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Free-Forming of Customised NFRP Profiles for Architecture Using Simplified Adaptive and Stay-In-Place Moulds

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Abstract: Design and production technology of natural fibre reinforced polymers not only aims to offer products with a lower environmental impact than conventional glass fibre composites but also caters for designers' needs for the fabrication of lightweight free-formed architectural components. To combine both characteristics, the forming process itself, once scaled up, needs to be based on efficient material moulding strategies. Based on case studies of adaptive forming techniques derived from the composite industry and concrete casting, two approaches for the mass production of customised NFRP profiles are proposed. Both processes are based on foam from recycled PET, which is used as either a removable mould or a stay-in-place (SIP) core. Once the textile reinforcement is placed on a mould, either by helical winding of natural fibre prepregs or in the form of mass-produced textile preforms, its elastic properties allow for the free-forming of the composite profile before the resin is fully cured. This paper investigates the range of deformations that it is possible to achieve by each method and describes the realisation of a small structural demonstrator, in the form of a stool, through the helical winding of a flax prepreg on a SIP core.

Keywords: natural fibre reinforced polymers; biocomposite profiles; adaptive moulding; stay-in-place formwork; helical winding; automated preforming

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1. Introduction

The construction industry, which is responsible for nearly 50% of global CO_2 emissions, is under constant pressure to reduce its environmental impact [1]. One of the ways of tackling this challenge is to shift towards a wider use of materials based on yearly renewable natural fibres (NFs) [2]. However, due to their relatively poor mechanical properties, their use in any other applications than insulation materials requires combining them with polymer matrix [3]. This then leads to the development of a new category of biocomposite building materials, which, aside from plastic wood composites (PWCs) and other types of extruded biocomposites utilising agricultural leftovers, are not yet commonly used in construction [4].

Natural fibre reinforced polymers (NFRPs), which utilise long, staple fibres as a reinforcement, make it possible not only to increase the use of yearly renewable resources in construction, but also to profit from their characteristics as lightweight composite materials [5]. This positions them as an alternative to glass fibre composites and certain timber products [6].

On the other hand, extensive possibilities of forming NFRPs through additive fabrication processes provide a solution for the realisation of free-formed architectural design driven by the development of CAD software [7].

However, substituting glass- and carbon fibre reinforcement with NFs one does not automatically lead to more sustainable construction practice [8]. The wide use of NFRPs would impose a change in numerous steps of the building realisation process (material logistics, prefabrication technology, construction site logistics, material performance over time, building use duration, and recycling scenarios), which would affect the overall environmental impact of a building [9]. Additionally, certain problems typical of thermoset fibre reinforced polymers (FRPs) have not been solved yet, such as recycling difficulties. Consequently, an assessment of the sustainability of introducing NFRPs into free-formed architecture needs to go beyond the material aspect and take into consideration the environmental impact of the forming strategies used [10–12].

Fabrication technology of NFRPs derives from the production of FRPs for the automotive and aircraft industry [13]. However, different requirements and realms of the construction industry (the scale and size of elements, quality and safety requirements, batch sizes) mean that an approach that is economically and ecologically feasible in that context does not fulfil the sustainability requirements once applied to the production of NFRP building elements. The use of solid moulds for the production of free-formed FRP elements is justifiable in the automotive industry where production batch sizes are counted in the thousands. A large portion of building projects are individual cases, additionally intended to be unique in their architectural expression. Consequently, the production of customised FRP elements based on single-use moulds or preforming systems is not feasible and different strategies should be considered [14].

Current efforts to introduce NFRPs in construction proceed from the use of FRPs that has been taking place since the 1970s [15]. Back then, the first FRP decks and superstructure members of bridges were realised. Since then, FRPs have been used for the production of standardised components—decks, structural profiles, and cables—utilised in pedestrian and road bridges in the U.S., Japan and Europe. Parallel to that, externally bonded FRPs and FRP ropes have proven to be an efficient technology for the repair of damaged concrete structures, effectively extending their service life [16]. Currently, pultruded glass fibre profiles with standardised sections of C, L etc. are a common alternative in applications where corrosion-resistant materials are required [17].

Pultrusion being one of the most energy-efficient composite profile production techniques predestines it to be an adequate method for the mass production of NFRPs [18]. This theory was verified in the *LeichtPro* project, in which mass-produced pultruded profiles, reinforced with 100% flax rovings, were exclusively used in the structure of an active-bending pavilion [19]. The geometry of the unique free-formed roof structure was simulated and digitally modelled based on the elastic properties of the profiles. Later, the realisation of the geometry required the cutting and connecting of the profiles, which in its material processing concept did not pose additional difficulties to the realisation of bending active structures from other types of materials.

The whole structure was made from only one type of standardised NFRP profile, a pipe with a constant dimeter of 25 mm. Except for their length, which after cutting reached up to 14 m, the profiles were not customised in any way. It was only possible to form the free-formed geometry of the pavilion through their subsequent elastic deformation. If a different structural principle were required, these profiles would have to be cut to a much shorter length and a greater number of connections would have to be used. Consequently, a different type of profile or building elements may have been used.

In the context of architectural scale, the realisation of free-formed surfaces requires its discretisation into smaller, sometimes unique free-formed elements, suitable both for prefabrication and transport to the site [14]. An alternative approach presumes the design and fabrication of a limited range of different free-formed elements, which can be arranged together into various unique constellations of free-formed objects. This bottom-up approach already presumes a more resource-efficient moulding strategy, by finding a balance between producing as few moulds as possible while at the same time not compromising on the unique architectural expression of the assembly. In both cases, the complete elimination of a mould capable of producing only one type of geometry could bring further savings in the materials and energy consumption used in the production process of NFRP components.

2. Mould Concepts

In the context of the formwork for building elements, a range of strategies for substituting single-geometry moulds have already been established for working with concrete, before the introduction of FRPs into building construction [17]. Since the realisation of the first concrete double-curved shells, which required starting by building scaffolding of the same size as the final structure, only to disassemble it later, it has become clear that the replacement of this step with a less labour-intense one is necessary to reduce the work intensity of erecting such structures [20]. Although the choice between prefabricated discreet elements delivered to the site, modular moulds for casting on site, or pneumatic scaffoldings is determined by the type of structure to be built, all of these strategies serve the purpose of saving on the work time and material spent on building moulds [21,22].

Some of the concrete shaping strategies based on the concept of adaptive moulds can be integrated into existing processes of manufacturing FRP components for the purpose of upscaling NFRP material technology for use in building structures.

2.1. Adaptive Moulds

An adaptive mould, the geometry of which can be reversibly modified after each use, is the most straightforward alternative to a solid mould with fixed geometry [23]. Industrial interest in reconfigurable and flexible tooling began in the late 1980s in relation to the production of composite aerostructures. Such functionality can be achieved either by deformation resulting from a mould's material's elastic properties or by a mould being designed as a set of reconfigurable elements [24].

2.1.1. Elastic Moulds

Conceptually, the contact area of a mould is an elastic, deformable surface. Its deformation is then actuated by a series of pistons, the retraction of which affects the surface. Once automatised, a series of pistons actuate the surface based on data sent from CAD software. This concept has been realised in several ways, differing in terms of the technology used for transferring the geometry from pistons to the finish surface.

- CYKONI Dynapixel [25]. A matrix of discrete pins are positioned closely enough to each other to form a possibly continuous surface. The final geometry of the pins (rectangular, hexagonal, round) and their orientation to each other affect the resulting discreet surface. In order to achieve a smooth surface, further elastic layers need to be applied. On the other hand, dense deposition of the pins makes the mould suitable for withstanding high forming loads.
- ADAPA Adaptive Moulds, Denmark [26]. The elastic surface is reinforced with a net of glass fibre nods loosely connect with the forming surface. This makes it possible to reduce the number of physical actuators used per m^2, leading to greater resilience of the system. The system as a product is scalable and can be produced with working area dimensions great enough for the fabrication of large façade panels and other similar architectural components.

2.1.2. Dynamic Mould System (DMS) [27]

The drawback of mechanically actuated solutions is their high level of technical complexity, the costs of initial investments, and their weight, which means they can only be used stationarily for the production of prefabricated components which are later transported to a construction site.

DMS is an analogue shape-memory panel. Mechanical actuators are replaced with lightweight foam blocks and a pneumatically-actuated locking system. This creates a mould of similar forming capabilities, but compact enough for on-site use. The DMS surface can be transported to the site flat, set in the desired shape on site, repetitively used for the casting of free-formed concrete elements, reversed to a flat form, and then transported to a new location and reused for casting a different geometry [28].

The mould stays in shape due to the principle of multiple textile layers locked against each other with surface friction generated by vacuum pressure. The product consists of multiple textile layers closed inside a vacuum bag.

- Before the forming starts, the pressure inside the bag matches the atmospheric pressure.
- The DMS is deformed to a desired double-curved surface, for example with a pin matrix.
- Air is evacuated from the vacuum bag until the vacuum level is high enough to compress the textile layers until they stay in place due to friction.
- The mould is used repetitively for the casting of concrete elements.
- Vacuum pressure is released until the textile sheets can slide against each other again and the mould can be returned to its original shape.
- The whole procedure can be repeated.

The concept, although patented, has not been used in a full-scale construction project yet. Although it was developed for the purpose of casting concrete elements, the product can be also utilised as surface mould for the vacuum infusion of biocomposite panels.

The product itself does not solve the problem of the initial transfer of digitally modelled geometry to the DMS surface. This still needs to take place with a pin matrix. However, DMS can stay in its given shape, be used for casting several times, and then shaped again. Due to its low-tech operation nature and compact dimensions, it could be integrated into a composite production workflow, making it possible to save time and resources consumed on mould preparation.

2.2. Stay-In-Place (SIP) Formwork

An opposite approach to a reusable mould is the use of lost formwork, from relatively cheap material. This strategy is commonly used in the casting of concrete structures. Unlike regular formwork, which is removed once concrete gains sufficient strength, lost formwork, for example in the form of corrugated steel, stays in place. Lost formwork products can be divided into two general types:

- "Non-participating" formwork, which does not contribute to the load-carrying capacity of the final structure;
- Formwork products, which together with in-situ concrete, contribute to the load-carrying capacity of the structure, creating a composite construction.

Lost formwork may also be designed to play a second role—XPS forms acting as a thermal insulation layer in the finished structure.

Foams and other lightweight cores are also used in the forming of FRP parts. However, in this case to achieve the high-quality finish and possibly the low weight of the elements, a core must be removed [29].

The presence of a forming core in NFRP elements for use in construction does not necessarily pose a significant problem in terms of additional weight. As in the case of SIP formwork in concrete, its presence contributes to structural properties (although, due to the lack of information on its long-time performance and durability, it is not currently considered in structural calculations of FRP elements) and has an impact on the overall thermal insulation properties. Thus, the core removal step can be omitted in the processing. Furthermore, the geometrical design of the element also does not have to facilitate that.

SplineTEX® (superTEX composites GmbH, Telfs, Austria) is a process delivering free-formed FRP hollow profiles [30]. In this technology, almost any type of tubular braided reinforcement (not only carbon and glass fibre, but also hemp and flax) can be embedded in between two layers of in- and outliner and then infused with resin, turning it into a prepreg-like hollow preform. Depending on the number of parts to be produced, the complexity of their geometry, the type of resin matrix, etc., a specific forming process can be selected. After the forming, the liner foil is removed and a clean composite part is obtained.

This technology has been used for the production of parts for the automotive and aircraft industries, sport accessories, as well as spatial structural demonstrators.

From the perspective of strategies for forming with minimal moulds, a particularly interesting variation of the system is splineTEX®plast, which features a hybrid aluminium-FRP composite profile. A grooved aluminium pipe is a core onto which a carbon or glass fibre braided tube is slipped. Then, the layup is sealed between the two layers of liner and infused with resin. While the resin is still in its liquid form, the plastic characteristics of the aluminium core allow for the free deformation of the splineTEX® prepreg. To settle the prepreg in its final desired geometry, it does not need to be settled in a classic solid mould, but can also be fixed only in key points, and the CNC can be winded on a mandrel (for spring production), bent, or even formed by hand—the prepreg will remain in place due to the plastic aluminium core [31]. Once the resin is cured, the foil liner is removed but the aluminium core stays inside.

3. Challenges

A common challenge in all of the strategies is the more fragile nature of the mould, which often does not allow for operations such as applying high pressure and/or heat or assembling textiles (or prepregs) directly in the mould. Thus, from the perspective of a design and fabrication party engaged in a building construction process and the casting of a free-formed NFRP architectural component, the outsourcing and automating of the following production steps need to be considered:

- Combining fibre reinforcement with matrix → prepreg;
- Textile preform preparation.

The analysis of the aforementioned moulding strategies leads to the proposal of two workflows for the mass production of NFRP profiles, which enables customisation of the profile curvature and section without requiring the use of solid moulds.

4. Combining Fibre Reinforcement with Matrix → Prepreg

The challenge of the prepreg concept is the limited pot time and gel time of the resin matrix, which predetermines the time frame for forming the geometry of the future component. Due to the sheer size of panels and profiles in architectural projects, this is a growing problem in any upscaling attempt.

If commercially available prepregs are used, they need to be transported and stored in cool conditions [32]. The use of resins optimised for such handling procedures leads to the need for heating parts in autoclaves after the forming process.

The design process of the parts can rely only on the range of available prepreg products. Although the offer of carbon fibre prepregs is already widespread, the first NFRP prepreg products will only appear on the market in the near future.

If the design process can accommodate these limitations, the prepreg path could offer several advantages. Mass-produced prepregs could offer the highest possible consistency of composite material parameters, surpassing resin infusion of dry textiles in the mould. Relying on externally provided prepregs could enable the production of NFRPs by smaller production facilities, without equipment for the storage and handling of resin and accessories for the infusion process [33].

4.1. Experiment 1: Customised Profiles Form NFRP Prepreg—Lost Formwork, Which Becomes a Funtional Part of the Component

4.1.1. Goal

This concept is based on use of NF pre-impregnated rovings and their helical winding (HW) on an elastic core. Then, in the time frame between the pot time and the gel time, the core is deformed to a curved form and left until fully cured.

In this concept, the core plays two roles:

- Its geometry determines the geometry of the resulting profile.

- After fabrication and forming, the core is neither removed nor destroyed, but becomes a part of the component in which it acts as space filler for the profile.

Moreover, depending on the application and type of material, it can play an additional thermal insulation or fire-retardant role.

This experiment is intended to prove if the concept can be used with currently commercially available semi products and technologies, proving that it could be used in composite design and fabrication practices without high investments into new technologies.

4.1.2. Winding Process

The aim is to verify that the traditional filament HW technique, based on the 2-axis classic lathe-type, is sufficient to realise the concept of customisable profiles. The wet NF rovings are placed by a horizontally moving carriage on a spinning mandrel. The fibre angle can be controlled by the rotation speed of the mandrel and the position of the carriage. Wet NF rovings can be fed directly from the resin bath.

Currently, it is standard practice to use a highly automated setup. However, in the case of this experiment, the analogous procedure was performed by a manually fed and controlled lathe, which made it possible to test different combinations of core geometries and rovings faster. Manual winding does not offer as high consistency and repeatability as the CNC alternative. Thus, to achieve the highest possible precision of the wound path:

- Winding paths were sketched on cores and then followed;
- A cardboard template with a desired winding angle was cut and used for the constant verification of the winding process.

Although the level of precision achieved in this control process exceeded even the initial expectations, any further tests of this concept in a larger scale will use an automated setup.

4.1.3. Materials—NF

The concept uses NF roving prepreg and lightweight core material, which combines sufficient durability in the winding process and sufficient elasticity for the forming stage.

The choice of all the materials used in the experiments was intentionally restricted to off-the-shelf products readily available on the market in Europe.

Flax and Hemp are dominant NFs cultivated in Europe which are used for the production of reinforcement for composites. Flax fibres have a higher tensile strength (800–1500 MPa) than hemp (550–900 MPa). Rovings and textiles made from flax are more abundantly present on the market than those of hemp.

At the time of the project, no ready-to-use NF prepregs products were available on the market. Based on our own experiments with the preparation and storage of prepregs, it was assumed that such commercial product could be based on basic NF rovings, for example, non-twisted 100% flax roving TEX2400, produced by Depestele, and already tested in several biocomposite architectural demonstrators [34].

4.1.4. Materials—Resin

Both experiments considered production methods oriented at the use of thermoset matrices, which offer greater strength and easier application on smaller batches than thermoset ones.

The selection of the thermoset matrix was, at least partially, limited to biobased products. Among the ones reviewed, biobased resin system Cardolite Formulite 2501A + 2401B featured one of the highest tensile modulus (3134 MPa) and flexural strength (113 MPa) values [35]. Both components of the system are made 34% from renewable resources, which include cashew nutshell liquid (CNSL). The pot time (95 min at 25 °C) was sufficiently long for the requirements of the test. The system also offers a range of additives for decreasing the viscosity and extending the pot time (albeit at the expense of lower strength). Additionally, it showed lower bubbling than other epoxy resin systems, once in contact with the NF rovings, which were not previously dried.

Automated prepreg production could take place either by a conventional dip-type resin bath or in a bobbin infusion process, such as TPreg® [36] for an even shorter manufacturing time. Both techniques were tested with the chosen resin and NF and proved suitable for biobased prepreg production.

In the case of the prepreg workflow, the pot time of the resin system needs to cover both the prepreg preparation and the component fabrication times. As the curing of the resin system used can only be halted when stored at a near 0 °C temperature, it was preferred to perform prepreg preparation and winding in the same room, using the possessed resin bath setup, rather than outsource the TPreg® production to an industrial partner and handle the transport of the spool in a cooler.

4.1.5. Materials—Core Foam

A suitable core material needs to feature a balance of the following three characteristics:

- It is sufficiently durable to withstand fixing in lathe and spinning;
- Its surface is hard enough (in particular on the edges) to withstand winding roving under tension;
- It is elastic enough to enable deformation without cracking.

Additionally, the product should be, at least, either derived from renewable resources or biodegradable (or ideally both). Thermal insulation properties would be an additional advantage.

Insulation boards based on pure wheat or hemp straw and timber dust would be ideal products regarding their natural origin. Unfortunately, they are too brittle once cut into blocks of app 15 × 10 cm in section.

Products considered from natural fibres and binders, such as insulation blocks and panels made from a mixture of natural fibre and concrete, do not show sufficient elasticity.

Biobased foam products seemed optimum to this application in terms of both their physical characteristics and sustainability. However, no fully biobased product was found to be widely available on the market currently.

ArmaPET® Eco50 foam [37], made from recycled PET, fulfilled the first and third requirements. As a product, it is intended to be used for various applications, including:

- Sandwich composite panels;
- The external insulation of buildings (behind weather protection layer) with a thermal conductivity value of 0.036 W/m*K;
- By being made from recycled resources, its use aligns with the concept of delivering more sustainable composite materials.

4.1.6. Fabrication

The ArmaPET® block was cut into a 1m long profile. Instead of a regular square section, a rhomboidal section of 12/8 × 6 cm was chosen. In this way, it was possible to check the behaviour of the prepreg on core edges of different angles (at 60° and 120°).

Before the test fabrication, the core was tested to ascertain the extent to which it can be bent before cracks occur. Initial tests proved that the core, with the section as described, can be safely bent up to a radius of 6 m.

It was also observed that the speed of deformation may affect at which radius cracking would start to occur. While bent gradually, the foam porous structure adapts in the compressed parts rather than cracks. With a very low forming speed, an even smaller bent radius could be achieved.

The core was then fixed in a lathe and ready for winding. The core was not treated with any other product, as the rough surface of the core is intended to provide sufficient bonding with the prepreg.

The fabrication consisted of two steps. First, a single flax roving was impregnated in a dip resin bath and rolled on a spool. Then, it was fed from the spool during the winding around the core.

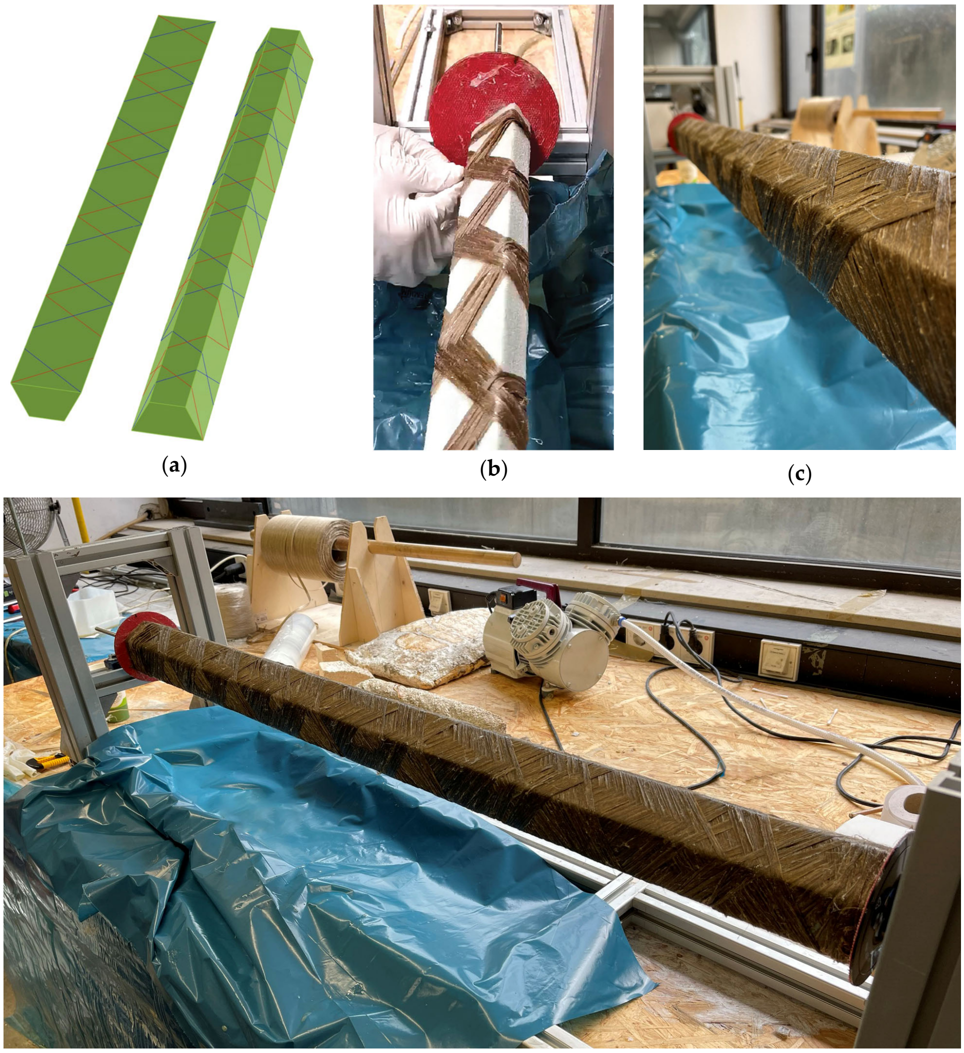
To practise and become familiar with the custom-built winding setup and later fixing the profile in a curved position, the first profile was made by winding the wet roving at an angle close to 90°. This angle is the easiest to make by hand, but results in a fibre orientation only perpendicular to the profile, thus not providing any flexural strength.

The profile was then fixed in a curved position and left for 24 h of curing. Once it was dry, the profile ends were released. In this moment, the thin composite hull cracked and the profile immediately snapped back to the original straight shape (Figure 1). This effect was expected. Although it was not planned to set the winding angle for achieving specific flexural strength, in all further tests a lower winding angle was used to set the cured profiles in the curved position.

Figure 1. A cured profile with a winding angle close to 90° snaps back to its original straight shape immediately after being released (frames taken within 3 s).

Later tests showed that the angle of 50° was low enough to fix the deformed core in position after curing, and at the same time, high enough to eliminate any uncontrolled sliding of prepreg roving on the edges of the foam and enable a flawless manual winding experience.

Winding was carried out with one roving at a time, at a constant speed and angle, going from one end to another, until complete coverage of the core with roving (Figure 2) was achieved.



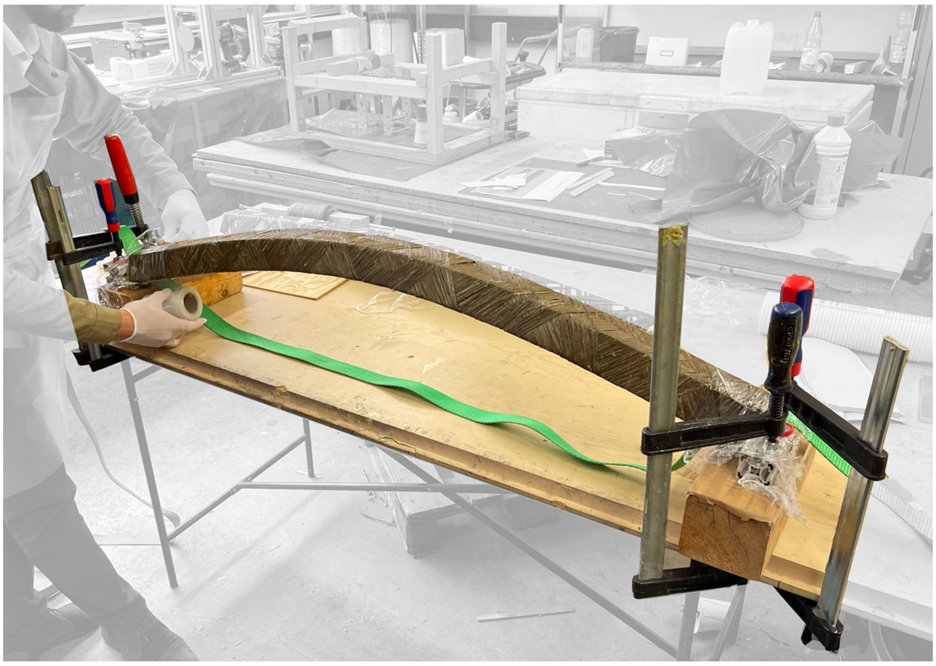
(**a**) (**b**) (**c**) (**d**)

Figure 2. (**a**) Preview of a winding path, later sketched on the core to support the manual winding process; (**b**) Binding process in progress; (**c**) Winding pattern at 50° angle; (**d**) Accomplished winding process, before the forming stage.

Shortly after finishing the winding, the component was removed from the lathe and placed on a table for final forming. The component was fixed on the edges and the middle part moved gradually up. Meanwhile, the fibre deformation was observed. The process was stopped once a radius of 6 m was reached, as the first signs of possible deformation of the fibre paths occurred. The bent component was fixed in position, and wrapped with heat-shrinking tape, to achieve a possibly smooth finish and consistent compression on the fibre reinforcement (Figure 3).

The component was left for curing in a room temperature for 24 h. After that, while still fixed, it was postcured in an oven at 70 °C (4 h) and then at 90 °C (2 h).

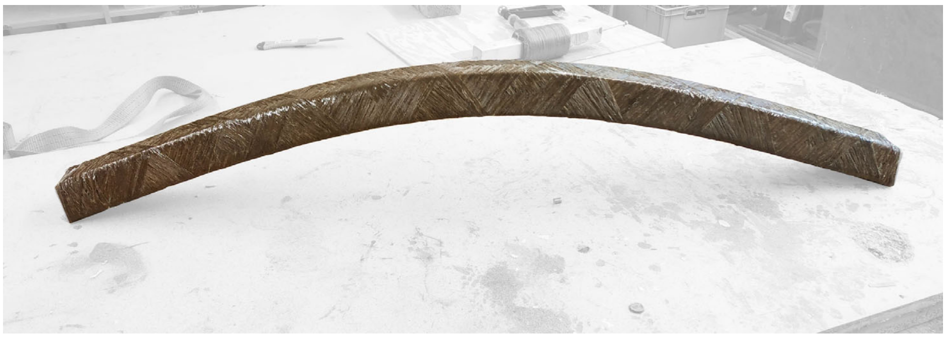
Finally, during the removal of the frame, it was observed that the curved geometry of the profile did not snap back to its straight shape. At the chosen dimensions of the profile, one layer of prepreg winded at 50° was sufficient to counter the elastic force of the core (Figure 4).



(**a**)

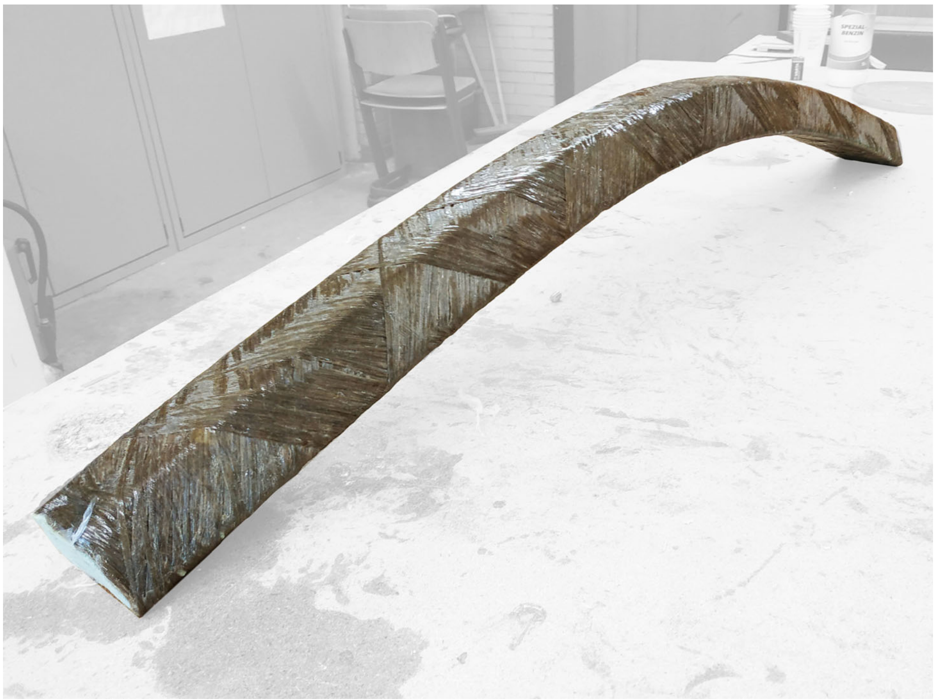
(**b**)

Figure 3. (**a**) The wet profile placed in the curved form in a fixing rig, being wrapped around with heat-shrinking foil (**b**) Curved profile after curing, additionally tensioned with the belt, to secure it during the transport to the oven for post-curing.



(**a**)

Figure 4. *Cont.*



(**b**)

Figure 4. (**a**,**b**) The finished profile, after curing and post-curing, removed from the forming rig.

4.1.7. Design Case

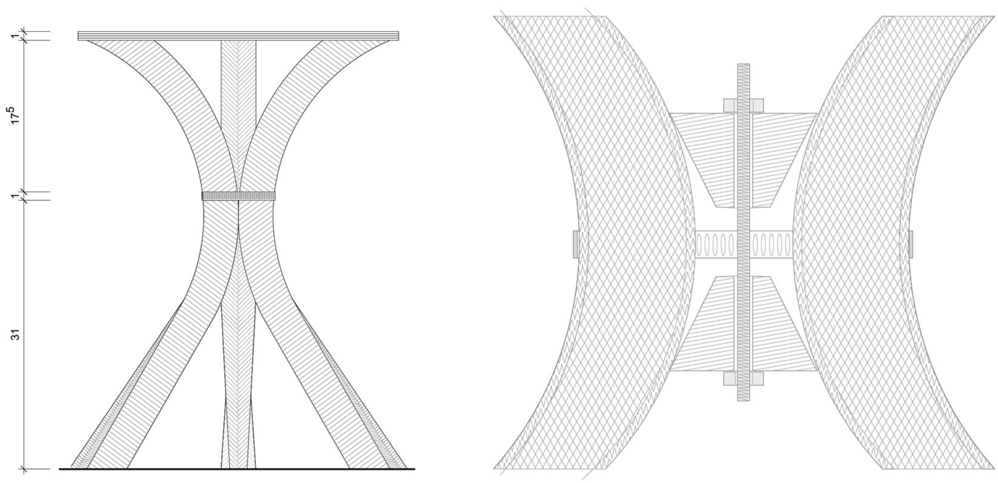
The experiment showed how the basic 2D HW setup can be used for forming a range of profiles with differentiated curvatures. Additionally, the forming concept can be used with other geometries, going beyond the proportions of typical profiles.

In the second stage, the intention was to use the workflow in a design and fabrication case of a small structural demonstrator—a stool. The overall dimensions of the demonstrator had to be limited due to the work intensity of the manual winding process. The minimum dimensions of the core, and the width of a roving path, etc., had to be taken into consideration when preparing a digital model of the stool.

Through the analysis of various design options and fabrication constraints, the decision was made to design the stool as a demountable object consisting of a seating plate supported by 3 curved profiles. The profiles were curved to the inside of the stool, both to provide more space for the legs and to create a connection point for structural stability.

The overarching goal of this design study was to illustrate that the same analogue fabrication platform can be used for the realisation of a range of different profiles without changing any fabrication parameters. However, although it was tempting to prove this point by designing the stool as an asymmetric structure with 3 profiles of different curvature, this was judged to be unfavourable in the case of such a small-scale object. Instead, a series of 3D stool geometries were generated using Rhinoceros + GH of different heights and widths. They all featured leg profiles of the same section, however with changing curvatures. Consequently, each of the designs could be realised using the same cores and winding setup while the curvature was customised according to the digital model only in the last forming stage.

The final model of a stool selected for final production is 49 cm high and has 3 profile legs of 56cm length, with a variable bent radius reaching down to 25 cm (Figure 5). The cross-section of the profile is set as an equilateral triangle. This section of the foam core facilitates the later bending of the core (and the whole profile) towards one of the edges. Secondly, as the most compressed area of the profile section is an edge, rather than a side, this reduces the amount of winded fibre roving subjected to deformation, making it possible to achieve a greater bending radius before distorting the fibre layout.



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

Figure 5. (**a**) Final stool variation chosen for final realisation; (**b**) detail of the connection point to be made with an expansion plug and a hose clamp.

Additionally, the flat surface on the opposite side facilitated the creation of a connection knot. In order to avoid perforating the composite structure, 3 profiles were pulled together with a worm drive hose clamp, while from the inside they were compressed with a wooden expansion plug. The top plate and profiles were kept in position with wooden pins, preventing any sliding, but allowing for the quick removal of the seating plate.

The winding procedure was unchanged—first, a prepreg was prepared on a spool and then it was winded on a foam core placed in lathe. The different proportions of the core made it possible to further reduce the winding angle to 45° without the prepreg sliding on the core, thus achieving higher bending stiffness of the finished composite profile. The prepreg was continuously wound until reaching coverage with 2 complete layers of fibre reinforcement.

Immediately after winding, the uncured component was wrapped with foil and removed from the lathe for forming. In this case, the designed profile shape was recreated using a pin board as a rig, in which the uncured component was placed.

After 24 h curing in room conditions, the rig was placed in the oven for post-curing at 70 °C (4 h) and then at 90 °C (2 h).

In the final step, both tips of the profile were trimmed to face the floor and top plate, and then connected together (Figure 6).

Destructive tests of the unique demonstrator were not intended at that stage. However, to verify its potential, the stool was placed on a smooth ground and load of 80 kg was placed on top, resulting in deflection of legs by 2 mm. The test was repeated 3 times with the same deflection, without causing any damage to the profiles.

4.1.8. Design Output

The predetermined scale of the experiments made it possible to conclude the design process with the successful delivery of a small functional loadbearing object. The process showed potential in enabling the recreation of a diverse profile of geometries without any time-consuming changes to the fabrication setup. However, the exact structural capacities of the components from both tests were not determined.

This small scale posed difficulties in proposing a stool concept which would make it possible to incorporate profiles of different curvatures into a single stool, while preserving normal functionality. The use of a wide spectrum of customised curved beams should be tested by upscaling, in the concept of a small canopy/pavilion, in which curved beams form the roof truss. Consequently, profiles would then be subjected to loads coming from different directions and acting on the profiles ends, rather than in their central area, leading to reconsiderations of the required fibre layout along their length.

Additionally, a small diameter of the profiles and thin composite hull made drilling in the composite, or sanding its surface, vulnerable to cracking and delaminating. Thus, it did not make it possible to design and test the connection detail based on solutions used in FRP structures (bolted or bonded connections), rather than furniture.

(**a**)

(**b**) (**c**)

Figure 6. (**a**) Finished curved profiles, to be used as stool legs; (**b**) Profiles connected together; (**c**) Finished stool with a seating plate.

4.1.9. Upscaling Challenges

These challenges need to be verified through the realisation of an upscaling concept, which would ideally not only use them as loadbearing elements, but also rely on the thermal insulation properties of the core.

In order to determine potential challenges in the upscaled production process, components of a greater length and diameter should be produced (up to 6000 mm, which is a common max. length of off-the-shelf aluminium and pultruded glass fibre profiles).

- The total length of the components is dependent on the total length of the core. The ArmaPET® used is available in blocks with a length of up to 2445 mm off-the-shelf or up to 3000 mm on request. A longer core would first need to be assembled from several overlapping thinner layers bonded with glue.
- A successful winding and forming process depends on the relation between the length and height of the profile. The lower it is, the higher the resistance of a spinning core to torsion and buckling when wound on. However, a higher ratio increases the wet profile's ability to adapt to a curvature for the curing process. Tests on a larger scale should determine the range of profile dimensions feasible for both winding and forming.
- Rovings are made of staple natural fibres that may break under high tension. Also, a relatively delicate core, especially when the first layer of fibre is deposited directly on the core, may not be able to withstand higher loads. On the other hand, higher filament winding tow tension increases fibre volume fraction [38]. Thus, a winding process on a larger scale requires an optimum range of filament winding tow tensions for given NF roving and core materials.
- More data on the relationship between the actual winding pattern, number of fibre layers made, specific core material dimensions, and resulting structural capacities of a biocomposite profile need to be acquired. This should be achieved by a series of mechanical tests of components fabricated with an automated prepreg production and automated winding setup to avoid any discrepancies in material qualities resulting from manual fabrication.

5. Automating Textile Preform Preparation

5.1. Advantages and Disadvantages

Thanks to the relatively uncomplicated process of HW, it is possible to use prepregs in the forming process. However, at least in its basic form, its geometry-forming capabilities are limited by a concept spinning lathe and use of rovings only. To form a profile section such as L or C etc., a fabricated component would need to be cut in half, breaking the continuity of the fibre reinforcement.

If a textile preform with more complex fibre syntax is required, it is advantageous to reverse the steps and first prepare the adequate textile preform, which can later be infused using a simplified elastic mould.

The manual building of a textile layup is a labour- and time-consuming process, which is easiest to perform using a solid mould with a fixed geometry [39]. There are a range of highly customisable textile assemblies, such as TFP sheets [40], multilayers stitched 3D preforms, braided nets etc., which can be made-to-order in textile manufacturing companies that are already in possession of sophisticated CNC machinery for the production of small batches of customised preforms on demand. As automated textile production takes less time than the whole lamination stage, a single textile manufacturing shop could supply a greater number of independent manufactures producing composites out of pre-ordered preforms.

5.2. Experiment: Reusable Elastic Moulds for Customisation of Profiles

5.2.1. Goal

This experiment illustrates how one series of biocomposite profiles of typical open section (L, C, H et) can achieve a customised curvature in a forming stage with a set of elastic moulds, while only one type of NF preform product is used for the whole batch.

As such sections could not be produced using HW without further trimming, other NF textile products, with multidirectional reinforcement, can be used. The desired thickness of a profile wall is achieved through the layup of several NF textile layers.

The forming mould uses the same elastic core made from ArmaPET®. In this case, the intention is to remove the core after each forming cycle and reuse it in a following one. The mould is designed with as minimal dimensions as possible, which are sufficient to form the desired shape. Any excess of material is avoided, as it increases the amount of force needed to deform it.

Small dimensions of the mould make it difficult, if not impossible, to build a textile layup without additional gluing, which could affect the resin infusion process. Thus, the concept presumes the use of NF textile preforms produced in automated preforming (AP) processes [39].

AP was initially developed with the intention of mass producing large batches of carbon fibre textile preforms, with standardised sections such as C, H, L etc., for the aircraft industry. However, the concept could also be adapted to work with NF textiles to satisfy potential demand from the construction industry for preforms of typical sections for further forming to desired components.

At the moment, no such product has been made available on the market. However, parallel to the presented experiment, the authors are working on the experimental fabrication of an NF H-section preform. Thus, in this experiment, the preforms required were manufactured manually, with respect to the fabrication constraints which would be imposed by the AP system used in the future. The results of this experiment will be used for further attempts to form profiles realised in an automated way.

This experiment determines:

- To which extent NF textile preforms for profiles can be deformed in a flexible mould, before creases start to affect the fibre layout of the reinforcement.
- How a simple mould, based on the elastic deformation of foam, can be successfully used in repetitive profile forming and the vacuum infusion process.

5.2.2. Design

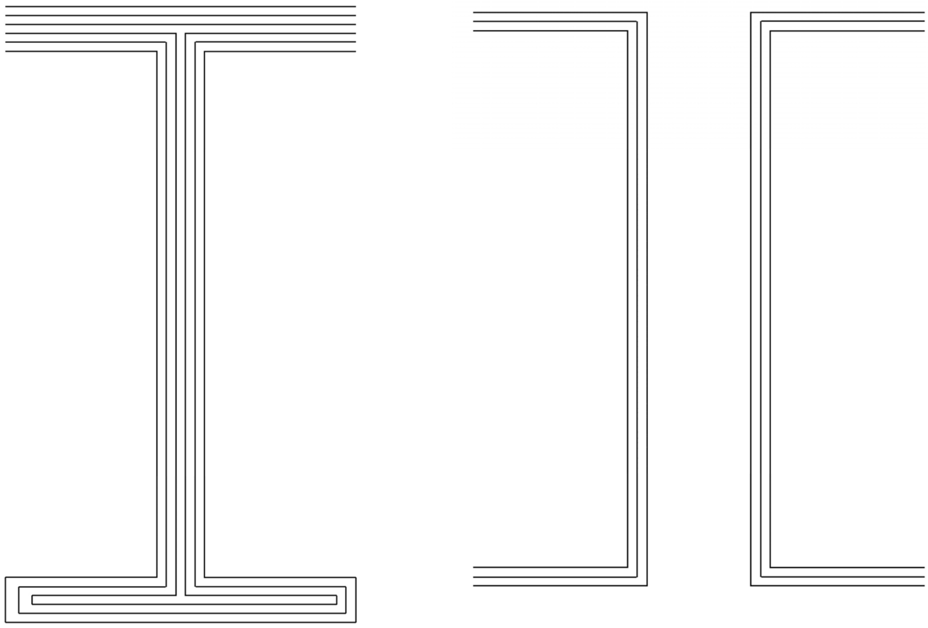
The forming experiment was made on textile preforms for a C-profile 4 × 16 cm and an H-profile 8 × 16. The desired wall thickness was set to 2 mm, which is achieved using 3 layers of 300 g/m^2 Bcomp 100% flax textile.

5.2.3. Materials—NF

A range of laid (ex. TerreDeLin), woven (Bcomp) and knitted technical (ex. Texinov) NF textiles, in different grammages, are currently available on the market. Apart from obvious differences in their structural properties once used as composites, they have very different requirements regarding handling. UD flax tapes and certain types of woven textiles have a tendency to fry and roll once trimmed to shorter fragments. As the potential use of the chosen textile in the AP process was the most important criterion in this case, 300 g/m^2 woven 100% flax textile from Bcomp was chosen due to its robustness. When trimmed and folded, no sprayed glue was required.

The precise placement of 3 loose layers of textile on this mould sliding was close to impossible. Given that, in a real application scenario, a much higher number of layers would be needed, it is necessary to bind them beforehand into a preform.

As AP-produced preforms were not yet available at the time of the experiment, 3 precut textile layers were stitched manually using a sewing machine. Then, 2 C-preforms were stitched back-to-back, forming an H-preform, as the same forming principle is used in AP (Figure 7). As a result, several 100 cm long C and H preforms were made for further forming tests.



(a) (b)

Figure 7. (**a**) Textile layup that can be realised with an AP fabrication platform; (**b**) Analogue textile layup, fabricated manually, for use in the experiment.

5.2.4. Materials—Mould

The same ArmaPET® foam was chosen as the mould material. To achieve an external profile width of 160 mm, it was trimmed to 155 mm in width and 60 mm in height (more than the wall thickness). However, as this time after forming and curing the core needed to be removed from the composite, it had to be treated with an elastic release agent, which would not wrinkle in the forming stage. For that purpose, silicone KDSV-25 ®R&G Faserverbundwerkstoffe GmbH, Waldenbuch, Germany was used and applied with a brush, creating app. 1.5 mm layer and 158 mm width of the core block in total.

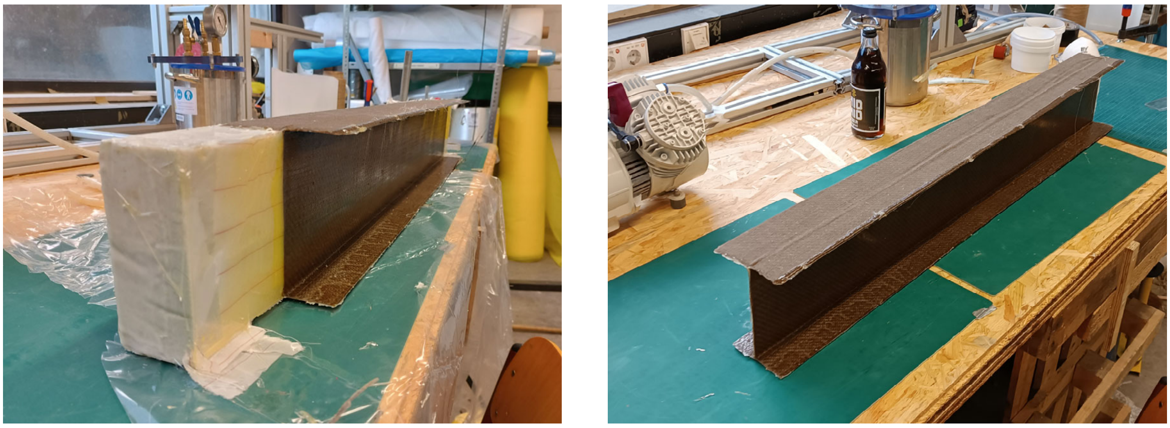
5.2.5. Fabrication

In the first place, it was necessary to validate if the prepared cores could be separated from the composite after forming and curing. For this purpose, the moulds were used for laminating the preforms in the basic straight form, though a vacuum infusion process. Although the scale of this experiment was small enough to infuse the textiles first and then place them in the mould wet, the goal was to prove that such a simple mould and vacuum bagging process can be used for forming much longer curved profiles with a larger section.

The flax textile preform was placed between two silicone-coated cores, together with additional layers of peel ply and resin flow mesh to facilitate a resin flow perpendicular to the profile direction. The setup was sealed in a vacuum bag sleeve for the resin infusion process. The profile was infused with the same resin system Cardolite Formulite 2501A + 2401B. After 24 h of curing in room conditions, the mould was separated from the composite piece, without damage to the silicon coating, ready for its next use (Figure 8).

Once the reusability of the mould was confirmed, in the second attempt its forming capabilities were investigated. Three cases of textile preforms were tested:

- C-Preform curved outwards;
- C-Preform curved inwards;
- H- profile curved.

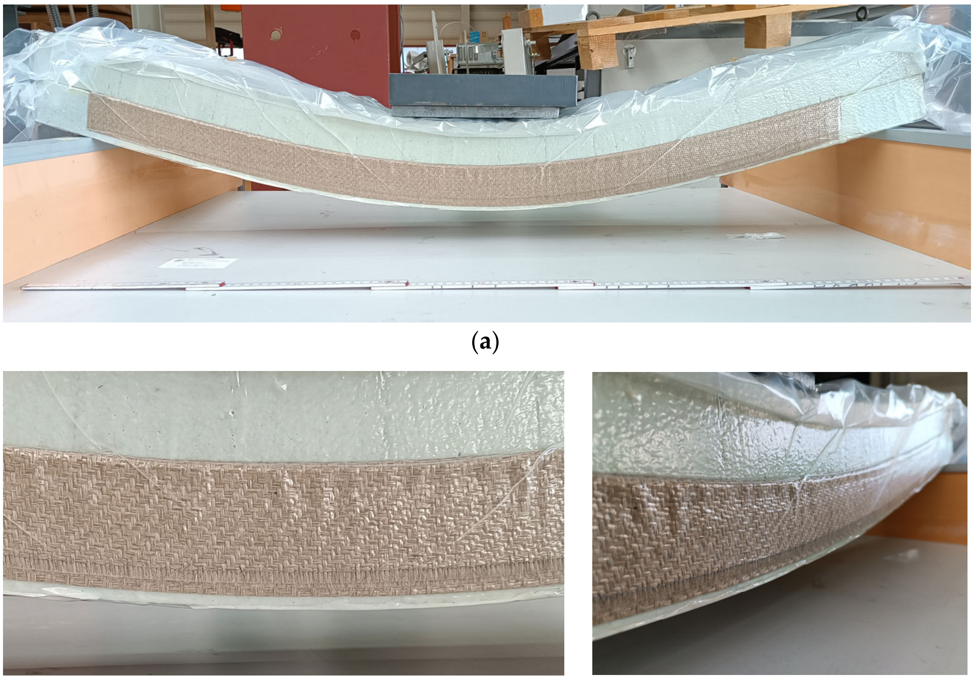


(**a**) (**b**)

Figure 8. (**a**) Unpacking of a cure profile from reusable flexible mould; (**b**) Finished profile.

In each case, the preform was placed between two mould pieces, then sealed in a vacuum bag. At this point, peel ply and resin flow mesh were not used, to allow for the observation of the textile behaviour under deformation. Thus, at this point resin infusion was not performed.

Before forming, the excess air was removed from the bag with a vacuum pump, but the atmospheric pressure was still preserved. The setup was supported on both ends and incrementally loaded in the centre to cause deformation of the mould until it reached a certain bending radius in the middle part of the mould (Figure 9). After each loading, the deformation of the textile preform was observed. In each case, the test was stopped once potentially critical deformation of the textile was observed (Table 1).



(**a**)

(**b**) (**c**)

Figure 9. (**a**) Deformation of C-Profile inwards at 6m radius; (**b**,**c**) Visible deformation of textile layup (Fail).

Table 1. Results of the deformation experiments for 3 types of textile preforms, to determine the curvature radius at which textile deformation starts to occur.

Radius	C-Profile Inwards	C-Profile Outwards	H-Profile
12 m	Pass	Pass	Pass
9 m	Pass	Fail	Fail
6 m	Fail	Fail	Fail

The foam cores of the mould were able to withstand the deformations without any damage. Deformations and creases in the textile preforms occurred before any damage to the foam core surface could be observed. Within the limits of the experiment, their adaptability surpasses that of textile preforms. Although more tests oriented at determining the fatigue of moulds in relation to their geometrical proportions should be conducted, at this moment it was observed that one set of moulds could be used for the production of at least several profiles, each of a different curvature.

Although the same textile preforms were used in each of the tests, different results were achieved depending on the direction of bending. The ability of a preform to adapt to the curvature depends on the freedom of movement of single textile rovings, resulting in textile ability to drape and stretch. Through deformation, single rovings of textile move against each other, while maintaining the woven pattern. However, this is strongly determined by the type of bonding of layers: adhesives or the density of the stitching pattern and the cross-section of the profile. The thicker the profile, the higher the compressive force that acts on the textile inside the bending radius, resulting in earlier fibre deformation.

Due to these numerous parameters, the specific results are valid only for the preforms of the exact dimensions and binding technique. Upscaling of the profile thickness will unavoidably lead to different results. Increasing the total preform length may also slightly affect the ability to adapt to the curvature.

Due to the time constraints, out of all the preforms tested for deformation, only one will be chosen for lamination in curved form at a later stage.

5.2.6. Results and Outlook

The proposed adjustable moulds were able to form textile preforms in diverse curvatures. However, the feasibility of the process relies greatly on the possibility of sourcing mass-produced textile preforms from external textile manufacturers in specific dimensions, for later forming. Thus, the following step is to verify the possibility of AP of NF textiles. Tests carried out should provide information on the production constraints, such as the maximum number of layers, the categories of textiles suitable for the process, types of preferred binding techniques, the maximum length, etc.

6. Conclusions

Both experiments were intended to verify the possibility of producing customised NFRP profiles, according to the designed curvature, based on the use of low-tech reusable moulds inscribed in the additive processes of the mass production of NF textile products. Flax fibre textiles and rovings, currently available on the market, were able to adapt to forming within defined constraints. The range of achieved deformations (up to 6 m with the HW profile and 9 m with the profile from a textile preform) was not small enough to explore its design potential with small-scale demonstrators (such as the stool), but it did allow us to speculate about the use of curved NFRP profiles in design scenarios at an architectural scale. Possible use cases could encompass any applications requiring curved elements for the recreation of its geometry, starting with a substructure of partition walls (Figure 10a) and façade fragments, either in combination with other timber elements or exclusively from NFRP profiles [41]. The ultimate challenge would be to produce free-formed structures (inspired by similar timber frameworks), in which single NFRP profiles are customised not only in relation to their curvature, but also in relation to their specific textile reinforcement, individually tailored to the loads carried in the structure (Figure 10b) [42].

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

Figure 10. Speculation on the possible use of customised NFRP profiles: (**a**) as a hidden substructure giving shape to a partition wall, further covered with formable panels (balsa boards, gypsum boards, textiles, and other NFRP panel products); (**b**) as a free-formed framework from customised NFRP profiles.

This study sets out the first work package, aimed at the formulation of a concept, which awaits further development in the second phase, oriented at providing more information on the structural performance of NFPR profiles and other upscaling challenges:

- In the first place, both fabrication approaches need to be tested on larger elements (with a profile length of up to 6 m, a height of up to 200 mm, and a wall thickness of up to 40 mm) to determine the range of element sizes within which these could be used. These tests should be made using an automated HW platform and textile preforms fabricated using AP processes to ensure the repetitiveness of the results.
- Although each experiment was limited to one type of geometry and textile layup, it showed that numerous variables affect the maximum bending radius which can be achieved. Further tests will include expanding the range of tested scenarios to other profile geometries, a greater number of textile reinforcement layers, and, in the case of AP, other binding techniques—including different stitching patterns. Then, a complete datasheet of the forming capabilities of given types of textiles can be generated for each method, making it possible to refer to the production method in the design process.
- The fabricated elements can be used in mechanical tests to acquire data on their mechanical properties (tensile strength, bending stiffness) and failure modes (damage to resin, matrix and core), in order to ultimately use them in structural simulations, which would indicate to which extent they could be used in the aforementioned cases.
- ArmaPET® core was chosen for first tests as it is a widely available product with a production process based on the recycling of raw materials. However, in further tests potential fully biobased alternatives should be considered, both biodegradable and derived from renewable resources. Although a range of bio-based PU, PLA, starch, PHA, and cellulose foams could fulfil the technical requirements, global production capacity is still limited and its growth is only expected in the future, in response to the rising demand for this category of products [43]. At the moment, a product to consider is BioFoam® from BEWI group—a particle foam made from expandable PLA, which is 100% recyclable, originating from vegetable waste. Both its properties and appearance are very similar to those of EPS.
- In general, all natural fibres feature increased porosity in comparison to glass fibre. Flax fibre has a lower density (ca. 1.45 g/cm^3)than glass fibre (ca. 2.5 g/cm^3), which results in lower thermal conductivity [44]. This effect is also expected to be observed in the case of HW profiles on an insulating foam core. However, actual thermal conductivity tests in the second phase need to be carried out to define to which extent

this effect can be observed at the level of a whole component and utilised in a design of a façade based on such profiles.

Ultimately, all the collected data should be utilised for formulating a complete workflow encompassing both the design case of a structure and the fabrication process of a building component in a 1:1 scale, making it possible to assess the actual production capacity it is possible to achieve.

This will lead to questions about using such profiles for more complex geometries, such as branching structures. At the time of the experiments, only the production of single profiles was considered, which could be connected into more complex structures by bolted or bonded connections. In the case of textile preforms, a branching structure could be fabricated as a single element from several textile preforms and moulds infused with resin in one vacuum bag. However, building such a setup for vacuum infusion would be complicated and time-consuming to the extent that any curvature adjustment based on elastic moulds would be practically impossible.

When considering external use scenarios, weather resistance will pose a similar challenge as in the case of all other NFRP products [45]. Thus, the necessity of using protective coatings and/or additives to the material recipe is not expected to be reduced by these production workflows on their own.

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