Towards Environmentally Sustainable Bio-Based Load-Bearing Components in Buildings: The Feasibility, Early-Stage Development and Testing of Five Possible Building Components to Meet Specific Performance Requirements

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Abstract. The growing demand for sustainable building materials is stimulating considerable research on bio-composites intended for the construction sector. Despite the technical challenges associated with their durability and fire resistance, bio-composites can provide environmentally friendly, load bearing components with useful mechanical properties. This paper provides an overview of the current research activities at TU Delft Department of Architectural Engineering and Technology in exploring five plant fibre reinforced polymer (PFRP) composites for various load-bearing applications. In addition to mechanical performance and durability, each bio-composite achieved one or more characteristic that improves the environmental sustainability of the bio-composite, namely: 100% bio-based; fabricated with simple low-tech equipment; sourced from bio-genic waste streams; assembled into a functional meta composite; formable into complex 3D shapes; and reformable at end of life. The findings presented in this paper provide useful insights of the material selection and manufacturing methods for each of the PFRPs and corresponding data from the performance testing. Moreover, the paper provides overarching observations across the five bio-composites and key recommendations for the future development of environmentally sustainable PFRP load-bearing components.

Keywords: Bio-composites · Plant fibre reinforced polymers · Natural fibers · Biopolymers · Building products · Load-bearing applications

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1 Introduction

In the context of the rapidly evolving global demand for sustainable and environmentally responsible buildings, bio-composites have emerged as a compelling alternative to traditional construction materials. Bio-composites are made from bio-based constituent materials, such as natural plant fibres, which give the composite its strength and stiffness, and the matrix (or resin), which binds the fibres together and protects them from the environment [1]. Plant fibres exhibit remarkable strength comparable to glass-fibres [2]. Fibers can be in the form of continuous long filaments, short fibres or small discrete particles. Long fibres can also be processed further, for into filaments, sheets, or mats which eases handling and positioning of the fibres in the production process. The fibres can be strategically positioned in a composite end-product to enhance properties, such as strength and stiffness, where they are most needed. The chosen layout is known as the fibre architecture. Resins, on the other hand, are almost always polymers. These can be either petroleum-based thermosets such as polyesters or epoxies or biobased thermoplastic polymers such as PLA or PHA, or bio-based thermosets such as furan.

There are many advantages associated with the use of bio-composites, chiefly their low environmental impact. In contrast to conventional materials such as concrete and steel, the production of bio-composites typically involves lower energy consumption and fewer greenhouse gas emissions. Furthermore, bio-composites can now be completely made from biologically renewable resources and therefore, and be completely biodegradable [2]. Bio-composites combine good mechanical properties with low density and therefore are lightweight, while their constituent renewable resources are widely available and relatively inexpensive [3].

Nevertheless, bio-composites have a small market-share in the construction materials industry. Their adoption has been limited by several practical and technical challenges and regulatory barriers. In terms of composition, some of these challenges stem from the polar and hydrophilic properties of natural fibres and/or their incompatibility with the non-polar properties of polymers which may require chemical treatment [4]. Additionally, bio-composites can be susceptible to insect and microbial attacks, which can further reduce their lifespan [5]. Bio-composites are also subject to degradation and to an extent reduced mechanical properties when subjected to sustained loading [3] or UV irradiation [6]. They are also flammable, often requiring flame-retardant treatment [5, 7].

Research was therefore undertaken at TU Delft to explore the feasibility and support the early-stage development of five different PFRP composites for distinctly different load bearing end-applications in buildings. Each one of the five PFRP composites is intended for a specific load bearing end-application (e.g. roof truss, floor slab, façade cladding). The material composition, manufacturing and performance testing of the five PFRPs are described in Sect. 2. This is followed by a discussion about the distinctive characteristics of the each of the PFRPs in Sect. 3 and overarching conclusions and opportunities for future research in Sect. 4.

2 Material Composition, Manufacturing and Performance

The five PFRP porotypes are shown in Fig. 1. The following Sub-sects. (2.1–2.5) provide further details on each of the novel PFRPs in turn, namely the: (i) original motivation; (ii) composition; (iii) manufacturing; (iv) mechanical (and other) performance characteristics, and (iv) applicability to real-world products or parts of product systems.

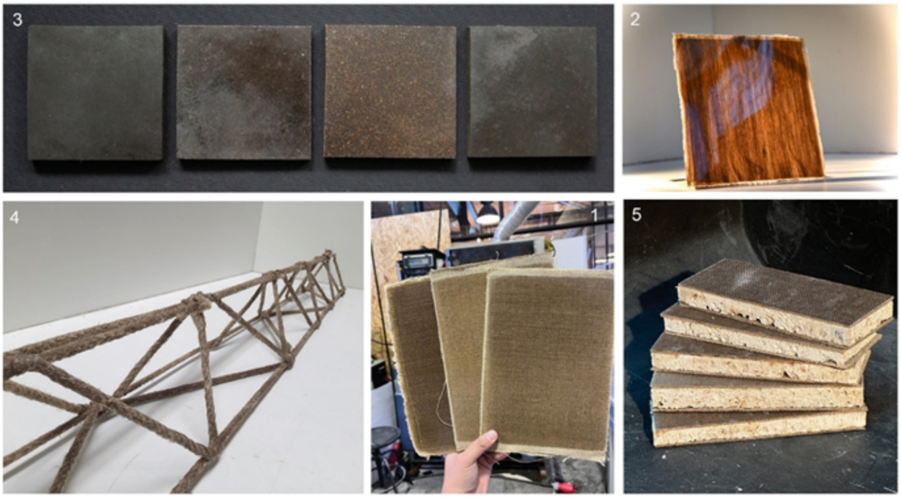

Fig. 1. Overview of PFRP prototypes: 1. Flax-PLA Laminate (Sect. 2.1), 2. Flax Fiber Reinforced Composite (Sect. 2.3), 3. Bio-waste-based composites (Sect. 2.3), 4. Truss-to-GO (Sect. 2.4) and 5. PLAX (Sect. 2.5).

2.1 Reformable Flax-PLA Laminate

This study explored natural flax composites with thermoplastic biopolymers to develop low-carbon, load-bearing bio-composite laminates that are reformable at end of life without loss of mechanical performance [8]. Such a PFRP represents a promising milestone in the research of low-embodied-energy alternatives to high-embodied-energy sheet metals. The Flax-PLA composition selected for this laminate aligns with circular economy principles by encouraging resource reuse and retaining product integrity throughout multiple use cycles. The study provides a roadmap for further research and development, including environmental testing and scalability, indicating it's potential to impact low-emission construction practices. The product system adapts to both urban and agricultural economies, accommodating low-tech infrastructure to enhance resource resilience against ecological uncertainties.

Material Composition. Woven technical flax in twill weave was chosen for its similar tensile strength in both warp and weft direction, owing to the integrity, interlocking characteristics and strength of twill weave. Polylactic Acid was the best fit as a 100%

biobased, biodegradable thermoplastic matrix known for its good mechanical performance when combined with flax. 30 μm thick PLA film format was used for its compatibility with various laminate forming techniques. All twill weave fabric reinforcement layers and PLA films were layered according to prescribed mass fractions and stacked in a symmetrical unidirectional configuration to ensure uniform fibre - matrix impregnation.

Manufacturing Process (Fig. 2). Four variants unidirectional laminates were prepared in two fibre-matrix mass fractions of 70:30 and 60:40. The objective was to develop a circular process for sheet-forming that utilizes pressure and heat in a simplified, reproducible manner. The final technique was a variation of resin film infusion and thermoforming, involving two hydraulic hot presses. The first machine was preheated to 165 °C to melt the PLA at high temperature profile and the subsequent machine to consolidate the composite at room temperature and low-pressure profile. The stack was placed in steel plate molds for contact with the heated press for 8 min and 12 min for the 70:30 variants and the 60:40 variants, respectively. The setup was then transferred to the second press for 5 min of ambient pressing as the PLA cools. This method is scalable with reduced waste and reusable settings. The laminates produced were as desired: stiff, bendable, 100% biobased sheet material, with no odour or handling issues.

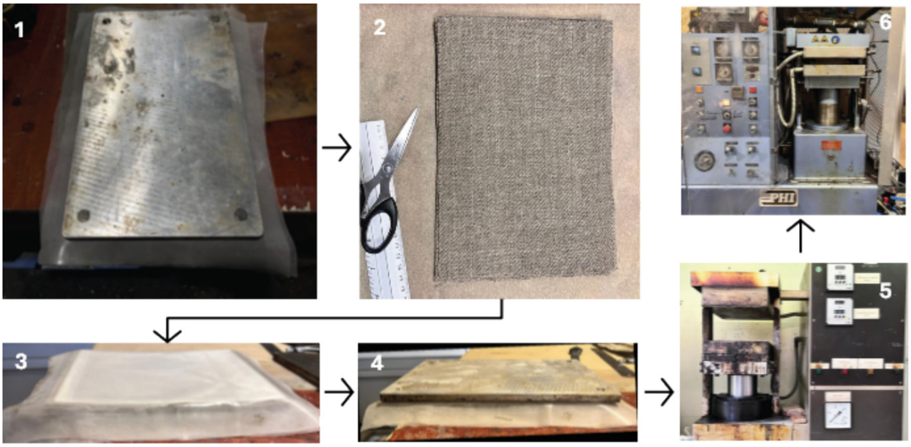

Fig. 2. Manufacturing of Reformable flax-PLA laminate: (1) Preparing the mold; (2) Cutting the flax fabric; (3) Stacking flax fibre, PLA film and protective silicone sheet: (4) Placing the top mold; (5) Hot-pressing; (6) Cold pressing.

Performance Testing. The proof-of-concept for this material was a bio-based 'developable' panel - a geometric laminate that could be reverted to a flat state for reuse at end of life. A sheet-reforming process was therefore developed based on 'sag bending' and vacuum thermoforming principles to confirm the initial 'developability' of the Flax-PLA sheets. The reverse forming process uses vacuum technique at the PLA glass transition temperature thereby maintaining the PLA's integrity. Mechanical tests and surface quality assessments were performed, in particular, flexural strength and stiffness were measured before and after reshaping, thus demonstrating that structural properties remain within permissible design limits. The tensile failure was localized within the bending regions for the reshaped specimens, but the mode of failure was similar to that observed in the unshaped specimens and the reduction in tensile strength from the reshaping cycles was in the order of 15%, indicating that repeated shaping cycles did not cause significant degradation of the PFRP's properties. Preliminary weather testing found that the material maintained structural integrity and retained surface quality post-reforming cycles and outdoor exposure, suggesting that it is suitable for diverse structural applications.

Application Range. The robustness of the laminates makes it suitable for various uses within the building products sector. It could serve as an eco-friendly material for interior partitions, ceiling and wall panels, and interior furniture such as tables, chairs, and shelves. Additionally, it could be utilized as laminates in ancillary structures such as staircase railing systems and temporary structures, such as pavilions. The bio-composite fabrication and novel reshaping methodology can be implemented with relatively inexpensive infrastructure and machinery, making it accessible and adaptable across different markets and socio-economic contexts. This potential extends throughout the technical products sector, suggesting a multitude of future applications.

2.2 Free-Form Flax Fiber Reinforced Composite

This study highlights the potential of natural fibre composites to replace petroleum-based materials, addressing both environmental concerns and performance requirements [9]. By integrating green materials into the building envelope, the project introduces a novel approach to façade construction, contributing to the evolving field of sustainable architecture. One of the principal requirements for this study was the formability of the bio-composite into a complex free form shape, typical of contemporary façade cladding panels.

Material Composition. This research utilizes a composite material composed of flax fibers as the reinforcement and a bio-based epoxy resin as the matrix. Flax was chosen for its excellent tensile strength, availability, and suitability for façade applications. The epoxy resin, sourced for its eco-friendly properties, offers strong adhesion, chemical resistance, and durability. The composite's lightweight nature combined with its mechanical robustness presents a sustainable alternative to conventional building envelope materials. This composition ensures a balance between mechanical performance and environmental sustainability.

Manufacturing Process. (Fig. 3) The manufacturing process employed is Vacuum-Assisted Resin Transfer Molding (VARTM), which ensures a uniform distribution of resin and minimizes voids in the final composite. The process involves preparing the double-curvature mold, placing the flax fiber layers, sealing with a vacuum bag, and infusing the resin under vacuum pressure. This technique not only enhances the composite's mechanical integrity but also provides a high-quality surface finish essential for façade applications. The careful layering and infusion steps ensure consistent quality in the produced panels.

Performance Testing. To evaluate the material's suitability for façade use, various tests were conducted, including bending and tensile strength assessments, water absorption, UV radiation exposure, and high-temperature endurance. These tests were performed before and after subjecting samples to accelerated weathering conditions to simulate outdoor exposure. They showed that the reduction in mechanical performance after aging was less than 10% in all PFRP compositions tested. This demonstrated the composite's durability, maintaining its structural properties, however its physical appearance was affected by weathering, which raises the possibility of using a protective coating.

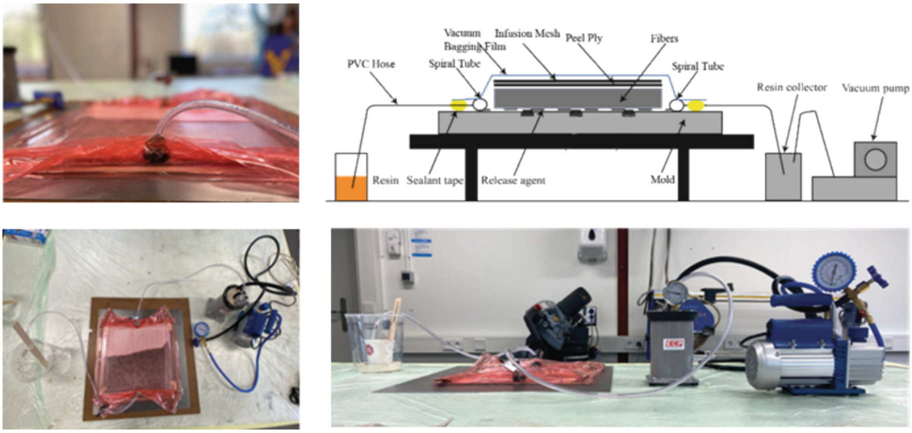

Fig. 3. Manufacturing free-form flax fibre composite showing vacuum-assisted resin transfer process and close-ups of specimen and vacuum bag during the infusion process.

Application Range. This flax fibre-reinforced composite is designed primarily for use as a façade material. Its lightweight, durable, and eco-friendly properties make it suitable for cladding, sandwich wall panels, and external skins in both residential and commercial buildings. The material's flexibility in design allows for customization to meet architectural requirements while maintaining functional integrity. Its ability to withstand environmental exposure ensures longevity and minimal maintenance.

System Design. The façade system design incorporates modular bio-composite panels mounted using floor slab brackets and prefabricated unitized systems for efficient assembly and maintenance. The system allows for seamless integration with existing building technologies and can be adapted to different architectural styles. The design focuses on maximizing the material's performance while providing aesthetic and functional value. The bio-composite panel's adaptability offers architects the freedom to explore innovative designs.

2.3 Bio-Waste-Based Composites

The composites explored in this project were made of a furan resin matrix filled with granular fillers from different by-products of the food industry [10]. The innovation lies in utilizing locally sourced food industry waste as fillers in bio-composites. This approach reduces the carbon footprint of building materials while decreasing reliance on virgin resources. Additionally, this study contributes to the knowledge of integrating bio-based fillers with biopolymers and explores compatibility and processing challenges.

Material Composition: In the initial phase of this study spent coffee grounds, cacao bean shells, cherry pits and walnut shells were investigated for their use as bulk fillers. This was followed by experiments on the mix characteristics of the most promising fillers such as optimization of particle size and filler-to-matrix ratio.

Manufacturing Process (Fig. 4): Samples were produced by drying and milling the filler material to particle sizes smaller than 125 μm, which were then mixed with the resin in a heated mixer, adding a catalyst and linseed oil as a releasing agent. The molding compound was then compression molded at 150 °C, fully curing the resin. In different variants, filler particle sizes up to 500 μm and filler loads between 35% and 55% were tested. Flat specimens were produced for mechanical testing, but the compression molding technique is also suitable for more complex geometries.

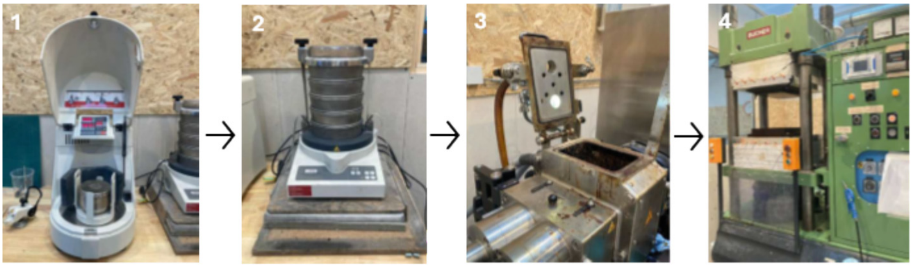

Fig. 4. Manufacturing of bio-waste-based composites: (1). Milling; (2) Grinding; (3) Sieving: (4) Kneading: (5) Hot-pressing.

Performance Testing: The specimens produced were subjected to bending, impact, water absorption and freeze-thaw cycles. Those with a higher percentage of inert fillers, that had lower amounts of soluble compounds, showed higher mechanical strength and lower moisture absorption. Colour changes, similar to the weathering of untreated natural wood, were observed in most samples. A blend particle sizes was beneficial because it resulted in smaller quantalities of resin needed for the same mechanical strength for the composite. The most promising variant was the composite with 55% walnut shell filler in a blend particle sizes, which achieved a mean bending strength of 49 MPa and a means impact resistance of 2.33 kJ/m^2.

Application Range: Based on its performance in testing, the bio-waste-based composites investigated in eths study could be useful in a variety of exterior or interior applications, ranging from facade elements to roof tiling, outdoor furniture and appliances. The material has a wide range of shaping options and is easy to machine.

Product/System Design: The material properties suggest suitability for a range of low embodied carbon products. In a simulation of flat façade cladding, the 55% walnut-filled furan composite had a significantly lower carbon footprint in primary production and processing compared to conventional cladding materials such as steel, aluminium, ceramic tiles, and granite, although long-term durability was not tested.

2.4 Truss-to-GO

Truss-to-GO is a novel construction technology for PFRP lattice structures such as trusses and space frames [11]. The ambition was to develop an in-situ fabrication method for these structures, using a continuous Flax- FRP (Fiber Reinforced Polymer) composite-technology-based 'rope' that can be compactly transported to site in a spool, and manually 'woven' into truss-like shapes and finally cured and rigidified. Although the use of natural fibres in FRP composites is an increasingly well-established technology, Truss-to-GO provides the following key advantages: (i) **Low tech and decentralized**. Truss-to-GO is an 'out of factory' fabrication model, allowing for in-situ fabrication in construction sites that have little to no established infrastructure, as electricity and water are not required; (ii) **Composite fabrication difficulties addressed**. The technology offers a novel way to achieve consolidation pressure without a vacuum bag or other apparatus, and a continuous seamless joint of significant mechanical strength for the truss node; (iii) **High speed and convenience**. The product is eventually envisioned as a spool of pre-impregnated braided textile that can, along with a modular collapsible reusable jig, be transported by truck and deployed in remote locations with a very simple and high-speed fabrication workflow as suggested by the sampled prototypes. However, the development of a more suitable epoxy is still pending- one that can be cured in atmospheric conditions on site, before and until which it can safely be stored and transported in an inactive B-stage.

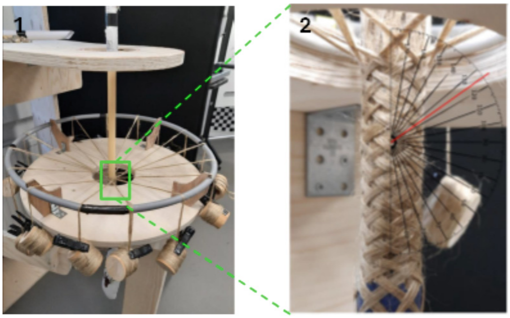

Fig. 5. Manufacturing of braided flax rope showing: (1) manual barding apparatus; (2) close-up from below of braided rope with braid angle of 55°.

Material Composition. The Fiber Reinforced Composite consists of a flax fibre reinforcement and a 2-component epoxy polymer. No additional fillers or admixtures are employed. For this research, Lincore FR 520 (Depestele Group) flax fibre rovings are used, along with Epikote Resin L20 (Westlake Epoxy) and Epikure Curing Agent 960 (Westlake Epoxy). Initial mechanical tests conducted on these materials show that: the

Lincore Flax rovings have an average tensile strength of 694 MPa and Young's Modulus of 58 GPa, whereas neat resin blocks of Epikote and Epikure prepared to manufacturer's guidelines exhibit average tensile and compressive strengths of about 55 MPa and 130 MPa respectively.

Manufacturing Process. The product consists of a 2-stage workflow: (i) The Preparation of a hollow braided textile with a core of timber beads (Fig. 5), and; (ii) the fabrication of the truss-form on a specially designed jig. The **braided textile** consists of flax rovings braided into a 6-layer hollow coaxial textile of 25 mm internal diameter using a maypole braid pattern with a ± 15 degree braid angle and 24 rovings per layer, braided at 5 N braid tension per roving. Incorporated into the hollow is a string of timber beads of 22 mm in diameter and 30 mm height. The **truss is fabricated** by manually weaving the braided textile into the shape of a truss (Fig. 1. 4) as follows: First, the 'chords' of the truss are set up with braided textile pre-impregnated in the epoxy resin in uncured state. End-tension of 450 N to 500 N is applied to these chords, creating a 'Chinese-finger-trap'-like constriction of the wet braid against the beaded core to achieve the consolidation pressure in the textile that is typically achieved with a vacuum bag or similar method. Second, the 'struts' are woven in using the same process, but in this case, the post-tensioning effect is created by pulling the chords apart using the special apparatus of the jig. The epoxy is allowed to cure in this state for 24–36 h in ambient conditions.

Performance Testing. The mechanical strength and stiffness of salient parts of the Truss-to-GO system (the struts, joints etc.) were tested in turn and reported in Table 1.

Table 1. Mechanical Test Results on fabricated PFRP samples

Test	Sample	Result	Remarks
Compressive Strength	Hollow cylindrical braid- 6 layer coaxial	77.5 MPa	Failure by local Micro-buckling
Youngs' modulus, Compression	Hollow cylindrical braid- 6 layer coaxial	29 GPa	-
Tensile Strength	Tensile test coupon (25mm strip)	75 MPa	Brittle failure in coupon midsection
Youngs' modulus, tension	Tensile test coupon (25mm strip)	31 GPa	-
Joint Strength	60 deg. Truss joint	70 MPa	Failure in compression strut precedes nodal failure

Application Range. The research and results suggest that high-speed and low-tech fabrication of FRP trusses in an in-situ manner is possible, with little on-site infrastructure and preparation needed. However, the effects of humidity, weathering, creep, fatigue and other relevant parameters are yet to be investigated. If these are successfully managed, the technology can be used as structural frames for remote construction, rapid-response construction and low infrastructure construction environments such as disaster relief camps or expedition camps.

2.5 PLAX

PLAX is proposed as a biobased alternative to carbon-intensive materials in the building industry, primarily to develop a biobased foamed core sandwich panel that could outperform conventional flooring systems [12]. The principal innovation is the foaming of bio-based materials for a lightweight yet stiff core. To identify the core material, different foaming techniques are explored to achieve aerated materials. The final approach involves foaming PLA, in a simple baking process with the addition of a foaming agent. The foamed PLA core is subsequently bonded to flax fibre face sheets, thereby producing a bio-based sandwich composite.

Material Composition: PLAX is composed of PLA (Polylactic Acid), a biobased polymer made from corn starch, and flax, a natural fibre.

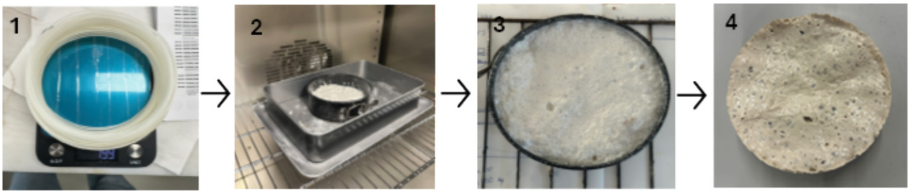

Fig. 6. Manufacturing of the foamed PLA core showing (1) weighing of PLA; (2) heating in oven; (3) adding of foaming agent; (4) demolding.

Manufacturing Process. The workflow consists of three main production stages: core, face-sheet, and composite production. For the **core**, various bio-based polymers and foaming techniques were tested to develop a lightweight, shear-resistant material. Ultimately, 'foamed PLA' was selected based on its ease of production and minimal resource requirements (Fig. 6). Firstly, waste PLA was collected from a 3D printing lab. The material is then heated, and a foaming agent is added to create a lightweight structure. Subsequently, the material is left to cool. For the **face-sheet**, PLA films were chosen as the matrix due to its compatibility with the core, while flax fibres were selected for reinforcement. Flax fibres and PLA films are stacked layer by layer with a 50% mass ratio and pressed together using a steel mold and a hydraulic press, at pressures ranging from 75 to 100 kN with intervals. The final stage is **composite production**, where the face-sheets and core are laminated. Two lamination methods were explored to bond the face-sheets to the foamed PLA core: melting the matrix in the factsheets sufficiently to bond them to the core and using a two-component epoxy adhesive to bond the face-sheets to the core.

Performance Testing. Mechanical tests were performed to determine the shear properties of the novel foamed core material. The mean core shear strength was found to be

1.24 MPa. Additionally, the material is recyclable, bio-based, and has a relatively low environmental impact.

Application Range. In addition to load bearing flooring systems, PLAX has the potential for other non-structural uses such as acoustic tiles, insulation panels, wall panelling, but adequate protection may be required due to the low glass transition temperature of the PLA.

Product/System Design. A building floor panel was designed using the performance test data from this study. Additionally, a simple production was proposed with a simple and linear process for laminating the core to the face sheet without resorting to non-bio-based materials. Overall, the performance of PLAX was compared with conventional loadbearing flooring systems such as concrete hollow core system. It was found that PLAX is has a significantly lower environmental impact, but is more costly.

3 Discussion

Each of the five prototype bio-composites presented in this paper were developed for a particular load bearing end-application e.g. a rainscreen façade panel capable of resisting out-of-plane wind pressure and impact from maintenance and cleaning operations; a structural floor system for buildings supporting superimposed live and dead loads; a space truss system to resist out-of-plane wind pressure and snow loads.

The performance data obtained in these studies show that the salient mechanical characteristics (e.g. strength, stiffness, impact resistance etc.) of these early-stage prototypes are at or above the values needed for the intended end-applications in the construction industry.

In general, the bio-composite prototypes also showed adequate resistance to durability and weathering (e.g. UV, water absorption, freeze-thaw cycles), with relatively minor reduction in strength after ageing, but the aesthetic appearance of some of the bio-composites was significantly affected, typically loss of shine and discoloration, in a manner similar to untreated timber.

Other performance characteristics such as fire resistance (including combustibility, spread of flame, residual performance after fire events), thermal conductivity, acoustic transmission and insect attack were not assessed in these studies. These properties could be pivotal for real-world feasibility of these products.

In addition to the performance levels necessary for the "use-stage", the PFRP prototypes reported in this paper exhibited other desirable attributes that impact the "product-stage", "construction-stage" and "end-of-life stage" of the construction product lifecycle, thus affecting the whole-life environmental sustainability of these future products (Table 2).

Table 2. Useful attributes of the PFRP protypes developed in this study

Desirable attribute	Bio-composite prototype				
	Reformable flax-PLA laminate	Free-Form Flax Fibre Composite	Bio-waste-based composites	Truss-to-GO	PLAX
100% bio-based	✓		✓		(✓)
Sourced from bio-genic waste streams			✓		
Fabricated with simple low-tech equipment	(✓)	✓	(✓)	✓	(✓)
Assembled into a functional meta composite				✓	✓
Formable into complex 3d shapes	(✓)	✓	✓	✓	(✓)
Reformable at end of life	✓	(✓)	(✓)		

✓ Achieves attribute (✓) Could achieve attribute with minor modifications.

4 Conclusions

The aim of this paper was to describe the recent research performed at TU Delft's Department of Architectural Engineering and Technology into the feasibility of bio-composites for a variety of load-bearing applications in buildings ranging from structural flooring systems to free-form cladding, through to space trusses. To this end five different PFRP composites were explored each for a different end application.

From the prototyping and testing performed to date, it was found that the PFRP composites achieved (or have the potential to achieve) the strength stiffness and impact resistance required for the intended end applications. It was also found that the resistance to weathering was adequate, but the bio-composites were prone to discoloration in a manner similar to untreated timber.

In addition to the mechanical performance and durability, it was found that the five bio-composites offered different benefits in terms of flexibility of production (e.g. assemblable into a functional meta composite) and circularity potential (e.g. sourced from bio-genic waste streams; reshapable at end of life). But it was found that every one of the five bio-composite prototypes was formable (or had the potential to be formed) into complex 3D shapes and could be manufactured with relativity simple low-tech tools.

While this provides a promising future for load-bearing bio-composite components in buildings and suggests upscale potential, a detailed analysis of upscalability of these five prototypes has yet to be performed. Other important characteristics such as fire resistance, thermal conductivity, acoustic transmission and insect attack where not investigated in these studies and are essential for assessing the feasibility of the proposed bio-composites for building applications.

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