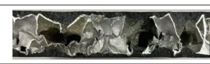
The Rymfelt recycled carbon fibre (rCF) nonwovens were supplied by Rymyc Slr. (Campignano, Italy), With the areal density of 800 g/m^2. The RFCs were obtained from high-tensile CF waste, recovered from EoL composites by pyrolysis, and remanufactured by carding, crosslapping, and needle punching. The reference carbon fibre reinforcement was a 200 g/m^2 unidirectional textile of PX35 CF supplied by Zoltek Inc. (Bridgeton, MO, USA).

A standard laminating epoxy system of component A – IPOX MR 3010 modified bisphenol A/F resin (epoxy-equivalent: 175–190 g/equiv.; epoxy value: 0.52–0.57 equiv./100 g; viscosity at 25 °C: 800–1200 mPa·s, density: 1.10–1.15 g/cm^3) and component B – IPOX MH 3124 modified cycloaliphatic amine hardener (amine value: 450–470 mg KOH/g; viscosity at 25 °C: 40–70 mPa·s, density: 0.95 g/cm^3); Ipox Chemicals GmbH, Germany, was used as the matrix material. Resin components IPOX MR 3010 and hardener IPOX MH 3124 were mixed at a mass ratio 100:33.

A commercially available open-cell AlF produced by Aluinvent Zrt. (Felsőzsolca, Hungary) It was selected as the core material. The AlF panel is made from modified EN 6061 aluminium alloy (96% aluminium, 2% magnesium, 1% oxygen, 1% silicon, and calcium) produced by a continuous casting process using the gas injection method. The open cell structure achieved by the gas injection resulted in a typical cell size of 10–30 mm, and cells run through the whole thickness of the plate and are open on both sides. The Al foam core has a nominal thickness of 15 mm, a 135 kg/m^3 density, and is 100% recyclable. The structure of the AlF is illustrated in Figure 2.

Sandwich panels of 600×400 mm were manufactured by hand lamination and compression moulding (Table 1). Reference samples consisted of four plies of carbon UD in the facesheets and an Al foam core, and were fabricated by hand lamination. The

Table 1. Produced specimens: reference: UD-AlF, RCF-AlF, RCF-AlF-comp.

Specimen	AlF	UD-AlF	RCF-AlF	RCF-AlF-comp
Materials	Aluminium foam	PX35 CF unidirectional textile, AlF	RYMFELT recycled carbon fibre mat, AlF	RYMFELT recycled carbon fibre mat, AlF
Layup	Al foam	[04/AlF/04]	[rCF/AlF/rCF]	[rCF/AlF/rCF]
Sandwich manufacturing	None	Hand layup	Hand layup	Wet compression
Surface				
Cross section				
Face sheet thickness [mm]	–	01.47±0.37	03.68±1.09	01.43±0.60
Total thickness [mm]	15*	15.17±0.05	17.78±0.17	12.38±0.02

*nominal thickness

facesheets were impregnated with epoxy resin and laminated onto the Al foam core. A thin adhesive layer of epoxy resin was applied to the surface of the Al foam core to ensure proper bonding between the components of the sandwich structure. The same procedure was used to fabricate the first rCF reinforced sandwich. Here, only one ply of rCF nonwoven was used in the facesheets to match the fibre content of the reference UD. Due to the structure of the rCF reinforcement, the fibre volume fraction of the facesheets remained low, as excess resin was not removed by external pressure. The crosslinking of the resin took place at room temperature, and additional annealing was applied for two h at 80 °C. To improve the properties of the facesheets, rCF-Al-compressed samples were compressed and moulded for one hour at 90 °C at 10 bar of pressure after the lamination procedure described previously. Test specimens were cut with a vidia blade saw (Mutronic Diadisc 4200, MUTRONIC Präzisionsgerätebau GmbH & Co. KG, Rieden, Germany).

The cell size of the aluminium foam, employed as the core material in the sandwich structures, was characterised using optical methods. A Keyence VHX-5000 optical microscope (KEYENCE CORPORATION, Osaka, Japan) and MATLAB R2024a (MATHWORKS,

Natick, MA, USA) image analysis software were utilised for the measurements. The software's image recognition capabilities allow for the quantitative assessment of surface area, which enables the determination of the surface area of individual foam cells. This approach facilitated a consistent and reliable evaluation of the cellular morphology of the aluminium foam.

Three-point bending tests were conducted on the composite sandwich materials per the EN ISO 14125:1998 standard. The experiments used a Zwick Z020 universal testing machine (ZwickRoell AG, Ulm, Germany) equipped with a 20 kN load cell. The support span was set to 64 mm, and the crosshead speed was maintained at 2 mm/s throughout the tests.

Through-thickness compression and quasi-static indentation tests were conducted on the composite materials per the relevant standards. The experiments used a Zwick Z020 universal testing machine (ZwickRoell AG, Ulm, Germany) equipped with a 20 kN load cell. Compression tests were carried out per EN ISO 844:2021 on flat-surfaced, rectangular specimens. with nominal dimensions of 100×100×25 mm. Quasi-static indentation tests were performed following a modified ASTM D6264:2012 procedure, with the loading speed reduced to 2 mm/min to simulate low-velocity puncture behaviour. A flat cylindrical indenter with a 15 mm diameter was used, and force–displacement data were recorded to evaluate the damage resistance of the composite structure, and the maximum indentation force values were compared.

3. Experimental results

Firstly, we analysed the structure of the AlF used. We made photographs of the surface of the AlF sheet and used the image processing module of MATLAB R2024a (Figure 4) to calculate the average cell size.

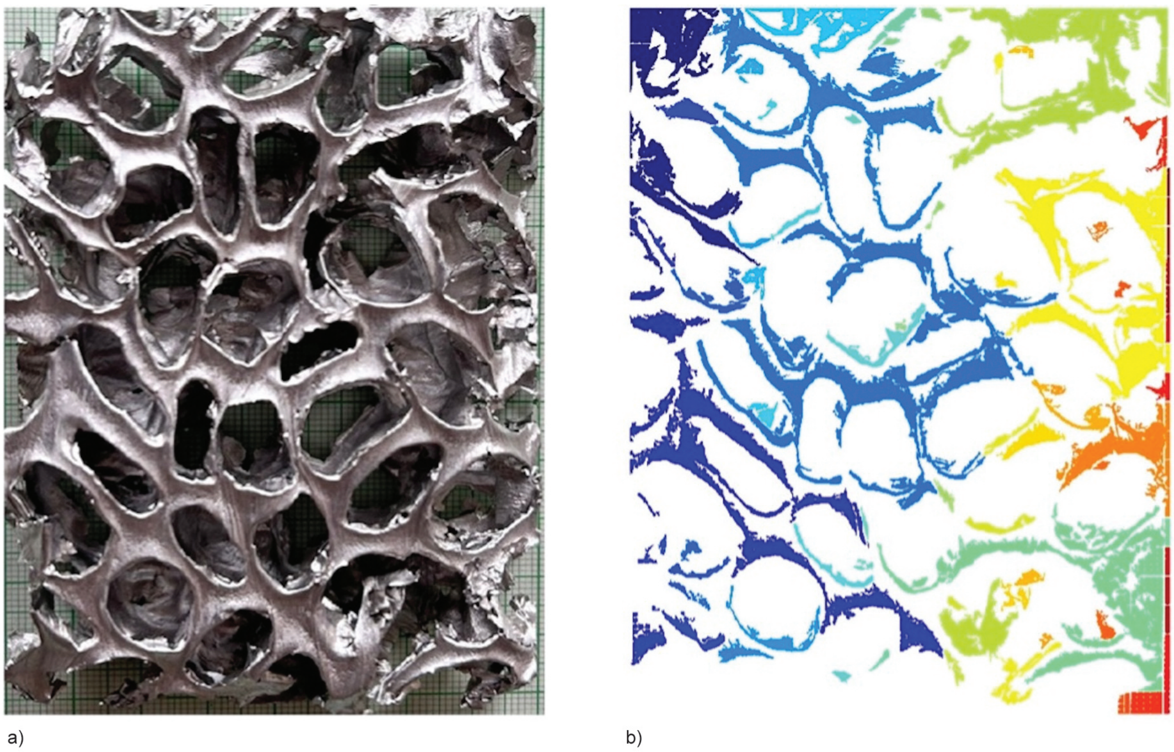


Figure 4. Results of cell identification: a) original photograph b) the identified cells by MATLAB.

We validated our method with an optical microscopy study. Based on the image processing, the average cell area was 149.27±14.93 mm^2, the average length of the cell main diagonal was 28.90±14.04 mm, and the average length of the cell side diagonal was 10.20±5.08 mm.

We calculated the density of samples (Figure 5) using the geometrical method. The bar chart illustrates the density values of four materials used in hybrid sandwich composite structures. AlF serves as the core, and various fibre-reinforced composites form the skin layers. As expected, the AlF exhibits the lowest density at approximately 120 kg/m^3, owing to its highly porous structure and functioning as a lightweight core. When unidirectional (UD) fibre skins are applied to form a sandwich structure, the overall Density increases to around 370 kg/m^3, reflecting the addition of more compact and aligned fibre layers. A further increase in density is observed in the sandwich using fibre mat skins, reaching about 650 kg/m^3, likely due to greater resin uptake and a denser reinforcement network. The highest density, approximately 830 kg/m^3, is seen in the sandwich composite with fibre mat skins processed through hot pressing – a result of improved fibre-resin consolidation and reduced void content in the skin. This progression highlights the significant influence of reinforcement architecture and manufacturing method on the structural density. While hot-pressed fibre mat skins may enhance mechanical performance, they also increase the weight, due to excess resin flowing trapped inside the core, which could be a limiting factor in weight-sensitive applications. The stark contrast between the low-density and high-density skins underscores their complementary roles: the core ensures lightweight and energy absorption, while the skins provide mechanical strength and stiffness. These findings emphasise the importance of carefully selecting materials and processing techniques to tailor hybrid sandwich composites for specific structural demands.

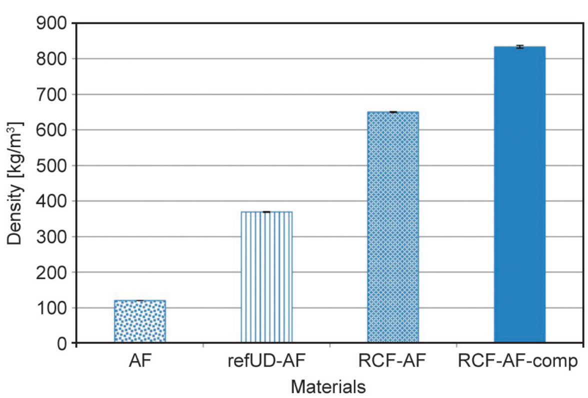


Figure 5. Results of density measurements.

We analysed the flexural properties (strength and modulus) of the produced sandwich structures

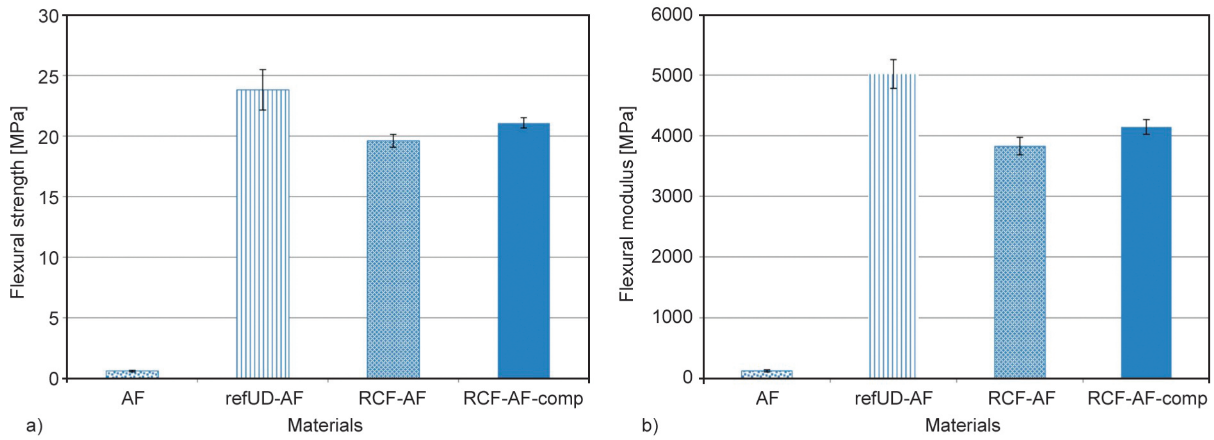


Figure 6. Flexural properties of sandwich structures: a) flexural strength, b) flexural modulus.

(Figure 6). The mechanical performance of the hybrid sandwich structures is characterised by their flexural strength and flexural modulus, as presented in the figures. It has been demonstrated that when the composite structure is reinforced with unidirectional (UD) fibre skins, the sandwich structure attains its maximum flexural strength of approximately 24 MPa and a flexural modulus of approximately 5100 MPa. This is consistent with the highly aligned fibre architecture, which is efficient.

Transfers and resists bending loads along the primary fibre direction. The findings emphasise the noteworthy contributions of UD fibres, particularly when aligned with the bending direction, to enhanced stiffness and strength. The sandwich composite with fibre mat skins demonstrates a reduction in flexural strength (approximately 19 MPa) and modulus (approximately 4000 MPa) compared to the UD variant. This reduction is hypothesised to be a consequence of the random fibre orientation within the mats, resulting in reduced effective stiffness and strength in the bending direction. However, this orientation may also confer enhanced isotropy and damage tolerance. It is noteworthy that the implementation of hot pressing on the fibre mat sandwich enhances both mechanical parameters. Specifically, the flexural strength substantially increases to approximately 21 MPa, while the modulus experiences a notable rise to around 4300 MPa. This observation indicates that applying high pressure during the manufacturing process enhances the fibre wet-out, resin-fibre bonding, and overall consolidation, thereby improving the material's load-bearing capacity despite the reinforcement fibres' random orientation.

We calculated the compression strength of the samples (Figure 7). The compression strength results offer additional insight into the structural integrity of the core and skin-layer interactions within the sandwich composites. As demonstrated in the figure, AlF alone exhibits a modest compressive strength of approximately 350 kPa, characteristic of lightweight cellular metals. These metals are primarily designed to absorb energy rather than to bear significant compressive loads. The compressive strengths of the sandwich structures with UD fibre and fibre mat skins demonstrate a comparable range, varying from approximately 350 to 500 kPa. These values indicate that the outer skin layers do not significantly improve the core's compressive load capacity under normal fabrication conditions. The hypothesis is that, in their unpressed state, the skins primarily contribute to bending and tensile performance rather than to through-thickness compressive reinforcement. The sandwich made with hot-pressed fibre mat skins has an impressively higher compressive strength of over 4000 kPa, due to the excess resin filling some of the cells, creating a more concise core which is more resistant to compressive forces. This improves the sandwich's ability to distribute and resist compression, due to the enhanced bonding between the layers and reduced air pockets.

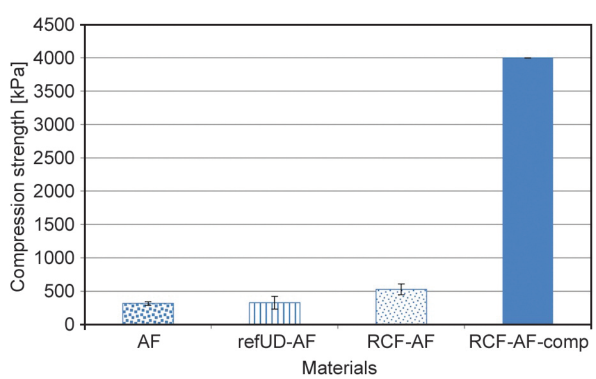


Figure 7. Compression strength of sandwich structures.

The results suggest that local buckling of cell walls is reduced, enhancing the overall compressive strength. The sandwich made with hot-pressed fibre mat skins has an impressively higher compressive strength of over 4000 kPa, showing the importance of hot pressing in making the skin layers denser and strengthening the connection with the core. This improves the sandwich's ability to distribute and resist compression, due to the enhanced bonding between the layers and reduced air pockets. This substantial improvement, which is almost an order of magnitude higher, demonstrates the crucial role of hot pressing in densifying the skin layers and enhancing the interface with the core. The result is a much more robust, consolidated structure capable of effectively distributing and resisting compressive loads. The improved interfacial bonding and reduced voids will likely prevent local buckling and delamination, thereby strengthening the overall compressive performance.

We calculated the maximum indentation force to for all samples (Figure 8). The perforation resistance of the materials, measured as maximum indentation force in newtons [N], provides valuable information on their damage resistance – critical parameters in structural, aerospace, and protective applications. The data demonstrate a transparent performance gradient across the material configurations. The AlF itself offers minimal resistance to perforation (~900 N), which is to be expected due to its highly porous and brittle nature. The object under discussion lacks the structural continuity and toughness necessary to resist concentrated loading, such as that caused by the indentation forces. A significant improvement has been observed in the performance of the sandwich structures. The UD fibre-reinforced sandwich demonstrates a resistance to perforation of up to approximately 7500 N, a property attributable to the continuous fibres' directional strength. However, the matrix-dominated areas between fibre bundles, especially at off-axis load angles, may permit localised failure under concentrated force, mainly due to high shear forces. The sandwich with fibre mat skins exhibits superior performance, with a perforation force of approximately 9000 N. This is likely attributable to the random orientation of fibres, which provides more uniform reinforcement against multidirectional impact. This isotropic reinforcement has been shown to assist in the effective distribution of load and energy absorption, thereby reducing the likelihood of localised failure. The hot-pressed fibre mat sandwich achieves the highest resistance, which withstands perforation up to approximately 11 000 N. This result underscores the impact of processing: hot pressing densifies the laminate, enhances matrix-fibre bonding, and reduces internal defects, resulting in a more rigid and coherent structure that efficiently resists penetration.

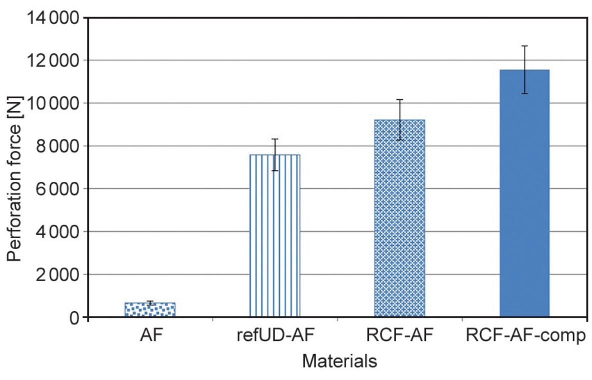


Figure 8. Perforation force of sandwich structures during quasi-static indentation.

4. Conclusions

This study presents a comprehensive analysis of hybrid sandwich composite structures consisting of a lightweight aluminium foam core and various fibre-reinforced polymer skin configurations. A primary innovation in this work is the utilisation of sustainable raw materials, specifically recycled AlF as the core and recycled carbon fibre mat as the reinforcement in the composite skins. These material choices are in alignment with current efforts to reduce environmental impact and promote circular material use in high-performance engineering applications.

Prior to mechanical testing, the internal structure of the AlF was characterised using high-resolution surface imaging and the image processing module of MATLAB R2024a, with optical microscopy providing validation. The mean cell area was determined to be 149.27±14.93 mm^2, with a main diagonal length of 28.90±14.04 mm and a side diagonal length of 10.20±5.08 mm. These metrics confirm the open-cell structure typical of foamed metals, contributing to the material's low density (~120 kg/m^3) and energy-absorbing capabilities. Mechanical testing demonstrated that the foam core alone has limited structural load capacity. However, a substantial enhancement in performance was observed when the foam was combined with composite skins. Sandwich structures with unidirectional (UD) carbon fibre skins exhibited the highest flexural strength (~24 MPa) and modulus (~5100 MPa), thereby emphasising their directional stiffness. However, these structures exhibited moderate compression (~400 kPa) and perforation resistance (~7500 N). In comparison, the sandwich structures made with recycled carbon fibre mats, particularly when hot-pressed, achieved the most balanced and superior performance. The hot-pressed configuration demonstrated a compressive strength of approximately 4000 kPa, a perforation force of approximately 11 000 N, and noteworthy flexural performance, exhibiting a strength of around 21 MPa and a modulus of approximately 4300 MPa. These enhancements are attributed to improved matrix infiltration, fibre consolidation, and reduced porosity during hot-pressing.

In conclusion, integrating recycled AlF and carbon fibre mats not only advances the mechanical efficiency of hybrid sandwich composites but also contributes to sustainable materials engineering. The results of the study demonstrate that the utilisation of hot-pressed recycled fibre mat sandwich structures represents an up-and-coming solution for applications that demand a synergy of light weight, stiffness, impact resistance, and environmental responsibility, particularly in aerospace, automotive, and protective materials sectors.

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