Truss-
TO-GO

A Novel Low-Tech Flax-FRP Technology for the In-Situ Construction of Lattice Structures

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Delft University of Technology
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Master of Science Thesis Report

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Abstract

Truss-to-GO is the name given to a Research-by-Design idea for a novel construction technology for Lattice Structures such as trusses and space frames. The ambition is 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. This thesis explores the first steps of such a technology, starting some of the mechanical properties that can be achieved by braided flax polymer composites as a single strut or chord in the lattice, with consideration for the pre-cure consolidation strategy for the composite. Further, the mechanical performance of a joint, or node, in the lattice is tested, and a proposal for the on-site infrastructures and fabrication workflow is developed. Finally, a simple comparison is made between the Truss-to-GO technology and some conventional lattice construction technologies, with insights about the potentials, limitations and future research topics for this ‘fantasy’ technology.

Contents

Part 1

WHY

1.1 Background

Finding efficient, effective, and intelligent ways to design and build our buildings and structures has always been a key concern and ambition. For the engineer, this is often a matter of structural mechanics, manufacturing and construction processes, in addition to a good understanding of the building's intended purpose and its requirements. This is a concern recorded as long ago as 20-30 BC, in Vitruvius's Ten Books on Architecture- the idea of *Firmitas* (Strength) being a key aspiration of the building engineer, in addition to *Utilitas* and *Venustas* (Functionality and Beauty). (Vitruvius, Rowland, & Howe, 1999)

Particularly after the industrial revolution and the addition of steel and reinforced concrete to the builder's arsenal of building technologies, the ability to span and enclose large spaces has grown. This leads to the obvious benefits of being able to create large modern factories, warehouses, stadiums, public buildings and other such structures that benefit from large scale. Thus, the building engineer ever strives to find ways to span and enclose larger spaces with structures that are robust (strong, stiff, stable, durable), yet using the least amount of resources. These structures must make practical, financial, and ecological sense. This is the modern concept of efficiency.

Among the various systems developed**, Lattice Structures** (trusses, space frames etc.) are a good answer to this problem as they are efficient and versatile. Though the technology of trusses is hardly modern, with records of timber trusses from Ancient Greece (Vintzileou, 2011), it can be argued that the more recent ability for mass production, steel and reinforced concrete technologies (that augment timber systems) have made the manufacturing and construction of trusses more accessible and convenient.

In fact, lattice structures are used to the effect of creating stiff, strong and material efficient skeletons in more than just building and civil applications; they are ubiquitous in the fields of automotive engineering, aerospace, and industrial equipment as well (Figure 1).

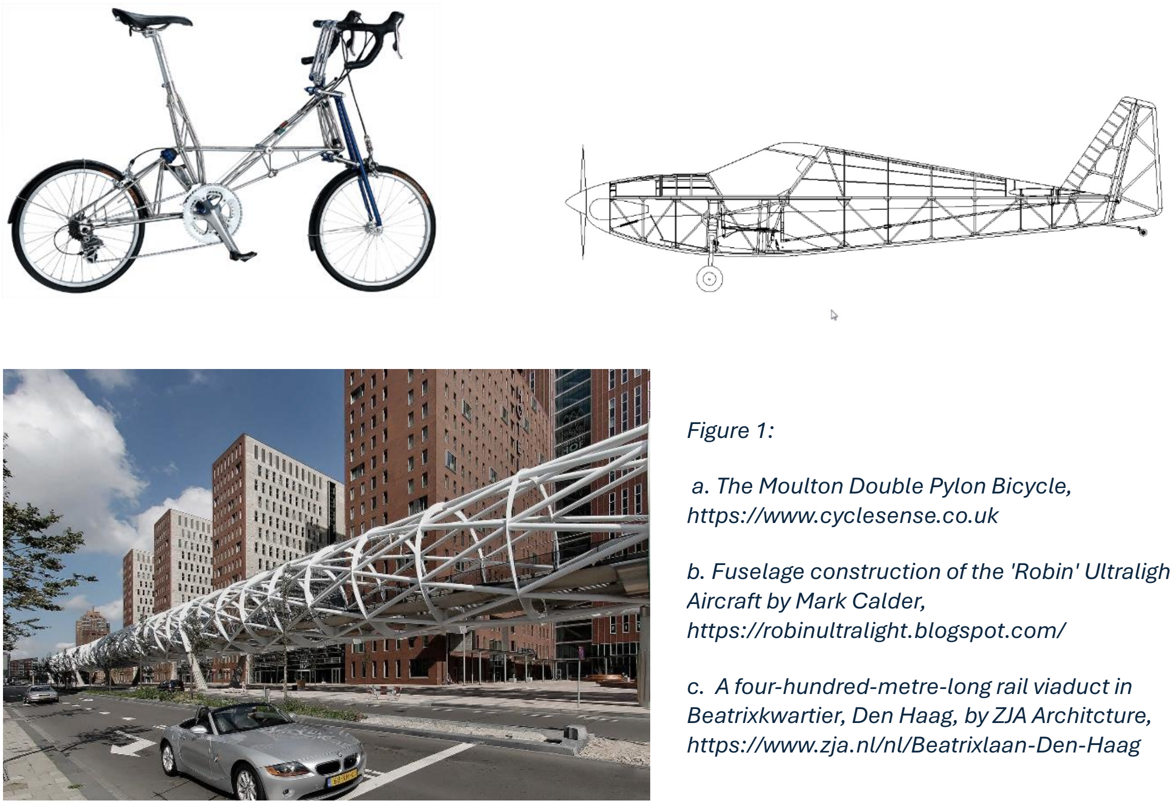


Figure 1:

a. The Moulton Double Pylon Bicycle, https://www.cyclesense.co.uk

b. Fuselage construction of the 'Robin' Ultralight Aircraft by Mark Calder, https://robinultralight.blogspot.com/

c. A four-hundred-metre-long rail viaduct in Beatrixkwartier, Den Haag, by ZJA Architcture, https://www.zja.nl/nl/Beatrixlaan-Den-Haag

Lattice structures in brief- struts, nodes, and the idea of triangles:

A lattice structure is formed by interlocking a set of linear elements, called struts (a loose term- here they refer to elements that carry compression as well as tension) into an aggregation of triangles. This aggregation may be two dimensional- called trusses/ girders, or three dimensional- creating tetrahedrons- called space frames. The triangle’s shape cannot change unless the length of its member changes, and this is the source of its robustness- all the struts are loaded axially, and materials are able to resist this more effectively than moments (of which there are none or very small amounts).

The struts are generally connected to each other either by a fabrication process (welding, timber interlock and so on), or with the aid of a distinct component (gusset plate, space-frame nodal hardware etc (Hibbeler, 2017). The point of connection is called a ‘joint’.

When a lattice structure is loaded with external forces, internal forces develop in the components. In the struts the forces are primarily axial, and the material must resist it. In the joints, there acts the combination of forces from all the elements connected to it, and the joint must withstand this combination through the integrity of its material.

Concisely put, the advantages and disadvantages of lattice structures are summarized in Table 1 (adapted from (Chilton, 2000).

Table 1

Figure 2: The combination of forces acting on a joint in a truss (a two-dimensional lattice structure), as visualized in steel connections, a. With a simple bolt passed through he members, or b. A gusset plate to which the members may be bolted, welded, or riveted. (Source: Chilton, 2000)

Table 1: Advantages and disadvantages of Lattice Structures (Adapted from Chilton, 2000)

Aesthetically speaking, it can be said that lattice structures, particularly space frames, look very ‘busy’ and ‘industrial’, which may not be the desired aesthetic in some cases. This is a matter of subjectivity and personal opinion. The other disadvantages, however, can perhaps be discussed more conclusively...

Disadvantages of Lattice Structures:

Expensive/ Time consuming to fabricate and erect: Metals (or alloys) like steel, aluminum, and timber are the usual candidates for the design of most space frames (Chilton, 2000)**.** Whereas trusses are material efficient and the materials themselves may not be the source of the high cost, **the components are required to be geometrically and dimensionally precise**. This involves the preparation of struts for jointing, and the preparation of joints themselves to a good degree of accuracy and precision. Particularly in the case of space frames this can mean expensive fabrication to fine tolerances. **The large number of joints** in some lattice structures and many space frames can also increase the fabrication and assembly time of such structures. Consequently, the need to make space frames easier to fabricate and erect has been the subject of engineers and product designers for the last several decades (Figure 3).

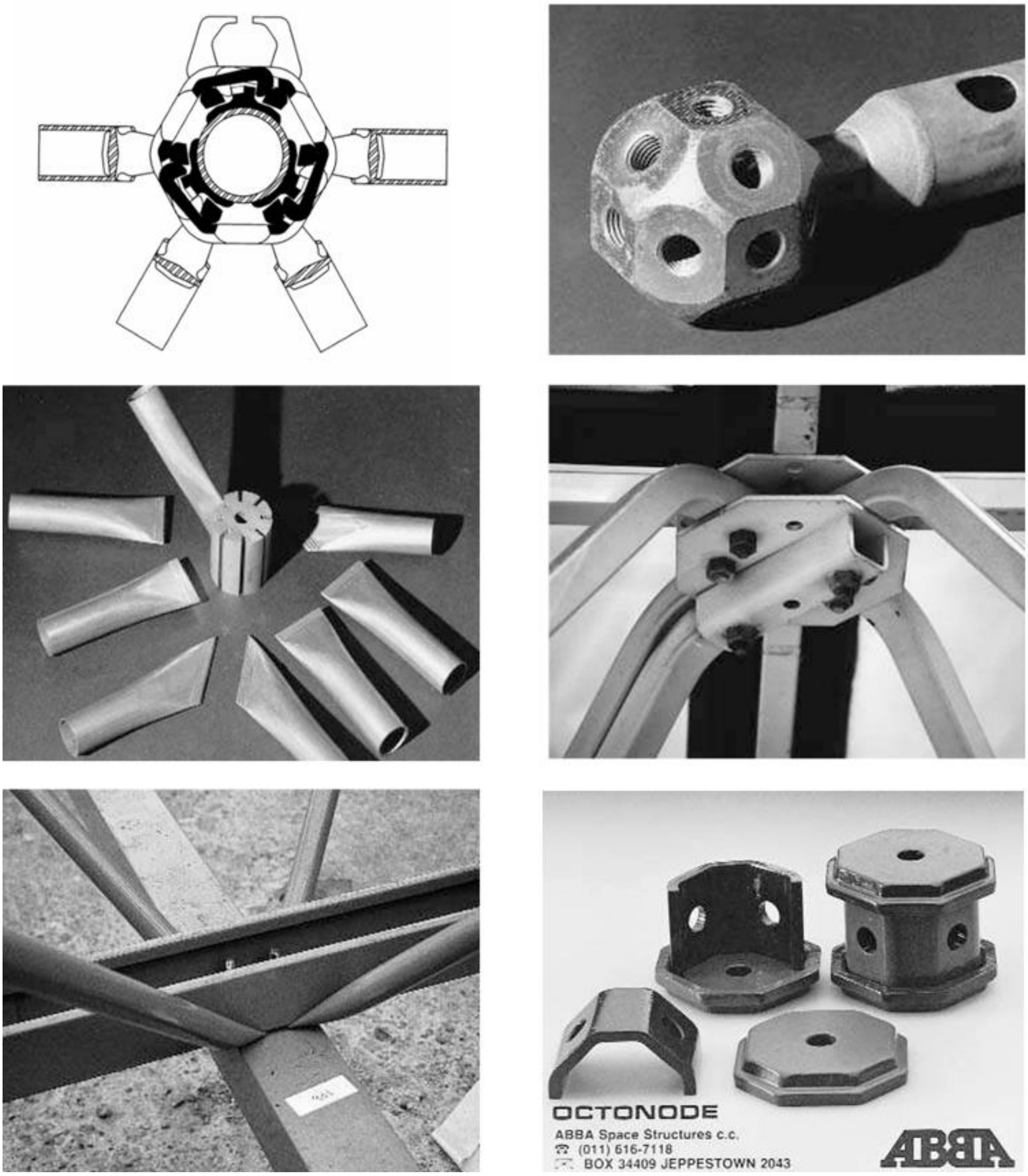


Figure 3: Some examples of Node design in Lattice structure Engineering (Source: Chilton, 2000)

a. Konrad Wachsmann's 'Universal Connector'- an intricate, die-cast arrangement that allowed up to 20 members to be connected at the node. b. A standard Mero KK node with 18 threaded holes and machined bearing surfaces (photo: Glyn Halls) c. Triodetic nodes- extruded cylindrical node with slots for 8 members (photo: Glyn Halls). d. Moduspan Node- a nodal plate to which cold formed members are bolted (photo: John Chilton). e. Harley Type 80 node joint- allowing for continuous chord members and some fabrication/erection convenience (Photograph: John Chilton).

Inconvenient for irregular geometry: Furthermore, in the case of lattice structures that are not aggregations of identical repetitions of triangles or tetrahedra,- in other words, irregular shape- the problem is exacerbated. The members and nodes do not lend themselves well to typical industry mass-repetition-production techniques (Johnston, Reed, Wang, & and Rosen, 2006) including any of the ones shown in **Error! Reference source not found.**, s ince the struts are of many varying lengths, and the nodes have differing angles between the struts and consequently cannot all be the same in their manufactured form (Chilton, 2000). They present significant difficulties for engineering, fabrication and execution until recent times, as evinced by the 1990's example of the Atlanta pavilion (visitor facilities, Olympic Games 1996) that was never built (Figure 4). Such a situation is possibly better suited to mass-customization manufacturing (additive manufacture or some other form of CNC manufacture etc.), which is relatively agnostic to geometrical variations, but these are still not well-suited for mass production and fall short in production scalability. (van der Linden, 2015). Further, such a scheme is likely to be more arduous to construct (and then slower and more expensive), as the erection effort resembles a 'jig-saw puzzle', where the struts and nodes are not interchangeable and each of the very large number of components must be employed in exactly the position it was intended.

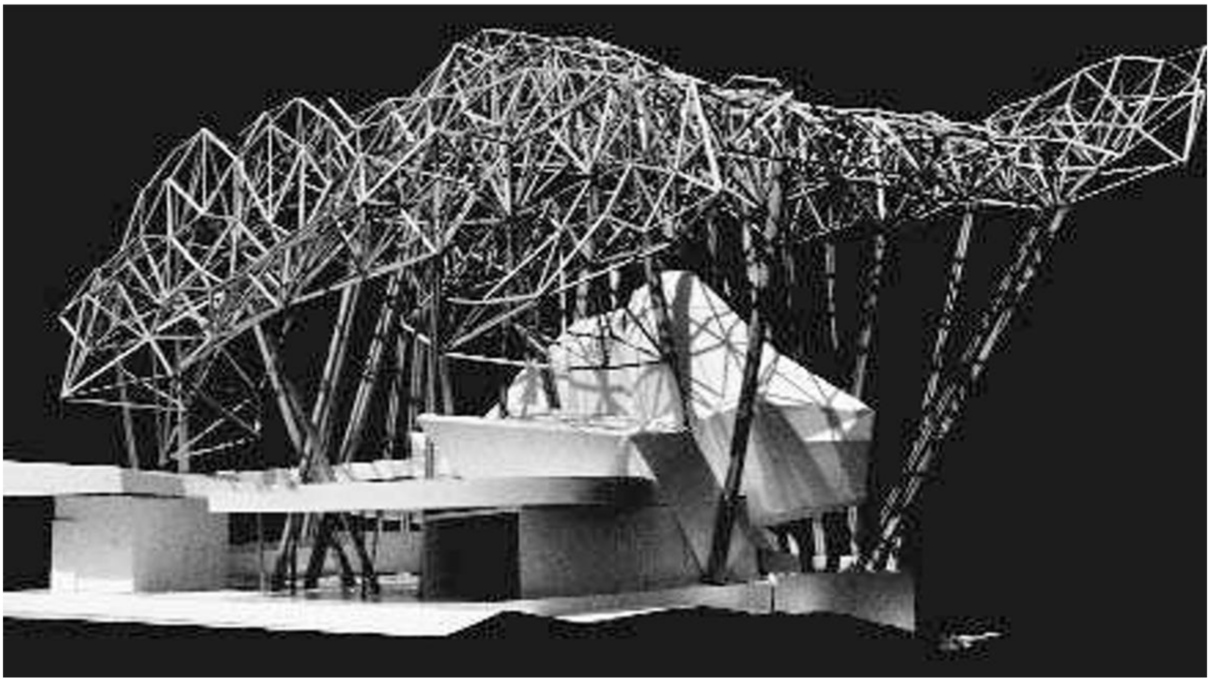


Figure 4: Model of the Unbuilt Atlanta Pavilion showing the geometrical complexity of irregular space frames (Source: Chilton, 2000)

This could also be a reason why investigations in **Topology Optimization of Lattice structures** may have limited potential for actionable construction- the results from the topology optimization are often irregular geometries, which create the same challenge for manufacturing and erection.

In the research by (Kim, et al., 2018), geometry optimized lattice structures, here referred to a s Lattice Cellular Material (LCM), was fabricated using an additive manufacturing robotic approach that was not only able to achieve the complex geometry generated by the stiffness-to-weight optimization process, but also the anisotropy problems of typical layer based anisotropy problems of additive manufacture . However, reliance on Additive Manufacture itself is still not well developed for the scale of manufacture that is required at the building level.

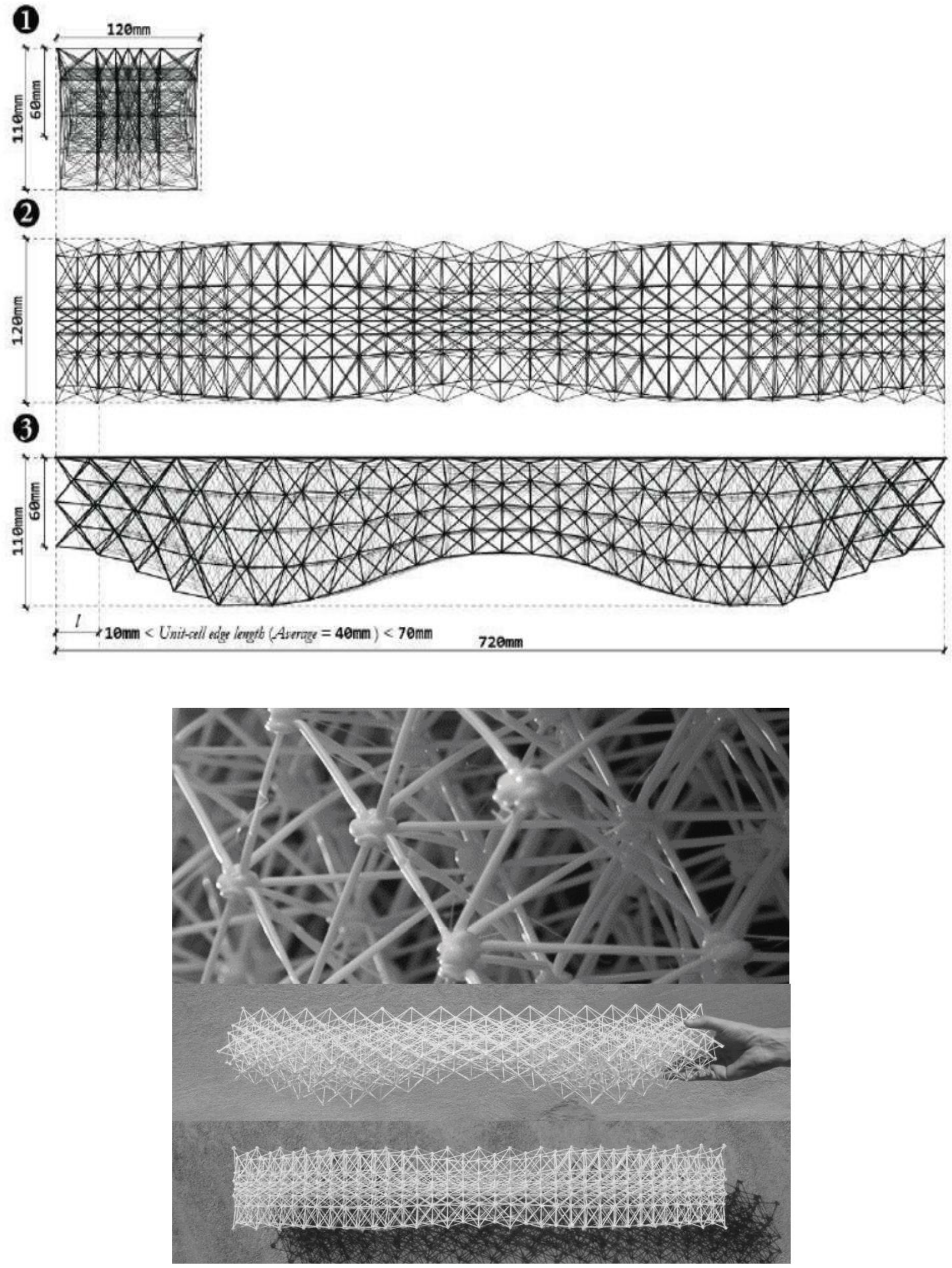


Figure 5: a. Orthographic documentation of the structurally optimized lattice using Global Morphing Techniques (GMT), b. Photo of AM manufactured case study (Source: Kim, et al., 2018)

Accessibility of Technology:

The construction of trusses in timber has long been known, and the simplest forms of timber connections using screws or nails are arguably quite an accessible technology in many part of the world today, in terms of cost. Working with metals can require higher levels of instrumentation (Chilton, 2000) as it often employs welding, or bolted fastenings involving special hardware that is often factory produced. In some parts of the world, like remote construction sites, or societies that are economically and technologically less fortunate, this may be a deterring factor for the application of this technology. The lightness of the structure, however, still favours the possibility of transportation of these building components to construction sites from facilities that are better equipped.

Ecological Argument:

Particularly in the case of steel or aluminium based structures, there may be a significant environmental footprint in the manufacture and preparation, as such materials are often high in embodied energy and carbon. However, Lattice structures offer the benefit of very low material volume for a given strength/stiffness demand. Naturally, this can be bettered with the use of an environmentally friendlier material (than metals and alloys) that can be used in similarly low volumes in a lattice structure, and fabrication and erection methods that consume less energy and resources.

An FRP based approach to lattice structures:

In recent research, there have been attempts to fabricate lattice structures using FRP's (Fiber Reinforced Polymers). To understand this better, some concepts about FRP's are introduced here. Specific case studies of fiber reinforced polymers employed for lattice structures are discussed in the Literature review- Case studies section

What is a Fiber Reinforced Polymer Composite?

A Fiber Reinforced Composite material is a hybrid material that is prepared by the combination of at least two constituent materials- a 'reinforcement', a 'matrix', and possibly other additional materials for specific properties. The resulting material is almost homogenous in macro-scale, and possesses new properties that are a favorable combination of its constituents, and cannot be achieved by either component by itself. The opportunity to combine these properties, and thereby 'tailor' them to the requirement of the product, is a crucial advantage of this material technology. This is done primarily by ***varying the type of fiber and resin matrix, the orientation of the fiber, and the fiber volume fraction (****discussed in* ***2.2*** *Desktop Research****).***

Key advantages of fiber reinforced composites are:

Higher strength and lightweight: FRP's can often have higher mechanical properties than conventional materials. For example, a carbon fiber tube can have a tensile strength in the order of 550 to 1050 MPa (Source; Granta Edupack 2022 R1). Compared with the much heavier structural steel (~7.8g/cm3) with a yield strength in the range of 250-350 MPa, or 6082 T6 aluminium alloy (~2.7g/cm3) with a yield strength of 255 MPa.

Manufacturing formability: FRP's usually include textile manufacturing and manipulation before the resin is applied or cured, allowing the formation of complex form like double curvatures etc. making them well suited for automotive and aerospace applications, among other industries.

Resistance to corrosion, creep and fatigue: FRP composites, especially epoxy FRP's, can often exhibit better properties compared to metals in these regards, as many of the commonly used fibres and matrices do not oxidize as readily as steel and do not rot like timber.

Why are FRPs a good idea for lattice structures (in principle?)

In theory, the internal forces that are developed in lattice structures and space frames are axial, i.e. in the direction of the members itself (assuming all member centrelines concur at joints and that the joins themselves act as pin joints). This means that the load case in each member is generally quite one dimensional and predictable, making FRP's an attractive candidate for application in such structures.

- The fibres can be aligned in the load direction, 'tailoring' the material for the load case, and the material can potentially offer extremely good performance for a given weight- an opportunity also observed by Potter et al (1998). Furthermore, in construction applications, the load conditions are arguably even more predictable and less dynamic than in automotive or aerospace applications.
- The benefits of lightweight structures, corrosion resistance, and energy damping are also interesting for application in the built environment.

However, there are some challenges to the application of FRP technology for lattice structure fabrication:

1) **Cost**: Carbon fiber based FRP's (CFRPs) are expensive due to the cost of the raw materials as well as the fabrication difficulty. Glass Fiber based FRP's (GFRPs) are relatively less costly as glass fibers are less expensive than carbon fibers, but they still require a high amount of energy to manufacture, ~100MJ/kg for the primary production, and between 2 to 25MJ for the composite fabrication (Source: Granta Edupack 2022 R1). There has been recent research **on Natural Fiber based FRPs**. Such FRPs offer sustainable and low-carbon alternatives to traditional materials, potentially impacting their cost and availability (Lamberti, 2016).

2) **Unsuitability to in-situ applications:** The preparation of FRPs from the raw resin and fiber is a process currently suited more to factory fabrications as there is substantial equipment involved in the compaction process (the application of pressure to the fiber matrix mixture to prepare the basic component form), and the curing process (oftentimes, the resins require high temperatures for polymerization i.e. curing.
3) **Fabrication of the lattice structure itself:** While there are several ways to prepare the linear elements (struts), such as pultrusion, press lamination, braiding, filament winding etc, the joints are notoriously difficult to prepare (Pedro, Camanho, & Matthews, 1997) due to the fiber discontinuity at the joints and that screws and nuts and bolts can compromise the performance. It appears that even with good design, bolted composite joints will be even half as strong as the basic laminate (Hart-Smith, 2001) **.** An alternative is welded connections, but this is possible only in thermoplastic based FRPs, which is still a relatively new technology that requires high tech instrumentation (Tijs, Turon, & Bisagni, 2021). This is further discussed in later sections- the Literature Case Study and the Approach and Methodology section.

Problem Statement

Based on the above arguments, the following are the tenets of the Problem, driving the motivation for this research work:

1. Lattice structures are extremely versatile structures with potential applications for a variety of industries where structural economy and high strength to weight ratios are desirable. **This warrants the pursuit of this class of structures for further research and development.**

2. Lattice structures are often characterized by long construction times and high costs, owing to the large number of components that must be manufactured precisely and fabricated. **This motivates the pursuit to make the manufacturing process simpler, faster and more accessible.**

3. With the exception of timber, the commonly used materials in lattice structures are steel and aluminium. **This motivates the curiosity to explore the possibility of constructing these structures with more environmentally friendly materials.**

4. FRP technology, particularly natural-fiber-based FRP, offers significant advantages for application in lattice structures, but present challenges of their own**.** FRP constructions are often difficult or expensive to mass fabricate due to the nature of the industrial process and materials and require careful engineering design for a good structural performance. They are rarely applied to the manufacture of lattices to the scale of building construction. **This motivates the pursuit to find a suitable combination of materials and manufacturing method for the fabrication of FRP lattice structures, producing products that are structurally sound, and feasible to manufacture**. Further, they must compare favourably against existing technologies of lattice structure fabrication.

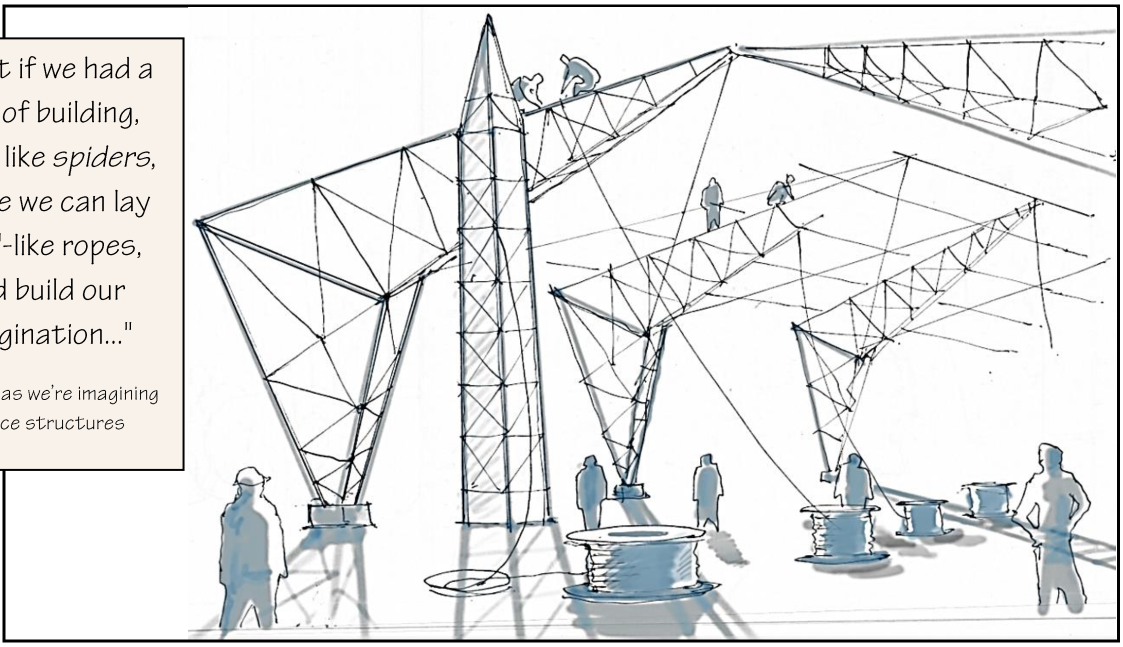
Part 2:

WHAT

2.1 **Objective and Research Question**

The engineer strives to improve design. The lattice structure is a formidable answer to the question of robust building structure. But as recorded in part A, there could be potential to improve this technology. FRP’s could be a way to achieve this.

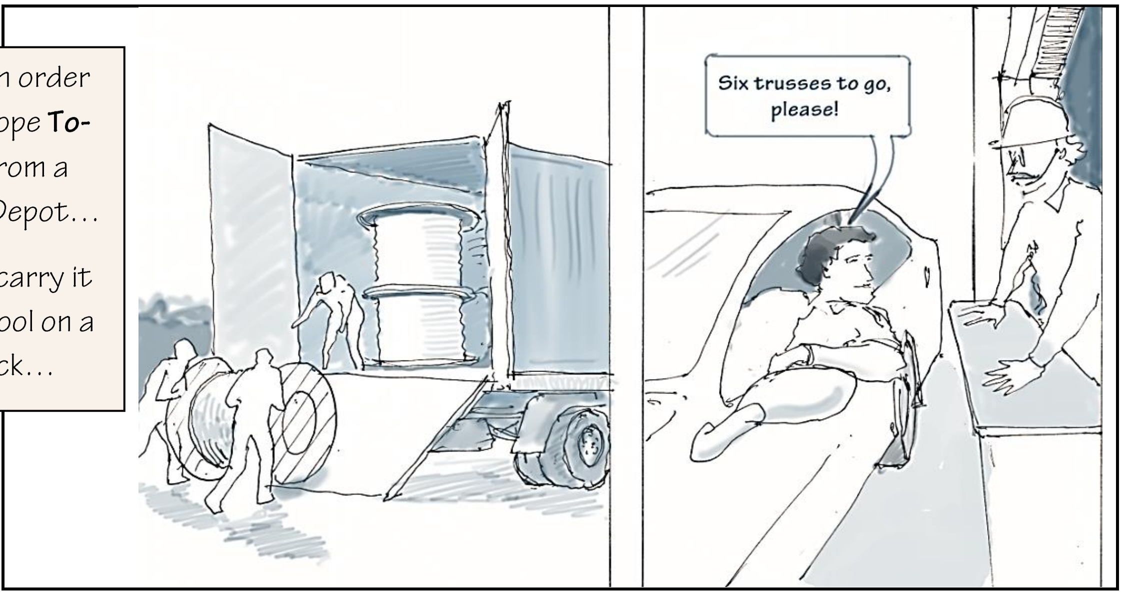
The motivation for this research started with a ‘flight of fantasy’…

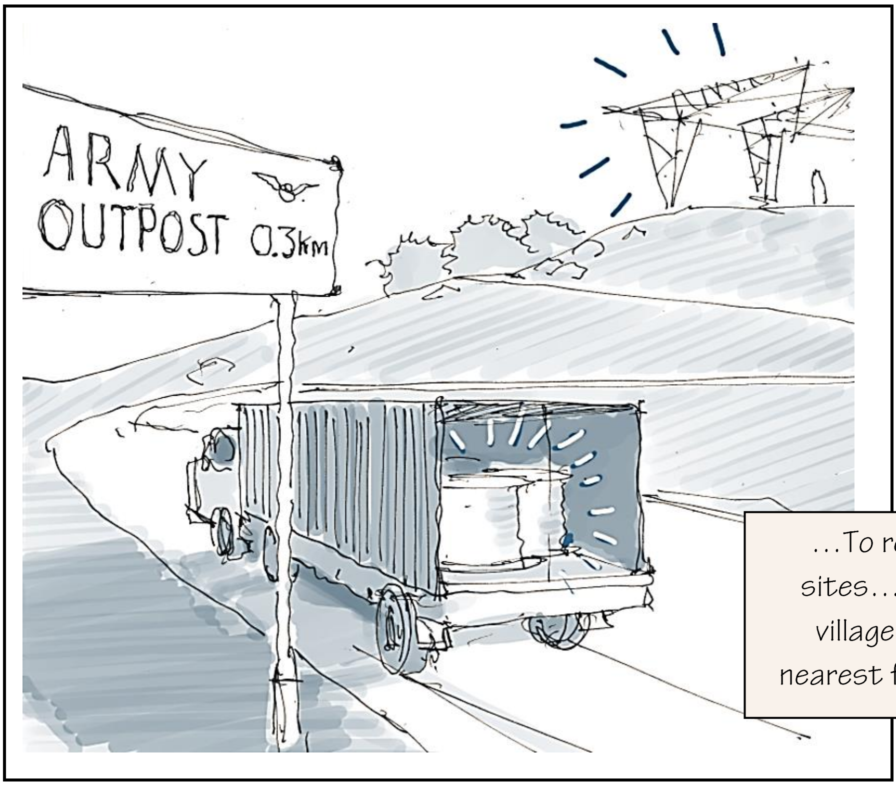


> "What if we had a way of building, much like *spiders*, where we can lay 'web'-like ropes, and build our imagination…"
>
> *as long as we're imagining lattice structures

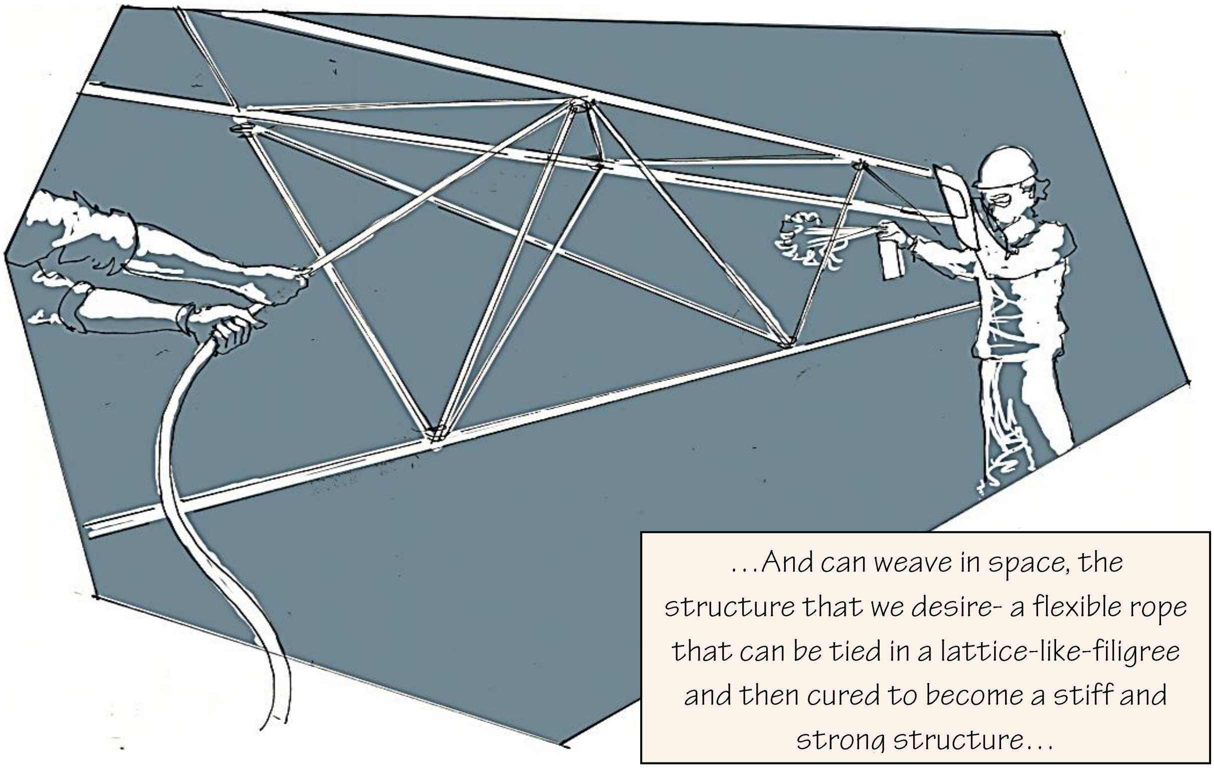
We can order this Rope **To-Go** from a Home Depot…

…We carry it in a spool on a truck…



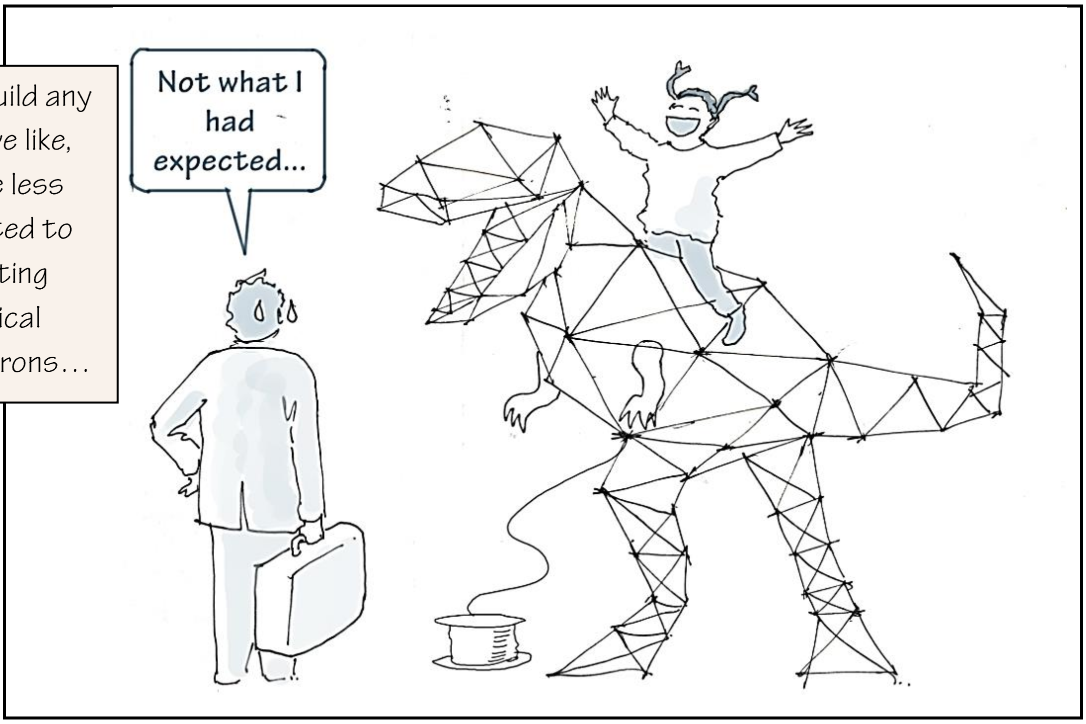


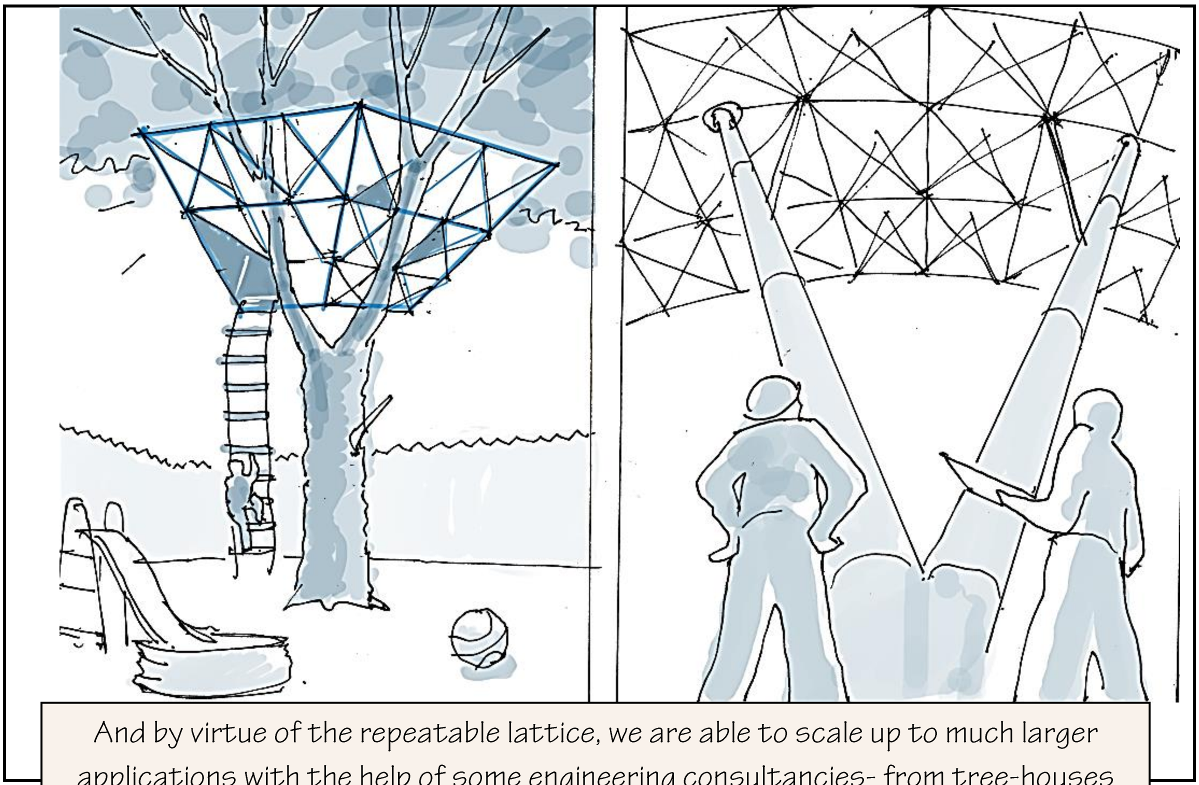
…To remote construction sites…. Up in the hills, or to villages far away from the nearest factory or workshop…



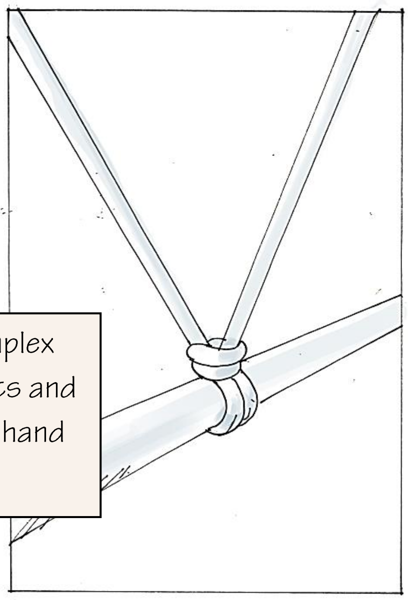
…And can weave in space, the structure that we desire- a flexible rope that can be tied in a lattice-like-filigree and then cured to become a stiff and strong structure…

We can build any shape we like, and are less restricted to repeating identical tetrahedrons…

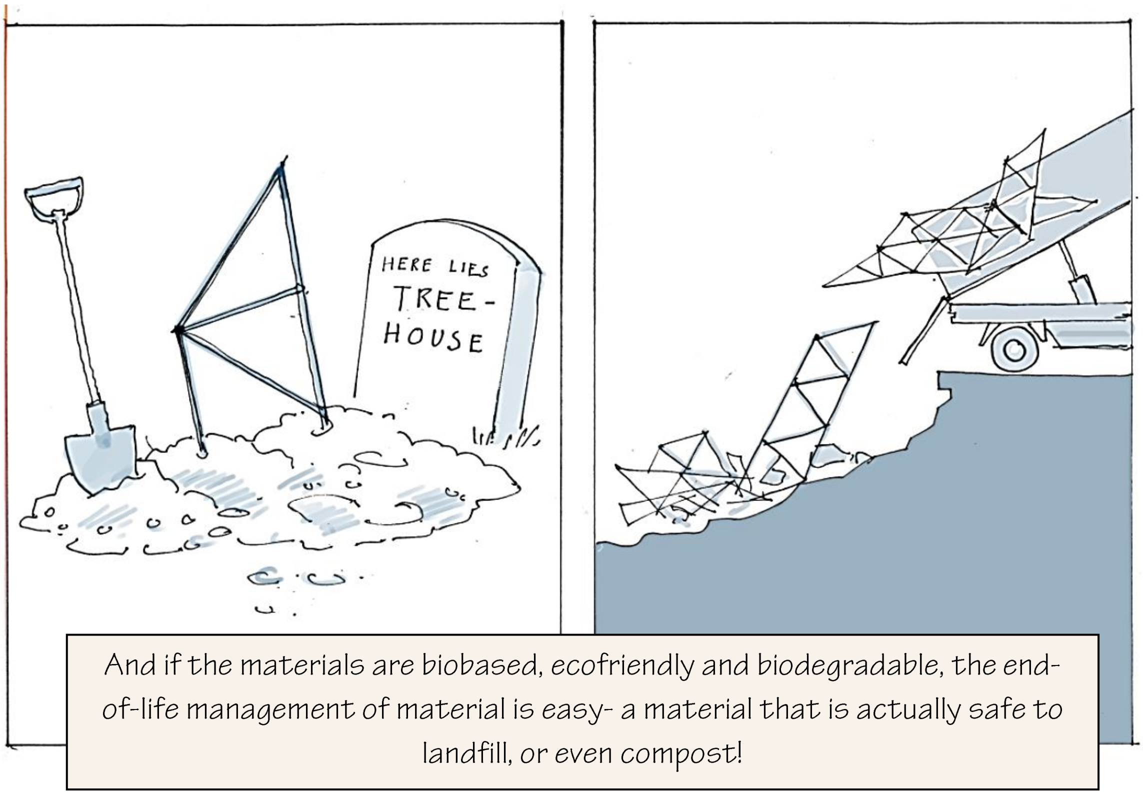




And by virtue of the repeatable lattice, we are able to scale up to much larger applications with the help of some engineering consultancies- from tree-houses to airplane hangars…



There are no complex connections of nuts and bolts, only simple hand lashings…



And if the materials are biobased, ecofriendly and biodegradable, the end-of-life management of material is easy- a material that is actually safe to landfill, or even compost!

… AND THAT'S THE FANTASY.

The Research 'Gap':

As will be elaborated in the literature review sections in the report, there are 3 key areas where there exists a research gap that can be addressed.

1. **The use of natural fibres for the manufacture of technical FRPs is still a relatively new field of engineering**. Whereas several principles of mechanics can be borrowed from the extensive knowledge and understanding of other FRPs such as glass and carbon fiber based ones, the mechanical performance and manufacturing viability with natural fibers and polymers is still being characterized in research today.
2. The existing methods for the manufacture of lattice structures using FRP or FRP-like technologies mostly still rely on relatively high-tech methods such as robot aided manufacture and complex assembly line setups. Simpler methods are still being tested for scalability. Finally, there is no proposal for a construction-site compatible in-situ fabrication method**. In other words, a site-friendly and low-tech method is still to be developed.**
3. The use of natural fibres and resins for FRP technology potentially opens up **ecologically favourable construction solutions**, in terms of embodied energy, carbon, and end of life prognosis. These values should be estimated for a bio based FRP lattice construction technology.

The Research Question

To explore this fantasy and research gap, the research question is-

Can a Novel Bio-Based FRP technology be designed and developed for the in- situ construction of Lattice Structures for Building Industry applications?

Research Sub Questions:

To better resolve the research, the following sub-questions are formulated. They can be clubbed into three 'domains' of investigation- **Material Fabrication, Lattice Fabrication and Erection, and Performance**

Material Fabrication:

- What are the environmentally friendly materials that will be recommended for the FRP cordage?
- What is the proposed process for the manufacture of the FRP cordage ?
- What is the proposed curing mechanism for the FRP cordage, that will rigidify it into the desired lattice strut?

Lattice Fabrication and Erection:

- What is the **on-site** procedure to fabricate and erect this cordage into the desired lattice-like structure?

- What are the site preparations, facilities and instrumentation required for this fabrication and erection?

Performance:

- For a given application, how does the proposed technology compare against a benchmark design with conventional technology and material- in terms of cost, material consumption and time.

Key Parameters to be met:

It is clear that the proposal for such a technology involves innovation on several different frontiers, and the creation of a product that appears not to exist in the market today (based on the review of existing literature). Therefore, it is likely not possible within the time period of this Graduation Project to thoroughly test the product on all the parameters that would qualify it as an actionable technology ready for industrial production. This is further elaborated in Scope and Focus'.

However, some **Key Parameters** have been set, which this proposed technology aims to meet thought its design and development. These are deemed to be the minimum requirement to qualify the technology as a meaningful answer to the research question. These are:

1. Structural Robustness	• The ability of the fabrication to withstand the loads of the chosen typical use case, and • Reasonable competitiveness against a benchmark fabrication made with conventional materials.
2. Ease of Fabrication/Erection	• A qualitative commentary on the feasibility of the proposed workflow for fabrication and erection, and competitiveness against benchmark fabrication techniques.
3. Economy and Eco-Audit	• An eco audit of the quantities of material and fabrication required for the given use case, and a reasonable competitiveness against the eco audit for a benchmark fabrication with conventional materials.

Scope and Focus

The pursuit of intelligent fabrication for efficient structures is very broad field of study and investigation, and some boundary conditions are set to focus the research

General Assumptions to be made:

1. **The 'truss and space frame' class of structures are meaningful and efficient enough to warrant further investigation.** The research is not a quest to find the most efficient long span structural system; such a question is likely too nuanced to propose a universal answer. It will vary on a case-by-case basis, and depend on a lot of parameters.
2. **The 'truss and space frame' class of structures is a candidate suitable enough for the application of the bio-based composite filament winding fabrication approach**: In other words, it is not in the scope of this research to explore whether this kind of product or fabrication is better suited to some other class of efficient structures, such as tensile structures or shell structures.
3. It is accepted that the **outcome of this research is open ended** and may conclude with the learning that it is unfeasible to apply biobased materials and FRP technology for the fabrication of trusses, and that the developed product is simply not strong enough, practical enough, or economical enough to recommend as a feasible technology for the industry today.

Scope: Material Science

1. The development of the FRP includes trials on the fibres and resin matrix. However, no investigations into the detailed molecular chemistry of the fibres, resins, and their interactions are attempted. The decisions for resin and fiber choices and use are made based on recommendations and clues from the research done in FRP science, and with the advice of the subject experts who guide the research (see Acknowledgements). Identifying the shortcomings in the chemical and microphysical behaviour are accepted as the farthest point the research can be taken within the scope.
2. The micromechanics of FRP behaviour are not investigated. The decisions in the experimental phase are made more by simple observations of the material and their macro-observable behaviour during fabrication and load testing, and with the advice of the subject experts who guide the research (see Acknowledgements)

Scope: Final Proposal

Whereas the proposal is for a structural component of a building, the main domains investigated (as mentioned before) are the robustness, ease of fabrication, and eco-friendliness. This is by itself, not a complete investigation of the technology, and the following topics are **excluded from the research:**

1. Creep and fatigue behaviour upon loading.
2. Weathering behaviour, fire and frost resistance.
3. Thermal and acoustic properties.
4. End of Life processes for the product and material

2.2 Desktop Research

Principles of FRPs

FRPs necessarily consist of reinforcing fibres and a continuous matrix that binds them together. The resulting 'composite' material usually has properties that are superior to that of either of the individual materials. These advantages are achieved through a load sharing mechanism.

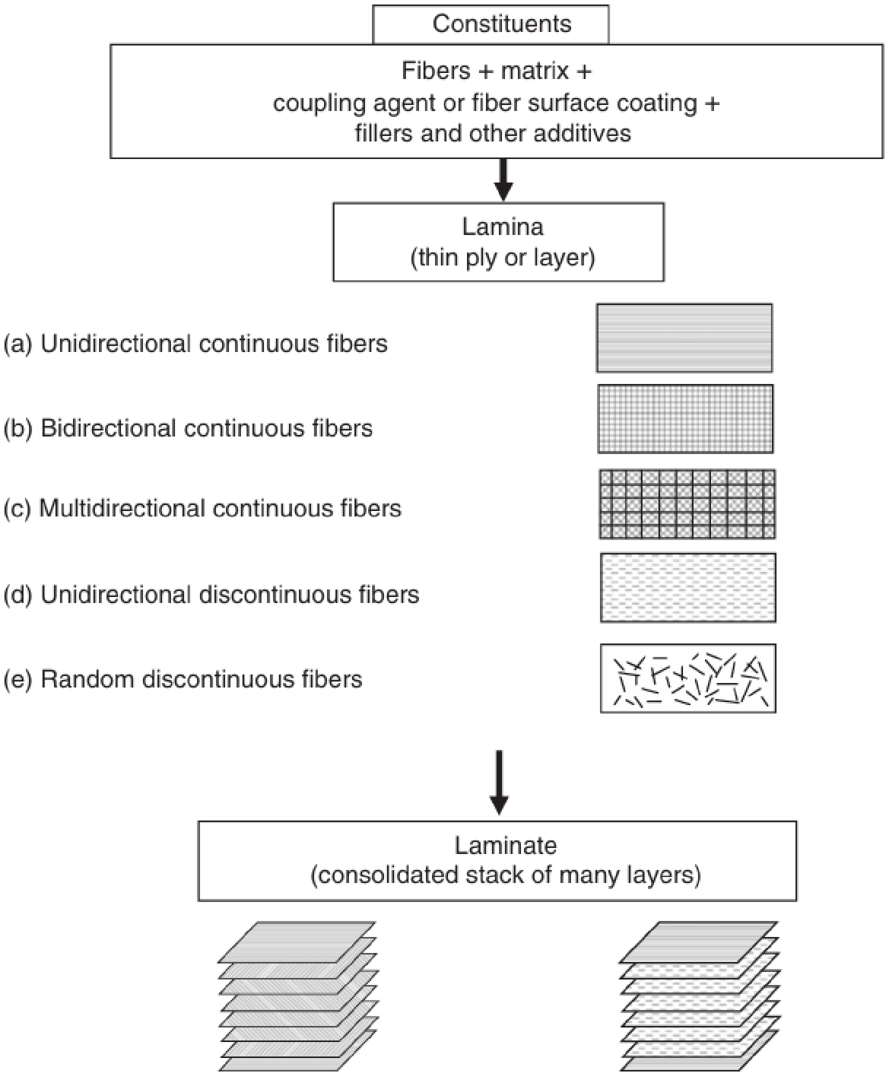


Figure 6:Building blocks of Fiber Reinforced composites. Adapted from (Mallick, 2007)

FRP’s may be classified at two levels (Miracle & Donaldson, 2001) based on the matrix composition, and based on the reinforcement type.

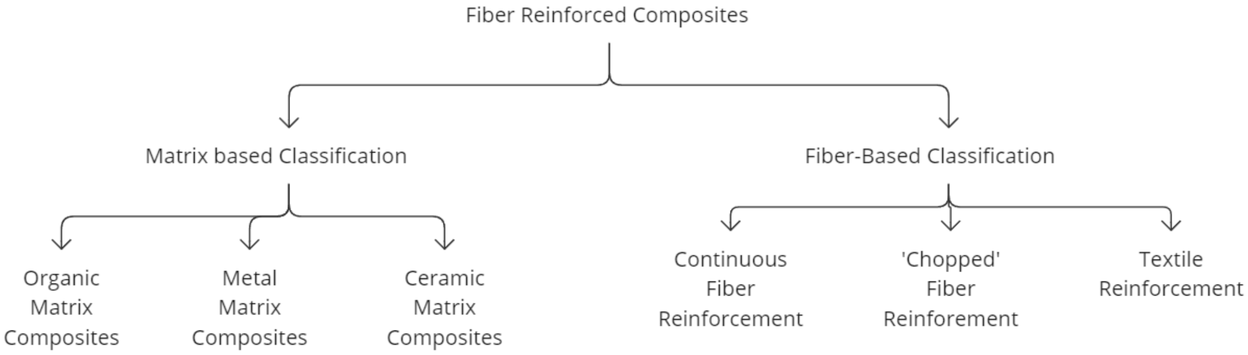


Figure 7: Classification approaches to FRPs. Adapted from (Miracle & Donaldson, 2001)

Products like Carbon Fiber reinforced polymers, or Glass fiber reinforced polymers (GFRP) are often continuous fibres or textile reinforcements in an organic matrix polymer.

Figure 8: Textile CFRP used In a bike frame (Octavio Passos/Getty images) b Fiberglass wind turbines Source: moldedfiberglass.com

For FRP’s designed for mechanical applications, the majority of the strength comes from the reinforcing fibers (Mallick, 2007).

Some key properties for the mechanical performance of FRPs:

1) ***Selection of materials*:** The choice of reinforcement and polymer matrix has a very high impact on mechanical performance of composites. Reinforcements like high modulus carbon fiber when used in composites are likely to endow superior mechanical properties when compared with glass or natural fibres that have a lower Young’s modulus and tensile strength. Similarly, the resin which provides the shear resistance between the lamina, affects the properties. This is one of the reasons epoxies are a very popular polymer choice, providing remarkable mechanical as well as aesthetic properties-

> *"Even though the elongation-to-failure of most cured epoxies is relatively low, for many applications epoxies provide an almost unbeatable combination of handling characteristics, processing flexibility, composite mechanical properties, and acceptable cost."* (Miracle & Donaldson, 2001)

2) ***Fiber Volume Fraction (FVF) :*** Simply speaking, this refers to the percentage volume of a composite that is the fiber reinforcement (the other fraction typically just being the matrix).

   It (v_f) can be expressed as:

$$v_f = \frac{w_f/\rho_f}{(w_f/\rho_f) + (w_m/\rho_m)},$$

   Where
   W_f = weight (or fractional weight) of the fibres in the composite
   W_m = weight (or fractional weight) of the matrix in the composite
   ρ_f = density of fibers
   ρ_m = density of matrix

   The FVF is an important Key Performance Indicator (KPI) for any composite. When the composite is loaded in the direction of the fibres, it is desirable to have a higher percentage of fiber volume, as it is the reinforcement that mainly takes up the load axial to it.

   However, when the composite is loaded transverse to the fiber orientations, higher FVF is not necessarily desirable, as the composite tries to bear the load through the matrix's shear properties. At micromechanical level, stress concentrations develop at the interface between the matrix and the fiber, and a higher fiber volume fraction may create more interfaces, therefore more instances of stress concentrations.

   Further, even when a composite is loaded in the direction of the fibers, an excessively high FVF is detrimental to the load carrying capacity of the composite, as it is likely that the fibres are not sufficiently encased, or 'wetted' in the matrix and that the composite does not behave as intended, at the micromechanical level.

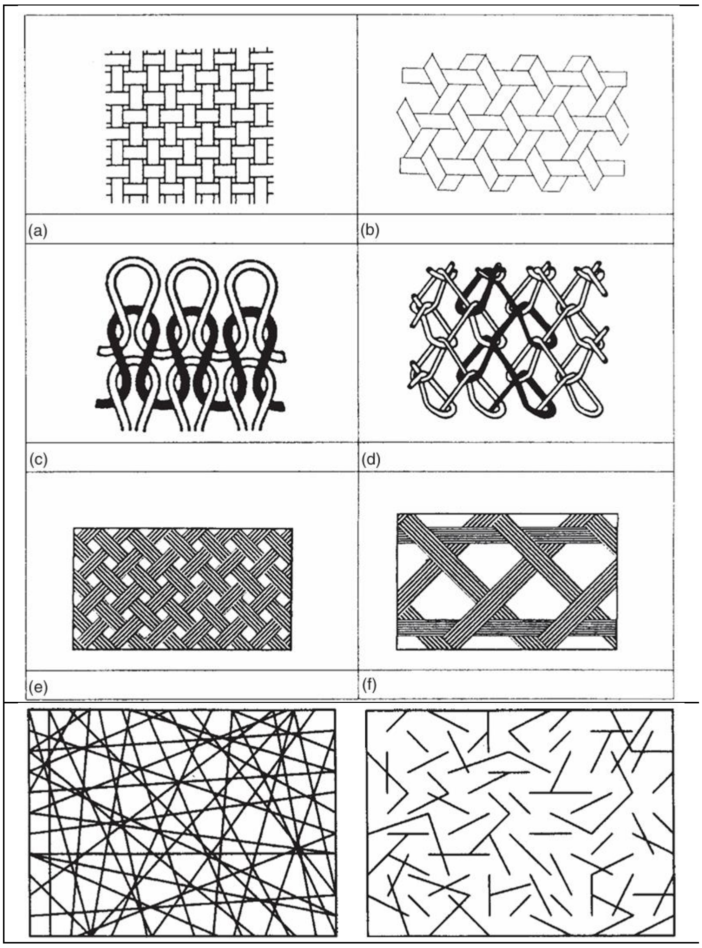
   This means that most products, fabrication processes and material choices have an 'optimum' FVF, which is determined through theory and experiments.

3) ***Fiber Architecture:***

This refers to the disposition, character and arrangement of fibres in a composite. It can be subdivided into the following characteristics:

- **Fiber continuity**: Continuous fibres are generally preferred for high performance composites as the y mobilize the polymer matrix better. However, they could be more demanding in terms of manufacturing processes etc compared to shorter or chopped fibres
- **Fiber orientation:** The orientation of fibres in the bolk of a composite plays a very significant role in determining the mechanical properties of a composite. Generally speaking, it is beneficial to orient the fibres in the same alignment as the principal stresses in the composite bulk, so as to load the fibres as axially as possible.
- **Fiber Crimping:** This referrers to bends and curvatures in the fibres resulting from the form of the composite. The mechanical performance of the composite changes in this region due to stress concentrations and force flows.
- **Fiber interlocking:** The interlocking of fibres is usually achieved in fiber textiles that are woven, braided, or knitted. Fiber interlocking can help to create an integrated behaviour of the laminas of the fiber composite (so that each lamina is not able to 'slip', delaminate or shear apart so easily. However, the interlocks also create bends in the fibres, which usually results in a compromise of mechanical characters because the fiber alignments are disturbed, and also due to stress concentrations at the crossovers.

Some examples of fiber layups are shown below (adapted from Mallick (2007)):



a) Bidirectional Fabric
b) Multidirectional Fabric
c) Weft-knitted fabric
d) Warp knitted fabric
e) Biaxial braided fabric
f) Triaxial braided fabric
g) Random continuous fiber mat
h) Random chopped fiber mat

Research: (Natural) Fiber Reinforcement

Among the Organic Matrix Composites, typically used reinforcements are:

- Carbon fiber
- Glass fiber
- Aramid Fibres
- Boron Fibres
- Natural fibres

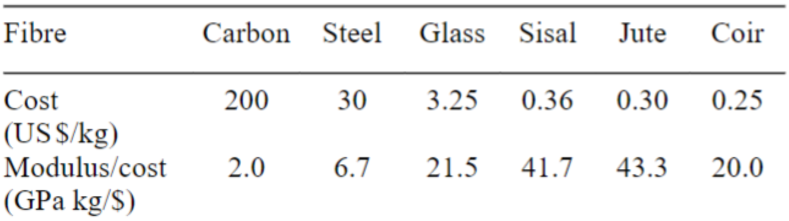
For the thesis, **the focus was on natural fibre based composites**, which are gathering more attention in recent years

Commonly used Natural fibres in composites are Hemp, Jute, Flax, Sisal, Ramie and coconut.

Why the increasing popularity?

There are several attractive advantages with natural fibres:

1. **Environmental advantag**e: Natural Fibres are biodegradable, and the energy required to produce and process them is relatively low (Mallick, 2007), (Mohanty, Misra, & Hinrichsen, 2000), (Miracle & Donaldson, 2001).
2. **Economy**: They are **cheaper** than synthetic fibres such as glass or carbon fiber (Mohanty, Misra, & Hinrichsen, 2000)(Granta Edupack 2022 R1).



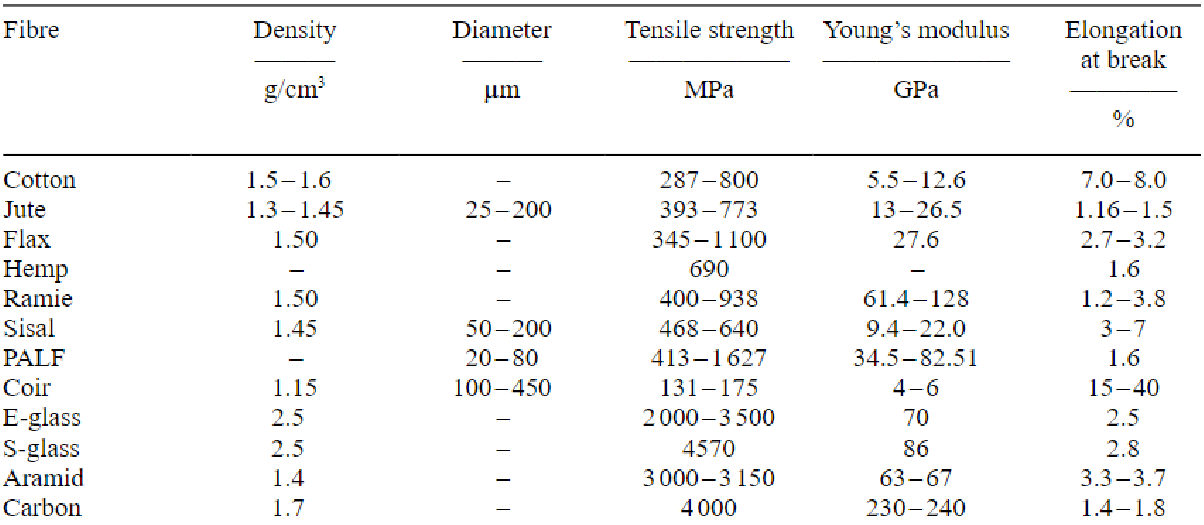
Fibre	Carbon	Steel	Glass	Sisal	Jute	Coir
Cost (US $/kg)	200	30	3.25	0.36	0.30	0.25
Modulus/cost (GPa kg/$)	2.0	6.7	21.5	41.7	43.3	20.0

Figure 9: Production costs of synthetic fibres compared with natural fibres (Owen, Ogunleye, & Achukwu, 2015)

3. **Lightweight**: At a range of 1.2-1.5gm/cm3, they are **lighter** than many synthetic fibres such as glass (2.54g/cm3) or carbon (1.8-2.1g/cm3).
4. Their E modulus is comparable to glass fibers (at 30-60GPa), making them competitive with glassfiber solutions in **stiffness** applications (Mallick, 2007)

Below are some technical properties of commonly used natural fibres

Table 2: Comparative properties of some Natural fibres with synthetic fibres. Collected by (Mohanty, Misra, & Hinrichsen, 2000)



Fibre	Density g/cm^3	Diameter µm	Tensile strength MPa	Young's modulus GPa	Elongation at break %
Cotton	1.5–1.6	–	287–800	5.5–12.6	7.0–8.0
Jute	1.3–1.45	25–200	393–773	13–26.5	1.16–1.5
Flax	1.50	–	345–1 100	27.6	2.7–3.2
Hemp	–	–	690	–	1.6
Ramie	1.50	–	400–938	61.4–128	1.2–3.8
Sisal	1.45	50–200	468–640	9.4–22.0	3–7
PALF	–	20–80	413–1 627	34.5–82.51	1.6
Coir	1.15	100–450	131–175	4–6	15–40
E-glass	2.5	–	2 000–3 500	70	2.5
S-glass	2.5	–	4570	86	2.8
Aramid	1.4	–	3 000–3 150	63–67	3.3–3.7
Carbon	1.7	–	4 000	230–240	1.4–1.8

In many ways, biofibers (or natural fibres) vary from the familiar synthetic fibres that are used in composites. Some notable points are:

- **Complex Microstructure (compared to synthetic fibres):** Most natural fibres get their mechanical properties from lignin and/or hemicellulose in the cell walls. These cells are aggregated into the 'fibrils' of the structure, which in turn have a complex arrangement to make up the fibres. The mechanical properties are dependent, among other things, on the cellulose/lignin content, as well as the angle between the fibrils and the axis of the fiber itself (they are not actually aligned in natural fibres). For example, in the case of flax, high lignin content and low microfibrillar angle endow it with superior mechanical properies compared to coir, which shows one of the lowest tensile strength, and is known to have low cellulose content and high microfibrillar angle.

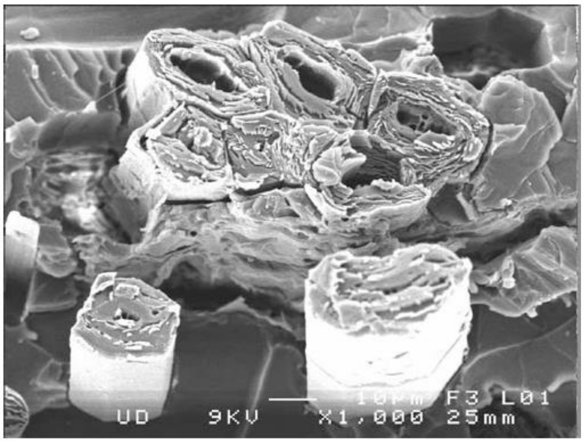


Figure 10: Section of a sample of composite flax fibres/ epoxy matrix. Source (Baley, 2002)

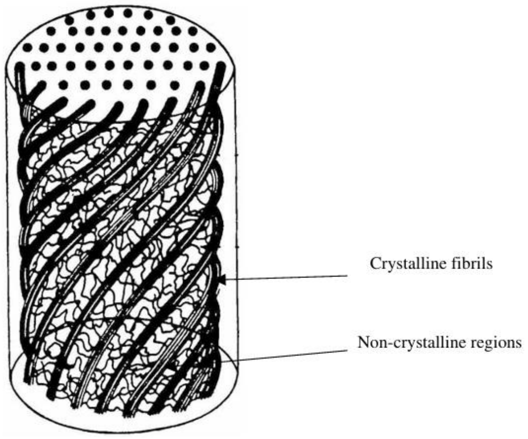


Figure 11: Illustration of flax fiber structure, showing helical arrangement of fibrils (Hearle, 1963)

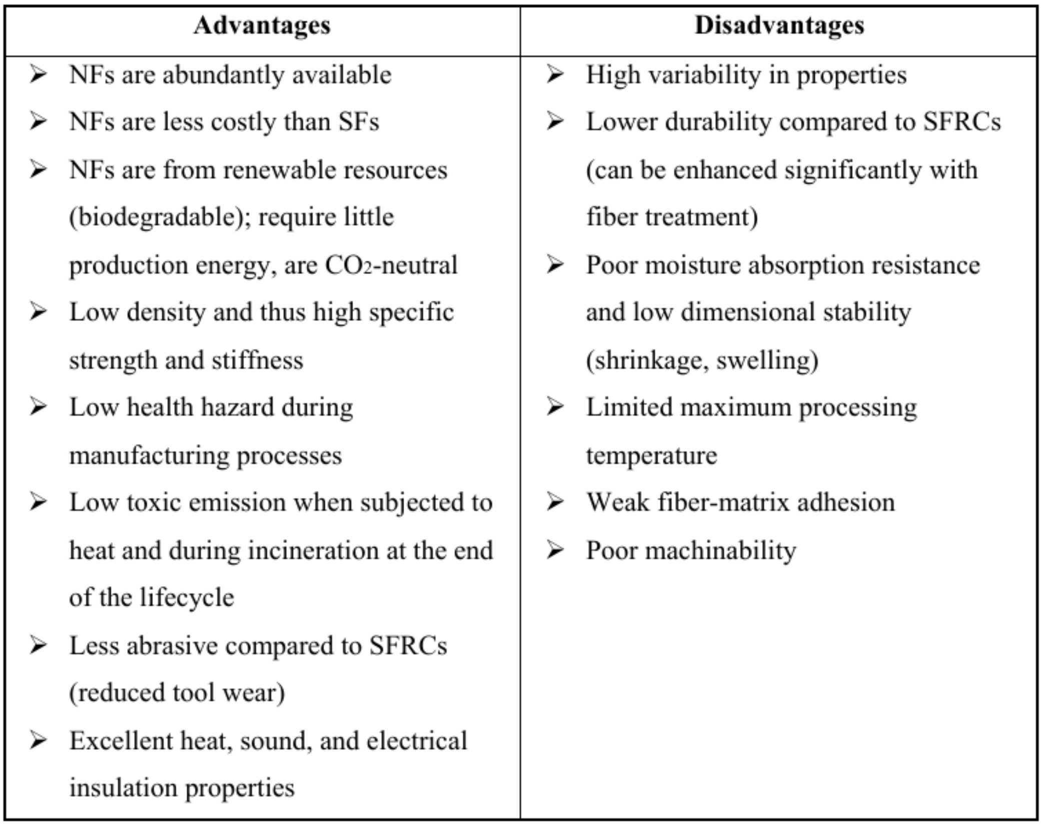
- **High variability in properties of fibers:** Unlike in synthetic fibres, the properties of natural fibres vary substantially even within the same species of plants , (Miracle & Donaldson, 2001) depending on where on the plants body the fiber was taken (Bledzki, Reihmane, & Gassan, 1996), the quality of the plants location (Bisanda & Ansell, 1992), the age of the plant (Barkakaty, 1976), and the preconditioning (Sathees Kumar, 2020).

- **Sensitivity to humidity and moisture:** Natural fibres are known to have substantial degradation of their mechanical properties such as tensile strength and yoiungs modulus with increase in moisture content (Moudood, 2019a), as the hollow lumen at the centre of the fibril takes up the water. This is why it is common practice to dr the fibres in a ventilated oven before preparing natural fibre composites.

- **Degradation with high temperatures and moisture:** Natural fibres usually degrade in their mechanical properties with increase in temperatures and have a limit of about 200 degrees, after which they begin to oxidise, depolymerize, or hydrolyze (Mougin, 2006), which means they cannot be used with some high processing temperature polymers.

- **Compatibility with polymers:** Unlike many synthetic fibers, natural fibres are hydrophilic (form weaks bonds with water at a molecular level), and many polymers, such as DGEBA epoxies and most thermoplastics are hydrobhobic. This results in poorer adhesion at the fiber polymer interface ((Bismarck, Mishra, & Lampke, 2005)

Natural fiber reinforced composites have been researched for the past few decades and are a relatively newer discipline, when compared to synthetic fiber composites. However, some aspects about them are known, as shown in Figure 12.



Advantages	Disadvantages
➢ NFs are abundantly available ➢ NFs are less costly than SFs ➢ NFs are from renewable resources (biodegradable); require little production energy, are CO_2-neutral ➢ Low density and thus high specific strength and stiffness ➢ Low health hazard during manufacturing processes ➢ Low toxic emission when subjected to heat and during incineration at the end of the lifecycle ➢ Less abrasive compared to SFRCs (reduced tool wear) ➢ Excellent heat, sound, and electrical insulation properties	➢ High variability in properties ➢ Lower durability compared to SFRCs (can be enhanced significantly with fiber treatment) ➢ Poor moisture absorption resistance and low dimensional stability (shrinkage, swelling) ➢ Limited maximum processing temperature ➢ Weak fiber-matrix adhesion ➢ Poor machinability

Figure 12: Advantages and disadvantages of NFRC', sourced by (Saadati, 2020)

Research: Resin Matrix (polymer)

The purposes of the matrix in an FRP are:

- To bind the fibers together, providing the physical integrity and the proper orientations of the fibers.
- To protect the fibres mechanically and chemically.
- To provide the transverse mechanical properties and interlaminar strength.
- To provide an inelastic response to ensure the proper distribution of stresses, particularly when some fibres are broken.

Among OMC's, typically used matrix materials can broadly be categorized into **thermoplastic** and **thermoset** polymers.

Thermoplastics *are a kind of polymer that can be softened upon heating. They have a glass transition temperature* (t_g) *heated up to which their polymer chain begin to slip and the material becomes soft. Upon removal of heat, they regain their more rigid mechanical properties.*

Examples of thermoplastics are Polypropylene (PP), polyethene (PE), polystyrene (PS) and polyvinyl chloride (PVC).

Thermosets *are polymers that are characterized by irreversible cross links between their polymer chains, making them often stronger and stiffer than thermoplastics. As the name suggests, however, the properties are 'set' once the crosslinking is completed, and cannot be remolded with the application of temperature. Epoxies, Phenols, and Polyesters are examples of thermoset polymers.*

Examples of thermoplastics are Epoxies, Polyesters, Polyimides, and Phenolics.

At a **molecular level:**

polymer materials consists of long chains of organic molecules (called monomers). In thermoset materials, these long chains are chemically 'cross linked' at various intervals. When they are chemically linked in this fashion, the material does not soften upon heating. This cross linking is called polymerization, sometimes simply called curing. In the case of many thermosets like epoxies and polyesters, the product is provided as a 2-component material- a starter, and a curing agent. These are mixed in a specific ratio to achieve polymerization, often with the aid of heat to facilitate full polymerization and crosslinking.

- Curing time is a function of temperature. Reducing the temperature will slow down the rate and extent of crosslink formations. This is used in the case of what is commonly called 'prepregs' (pre-impregnated textiles), which are fiber textiles already impregnated with an inactive polymer. IN the case of thermoset prepregs, it is required to refrigerate them in order to keep them inactive. These products are purchased, formed into the desired product shape on a mould or so, and then oven cured or autoclaved to form the cured and finished product.
- Properties of the thermoset are a function of the cross-link density in the molecular matrix. Typically, tensile strength, Tg, and Youngs modulus increase with more crosslinks. This is also why complete curing of thermosets like epoxies are crucial for mechanical performance.

In thermoplastic materials, these cross links are typically much weaker, as they are van der Waal's bonds or hydrogen bonds. With the application of heat, these bonds can be (temporarily) broken, and the monomers 'slide' relative to one another. Upon removal of heat, these bonds are restored.

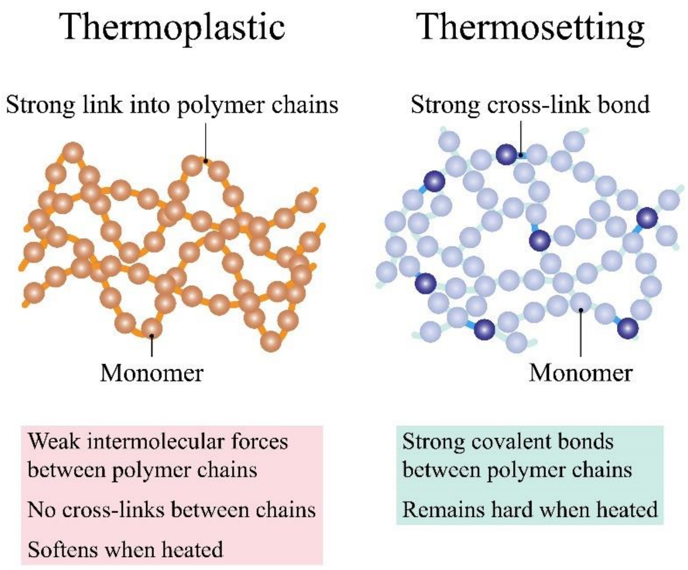


Figure 13: A schematic representation of thermoplastic and thermoset polymers. (Source : https ://resources.pcb.cadence.com/blog/2023-thermoplastic-vs-thermoset-plastics)

Selection of Polymers :

For high performance composites, the mechanical properties govern the choice of matrix.

Typically, the desired mechanical properties are (as summarized by Mallick (2007)):

1) **High tensile Modulus**
2) **High tensile Strength**
3) **High fracture toughness**

For structural applications in the built environment though, some additional attributes of interest are:

1) **Creep and Fatigue characteristics**: Mechanical properties (deformation, degradation of load carrying capacity) in the face of sustained or cyclic loadings.
2) **Resistance against the Elements**- Radiation, moisture, and some chemicals.
3) Thermal behaviour: the effect of elevated or very low temperatures upon the stress capacity and stiffness of the polymer.
4) **Compliance to manufacturing processes** and scalability
5) **Cost and environmental impact**.

Based on the review of the literature, the following considerations are summarized and remarked upon in the table below (collected from Mallick (2007), Steyer (2013), and Miracle and Donaldson (2001)):

Attribute	**Thermoplastic**	**Thermoset**	**Remark**
Mechanical			
Tensile properties	Excellent	Excellent	
Stiffness	Excellent	Excellent	
Compression Properties	Good	Excellent	
Fatigue resistance	Good	Excellent	
Creep resistance	Poor or fair	Good	
Damage and impact resistance	Good to excellent	Fair	
Manufacturing/practical			
Processing temperature	High (300- 400 C)	Ambient to medium	
Wettability to fiber	Low (highly viscous)	Good to high (low viscosity)	
Processing Pressure	1.38-2.07	0.59-0.69	
Processing time	Low (minutes)	Medium to high (hours to days)	
Recyclability	Can be recycled	Cannot recycle	
Ease of prepreg-ing	Poor to fair	Good to excellent	

Manufacturing Methods for FRPs

Below are some fundamental principles for the manufacture of composites:

1. **Curing requirements:** Generally, high temperatures are required to cure the matrix in an frp to the full extent (achieve the cross links in case of thermosets), and in thermoplastics that are more viscous, high tempertaures are needed to make the matrix wet-out the fibres.
   High pressures are needed to achieve proper consolidation of the composite, as well as achieve proper fiber penetration by the matrix and optimum wet out. Inadequate pressure will result in unwetted fibres, air voids and poor fiber volume fractions.
2. **Resin Flow**: The viscosity of the resin and its compatibility with the fibres (in both liquid composite moulding and bag moulding) in producing void free and fully impregnated composites.
3. **Consolidation**: This refers to the ‘coming together' of the composite- achieved by good pressure during curing. This allows for the removal of voids and defects in the plies and in between the plies of the laminate.
   Voids are critical defects in the bulk of a composite, where air is trapped in the composite. These defects greatly compromise the mechanical properties of a composite.

There are a variety of methods for the manufacture of fiber reinforced composites. Broadly speaking, they are all characterized by strategies for 2 questions.

1. **What is the method to lay up the fiber**

2. What is the method to combine fiber and polymer?

1. *Vacuum bag moulding process:*

In this process, the fibre textile is wither pre-impregnated or impregnated just before the moulding. The general idea is that the arrangement is placed on the shaping mould (or a flat surface, if the flat sheet composite is to be made), and enveloped in a bag on which vacuum is applied through the curing please. This bag generates the uniform atmospheric pressure that achieves the consolidation and shapes the textile to the mould. This arrangement can be done in an autoclave for resins that need high cure temperatures.

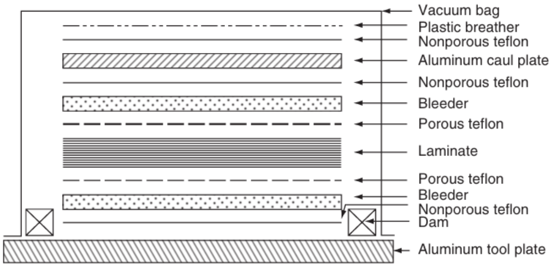


Figure 14: Schematic- bag moulding process (Mallick, 2007)

Advantages: Good for one off manufactures, requires minimal infrastructure (autoclave or oven is the main infrastructure), adaptable to changes in fibres and resin and other parameters as it is in principle not in a production line/

Disadvantages: Not suitable for high levels of production, requires substantial labour and skill as the layup and bagging is by hand. Larger products require substantial effort to be made this way and can be unfeasible at times

2. *Compression moulding:*

Ih this method, the composite is moulded into shape and cured while being pressed by a movable platen that can exert high pressure.

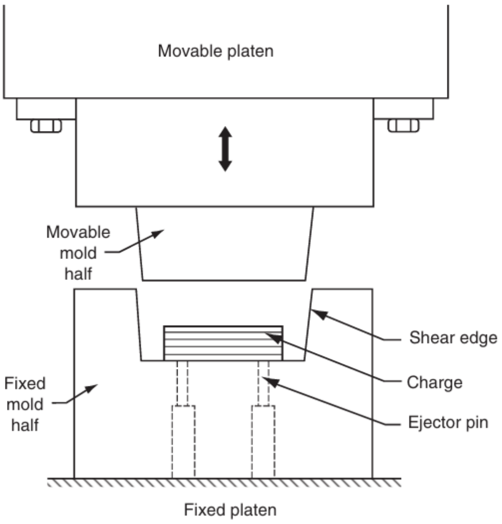


Figure 15: Schematic of compression molding process (Mallick, 2007)

Advantages: High production rates, particularly advantageous for complex geometries (the mould is specially milled to desired geometry) allowing for ribs, flanges, holes etc. This eliminates the post process steps, saving effort and money.

Disadvantages: economical though its repeatability only (same product over and over), suitable for smaller sized products.

3. *Other manufacture methods of a similar flavour:*

- **Resin transfer moulding**
- **Vacuum assisted resin transfer moulding (VARTM)**
- **Resin injection moulding**
- **Film infusion moulding**

Evidently, these methods are generally not suitable for lengthy composites.

Some manufacturing methods that are potentially better suited to the lengthy composites that may be useful for the manufacture of linear composite elements are listed below:

4. *Pultrusion*

Pultrusion is a commonly used molding process for producing long, straight members of constant cross section area. It is called pultrusion because it is similar to extrusion, but the matrix saturated fibres are ‘pulled’ through the heated die.

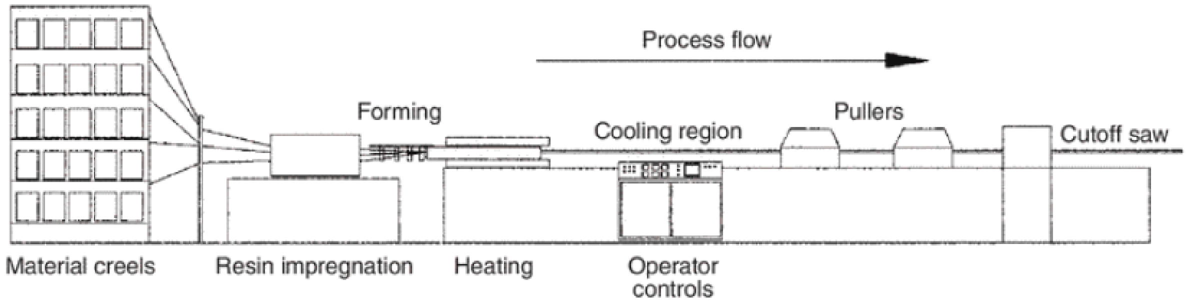


Figure 16: Schematic of pultrusion process (Miracle & Donaldson, 2001)

Advantages: There are several key advantages to the process of pultrusion. 1. Since it is a continuous process, any transportable length can be manufactured. The cut off saw is located to repeatedly cut off the continuous line to make the desired length. 2. Fairly complex thin walled cross sections can be prepared in this process, similar to extrusion in PVC or aluminium. 3. It offers tremendous versatility in terms on the choice of fibres and resins that can be usd and in recent times even thermoplastics can be pultruded. 4. The nature of the pressure drawing allows for extremely high fiber volume fractions (~70%) to be achieved (Alajarmeh, et al., 2023).

This makes pultrusion one fo the best candidates for producing linear continuous composite members.

Disadvantages: a major disadvantage of pultrusion is that there is a limitation on the fiber architecture that can be included in it. As the rovings are drawn linearly into the process, it is difficult to achieve fiber interlocked architectures without a preceding step that weaves or braids the rovings before they are drawn into the resin bath and heated die.

5. *Filament Winding*

In this process, a continuous tape of rovings is wound at high pressure around a rotating mandrel to make the composite. The rovings are passed through a resin bath before they are wound on the mandrel. This method is very well suited to the production of hollow shell composites.

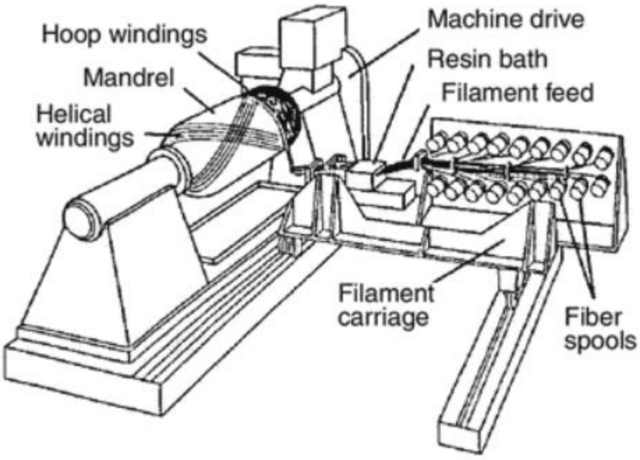


Figure 17: Typical filament winding setup (Miracle & Donaldson, 2001)

Figure 18: GRP pipe manufactured by filament winding. Source: (3 Incredible "Did You Know" Facts About GRP Pipes, 2020)

Advantages: 1. Low cost: The production is very fast due to the high fiber layup speeds. In addition, the tooling and infrastructure is relatively inexpensive for the production output. 2. The process is automated, as a CNC method can be used to comtrol the spinning mandrel and the roving feed movement to create the desired winding patterns. 3. The automation also results in a high precision of fiber layup. 4. The tension during the fiber layup, followed by friction on the mandrel or the fibres below, creates the necessary pressure to achieve consolidation without the need for an autoclave or other pressurization process. 5.

Disadvantages: 1. The expense and the complexity of the mandrel is the main disadvantage. Complex geometry mandrels cannot be retrieved as they become captive int the product ad must therefore be sacrificial. 2. There is a limit of the length of such products, which is a limitation of the machine setup. Thus it is better suited to hollow products of a finite length.

6. *Tube Rolling*

This involves the rolling of the chosen fiber textile (usually preimpregnated) about a roller at a high pressure. This is a favrourable method for the production of hollow cylindrical sections, but can also be used to make other radially symmetrical sections such as truncated cylinders etc.

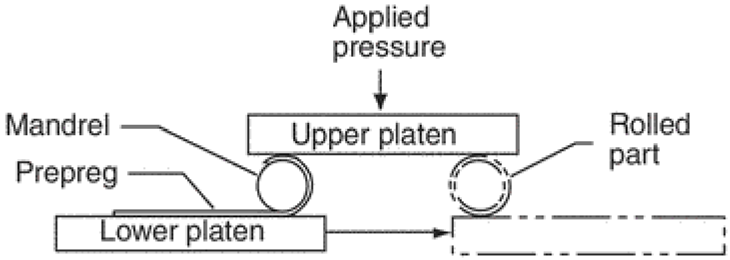


Figure 19: Schematic of tube rolling process (Miracle & Donaldson, 2001)

Advantages: High production rates 2. Relatively inexpensive infrastructure 3. Excellent surface finish 4. Fiber orientations from 0 to 90 deg are possible (Figure 20).

Disadvantages: 1. Limitations on the length of the product- governed by the size of the machinery. 2. Limitations to the cross-section size. 3. The cost of the prepregs that are used are generally higher than the resin bath rovings that are used for filament winding and pultrusion techniques as this is a separate manufactured product.

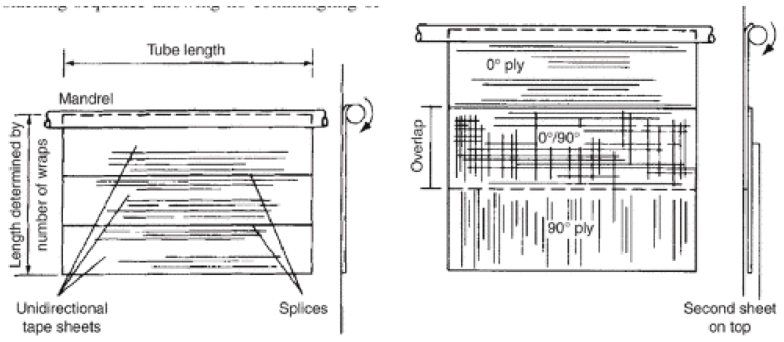


Fig. 8 Unidirectional tape, longitudinal ply rolling **Fig. 9** Unidirectional tape, 0/90° rolling

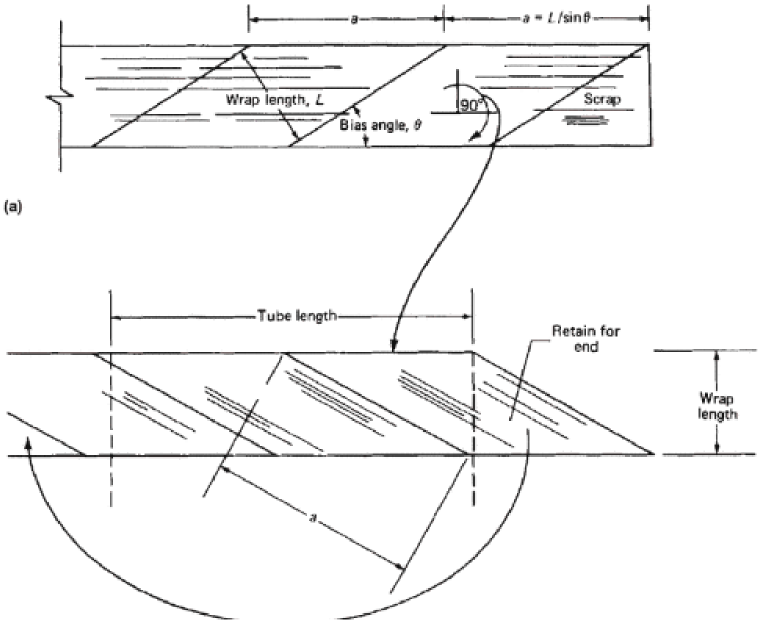


Figure 20: Fiber orientation methods in a roll wrapping process (Miracle & Donaldson, 2001)

7. Braidiing

In this method, two or more systems of yarns are braided together, with or without a core mandrel, to produce a continuous textile that is later on processed into a composite by a suitable resin impregnation method.

There are many kinds of braiding, based on the patterns by which the braids are interlaced.

Advantages: 1. A continuous textile can be produced (like pultrusion, unlike filament winding). 2. There are several architectures of fiber layups possible (unlike pultrusion-only linear, unlike filament winding where the buildup resembles a combination of angle plies) and complex shapes can be made if required (like in filament winding but unlike in pultrusion) 4. The interlacing of the rovings improves the micromechanical integrity of the composite (resists interlaminal failure) 5. It is automated (like filament winding and pultrusion) resulting in low manufacture costs and high production efficiency generally.

Disadvantages: 1. The fiber volume fractions achieved are typically lower than filament wound or pultruded sections because of neat resin pockets that develop in tbetween the interlaces (unless perfect braid locking is achieved). 2. The interlacing creates fiber undulations and crimps that result in stress concentrations and load transfer vulnerabilities in the fibers 3.

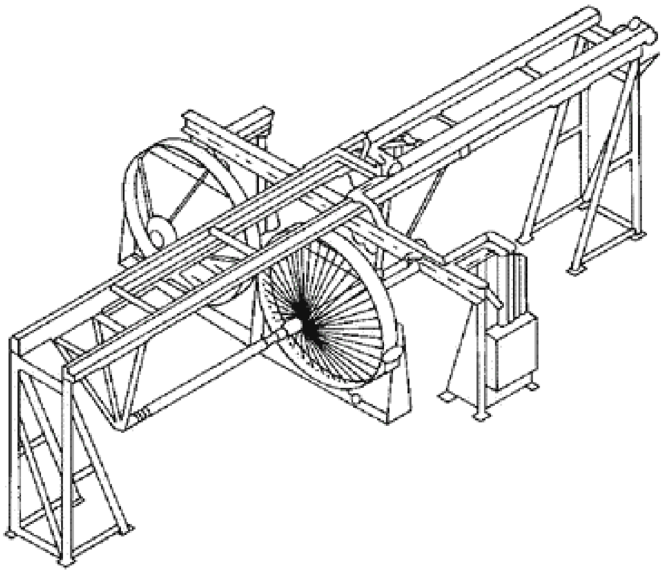


Figure 21: Illustration of a braiding machine (Miracle & Donaldson, 2001)

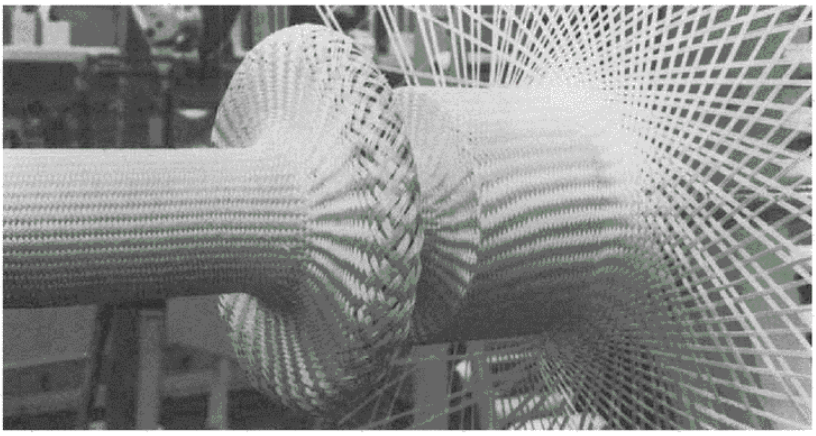


Figure 22: Formation of fiberglass preform for composite coupling shaft (Miracle & Donaldson, 2001)

8. *Twining*:

Also known as 'laid rope', this is a commonly used method for the manufacture of ropes. It involves the mutual 'twisting' of three of more individual yarns into the cordage.

Twining is not commonly used for the manufacture of composites, except in some specific instances where it is an improvement over completely unconsolidated resin impregnated fibres, as used in some of the coreless filament wound structures (Knippers, et al., 2015)

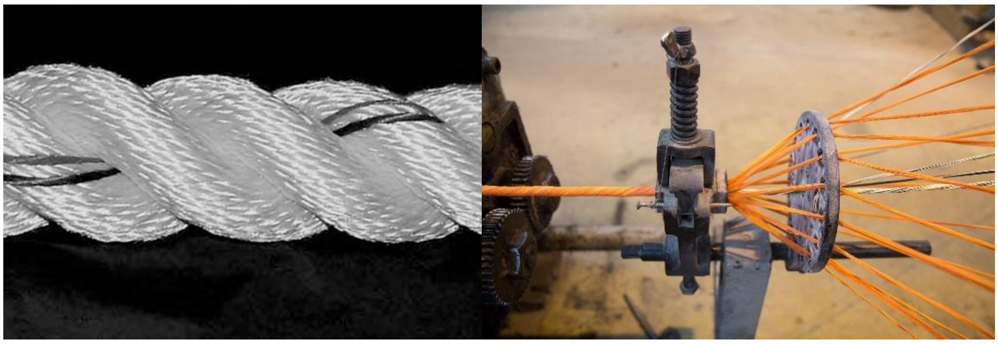


Figure 23: a. Twined rope structures (McKenna, Hearle, & & O'Hear, 2004) b. The making of twisted rope, source: /www.ravenox.com

Figure 24: a. Twisted filament wound glass and carbon fiber rovings used in the Research Pavilion 2012 by ICD and ITKE (Knippers, et al., 2015) b. Twisted impregnated carbon fibers as a method to improve the mechanical properties in the WrapTor truss (Woods, 2019)

FRP based Lattice structures- Some Case Studies

1. *The Assembled Composite Truss*

R Schütze in 1997 (citation) speaks of experiments with tubular foam-filled Carbon Fiber Reinforced Plastic (CFRP) rods used for the construction of a segment of a triangular prismatic truss. They recognize the importance of effective load transfer elements between the CFRP struts and chords for the structure to work as intended. A section of the proposed chord strut joint is shown in Figure (). The joint is prepared by filling the ends of the struts with a filler which is then cured and slitted. This is then slotted into a CFRP 'gusset plate' and adhered. It is already clear that this approach has equal, if not more complexity as a jointing method, than those done in traditional steel frame joineries, and mainly offers the possibility of ‘swapping’ steel or aluminium in traditional cases, with CFRP tubes.

2. *The GFRP Truss*

In 2011, Ju et al. [29] published work involving a glass fibre reinforced polymer (GRFP) truss concept. This structure features three longitudinal members that form a triangular prism, which are connected by helically wound members that run diagonal to the longitudinal axis, and vertical struts that run perpendicular to the longitudinal axis. See Fig (). This truss was tested to failure under three point bending for validation of a nonlinear FE model. The model which was in turn used to compare the bending stiffness per unit weight of he GFRP truss to identical geometry trusses made from CFRP, steel, or aluminium. Results of this study found the GFRP, steel and aluminium trusses had similar bending stiffness per unit weight and that the CFRP performed better.

3. *The IsoTruss® and derivatives*

This is one of the earliest examples of a filament winding based compsite truss construction. Initially developed at Brigham Young University, this method involves the filament winding of carbon fiber tows onto chords directly placed on a mandrel, forming the tetrahedral geometries during the helical winding of the tows. The chords are made of prepreg carbon fiber tubes, and several experiments have been done on the winding tow, from wet winding to prepreg. (citation). The manufacture of this product has been extensively patented by IsoTruss Inc, with applications proposed in bicycle frames, signal towers and other projects.

The IsoTruss® manufacturing process employs a 3d maypole braiding machine to wind the fiber tows onto either a sacrificial mandrel or an external mandrel that presents hooks in teh appropriate positions. As described byBenjamin KS woods in his review of composite lattice structures: *Initial analysis works on the IsoTruss® concept compared the technology to conventional steel beam configurations [6]. The work predicted that IsoTruss® configurations weigh between 1.2 and 19.5% of equivalent strength steel I-beams and solid shafts. Buckling behaviour has been investigated analytically by Sui et al. [11,14] and Rackliffe et al. [9], the latter of which included experimental validation through compression testing of four 3 m long IsoTruss® samples. These studies highlighted how the lattice beams can buckle globally, as an entire column, or via local modes. Dynamic analysis conducted by Sui et al. [15] found that short beams with a high helical inclination vibrate as a cylindrical shell and that longer beams with lower inclinations vibrate as a beam.*

2.3 **Approach and Methodology**

Digesting the Problem:

As suggested by the categorization of the research subquestions and the preliminary proposal, the research by design problem is broken down into three parts: **Part A, Part B, and Performance assessment**

Part A deals with the development of the cordage that can be wound into lattice configurations as per the proposal. It is a problem in FRP engineering. Is it the search for the 'magic rope'. The research in part A ends with a proposal for the design and manufacture of a FRP cordage, with some basic idea how to implement it in part B.

Part B deals with the development of the practical method to shape this cordage into the form of a lattice in an in-situ environment. The conclusions of part A serve as the starting point for this exploration.

Why do it this way?

Structural Idea:

The behaviour of a lattice structure and its failures mode can be categorized as

4) The failure of a '**member**': This can happen through buckling (compression), squash-like failure (compression), and yielding or fracturing in tension.
5) The failure at a '**joint**': once a lattice structure is loaded, there exist a set of internal forces (exerted by the participating struts and chords) acting at every joint, and the joint must have enough integrity to resist these concentrated forces. Failure of a joint results in redistribution of loads and new internal force paths in the lattice structure. When this cannot be resisted, the truss fails
6) The failure at **support**: This refers to a local failure at the interface of the lattice structure and the structural system that bears the lattice and transfers its load down to the substructure.

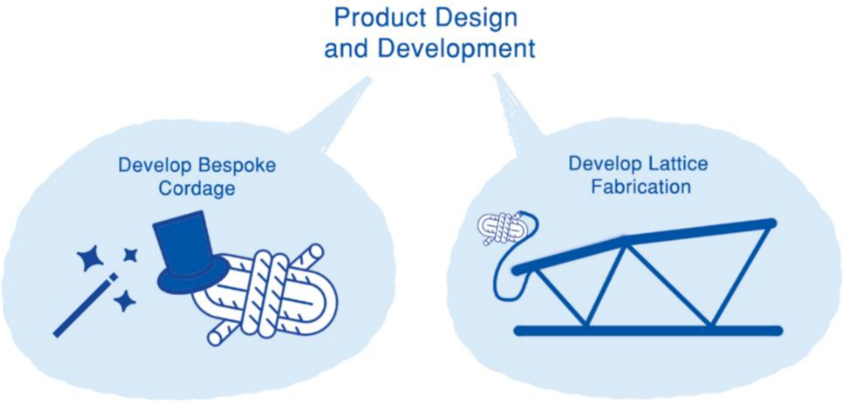
Any of these failures result in failure of the system, and the strength of the structure is determined by the most vulnerable of the above three: the governing failure mode.

Part A and B address points 1 and 2 respectively. Point 3 varies from structure to structure and is thus excluded from the scope of any detailed investigation.

Fabrication idea:

The 'fantasy' speaks of a rope that can be wound into a spool and brought to site, where it is cured. **This means that the manufacture of the rope is a factory process.** Part A deals with developing a rope which is strong enough, but also can be manufactured with known fabrication technology in factory setups today.

The rope once brought to site, must be shaped into the form of a lattice **in situ**. Part B delineates this method, **Interdependency of part A and B:**The design of the cordage is prepared keeping in mind the eventuality of conveniently forming it into a truss on site, and vice versa.



Part A- Overview:

As mentioned earlier, the objective Is to develop the cordage that can be cured on site. The KPI's (Key Performance Indicators) are Structural Robustness, Ease of Fabrication and Eco-Friendliness. It is a clear problem in FRP engineering.

For this aim, the research domains that are explored are:

1. **Material choice and Composition**: What kind of fibres shall be used? What kind of resins shall be used?
2. **Fiber arrangement** and method of compaction: How shall the fibres be laid up/aggregated and consolidated to prepare the FRP?
3. **Curing model**: How is the polymer proposed to be cured on site to form a rigid strut?

These are further explored in the chapter Part A- The Design of the Cordage

Part B- Overview:

A lattice structure's load bearing capacity is only as good as that of its joints, and there needs to be a definite workflow for forming the cordage into a lattice structure.

The research domains hence explored are:

1. What is the design for **preparing the joi**nt in the lattice structure?
2. What is the **failure strength of the joint** and how does it compare with the load bearing capacity of the strut/chord?
3. What is the **step-by-step site fabrication proposal** for the fabrication of the truss?

Performance Assessment and Evaluation:

The evaluation of the technology is possible mainly through a comparison with conventional technology. This also helps to quantify its attributes.

Benchmarking:

A simple lattice girder is considered for this as a design problem, with typical loads as may be expected from a lightweight roof and wind loads, and no other specific context. The design and member sizing shall be attempted with both the flax technology as well as conventional materials such as steel and timber. The resulting designs can be studied for weight, material efficiency, embodied energy and other attributes. This can be found in Section 'Structural Design- A hypothetical problem'

Methodology- a summary:

The process of this thesis research can be understood as shown in Figure 25 and Figure 26.

The nature of this research is a Top-Down approach, as it involves exploring a new fabrication method with a relatively new material science. The focus is on visiting as many topics as possible, to make a rounded commentary on the proposal as a whole, as opposed to a thorough investigation of a narrow niche.

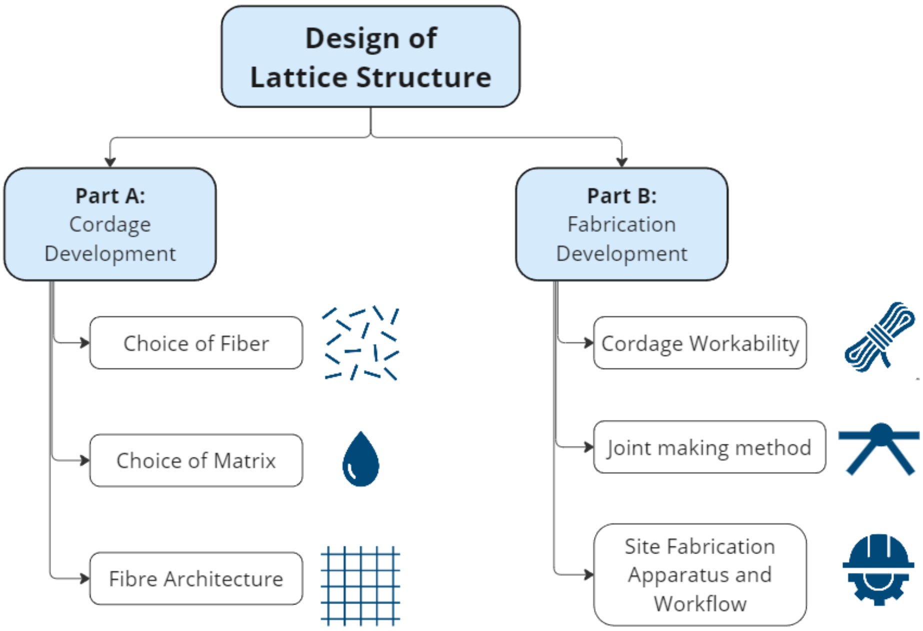


Figure 25: The Research by Design Process for Truss to GO

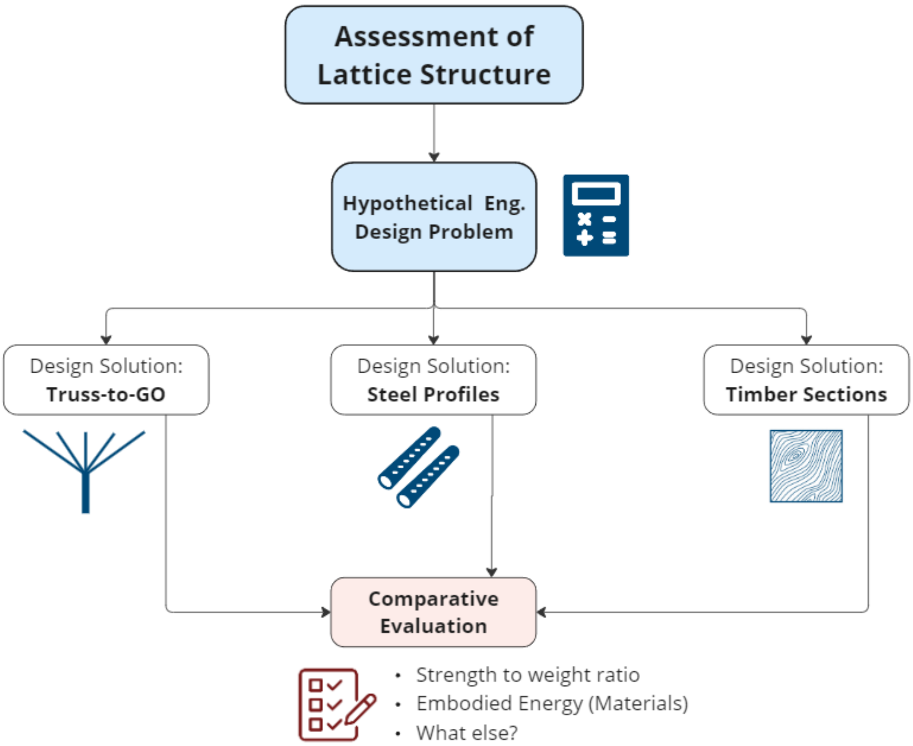


Figure 26: Contextualizing the research findings for Truss to GO

Part 3:

HOW?

3.1 The Design of the Cordage

Designing an FRP element- Topology Classification

The first question pertains to how the fibres are aggregated into a continuous flexible cordage, which is a result of the manufacturing method.

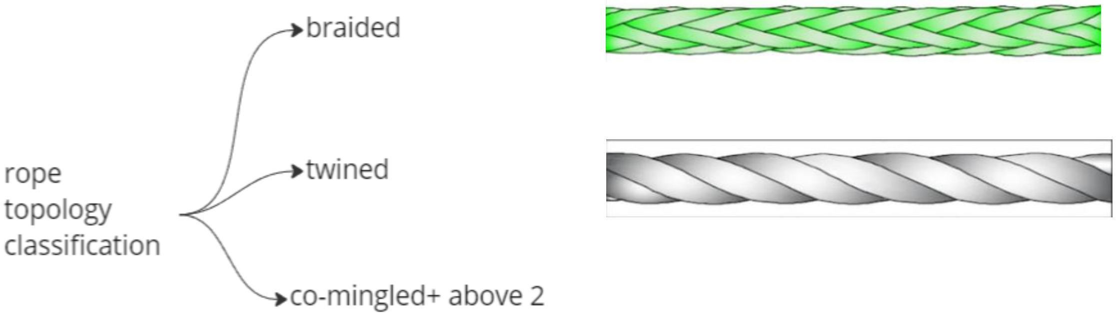
Choosing the correct manufacturing method:

The candidate methods to make linear elements are: Filament Winding, Pultrusion, Roll Wrapping (by hand), Braiding, twining Braid-trusion, Pullwinding, and comingling.

Method	**Remarks**	**Decision**
1. Filament Winding	Better suited to elements of shorter lengths and larger diameters. Not feasible for continuous cordage	Unsuitable
2. Pultrusion	Produces continuous elements, with fibres axially aligned, but includes a curing process (heated die) that outputs rigid segments	unsuitable
3. Roll Wrapping (by hand)	Cannot be used for continuous process, better for short segments of pipes. Challenges of scalability	Unsuitable
4. Braiding	Can be used for continuous cordage production. Resin impregnation can be a separate process (either on individual tows or the rope as a whole)	Potentially suitable
5. Twining	Can be used for continuous cordage production. Resin impregnation can be a separate process (either on individual tows or the rope as a whole)	Potentially suitable

6. CO-mingling/ air-jet texturing	Can be used for continuous cordage production. The polymer is mixed into the fibers as the cordage is made.	Potentially suitable

Based on these, Braiding, Twining and Comingling are considered feasible for further research.



Design of the Cross-Section

A useful parameter that is kept in mind is that with braiding, twining or commingling, it is possible to 'design' the layup of the fibres in the rope's cross section. This is particularly useful for compression design, where aspects of Moment of Inertia or increasing material Modulus at periphery can be explored.

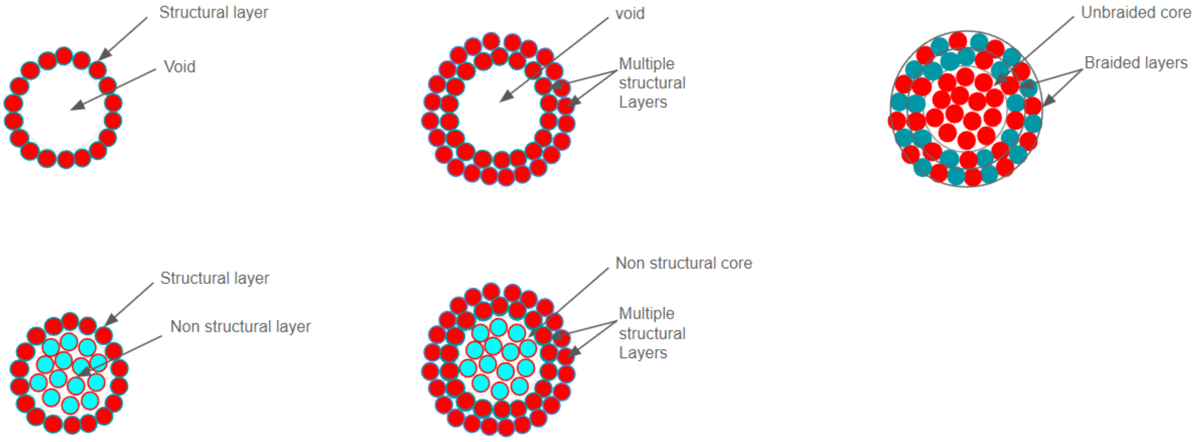
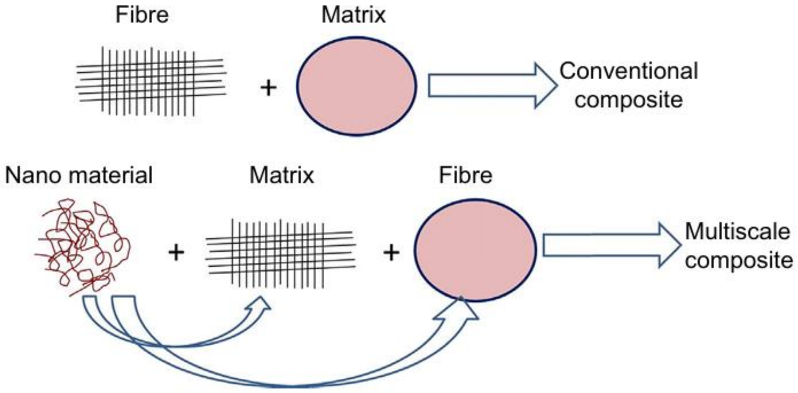


Figure 27: Schematic- The Cross Sectional 'Design' as a function of fiber disposition and make.

Additives/nanomaterials:

It is also possible to improve the strength of an FRP by improving the bond between the fibre and polymer interface at a microreinforcement or chemical level

A common way to do this is by the application of 'sizing' on the fibres. In plane mechanical properties, fracture toughness, and impact toughness are some of the properties that can be improved.



Caption: Concept of fabricating multiscale composites through different approaches. (Rana, Parveen, & Fangueiro, 2016; Rana, Parveen, & Fangueiro, 2016).

Decision 1: Choice of Polymer Matrix

The decision on the polymer matrix is closely linked to the manufacture and fabrication method and strategy, as discussed in the section ***Selection of Polymers :***

There can be two strategies to prepare the FRP truss on site.

1) **Case A**: **The cordage is a 'pre-preg'**- i.e. pre-impregnated. The resin, in its inactive B-State, already coats the fibres of the rope and is activated on site:

   In this method, the key requirements of the resin are:

   - It can be maintained at an uncured state without the investment of much energy.
   - It can be 'activated' on site with an instigating agent that is either available on site (solar radiation etc), or can be carried to site and applied onto the product (as a second component)
   - It is a bio-based resin, and ideally biodegradable, so that the fabricated product, particularly in remote applications, can be easily disposed of without environmental harm

2) **Case B**: **The resin is applied on site** upon the cordage during the lattice winding process.

In this method, the key requirements of the resin are

- It should have a long enough pot life that it can be mixed and prepared as a resin bath, through which the rope can be drawn before being tied into a truss or lattice form.

The preferred method is Case A. In this scheme, the tedious action of a resin bath, along with the setup required to draw several metres (or hundreds of metres) of cordage through the bath can be avoided. Wastage of resin and contamination from excess resin drips are also an issue with the on-site impregnation method proposed in case B.

To pursue any existing technologies that might make case A possible, a market survey was conducted at the JEC Forum 2024 in Paris, France.

The following well known polymer manufacture companies were approached and discussed with

Westlake Epoxy

ResiCare

ADITYA BIRLA CHEMICALS

Sicomin Epoxy Systems

ORSON RESINS & COATINGS

The learnings of the discussions w es of these com s were:

- There is presently no high strength laminating resin on the market that is activated with UV radiation to full curing.
- There are some high-performance adhesives that can be UV cured but this is not applicable for composite laminations.
- Most thermoset resin systems are either cured at room temperature, or with the application of heat.
- The above points are for all resins. Bio-based resins are a still newer technology and more time is needed for the above features to be achieved in the chemical engineering.

Outcome:

Based on these findings, it was decided to **remove the research into resin systems from the scope of the thesis.**

Not only is this a problem in chemical engineering, which lies outside the prior knowledge of the researcher's work, but also there are several areas on investigation within the Truss-To-Go proposal, and research into resin systems would further deepen the experimental matrix to a level that cannot be pursued in the given time.

It was decided to attempt the research using a 'substitute' epoxy resin, while the fibers, topology and manufacturing were the focus of the academic exploration.

The chosen resin was Westlake's Epikote resin L20, used in combination with Epikure Curing Agent 960.

This is a commonly used epoxy system with good mechanical performance (tensile strength 55MPa, compressive strength 130 MPa, as reported by Swiss composite + Hexion- see Appendix) and applications is plane and boat body composites. The resin also cures in room temperature within 24-30 hours, although post-cure at 60 deg C. is recommended. More information can be found in the Appendix.

Unfortunately, this resin system is a bisphenol-based resin system and does not meet the environmentally friendly criteria for the Truss-to-Go proposal. It is used purely as a substitute.

Decision 2: On the Reinforcing Fiber

In keeping with the vision of the product having a good eco-prognosis, natural fibres were the chosen class of fibres.

Among the natural fibres, **flax fibres were chosen** for the manufacture of the composite due to its high mechanical properties (see literature review), availability in the EU area, and relative cost-affordability.

The product was sourced in two forms:

1. **FLAXDRY- BL360**: A twill-woven fabric manufactured by EcoTechnilin (France) with an area density of about 350 gram/sqm (GSM) (courtesy NPSP, Delft, NL)
2. **LINCORE FR520**: A flax roving manufactured by Depestele (France) and provided by Greenboats GmbH . The roving is 4-8mm wide, 0.3-0.5mm thick, with a TEX count of 520 ± 20.

Figure 28 a: : Flaxdry BL360 , Source: eco-technilin.com, b: Lincore 520 flax roving, Source: www.circular-structures.com

Decision 3: Braiding as the chosen method to manufacture the Cordage Textile:

As mentioned in the section *Manufacturing Methods for FRPs* , the promising methods for the manufacture of the cordage were:

Braiding, Twining, and comingling.

- **Twining** can be used for continuous cordage production. However, from the point of view of composites, it is not ideally suited to the manufacture of an axially loaded composite, as each tow (or yarn) of fibres is twisted into a path that is close to 45 degrees (to the axis of the rope). As previously explained in the literature on composite science, It is known that the fiber orientation plays a key role in the load carrying capacity of the composite, and it is desired to align the fibres with the load direction to maximize its structural performance. For this reason, **twining is eliminated** for the purpose of this thesis.

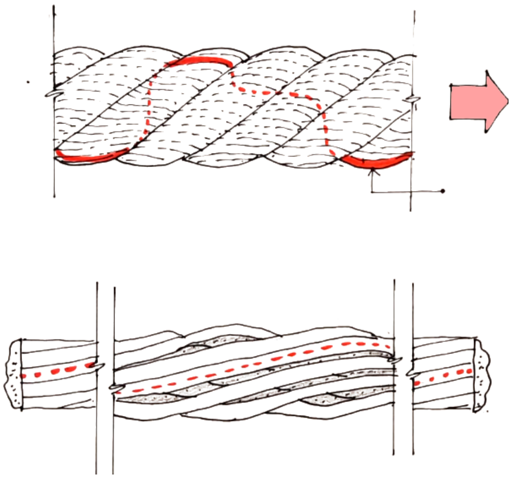


Figure 29: A single fiber in a twined cordage has a significantly convoluted path, first about the tow, and then about the rope itself. Further, the tows are vulnerable to being separated as shown, as they are not actually interlocked, unlike in woven/knitted/braided textile

- **Commingling** can also be used for continuous cordage production. However, it is suitable for thermoplastics, where the polymer is drawn into fibres that are 'commingled' with the reinforcement.

  Further, the process of commingling requires industry equipment and it was not pursuable within the timeframe of the thesis research.

  For these reasons, **commingling is eliminated for the purpose of this thesis.**

- **Braiding is the chosen method for the manufacture of the textile.** This is because of the following advantages which made it attractive for the thesis and as a proposal for the system itself.
  1) **Control of fiber orientation**
     The calibration of the braiding setup and yarn numbers allows for a large range of angles of fibres (with respect to the rope's axis). IT is possible to have a braid angle at as less as 10 degrees, which is favourable for an axially loaded composite.

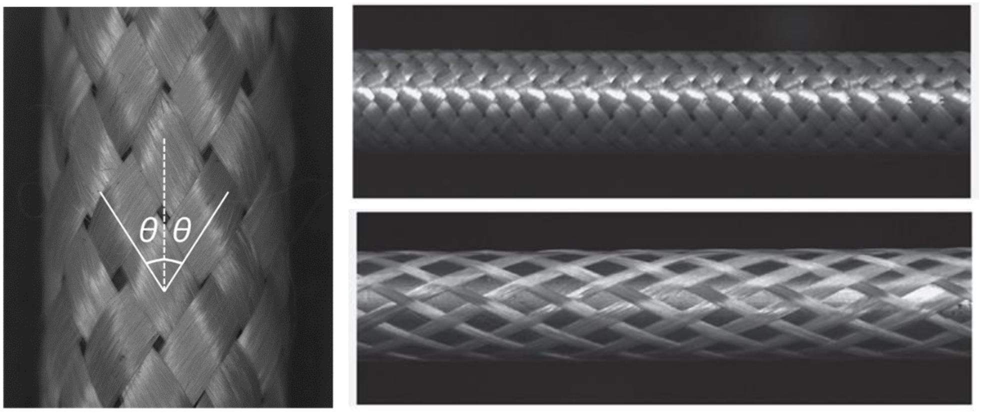


Figure 30: a. Braid angle in a graded rope, b. Deep and shallow braid angles creating different fiber alignments with the rope axis (Carey, 2017)

2) **Possibility to make 'Co-axials' (Fig needed)**

Braiding allows for a 'fiber-layup' via the process of overbraiding. This gives the possibility to aggregate the fibres with more control and effectively 'design' the cross section to achieve the optimum mechanical properties.

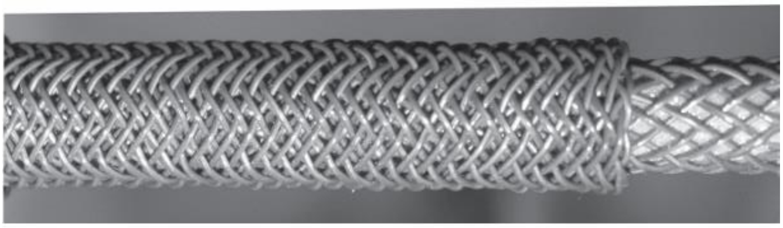


Figure 31: Overbraiding over a braid to create a 'coaxial' layup (Kyosev, 2015)

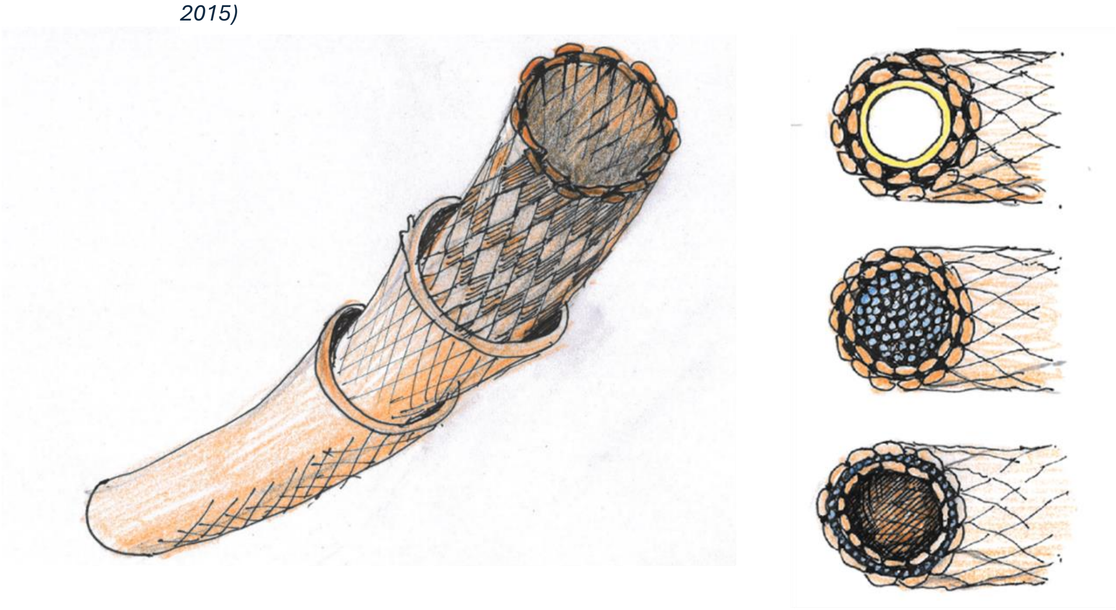


Figure 32: Overbraiding and braid angle calibration could offer good control on the fiber architecture and cross sectional design of the composite.

3) **Scalability of technology**

Braiding is known for its high levels of scalability, versatility (in terms of yarn numbers, braid angles etc) and production output. For a large continuous length of cordage to be produced at industrially meaningful rates, it is a favourable choice.

It is worth noting that a single braiding machine with a given maximum yarn carrier capacity can produce a variety of braid angles (by controlling rope uptake relative to maypole motion), and also ropes of lower yarn numbers than the maximum (i.e- a selective number of carriers can be engaged).

Figure 33: a. An example of a radial braid machine (courtesy Herzog USA), b. Photo of a 12 carrier braid machine at the Textielmuseum, Tilburg, NL

4) **Ideal interlocking of tows (fig needed)**
   Prominent failure modes of composites (especially in compression loading) include fiber buckling (or microbuckling) and delamination. The interlocking of the tows in a braid (which is not achieved in twining or commingling) provides a macromechanical advantage in structural behaviour in this regard.

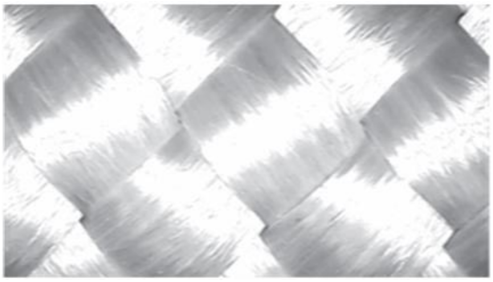


Figure 34: Close up of a 4 degree braid, showing interlocking of warp and weft yarns (Carey, 2017)

A special aspect of the braiding decision: The Consolidation Hypothesis

What consolidation is:

As explained in the previous section, to make a well packed, defect-free and void-free composite, there are 2 requirements in the manufacture stage:

- Good resin flow, in order to fully penetrate the fiber bulk
- Compaction- The close packing of the fibres in the textile

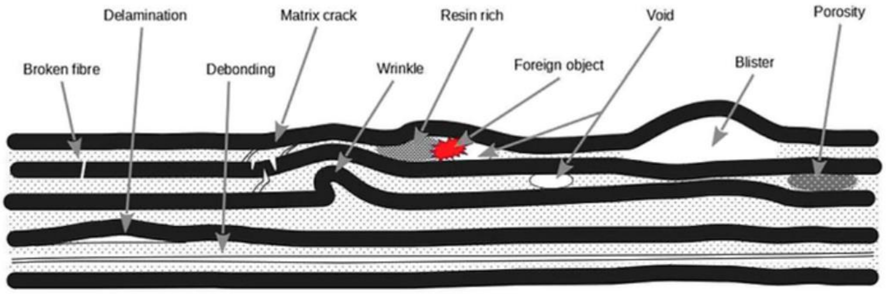


Figure 35: Illustration- Defects in Composite materials (ADDComposites, n.d.)

Typically, pressure is applied to achieve these- through vacuum bagging, hot pressing, pressured dies, hyperbaric chambers, and the like. This squeezes the air out and forces the resin into the full depth of the fiber volume.

In the case of filament winding, for example, the high tension of the feed itself presses the fibers into he the mandrel to achieve the consolidation. In tubular components of small sizes, it is often achieved through roll wrapping or some moulding process(as seen in bicycle frame manufacture).

How to achieve it for Truss-to GO?

The problem is that these compaction methods are a substantial demand for an in- situ manufacture on construction sites. Furthermore, the geometrical 'intricacy' or complexity of a lattice structure makes even a vacuum bagging style approach tedious.

As seen in the literature case studies, the filament wound trusses in the case of the IsoTruss or the Wraptor truss and other design attempts either accept no consolidation at all, or attempt it by a pre process, where shrink wrap, aramid twine, Kevlar tape etc is manually wrapped around each strut and chord to achieve the desired compaction. (**citation**).

For the Truss-to-Go, a novel Idea is proposed, whereby pressure is achieved through the braid mechanics itself. As seen in the familiar toy- the Chinene Finger-Trap, application of axial tension on a hollow braided structure creates a circumferential constriction in the structure, generating a compressive force that proportionally varies to the axial force applied. This idea is also applied to the 'constrictor clutch', a braided jacket that is used to clutch ropes without the need for hard anchors.

Figure 36: Figure 35: A Chinese 'finger-trap' (Harmon, 2021)

Figure 37: A Ronstan Constrictor Clutch (Courtesy: Hamilton Marine)

For truss to go, the fabrication setup for manufacturing a composite out of the braided cordage is as follows:

- The braid is a hollow braid, I.e the braiding of the individual yarns happens about a core mandrel that is later removed
- For resin impregnation, a new mandrel, specially prepared with resin release agent, is inserted into the hollow of the braid
- The resin is applied to the braid, and then the braid is axially tensioned with the mandrel still inside it

The hypothesis is that the constriction of the braid against the mandrel upon axial tensioning will achieve an consolidating effect similar to the pressuring effects of a vacuum bag. This approach of consolidation is more easily achieved on site and much more feasible than vacuum bagging.

In the experimental phase of Part A, this approach is tested.

The BRAID MACHINE! Decisions, Design, Behaviour and Output, Observations, Limitations

Initial Experiments: The Kumihimo Discs:

Braiding at a handicraft or hobby level is possible with a ‘Kumihimo’ disc- a soft handheld disc about which yarns are manually woven in and out of the slots. The braided product is formed at the central hole of the disc. The individual yarns are held in place by friction as they are slotted into the slits in the periphery of the soft material. There are several braiding patterns and designs possible with a Kumihimo disc, and some dummy trials were made using ordinary cotton yarn to observe the braid outputs and get a feel for the braiding process.

Figure 38: A foam Kumihimo disc used for an 8-yarn braid. (Horton, 2020)

Observations: Kumihimo braids:

Braids were produced using 4 and 8 yarns in a simple 4-over-4 process as seen in the figures below.

Figure 39: 4-over-4 and 8-over-8 Kumihimo braids prepared as trial experiments

- The true length of the braid was achieved by gently pulling the braided cordage. This allowed the individual yarns to slip into position.
- Typical maypole style patterns are somewhat difficult to achieve because of the way that slots have to be used and vacated.
- The yarn patterns that are achieved are fairly convoluted, as seen in the highlighted yarn. From the point of view of composites, it would suggest that such braid patterns are not suitable for structural application, as the fibres are not ideally oriented for load carrying.

Reaching out to industries:

Following the unfavourable results of the Kumihimo style approach, companies and industries were approached for a research partnership, to explore whether braid machines could be loaned or borrowed.

The companies and organizations that were approached are:

- NPSP, Delft, NL
- Prince Fiber, Dronten, NL
- Safilin, FR
- Textielmuseum, Tilburg, NL

None of the leads provided an opportunity for working.

Possible reasons for this were logistical or cost related, but it is also to be noted that the approach request was to be able to experiment with a variety of braid angles and yarn numbers to prepare very small quantities of braided cordage. Such a request is understandably difficult to accommodate on a productive braid machine that is to be reserved for research purposes.

The Working of Braid Machines

After unsuccessful industry partnerships, it was decided to investigate making a braiding device or machine in the Faculty of Architecture.

There were 2 possible approaches for the design of the device:

- A rotary device with yarn carriers that worked in the same way as an industry type motorized device.
- A braiding ‘apparatus’ without moving parts, over which braiding by hand is possible.

It was decided to make an ‘apparatus’ without rotors, because it was not clear at this stage of the research how many yarns would be required to make braid samples that were suitable for the research investigations. This was not known because the braid diameter could not be prospectively decided.

Making a braiding device: First Experiments:

- I used a stool from the Espressobar. It was round and had a hole in the centre, which was perfect for the braiding requirement.
- The system used a set of yarns with weights at one end (made of pebbles In socks- easy to calibrate the weight) which hung over the outer rim of the stool. The leading end passed down the hole in the middle where the braiding happened.
- Trails showed that the braiding was possible, as seen in the second fig
- There were some issues with it:
    1) Inconvenient height
    2) The yarns lay flat on the stool and the friction was fraying the yarns
    3) The core that was being braided over had no axial guidance, which was very important to have.

Figure 40: The 'Espressobar' braiding setup.

The Final Braiding Apparatus:

The finally built braiding apparatus was prepared using plywood and other readily available materials (Figure 41). It retained the key idea of manual braiding over a rotary braider as prototyped with the espressobar stool,but it had some key improvements that were necessary:

- There was a suspended rail a few centimeters over the flat table surface- this meant that the yarns make contact only on the rails and on the inner rim of the central hole through which the braid passes. This reduces friction and fraying damage to the rovings.

- There was a second platform suspended over the braiding table- this was a provision for placing spools in case a triaxial braid was later desired.
- There was a final third platform higher than eye level. It had a small hole whose purpose was guide the core of the braid and ensure axiality and keep the braid stable when the yarns were being braided.

Figure 41: The final braiding apparatus, as built and used in the Think Room, Faculty of Architecture TU Delft.

Figure 42: A 16-roving, shallow-angle braid in process

Functioning Of the Braiding Apparatus:

In principle, the apparatus involves manually braiding a pair of yarns, one at a time. The setup involves hanging the desired number of yarn spools around the circular rail with the yarns connected to the braid core (pipe or rod) that passes through the braiding hole. From the bottom of the braid core hangs a precisely calibrated weight.

The system can be imagined as a classic pulley system with the weight of the spools and the counterweight hanging from the core in the centre. The ‘pulleys’ in this case are the circular rail and the rim of the braid hole. Such a setup is, in principle, very convenient, because by varying the central counterweight, various equilibrium solutions can be achieved. From the braiding point of view, this allows for ‘braid cones’ of various proportions, ultimately allowing for control over braiding angle.

The setup sequence is as follows:

- Prepare the desired number of spools with a length of yarn and measure their weight.
- Lay them around the rail as seen in the photo/sketch and secure them to the rail with clips. Leave about 50 cm ‘tail’ towards the braiding centre
- Prepare the core piece with a hook at one end to hang the counterweight
- Prepare the core by passing it through the guide hole and the braid hole. Secure it to the guide platform with a clamp such that the lower end of the core hangs a few centimetres.

- Tape the yarn ‘tails’ to the bottom of the core, around 2-3 centimetres from the bottom. The taping should be very secure. Apply a zip tie or steel wire to tighten if required.

At this point the setup is ready for braiding. The braiding process is as follows.

1. In ‘hairdresser’ style, two spools are shuffled at a time, one passed over the other (if a single person works on it with two hands).
2. Then the same shuffle move is repeated with the next set of yarns, moving around the table in a clockwise or anticlockwise manner. This is continued till all the yarns have been shuffled.
3. At this point, all the yarn crossovers need to be pushed into the braid hole. This is important. Only when this is done does the braid cone ‘settle’ (it can be seen sinking down into the braid hole) and achieve the desired equilibrium state. (The friction between the crossovers make the braid cone act as a rigid grid-shell like geometry that hold its shape. If crossovers exist outside the braid hole, the friction in the crossovers interferes with the self-restoring equilibrium state of the yarns and counterweight.)
4. After this, the shuffle move is reversed, and using the first yarn from the first shuffle and the last yarn from the last shuffle. The one-over-one has to be reversed, and the moves are to be continued around the table in the opposite direction. This pattern then mimics the maypole braid.
5. For over-braiding a second coaxial layer over the existing braid, after the completion of the first braid, the entire setup and process is simply repeated over the existing mandrel.

Practically any braiding pattern can be applied. For this thesis, a simple 1 over 1 pattern was used, as this is one of the common patterns used for braided composites in a Maypole braiding system.

Advantages and disadvantages of the Braiding Apparatus

The setup allows for important benefits:

1. Since there are no slots or carriers, in theory **any number of yarns** can be braided (until the density of hanging spools becomes impractical)
2. The simple equilibrium system allows for setting **up any braid angle** based on the calibration of the counterweight with respect to the spool weights

The disadvantages are:

1. The braiding is essentially manual, so it is a slow process.

2. The height of the device limits the braid lengths that can be accommodated, particularly because the counterweight must hang free. The limit on the device used is about 85cm.

Initial Experiments with Flax

The first set of braiding experiments provided successful results in that consistent and uniform braids were possible. Some general observations:

1. The Flax rovings are much more likely to fray compared to carbon or glass fiber. Particularly in the crossover points between two flax rovings, the friction was sufficient to damage the flax and care had to be taken not to allow the rovings to slide much over one another, a concern usually not present with glass or carbon fibre rovings.
2. The friction at the contact points also caused the flax rovings to twist, resulting in some improper braiding layup upon the mandrel (see Figure 43). This is potentially detrimental to the braid quality, particularly in the case of overbraiding, where subsequent layers do not sit ‘snug’ on the layers underneath.

Figure 43: Initial Experiments with flax braiding on the braiding apparatus.

Final braid parameters:

By trial and error, the following parameters were discovered for the braid configurations

For a braid angle of **15 deg**. the following parameters achieved the result:

- Internal core diameter: **16mm (PVC pipe)**
- Number of yarns/rovings**: 24**
- Roving width**: 4-8mm**
- Spool (with rovings wound) weight:
- Counterweight: **1500 grams**
- Braid cone achieved**: 110mm** from braid ring

For a Braid Angle of **55 deg**, the following parameters were required:

- Internal core diameter: **16mm (PVC pipe)**
- Number of yarns/rovings: **12**
- Roving width: **4-8mm**
- Spool (with rovings wound) weight: **190g**
- Counterweight: **1500 grams**
- Braid cone achieved: **110mm** from braid ring

What do we need from a ‘strut’ member?

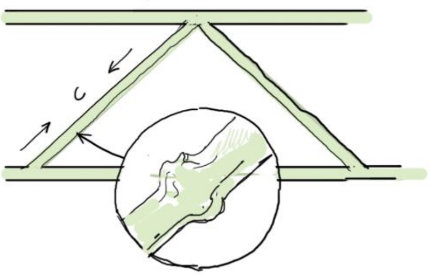
Before beginning with he experimental design and strength estimation of the FRP, we identify the mechanical capacities we require for an FRP element that will be used in the truss.

Simply speaking, a strut or chord in a truss is subject to compression or tension.

This means that it must have appreciable resistance against:

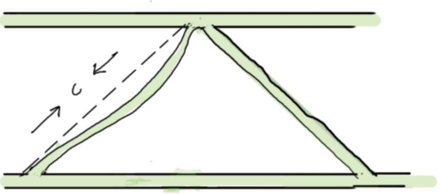
Squash Failure: when the compressive stress overcomes the integrity of the material, and it is locally crushed.

This is a function of the material property

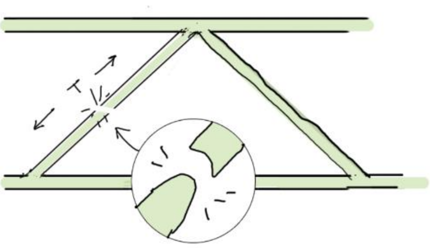


Buckling failure: The relatively slender elements under compression buckle to one side and lose compressive capacity.

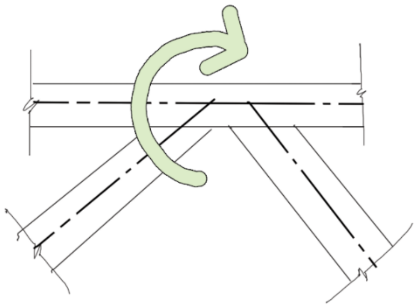
This is a function of the members geometry, and its defects and imperfections.



Tensile failure: Where the tensile forces overcomes the integrity of the material and it tears or breaks. A function of the material property.



. **Joint stiffness (a little bit):** In theory, most lattice joints are assumed to be ‘pin joints’, i/.e they require no moment carrying capacity. IN reality, there needs to be a small amount of joint stiffness, since there are imprecisions in the alignment and fabrications of members and centrelines are not always concurrentFurther, there are some loads on 2D trusses that are out of plane, and joint stiffness is useful in these situations. It is function of both material and geometry.



Chapter Conclusions:

1. The Natural fibre chosen for the research work is Flax. Lincore flax rovings from Depestele are used for this research.
2. A resin that possesses all the properties that are required to realize the product vision does not exist in the market today. For this reason, a substitute resin is chosen in order to continue researching other aspects of the product development. The resin chosen is Westlake's Epikote and Epikure 2 component epoxy.
3. Of the various ways in which FRP's can be manufactured, braiding is chosen as the best candidate. It appeared to be the best candidate for making continuous textile for the manufacture of FRP's. It offers control on fiber orientation, cross sectional fiber architecture (by over-braiding), good fiber interlocks, and Is a scalable technology.
4. It is also chosen to test a possible consolidation method by constricting action, circumventing vacuum bag or other more site-unfeasible compaction methods. Consolidation is crucial for good quality FRPs, so the strategy for consolidation is a challenge for the in situ fabrication of trusses,
5. A braid machine is developed after a few small scale experiments, upon which flax braids of varying yarn numbers and braid angles can be easily (but slowly) prepared.
6. The setup parameters are established in order to make braids in the range from 15 degree to 55 degree.
7. Before beginning with the experimental design and testing of the cordage that will be formed into a composite, the performance indicators are identified for a 'strut' or 'chord' member. They are Squash resistance, buckling resistance, tensile strength, and some stiffness at the joints.

3.2 **Experimental Research: Cordage Design (Part A)**

This section focuses on the experimental investigation into the mechanical and handling properties of braided flax FRP. (part A only).

The goal is to:

1. Prepare samples of the flax FRP using the braiding process, followed by a resin impregnation process
2. Estimate the mechanical properties of the samples and assess it in terms of the literature on similar braided composites.
3. Make a hypothesis about how the properties can be improved based on changes in the manufacture and design of the sample
4. Prepare new samples and repeat the test process until mechanical properties reach a plateau (cannot be improved within the timeframe and under the circumstances).

The set of experiments can be broken down as:

Series 1: tensile test of single roving:

Series 2: squat compressive tests of 3-layer braided tube composite vs roll wrapped woven flax braid

Series 3: squat compressive tests of 6-layer braided tube composite (vacuum bag)

Series 4: squat compressive tests of 6-layer braided tube composite (pre tensioning hypothesis)

Series 5: squat compressive tests of 6-layer braided tube composite, pre tensioned, with **lateral reinforcement.**

Series 6: Tensile test on braided composite.

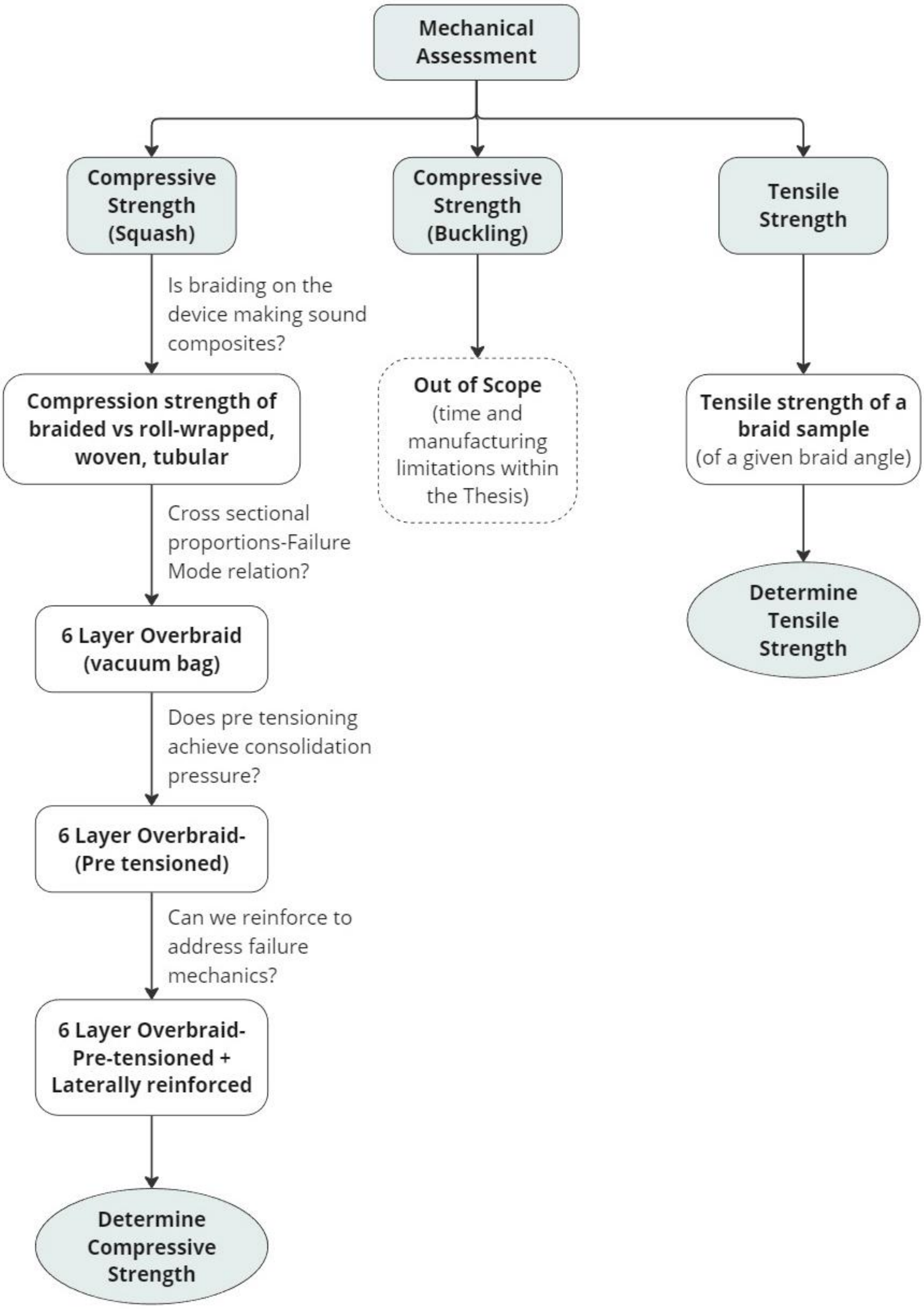


Figure 44: Experimental series for cordage development: A Flowchart

Series 1: tensile test of single roving

Objective: Simply to assess the tensile strength of a single roving of flax provided by the manufacturer, as this is used for the fabrication of the remaining composites for analyses

Background: As shown in literature review, natural fibres can have large variations in tensile strength and stiffness. This is due to the variations in plant growing conditions, year of harvest, effects of processing methods turning bast fibres into rovings, and the moisture content of the roving itself at any particular time.

Methodology:

Prior Preparation

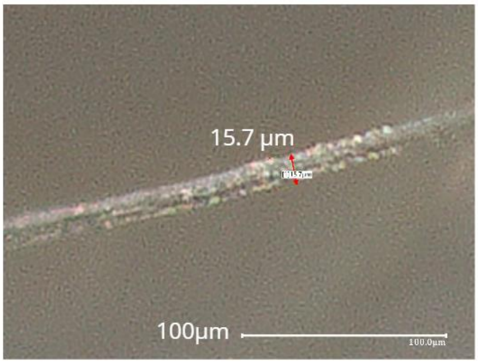
a. The flax rovings are first heated at 50 deg C in an oven for 10-12 hours to remove moisture.
b. A small portion of rovings are investigated under a microscope (name of microscope) to cross check the technical data provided by manufacturer reg. flax fiber diameter.

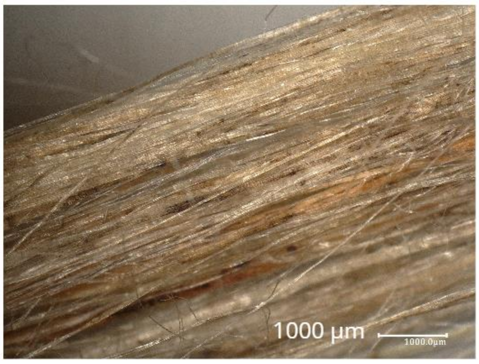
Test setup and procedure

c. Each sample of roving is prepared with a 120mm length and end tabs prepared with emery paper.
d. 5 such samples are prepared.
e. The machine used for the tensile test is a UTM, namely the Zwick Z10
f. The specimen end tabs are clamped in the end grips of the UTM
g. Tensile load is applied to the roving at a rate of 0.2mm/second, until failure. Test ends when the load drops with the fracture/tearing of the roving
h. This procedure is repeated for 5 samples.
i. Results are recorded, namely load at failure and millimetres of elongation
j. Using the data, the failure stress of the sample is calculated using the cross sectional area of the roving and the failure load
k. The percentage extension is calculated for the linear elastic portion of the load displacement curve to calculate the Young’s modulus

Observations, results, calculations, and inferences:

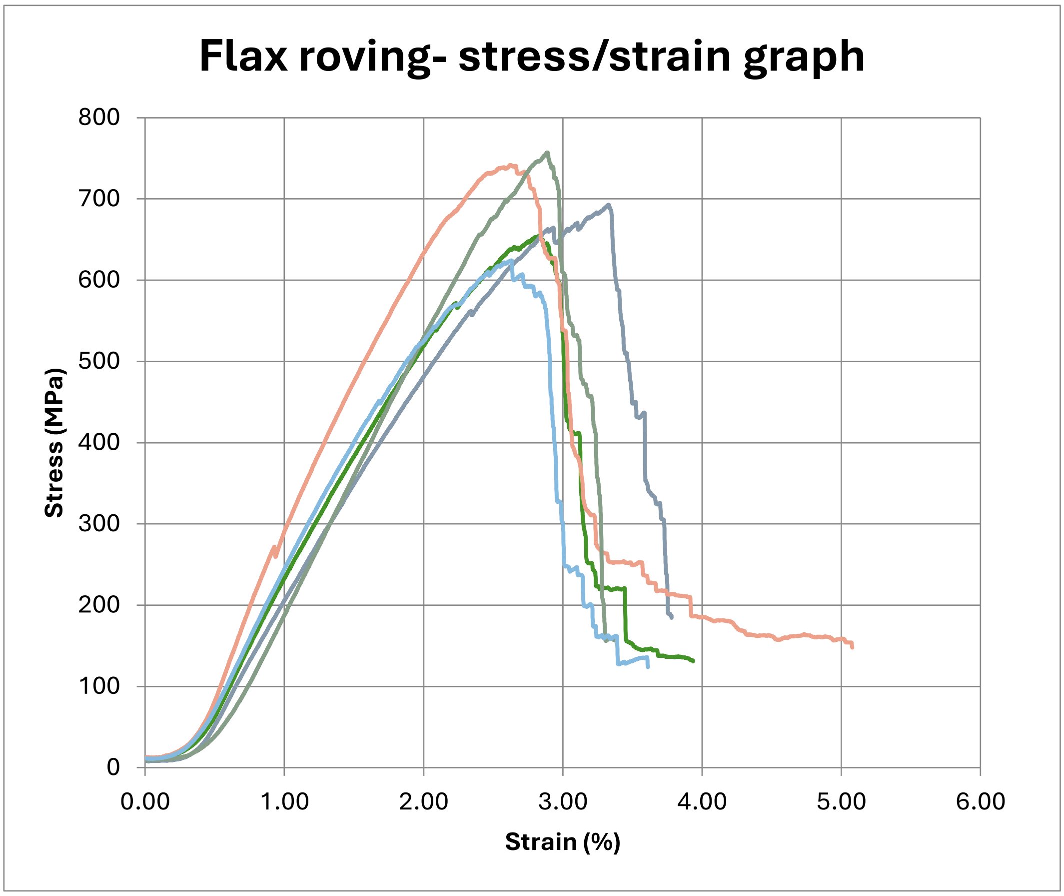
- Weight reduction: Upon heating in the oven at 50 deg for 10-12 hours, there was a 3% reduction in mass. (3.4g-3.3g). This can be attributed to loss of moisture, as literature suggests similar, and flax is not known to have any other volatile chemicals that vaporize at these temperatures
- The microscopic study across several images shows that the diameter of a single flax fiber is between 15- 16 µm. This is consistent with the literature on flax fibres.





- The cross section of a single 520 tex roving can be calculated as follows
  $(520) \times \pi \times 16^2/4 = 0.1044\text{mm}^2$

- Based on the load values and dimensions of the roving, the following values are obtained.



specimen	Tensile failure stress (Mpa)	Young's modulus (MPa)
1	654.8928301	55744.63739
2	692.9225849	52335.96833
3	741.9048324	66449.89426
4	757.1668369	61603.38704
5	624.327751	57961.74275
average	**694.242967**	**58819.12595**

These values are consistent with what is seen in literature.

Series 2: Squat compressive tests 1: 3-layer braid vs woven fabric

Objective: to assess whether the device makes acceptable braids for an frp manufacture, to compare against typical FRP made by roll wrapping- via squat compression test.

Background: Braiding and roll wrapping are two well-known methods to make composites.

Roll wrapping is used for smaller scale fabrications as usually only limited lengths can be handled in a rolling press or by hand. This method is an established method used for making tubular FRP elements.

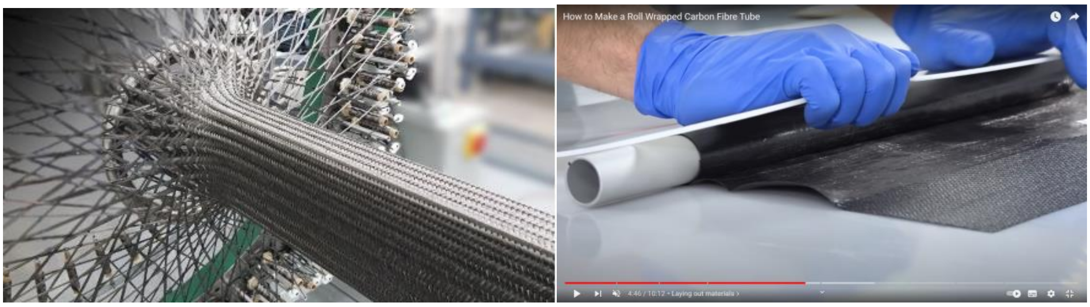


Figure 45: a. Braiding of carbon fiber, b. Roll wrapping carbon fiber prepregs to make a roll wrapped tube

The concept behind this test series is to make two sets of samples, one with braiding flax, and the other by roll wrapping flax twill weave. Then these tubular elements are cut into squat cylindrical samples for compression tests to assess their compressive capacity.

The general failure modes of a tubular composite in compression can be categorized as

a) Micro-buckling of fibres
b) Diamond shaped buckling
c) Concertina buckling
d) Euler buckling

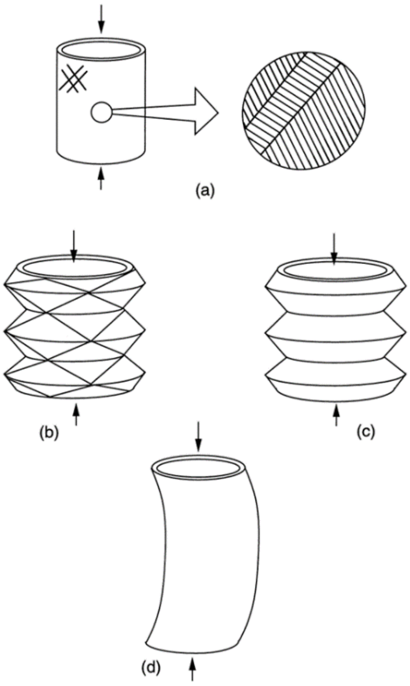


Figure 46: 4 modes of tubular composite compression failure, adapted from (Harte & Fleck, 2000)

Further, It is known from the literature that the load carrying capacity of the composite relies heavily on the orientation of the fibers, and the fiber volume fraction of the composite. As seen in this study by (Harte & Fleck, 2000).

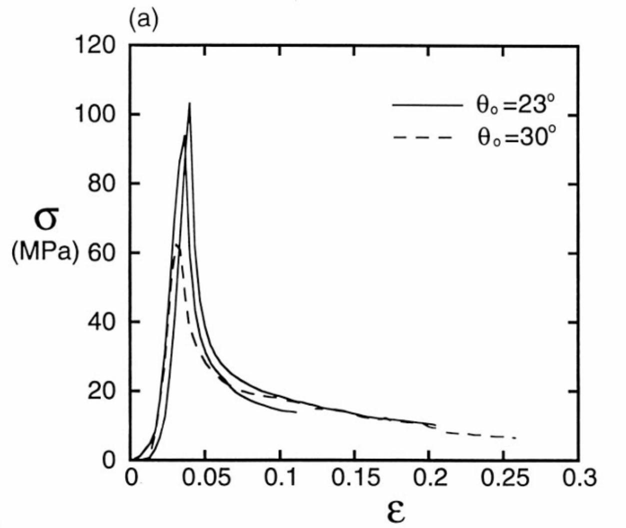


Figure 47: large variations in the failure stress of a single layer squat cylinder GFRP tube in compression braided at 23 and 3 degrees. Source: Fleck (2000)

Materials used, equipment used, and fabrication method:

Series 2a:

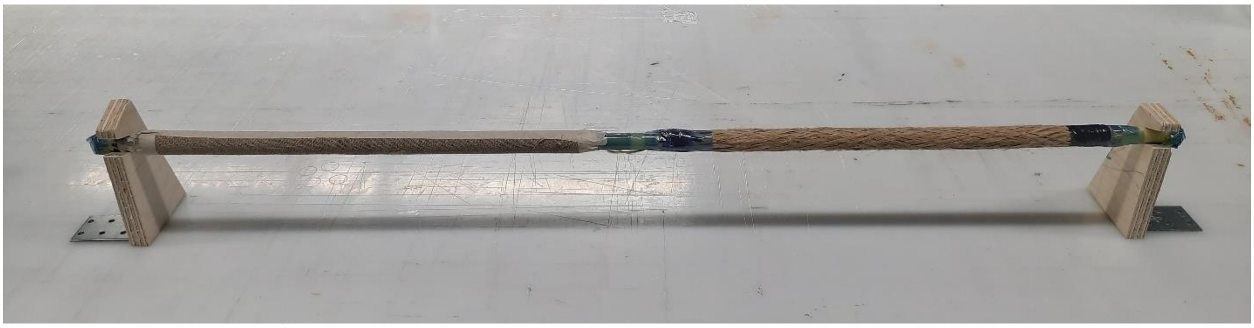
- Lincore flax 520 + Epikote Epicure 04901
- 3 layer overbraid, inner dia 16mm, braid angle 25 degree, pvc pipe as core
- Resin applied by brush and allowed to wick into braid

- Vacuum bagged at 930 millibar pressure for 24 hours

Series 2b:

- FlaxdryBL360 twill weave
- Rollwrapped around 16mm pvc pipe
- Resin applied by brush and allowed to wick into weave
- Vacuum bagged at 930 millibar

The resulting samples were retrieved, and the pvc core removed. The samples were then cut to 30mm squat cylinders with a diamond saw.



Testing procedure: The prepared cylinders were placed in the Zwick z10 and loaded at a rate of 0.2mm/second until they had defomed by 25% of their initial height.

Observations, results, calculations:

Fabrication process:

- Flax responds very well to brush application of resin as the fibres wick the resin at a high rate, compared to what is seen in carbon fiber or glass fiber textile.
- Woven flax does not lend itself well to roll wrapping as there is too little stiffness in the textile to make a tight roll wrap around pvc. This created a lot of slack, which resulted in deformed cross sections upon vacuum bagging.

- Interestingly, in the braided flax samples, the ‘pinching’ from the vacuum bag creates a **pattern of ridges** that are substantially thicker, and could possibly aid in compressive strength through geometry and resist buckling. However this is not a controlled process.
- Resin impregnation appears thorough in both the woven and braided samples.

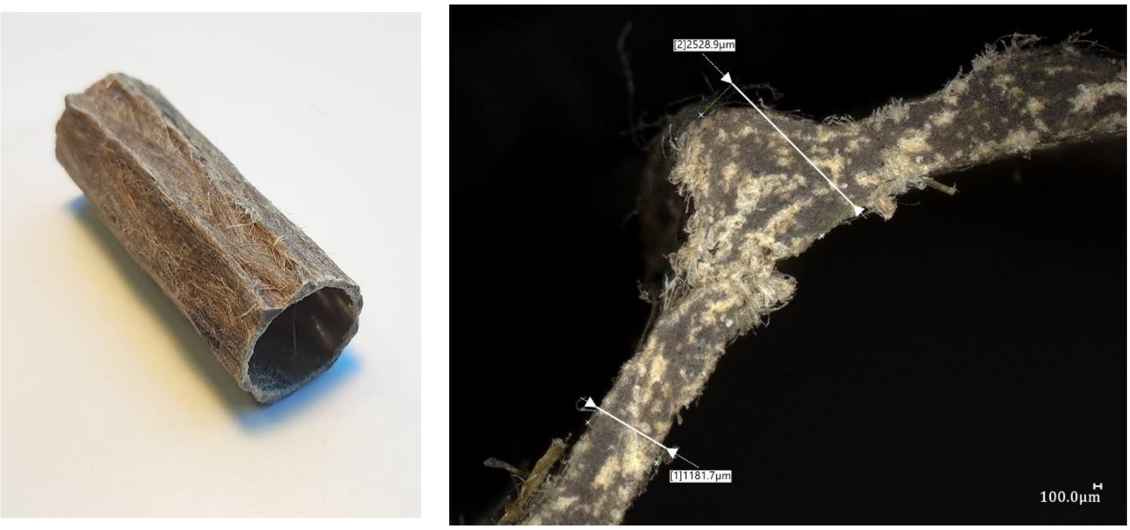


Figure 48: a. 'Ridges' formed by the pinching from the vacuum bag b. the ridge as seen under a microscope, showing the bundling of fibres

- In the woven flax composite, there appear to be defects and air voids in the cross section, that could also compromise the strength of the composite.

-

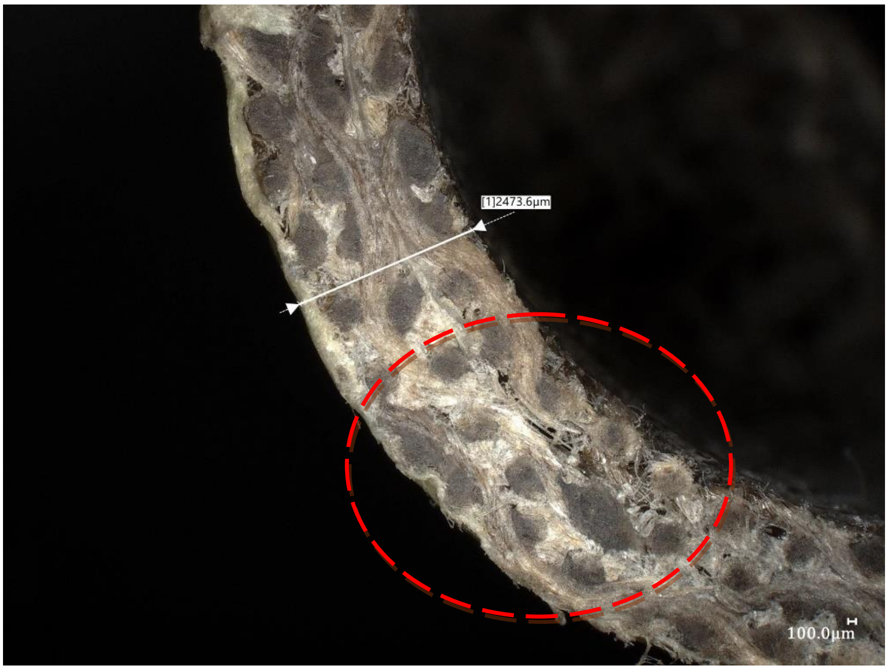


Figure 49: Cross section of woven flax composite as seen under microscope. The presence of voids and imperfections is apparent

-

Fiber Volume Fraction:

Weave cylinder:

Area of twill sample used: 600 cm^2

Weight of flax (W_f): 21.18g

Density of flax (provided by manufacturer (ρ_f): 1.45g/cm3

Volume OF falx in sample (V_f): 14.6cm3

Sample dimensions after impregnation: Length : 40cm, ID: 16mm, OD:19.8mm, CS area: **106.7mm2**

Sample weight (W_c): 42.76g

Density of epoxy (ρ_m): 1.15g/cm^3

Fiber volume fraction: $\frac{(W_f/\rho_f)}{(W_f/\rho_f)+[(W_c-W_f)/\rho_m]}$

= 43.76%

Braided cylinder:

Weight per length of flax braid (W_f): 0.29g/cm

Density of flax (provided by manufacturer (ρ_f): 1.45g/cm3

Sample dimensions after impregnation: Length : 13cm, ID: 16mm, OD:17.85mm, CS area: **44.92mm2**

Sample Weight: 18.04g

Sample Weight per Length (W_c): 0.59g/cm

Density of epoxy (ρ_m): 1.15g/cm^3

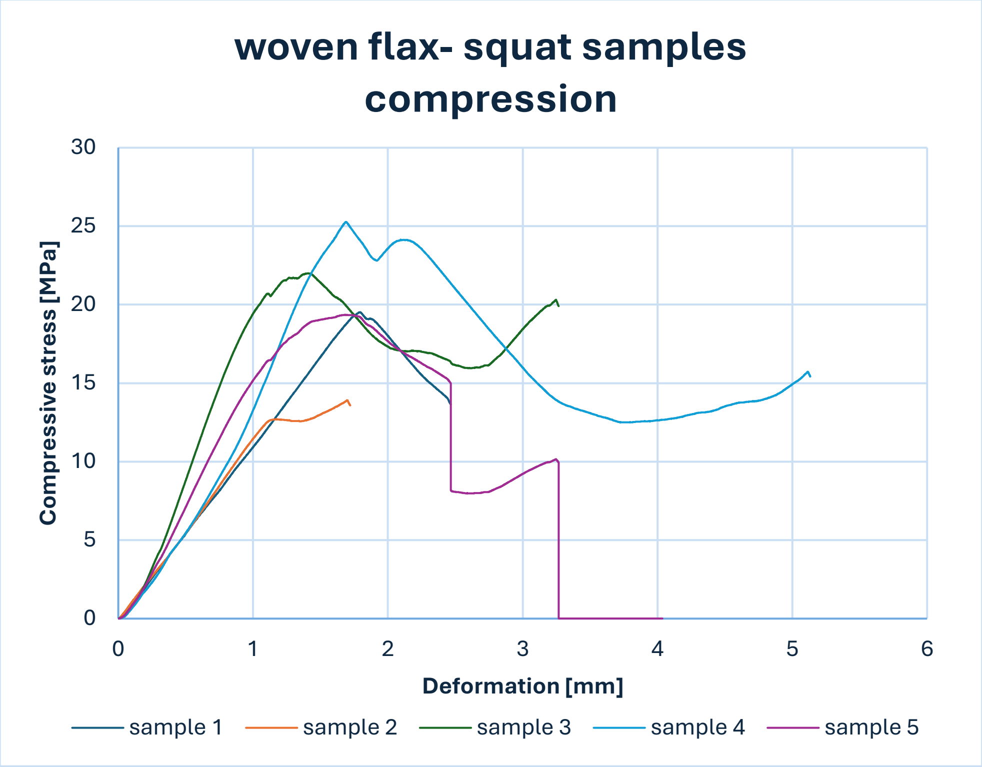
Fiber volume fraction: $\frac{(W_f/\rho_f)}{(W_f/\rho_f)+[(W_c-W_f)/\rho_m]}$

= **43.48%**

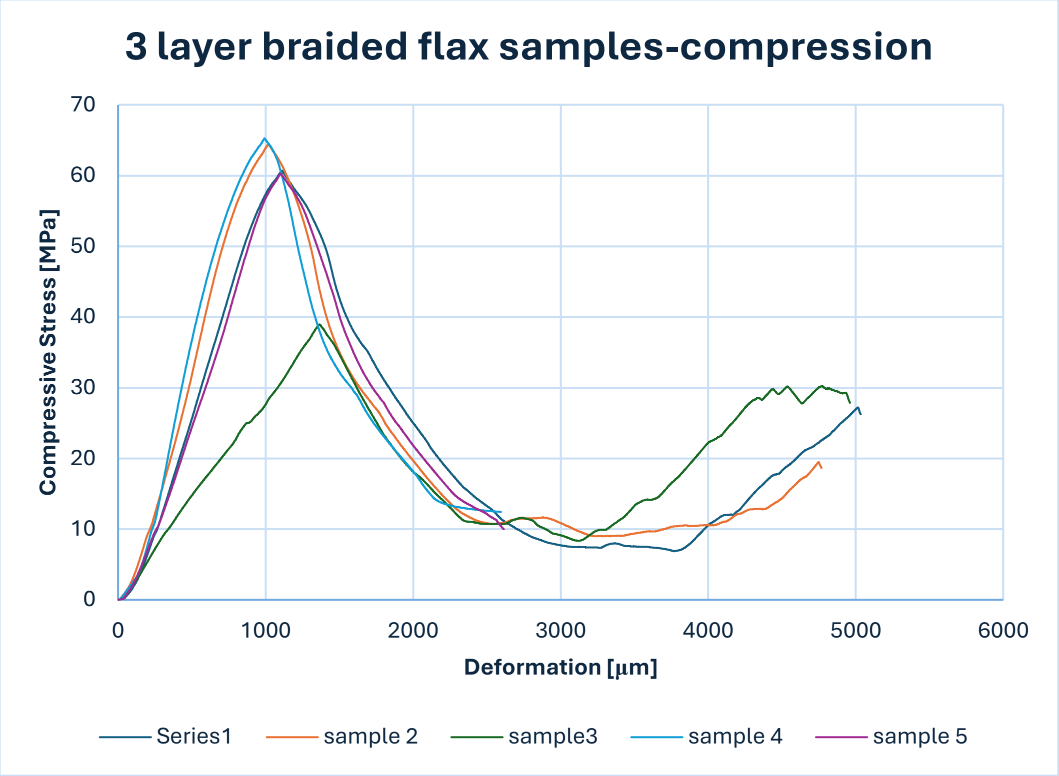
Load testing :

Based on the cross section areas of the cylinders, the compressive strengths are recorded.

Weave Cylinder:



sample	failure stress compression (MPa)
1	19.51699969
2	13.91726951
3	21.99339104
4	25.27137363
5	19.34459282
average	**20.00872534**



sample	failure stress compression (MPa)
1	60.70201527
2	64.42036577
3	38.9624606
4	65.24859619
5	60.30960915
average	**57.9286094**

Failure mode:

The woven sample of a wall thickness 1.9mm failed by a diamond shaped buckling similar to what is seen in thermoplastic tube sections under compression.

The braided samples failed in a distinct microbuckling pattern, as the polymer sheared. In some cases, they followed the 'natural fault' of the braid contours, at an incline, and in other cases they failed in a band perpendicular to the axis of the cylinder.

Figure 50: Failure pattern in braided composite (left) and woven composite (right)

Figure 51: Fiber micro-buckling in the braided composite, as seen under a microscope

Inferences and next steps:

1. There is an **inherent flexibility in flax textiles that creates play and slack**, especially around tight geometries and small radii of curvature, when vacuum bagged. This appears to be less of a problem for flax composites that are manufactured as panels or shell-like structures which are flat or have less acute curvatures.
2. The vacuum bag process results **in consistent fiber volume fractions** in both woven and braided samples, with a value between **43 and 44 percent**, which is reasonable for composites, as advised by researchers at TU Delft Aerospace.

3. The **benefit of appropriate fiber orientation is clearly apparent** when the strengths of the braided and woven flax are compared. Both products have near identical F.V.F, however the braided flax with fiber orientations at +25/-25 has a strength around 2.5 times greater than the woven sample with a fiber orientation of +25/-65 (based on how it is wrapped around the mandrel).
4. The ‘home-made’ braiding process seems to produce reasonably consistent fiber arrangement as 4 of the 5 samples have good agreement in their compressive strength. IT is not clear the reason for the significant deviation on sample 3.
5. The wall thickness of the braided flax, achieved by three layers of braiding is less than 1mm and results in a **‘thin-wall’ type cross section** which was not expected, and is **possibly unsuitable** for structural applications in a lattice girder, as it is vulnerable to local wall buckling and manufacturing imperfections.
6. The strength of about 60 MPa is not particularly impressive for a fiber-reinforced composite, especially considering that the neat resin alone has a compressive strength of 120Mpa (from technical datasheet). This might suggest that the fibres almost behave as a vulnerability or fault in the matrix bulk in compression.
7. The other possibility is that the composite is simply poorly manufactured.
8. ***Based on these results, it is concluded to proceed with the hand braiding process.***
9. ***The next series of test is aimed to <u>increase the wall thickness</u> of the composite tube using 6 layers of braid instead of 3, and repeating similar compressive tests to assess if <u>a thicker wall creates any difference in the failure mode or failure strength.</u>***

Series 3: Squat compressive tests 2: 6 layer braid

Objective:

To assess whether a thicker wall on the tubular cross section will change the failure mode and the compressive strength of the composite.

Background:

Considering the nature of the microbuckling that is seen ‘through-and-through’ the wall thickness, it it hypothesized that imperfections and faults in the braiding might lead to premature failure of the composite if the wall is too thin. As a hypothesis based on engineering intuition, the idea is to check whether increasing the bulk will change the failure behaviour of the composite.

Materials, equipment, and Fabrication method:

- Lincore flax 520 + epikote epicure 04901
- 6 layer overbraid, inner dia 16mm, braid angle 25 degree, pvc pipe as core
- Resin applied by brush and allowed to wick into braid
- Vacuum bagged at 940 millibar pressure for 24 hours.

The resulting samples were retrieved, and the pvc core removed. The samples were then cut to 30mm squat cylinders with a diamond saw.

Testing procedure: The prepared cylinders were placed in the Zwick z10 and loaded in compression at a rate of 0.2mm/second until they had defomed by 25% of their initial height.

Observations, Results and Calculations:

Fabrication Process:

- The vacuum bag again creates ridges, and of an even more significant proportion
- Resin impregnation of fibres appears thorough.

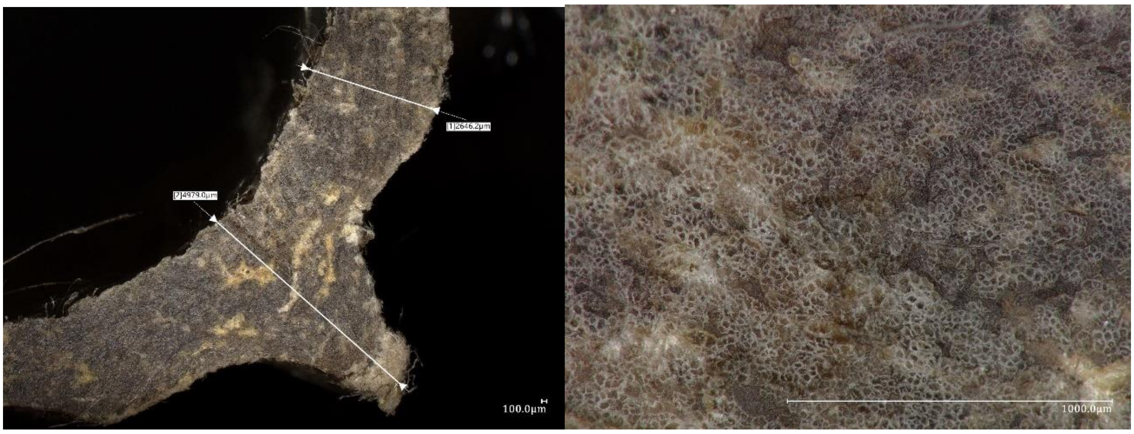


Figure 52: Top: Result of 6 layer vacuum bagging, showing 'pinching' effect of bag. Photo taken before removal of PVC mandrel. Bottom left: Cross section at a ‘ridge’ measuring 4.9mm, as seen under microscope. Bottom right: Cross section of composite bulk showing thorough impregnation of fibers.

Fiber Volume Fraction:

Braided cylinder:

Weight per length of flax braid (W_f): 0.81g/cm (28.5g over 35 cm)

Density of flax (provided by manufacturer (ρ_f): 1.45g/cm3

Sample dimensions after impregnation: Length : 30.2cm, ID: 16mm, OD:18.45mm, CS area: **145.2 mm2**

Sample Weight: 49.35g

Sample Weight per Length (W_c): 1.63g/cm

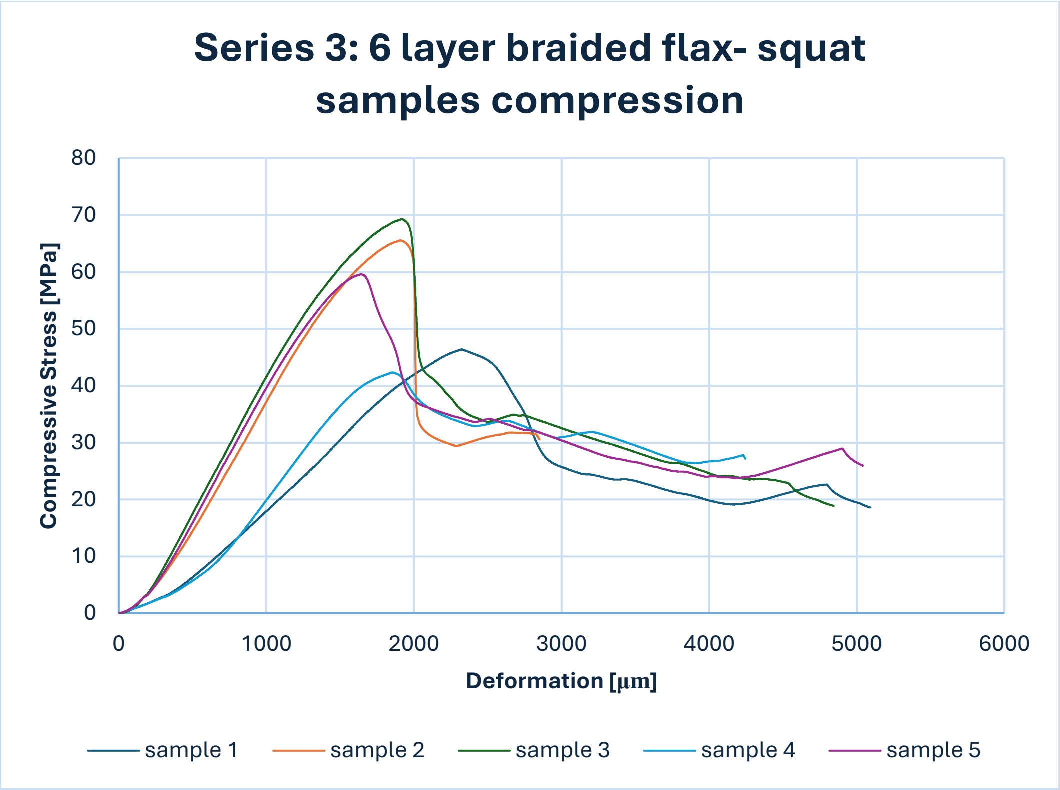
Density of epoxy (ρ_m): 1.15g/cm^3

Fiber volume fraction: $\frac{(W_f/\rho_f)}{(W_f/\rho_f)+[(W_c-W_f)/\rho_m]}$

= **43.9%**

Load testing:

Based on the cross-section area of the composite, the compressive strengths are recorded.



sample	failure stress compression (MPa)
1	46.40366736
2	65.58284371
3	**69.32177331**
4	42.34707919
5	59.63855754
average	**56.65878422**

Failure Mode:

- The failure mode in all 5 samples was through an **out-of plane** microbuckling
- The ridges appeared to 'break' the buckling band in most cases and limit them to small sections
- In all cases but one, the micro-buckling band was horizontal , i.e. perpendicular to the axis. In one sample the micro-buckling was induced along the seam of the braid. This is sample 4, which records the lowest compressive strength at 42.3 MPa

Figure 53: a. A sample of 6 layer braided composite before compressive test. b-f: compressive failure of 5 samples by microbuckling. F shows micro-buckling along the braid seam

Inferences and next steps:

- The FVF achieved through vacuum bagging remains at an acceptable and consistent 43.9%
- Contrary to expectations**, there appears to be a slight decrease** in **compressive strength** compared to the three layer braided composite. It is unclear at this exact stage what the reason might be.

  Possible explanations are: a. The increase in wall thickness increases the probability of defects in the composite, through a 'size-effect', b. there are imperfections in the braiding process of 6 layer braid. c. it is a coincidence and the sample size is too small to draw the conclusion that there is a decrease in strength capacity compared to series 2A.

- Hypothesis: The shape and profile of the microbuckling bands may suggest that the failure of the composite is very sensitive to fiber geometry and imperfections, as the failure progress shows the rest of the sample bulk appearing fairly intact, while the buckling band undergoes complete deformation.
- The ridges appear to help limit the microbuckling bands to small segments.

- **Hypothesis**: The consistent ‘out of plane’ nature of the failure suggests a particular vulnerability to the tubular composite flaring out in the squash failure. This may be due to the mostly axial orientation of fibres being **unable to resist a kind of ‘hoop force’ that develops in the cross section**. It may be possible to improve the compressive capacity **by introducing lateral reinforcement** with a layer of fibres aligned in a circumferential pattern that can resist the ‘flaring out’ through tension.

Series 4: Squat compressive tests 3: 6-layer pre tensioned braid

Objective

To assess whether an acceptable composite can be prepared without a vacuum bag procedure, using a pre tensioning method instead.

Background

Though the consolidation of a composite is crucial for optimum mechanical strength, the procedure of vacuum bagging is ill suited to an on site preparation of an FRP composite, because:

- The vacuum bag demands additional materials and electricity supply and a clean workspace free from dust and sharp objects. This is quite an ask at a construction site
- The intricate geometry of a lattice structure makes an application of a vacuum bag quite tedious and impractical. The joints in particular pose a major challenge to vacuum bag

Projects like the Iso-truss™ and its derivatives have shown the use of a post process to consolidate the fibres. Some trialled ideas are, braided sleeve, shrink wrap, aramid spiral wrap and twisting of tows. However, these methods over a larger scale could be labourious, particularly in off-shop on site situations.

Based on the idea of the Chinese finger trap, the idea for Truss-to-Go is to test whether sufficient constriction pressure can be achieved by axially tensioning the hollow braid about a non structural core mandrel such that a vacuum bag is not required to achieve consolidation.

Materials, equipment, fabrication:

- Lincore flax 520 + epikote epicure 04901
- 6 layer overbraid, 24 rovings/layer, inner dia 16mm, braid angle 25 degree, PVC pipe as core
- Setup on a custom pre tensioning jig with spring to measure tension
- Resin applied by brush and allowed to wick into braid
- Pre tensioned at a force of approx. 45 kg and excess resin allowed to drip off

Figure 54: the pre tensioning rig for a single tubular sample, b. excess resin drip-off upon tensioning

The resulting samples were retrieved, and the PVC core removed. The samples were then cut to 30mm squat cylinders with a diamond saw.

Testing procedure: The prepared cylinders were placed in the Zwick z10 and loaded in compression at a rate of 0.2mm/second until they had deformed by 25% of their initial height.

Observations, Results and Calculations:

Fabrication process:

- the pre tensioning requires careful design of the end grips as there can be a lot of slippage, particularly when the fibres are wetted.
- There was a slippage at one of the end grips before full tension could be achieved. Hence the tension achieved was no more than 30 kg.
- The surface finish of the product was of a poor quality, as the outermost layer was not constrained to lie flat on the cylinder surface. Further, some resin that did not drip off the braid surface and cured while on the product.
- Upon cutting of the sample, it was seen that the cross section was more uniform than the vacuum bagged Series 3, but also of a much higher wall thickness at 3.5mm approx., though the fiber count remains the same as in Series 3 (6 layer braid at 25 degree)

- Further, in the microscope are clearly visible a comparatively poorer consolidation, along with the presence of some poorly impregnated fibers and neat resin pockets.

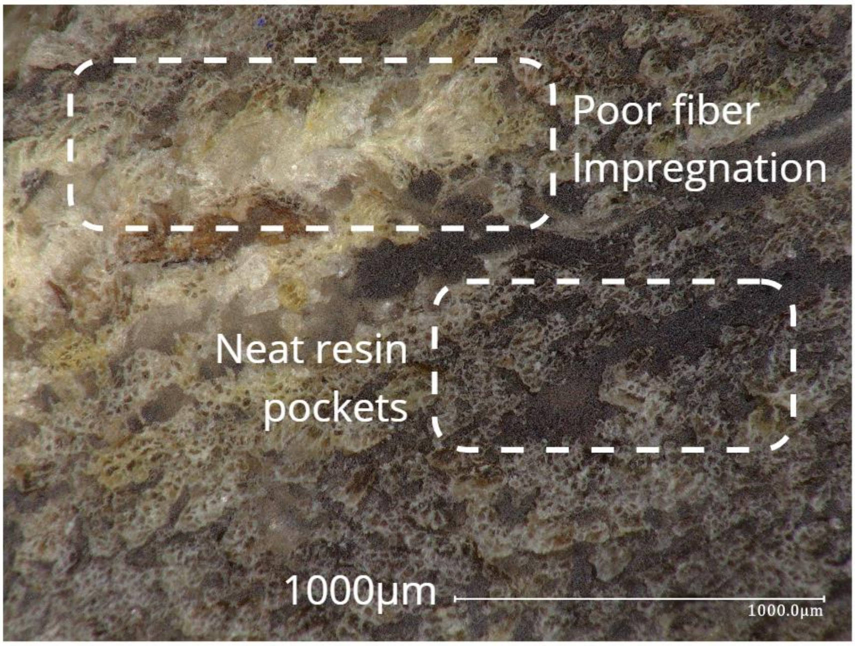


Figure 55: Cross section of pre tensioned braided composite showing defects

Figure 56: pre tensioned braided composite sample after diamond cutting. Defects within the cross section and a rougher surface finish to be noted

Fiber Volume Fraction:

Weight per length of flax braid (W_f): 0.71g/cm (36.1g over 55 cm)

Density of flax (provided by manufacturer (ρ_f): 1.45g/cm3

Sample dimensions after impregnation: Length : 41.2cm, ID: 16mm, OD:19.45mm, CS area: **214 mm2**

Sample Weight: 102g

Sample Weight per Length (W_c): 2.47g/cm

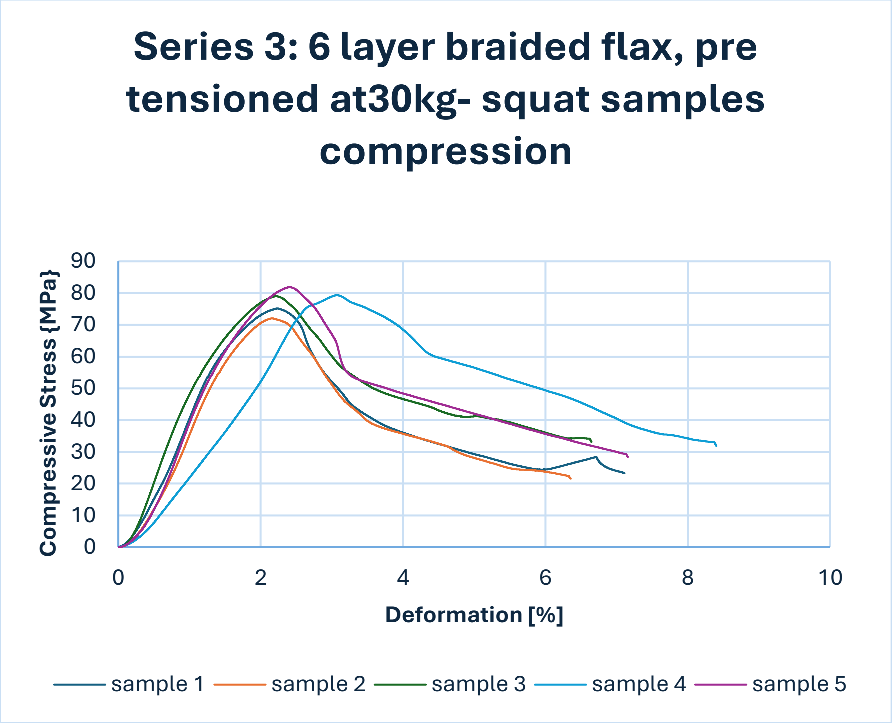
Density of epoxy (ρ_m): 1.15g/cm^3

Fiber volume fraction: $\frac{(W_f/\rho_f)}{(W_f/\rho_f)+[(W_c-W_f)/\rho_m]}$

= **24.2%**

Load testing:

Based on the cross section area of the composite, the compressive strengths are recorded.



sample	failure stress compression (MPa)
1	75.20228078
2	72.07438759
3	**79.06672569**
4	79.39097182
5	81.92195714

average	77.5312646

Failure Mode:

- The failure mode in all 5 samples was again through an **out-of plane** microbuckling
- The failure patters were a combination of compression at a single horizontal band as well as along the ‘contour’ of the braid, similar to what was seen in Series 3
-

Inferences and next steps:

- The FVF achieved through the novel pre tensioned method is a **much lower 24.2%.** By the standards of technical FRP composites this is quite low.
- Although the grip slipped and the desired pre-tension of 45 kg could not be achieved**, it is possible that the pre tensioning method does not create a compaction pressure similar to what is achieved by vacuum bagging**.
- Contrary to expectations, there is a **substantial increase in compressive strength** (77.5MPa) with this low-FVF composite when compared with the vacuum bagged series 3 with the fiber volume fraction of 43.9%
  This goes against the generally recommended FVF for composites in the range of about 50% or more.
  In the literature on the compressive strength of flax fibres, it is noted that for Flax FRPs prepared with the fibres aligned to load direction, the compressive capacity is significantly lower than the tensile capacity. However, it increases with an increase in fiber volume fraction, as observed by (SIngh & Bala, 2022).
  Based on these results and those of Series 3, it might suggest that even at low angle deviations of fibers from the loading axis, **the fibres only serve to weaken the composite in axial compression** (considering neat resin bulk compressive strength of 120MPa). The benefit of an increase in compressive strength may only be achieved when the fibres are perfectly aligned with the loading direction.
- **Hypothesis**: Based on the out-of-plane microbuckling failure patters observed in Series 4 as well as Series 3, **it is hypothesized that the compressive strength of the tubular composite can be improved by circumferential reinforcement at the outer later.** This is the purpose of the next set of tests, Series 5.

Series 5: Squat compressive tests 4: laterally reinforced jacket braids

Objective:

To assess whether circumferential reinforcement can improve the compressive capacity of a pre tensioned braided tubular composite

To assess which of two methods: helically wound rovings, or shallow angle braids, are more effective in creating the circumferential reinforcement.

Background:

Considering the ‘flaring-out’ failure pattern of many of the samples in compression so far, through engineering intuition it is hypothesized that ‘hoop reinforcement’ might create rings that can reinforce the cylinder through tension. This is analogous to recent studies of fiber reinforced composite jackets being used to reinforce concrete in axial compression .

Keeping with the idea of pre tensioning as a method to achieve compaction, as well as finding a method that is industrially established, the two approaches are selected, i.e. A filament winding style helical wrapping of the reinforcement, and a shallow angle overbraid over the usual 25 degree braid core.

Materials, equipment, and Fabrication method:

Series 5a:

- Lincore flax 520 + epikote epicure 04901
- 5 layer overbraid, inner dia 16mm, 24 rovings/braid layer, braid angle 25 degree, pvc pipe as core
- Followed by 2 layer overbraid, 12 rovings/braid layer, braid angle ~62 degree, providing a total roving deposition of 17m over 30cm product length
- Resin applied by brush and allowed to wick into braid
- Pre tensioned at 45kg

Series 5b:

- Lincore flax 520 + epikote epicure 04901
- 5 layer overbraid, inner dia 16mm, 24 rovings/braid layer, braid angle 25 degree, pvc pipe as core
- Followed by 17m of hand wound roving over 30cm at a tension of 2kg
- Resin applied by brush and allowed to wick into braid
- Pre tensioned at 45kg

The resulting samples were retrieved, and the pvc core removed. The samples were then cut to 30mm squat cylinders with a diamond saw.

Testing procedure: The prepared cylinders were placed in the Zwick z10 and loaded in compression at a rate of 0.2mm/second until they had deformed by 25% of their initial height.

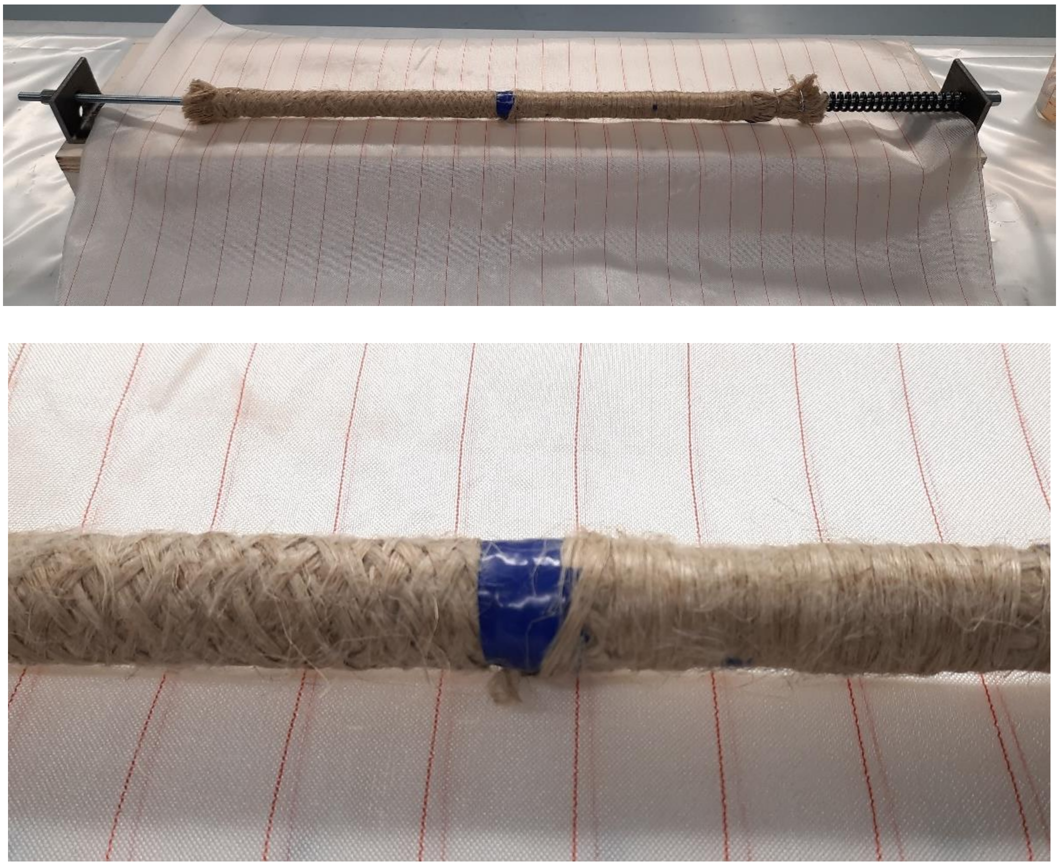


Figure 57: Series 5a and 5b prepared, with shallow braid reinforcement, and helical winding, respectively

Observations, Results and Calculations:

Fabrication Process:

- For Series 5a, The braid setup for the shallow braid layers worked effectively, depositing a uniform braid over the 5 layer deep angle braid. However, the resulting product was quite stiff in the lateral direction and transferring the pvc mandrel was difficult.
- For Series 5b, the filament winding setup was done by hand and resulted in a somewhat uneven deposition of helical filament around the 5 layer braid underneath. The The resulting product was extremely stiff in its circumference and transferring the PVC mandrel was very challenging.
- During the pre tension process for series 5b, **the helical winding did not extend** in tandem with the braid layers underneath, creating a ‘detached’ winding jacket over the tensioned braids, with gaps of unreinforced braid in some sections.
- During the pre tensioned process for series 5a, the shallow overbraid did extend in tandem with the deep braids underneath, but **did not seem to apply any substantial lateral constriction on the product**.

- The effect of the above 2 points was evident in the microscopic observations of the cured product in cross section, revealing a peripheral neat resin ring in both cases, with series 5 showing a larger deposition of neat resin due to the gap in between the helical windings and braid layers underneath.

Figure 58: Series 5a and 5b after curing. 5a shows a visibly lower constriction between the shallow overbraid and the deep braids underneath. Series 5b shows similar effect with the helical winding, with a complete detachment of windings in some sections.

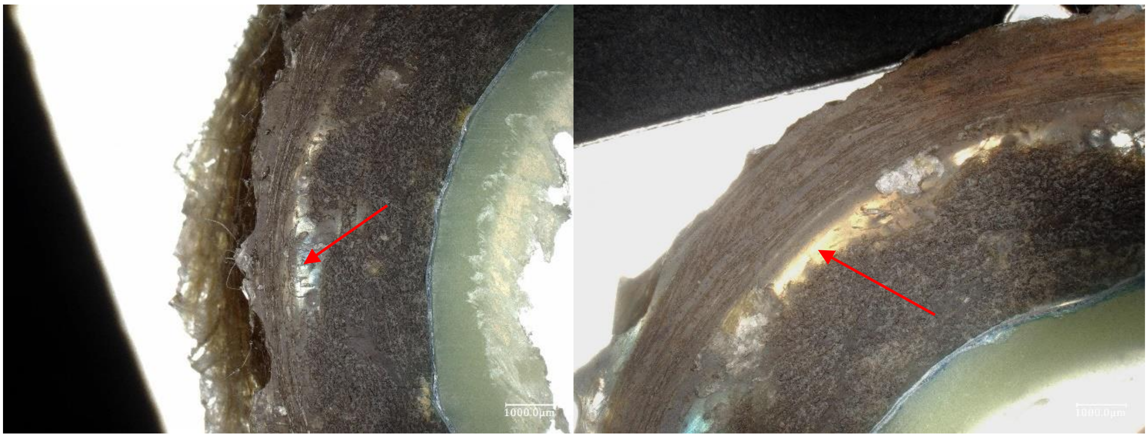


Figure 59: a. Series 5a showing signs of poor constriction from the shallow braid resulting in a neat resin 'ring'. b. Series 5b showing still poorer consolidation, with a larger near resin 'ring', and a resin rich swollen helical fiber ring. As seen under microscope.

Fiber Volume Fraction:

Series 5a: shallow braid reinforcement:

Weight per length of flax braid (W_f): 0.81g/cm (24.3g over 30 cm)

Density of flax (provided by manufacturer (ρ_f): 1.45g/cm3

Sample dimensions after impregnation: Length : 18.7cm, ID: 16mm, OD:24mm, CS area: **251.3 mm2**

Sample Weight: 47.65g

Sample Weight per Length (W_c): 2.55g/cm

Density of epoxy (ρ_m): 1.15g/cm^3

Fiber volume fraction: $\frac{(W_f/\rho_f)}{(W_f/\rho_f)+[(W_c-W_f)/\rho_m]}$

= **26.9%**

Series 5b: helical reinforcement:

Weight per length of flax braid (W_f): 0.78g/cm (24.18g over 31 cm)

Density of flax (provided by manufacturer (ρ_f): 1.45g/cm3

Sample dimensions after impregnation: Length : 20.6cm, ID: 16mm, OD:26mm, CS area: **329.8 mm2**

Sample Weight: 47.65g

Sample Weight per Length (W_c): 3.178 g/cm

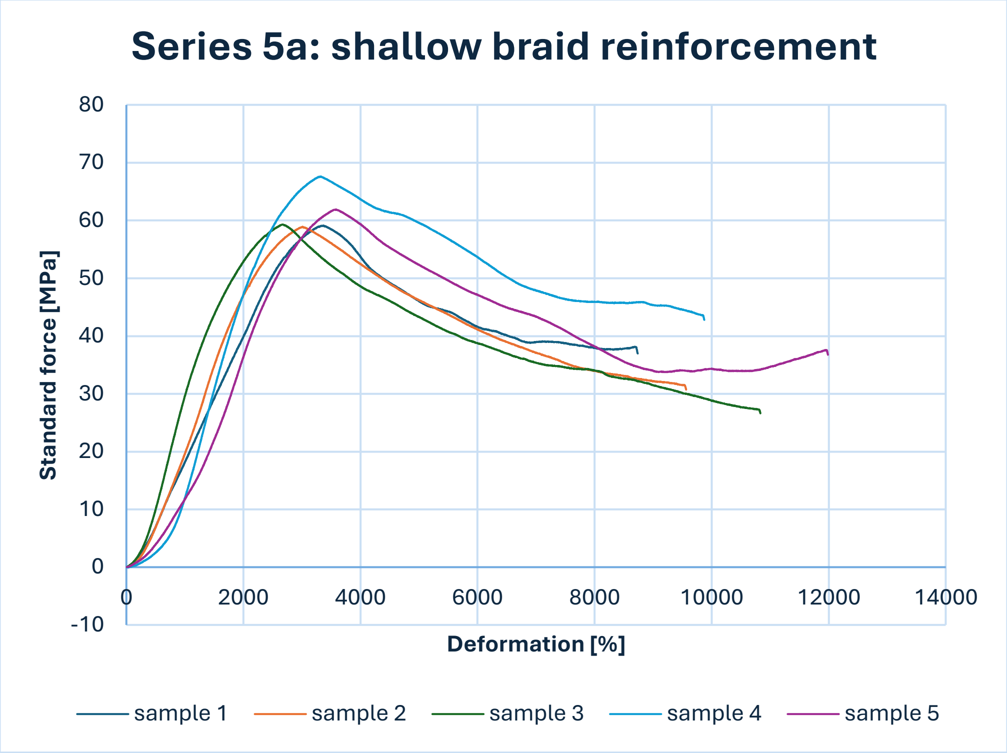
Density of epoxy (ρ_m): 1.15g/cm^3

Fiber volume fraction: $\frac{(W_f/\rho_f)}{(W_f/\rho_f)+[(W_c-W_f)/\rho_m]}$

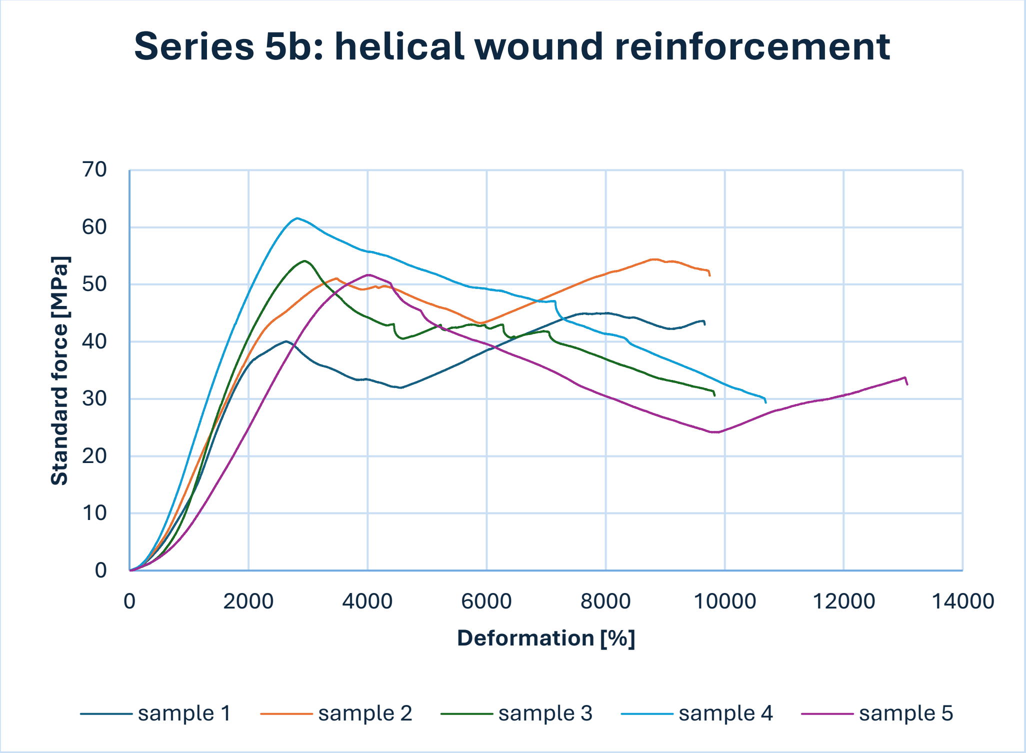
= 20.5%

Load testing:

Based on the cross section area of the composite, the compressive strengths are recorded.


Series 5a: shallow braid reinforcement

sample	failure stress compression (MPa)
1	59.11327854
2	58.89656212
3	**59.31268373**
4	67.62202965
5	61.89871879
average	**61.36865457**


Series 5b: helical wound reinforcement

sample	failure stress compression (MPa)
1	44.9796469
2	54.40431489
3	**54.12390125**
4	61.57799026
5	51.64432528
average	**53.34603571**

Failure Mode:

- The failure mode in all 5 samples was again through an **out-of plane** microbuckling.
- The failure patters were at a single horizontal band, similar to what was seen in Series 3 and 4
- Along with the buckling of the axal fibres, a fracture of helical reinforcement was also observed.

Inferences and next steps:

- As might be expected from the debonding observed between the circumferential reinforcement and the core layers, there is a poor quality of composite, characterized by many flaws and neat resin ring, and the lowest fiber volume fraction of all the series so far.
- Although the previous Series tests indicate that there may be a benefit in compressive capacity from resin rich braided composites, it is not the case in series 5, suggesting that the distinct fibrous core and resin rich ring are not mobilized effectively together to endow compressive capacity.
- The method of filament winding is usually done at high levels of tension and is not effective when loosely applied over a braid. Further, it is not an appropriate strategy for the pre tensioning method used in the Truss to Go.

- A very important conclusion is from the observation that the shallow braid angle outer layers do not constrict at the same rate as the axial core braid layers (for the same axial tension applied). This means **that varying braid angles are not to be combined in the layers of manufacture of the cordage** if a uniform constriction pressure is desired during pre tensioning.
- The explorations at improving the compressive capacity of the strut are now concluded. The key takeaway is that a compressive strength of between 55-80 MPa, depending on control of fiber volume fraction.
- At the moment, it is not clear whether the pre tensioning method is suitable for creating Fiber Volume Fractions Greater than around 35 percent.
- The tensile capacity of the braided flax composite is the next attribute to be investigated.

Series 6: Tensile tests

Objective:

To assess the tensile capacity of braided flax laminate.

Background:

Having determined the compressive strength of the tubular flax composite (and with slender section compression being removed from scope), the tensile strength remains to be determined.

The tensile test of a tubular braided composite is a challenging test setup, since it is difficult to attach grips to the tubular specimen by mechanical means, as this can easily damage the composite.

Tensile tests on such specimens have been conducted by (Ayranci & Carey, 2010). Here, special lathe turned tabs were adhered to the inner walls of the braided tubular composites by means of a high strength epoxy. Ax example of such a tab has been shown by Melenka (2016).

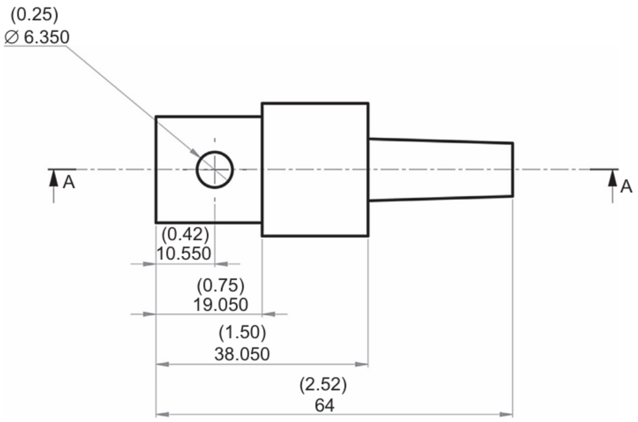


Figure 60: Example end tabls for the testing of tubular braided composites, from Melenka (2017)

Such a test setup is contingent on the adhesive bonding between the tab and the sample, whose strength must be greater than the tensile strength of the sample, in order to have a fracture in the sample and not at the support.

Due to the difficulty of this test setup, an alternative is proposed: to cut open the tubular braided laminate and prepare a panel like composite that can be tested using a conventional coupon tensile test.

Materials, equipment, and Fabrication method:

Series 5a:

- Lincore flax 520 + epikote epicure 04901
- 6 layer overbraid, cut open, fiber angle between 25 and 30 degree **(!!!)**
- Resin applied by brush and allowed to wick into braid.
- Vacuum bag at 935 millibar

The resulting samples were retrieved and cut with a diamond saw into the coupon shape for tensile tests as shown below (dog-bone shapes are not recommended for composites).

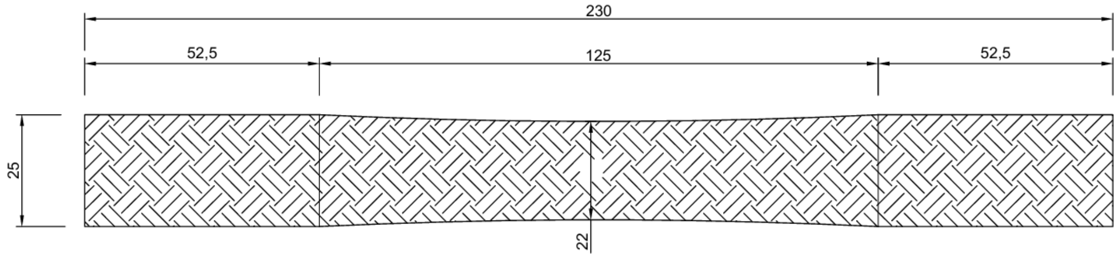


Figure 61: Design of tensile test coupon, similar to ASTM 3039

Since in this method a vacuum bag is used, the tensile strength will be for such a corresponding fiber volume fraction. Mathematical methods could be then used to compute the tensile strength for lower fiber volume fractions.

Testing procedure:

The samples are placed in the grips of the z10 and loaded at a rate of 0.2,,/second until fracture

Observations, Results and Calculations:

Fabrication Process:

- Upon cutting open the braid sample, it was discovered that the braid angle on one side and the other (the inside and outside of the tube before cutting) have a substantial difference in the braid angle

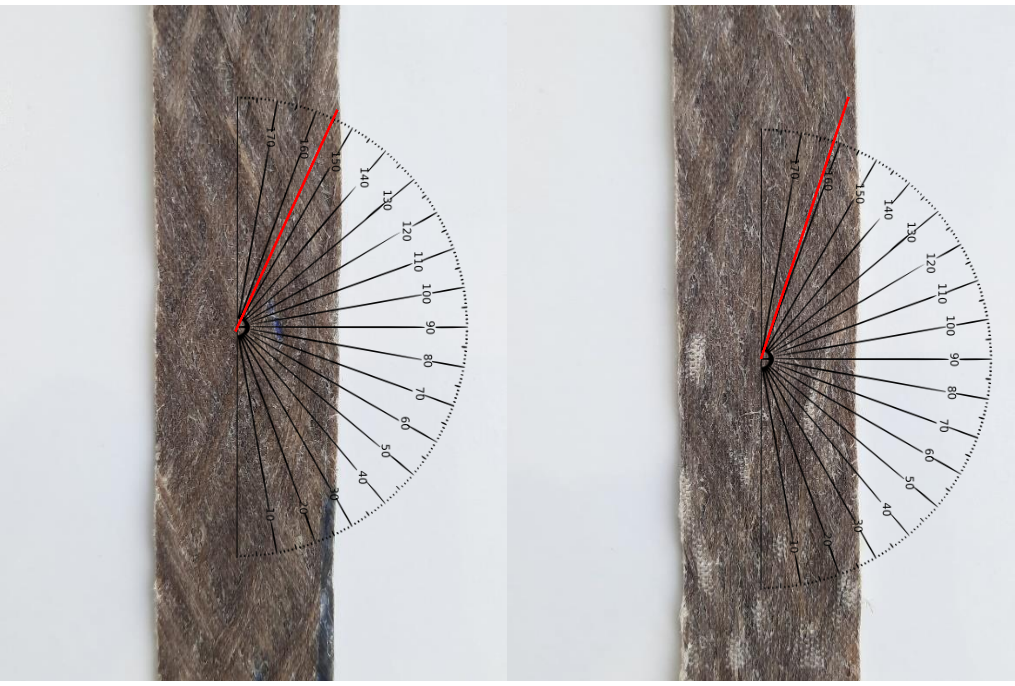


Figure 62: variations in braid angles at two faces of braided composite, from 18 degree to 25 degree.

- The cured braided panel showed, when help against the light, a substantial degree of variations in the distribution of flax tows.

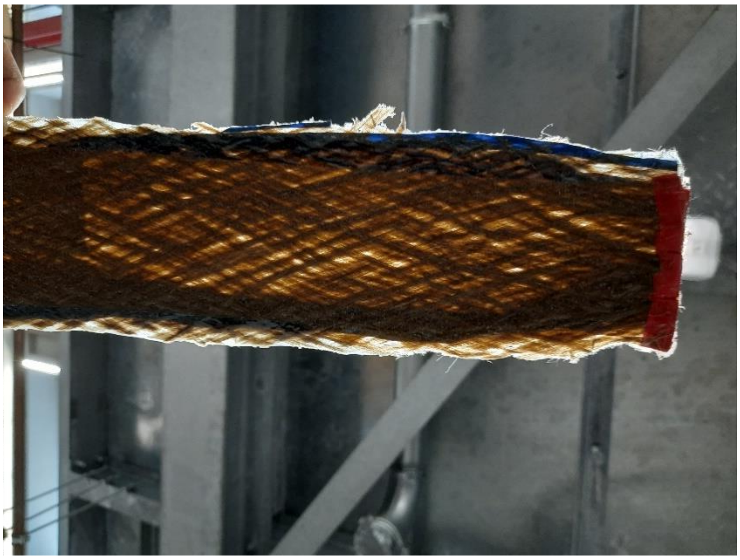


Figure 63: 6 layer braided composite panel held against the light, revealing variations in fiber distribution from braidng imprefections

Fiber Volume Fraction:

Weight per area of flax braid (W_f): 0.11g/cm (41.4g over 375 cm2)

Density of flax (provided by manufacturer (ρ_f): 1.45g/cm3

Sample dimensions after impregnation: Length : 50 cm, width 7.5 cm, area: **375 cm2**

Sample Weight: 70g

Sample Weight per area (W_c): 0.186g/cm2

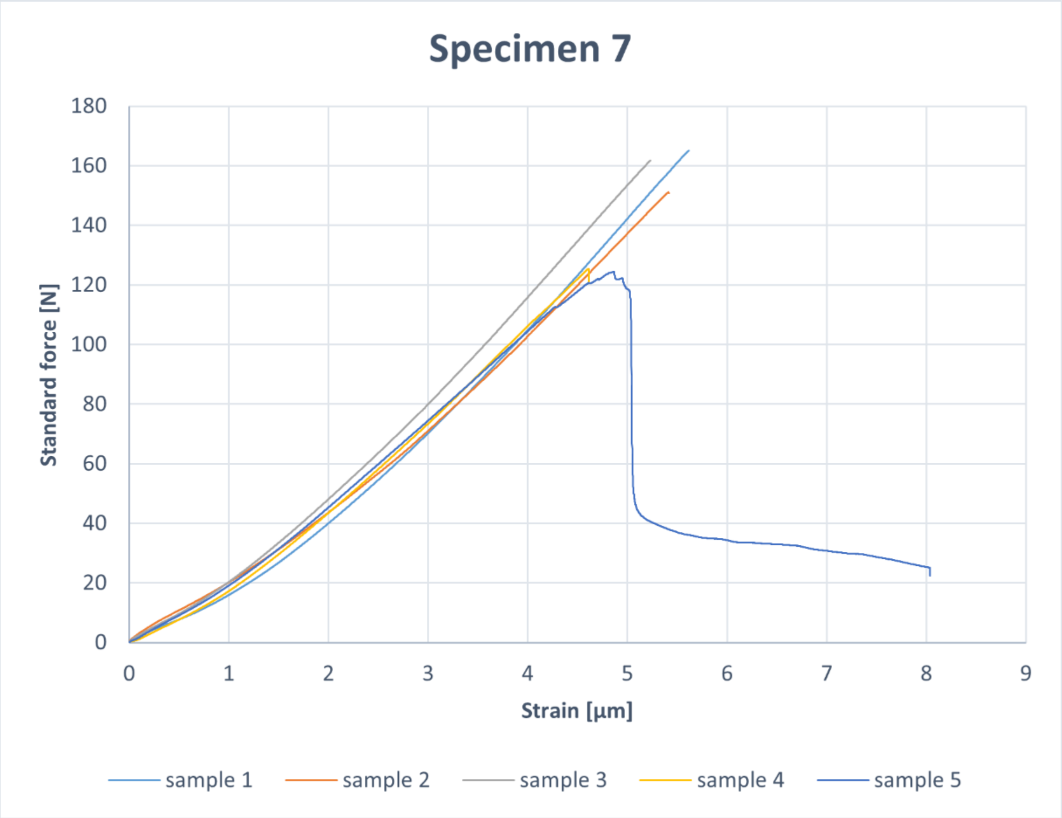
Density of epoxy (ρ_m): 1.15g/cm^3

Fiber volume fraction: $\frac{(W_f/\rho_f)}{(W_f/\rho_f)+[(W_c-W_f)/\rho_m]}$

=53 %

Load testing:

Based on the cross-section area of the composite (32mm^2), the compressive strengths are recorded.



sample	failure stress compression (MPa)
1	164.985199
2	151.1396179
3	**161.6764374**
4	125.3889542
5	124.4748764
average	**145.533017**

Failure Mode:

- The failure mode in 4 samples was through fracture between the grips. Sample 5 however fractured within the grip.

Inferences and next steps:

- The FVF of the composite at 53% meets the standards for composite laminates in literature and practice.
- The failure strength of the composite with the braid angle between 18-25 degrees is about 150 MPa.
- This is significantly lower than what is reported in literature, between 200 and 300 MPa (citations). This might be owed to the substantial effects of the fiber angle: The literature reviewed for flax composites were unidirectional and oriented I the direction of loading.
- The low strength of the flax composite when prepared as a laminate would likely further be compromised by the Low fiber volume fraction that is achieved through the pre tension compaction method, to about half the present value- to 75 MPa approximately.

Chapter Conclusions:

The experimental phase for part A is concluded with an understanding of the mechanical properties of the braided cordage in tension and compression

These are the following key conclusions:

1. We must demand the right epoxy in future, as it does not exist on the market today. The combination of high performance, bio based, bio degradable and site-curable attributes does not exist, or has not been identified yet.
2. Braiding is a potentially good candidate to prepare continuous cordage unlike many other FRP manufacture methods
3. Roll wrapping does not seem suitable for flax.
4. Braiding- by hand is tricky- the rovings rotate and may not lie flat.
5. Yarn numbers must be more precisely calculated to avoid resin pockets.
6. Braid angle- fibre angle effects are confirmed in flax braiding as well.
7. Consolidation is ok in vacuum bag composites (giving a FVF of about 50%) but remains untested with the pre tensioned one. It may be needed to apply a correction factor based on the F.V.F Rule of Mixtures.
8. The failure mode appears consistently to be microbuckling even for thin-walled elements.
9. Euler buckling was not talked about because it can be theoretically calculated with the E and anyway is likely quite inaccurate without the characterization of defect-based corrections using a Perry-Robertson equation or some such and I would have to do a lot of tests and then curve fitting.
10. Pre tensioning does not yield as good results as vacuum bag (FVF of only about 25%). But more work is needed, exploring different tensioning forces, and synchrony in braid angles, adjusting outer to inner layers to get the same braid angle.
11. Tension test of tubular braided samples is to be tested but a simplified equivalence can be computed by the rule of mixtures.
12. The problem of an internal mandrel is not yet reconciled with the fantasy idea of a spooling rope!
13. **The highest compressive strength from all experiments is about 75 MPa, and is achieved with a low FVF of 25%.**
14. **The tensile strength to be expected from the composite with a FVF of 25% is also approximately 75 MPa (**after correcting from 150Mpa for a 50%FVF based on the Rule of Mixtures).

3.3 The Design of the Joint + Experimental Testing

Now that the mechanical properties of part A have been characterized, the problem of how a truss is to be manufactured can be tackled.

What we need from the manufacture Process:

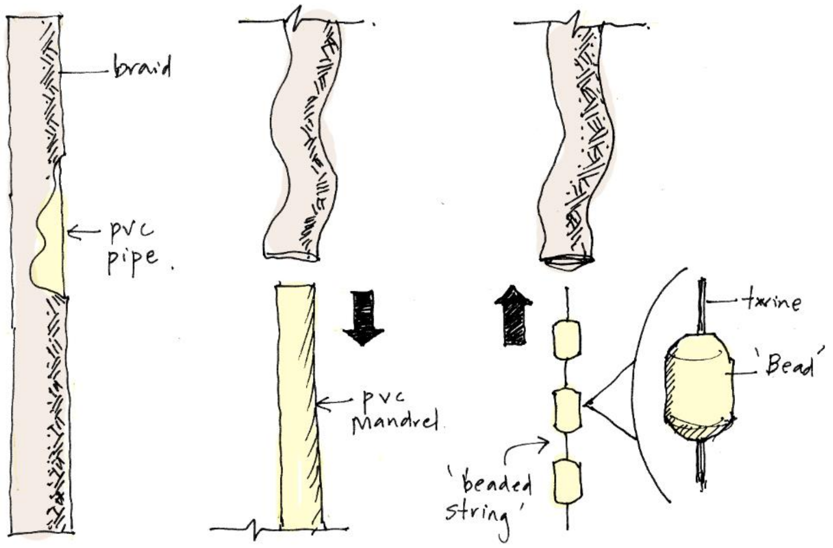
- That the cordage can be prepared with existing and ubiquitous manufacture technology
    - Braiding (and overbraiding) is an acceptable candidate for this requirement as the technology for its production is very well developed, with high levels of production efficiency.
    - The problem of the resin cannot be solved with the industry state-of-art. This is a matter of time and waiting.

- The cordage must be pre-impregnated with the polymer, and there is a mechanism in place to activate it on site.
  If such a technology cannot be developed, then the resin must be applied on site during the weaving of the lattice.
- That the cordage can be spooled, stored and transported compactly
    - The work in part A and the pre tensioning method is contingent on an internal mandrel against which the composite can be compacted. This is yet to be reconciled with the need to wind the cordage into compact spools for storage.

- That there is a workflow and design of necessary infrastructure for the on site tying of the cordage in the form of a truss
    - This is addressed in **3.3.2- The Proposed Model**

The Proposed model

To reconcile the need for a rigid mandrel with the ability to spool it and also prepare joints at the intersections of the strut members, **the novel idea of a 'discontinuous mandrel' is proposed.**

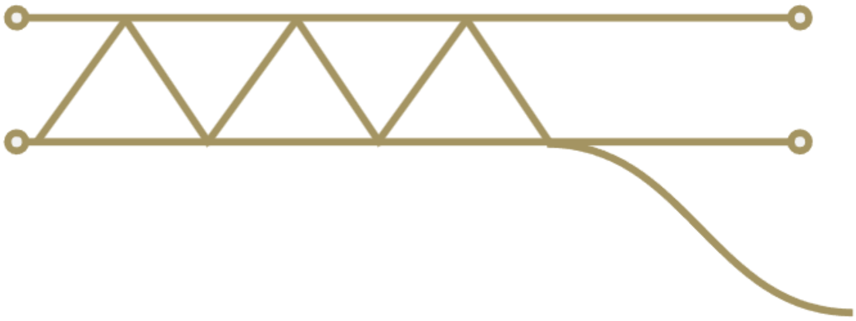


- The proposal is to replace the solid mandrel (pipe) with a 'beads on string' core.
- The beads shall be made of a smooth material with rounded ends. This can be plastic or polished wood or metal.
- The beads shall be connected by a string. This can be any form of slender cordage, such as metal or synthetic twine. It can also be made from natural fibre. It is only important that the string is tough and resistant to degradation and breakage
- The beads shall be able to slide along the length of the twine.
- For the production of the cordage, the manufacturing design must either allow for the braiding of the cordage directly around the beaded string, (with a temporary layer in between which is later removed or dismantled), or the beaded string must be introduced into the hollow braid as a secondary process.
- This allows for the cordage to now be spooled.

- For the tying of the cordage into a truss on site, it is proposed as follows:

  1. **Step 1**: Establishing the chords of the truss on site. This is done by laying the cordage product on a level surface and applying tension once the position has been fixed.

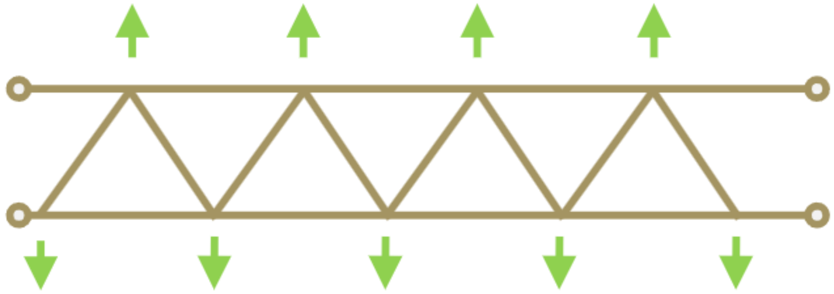
  2. **Step 2**: **Tying of the struts**. This is done by wrapping a second length of cordage in between the chords. At the chords, the strut cordage is wound fully at least once around the cordage. This is possible by shifting the beads at the joint portion of the cordage, creating a vacant hollow 'sock' that can be flexibly coiled tightly around the chord member.



This process is continued until the rough structure of the truss is formed.

Step 2.5: If the cordage design is not a prepreg, this is the stage at which the **resin is applied**. Because of the high wettability of flax, this can simply be done by a brush application. (A resin bath could also be opted for, prior to step 1, but it is not recommended based on the messy nature of handling wet cordage. Flax wicks resin very well, and a brush application is effective).

3. **Step 3**: **Tensioning**. A mechanism is activated to ‘draw the chords’ away from one another, thereby tensioning the struts in the truss for the purpose of composite consolidation.



- There are two aspects that now need to be investigated to assess whether a structurally sound truss can be constructed from this process.
  1. The structural properties of a strut segment formed by means of the ‘discontinuous mandrel’.
  2. The structural properties of a joint that is formed by this tying process.

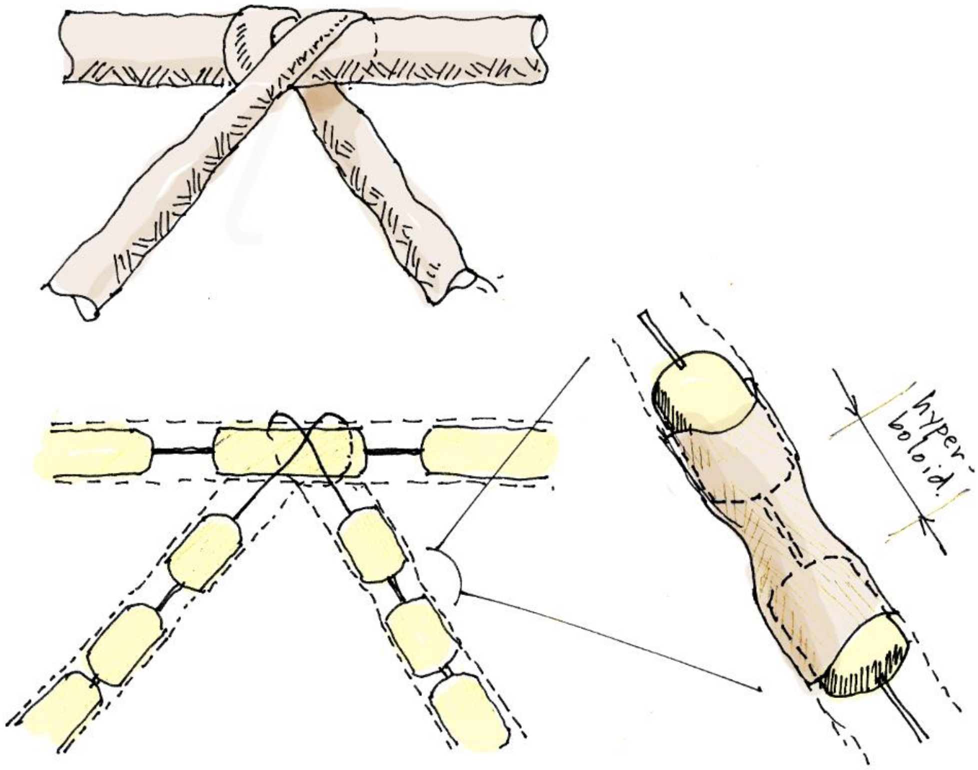


Figure 64: Illustration of the' Discontinuous Mandrel' concept

Experimental testing of a composite prepared with the ‘Discontinuous mandrel’

- A 6-layer flax braid is prepared per the usual parameters
- The solid pvc pipe is removed from inside the braid and replaced with a string of timber beads.
- Epoxy resin is applied.
- The flax is then tensioned as per part A practice, with a tension of 45 kg
- As a result of this constriction, a hyperboloid-like shape is expected to be developed.
- After a period of 24 hour curing, the samples are extracted and cut into short segments enclosing each hyperboloid.
- These segments are tested under compression similar to the investigation in Part A.

Figure 65: Setup to manufacture the strut compacted against the 'discontinuous mandrel'

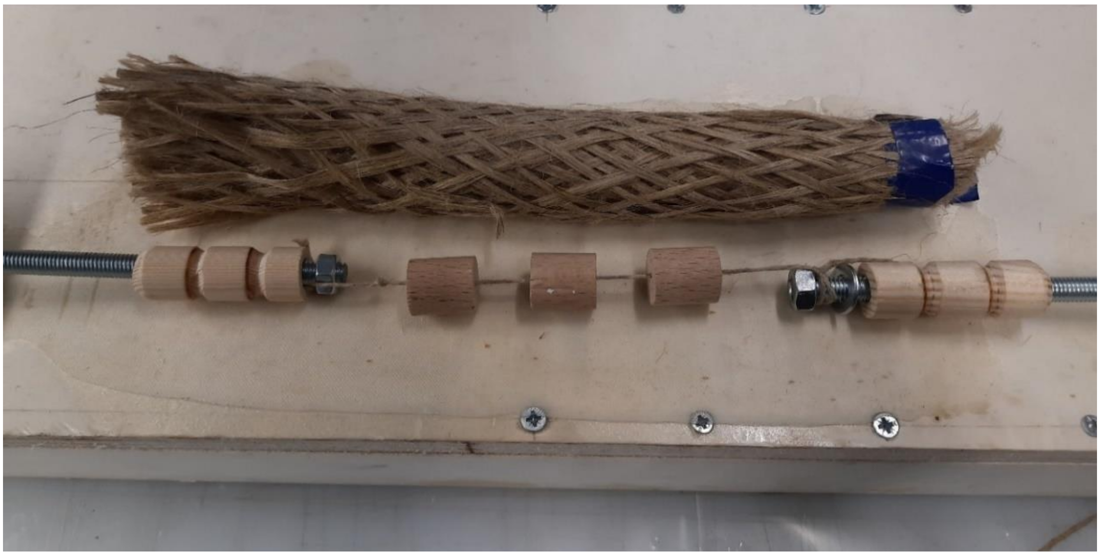


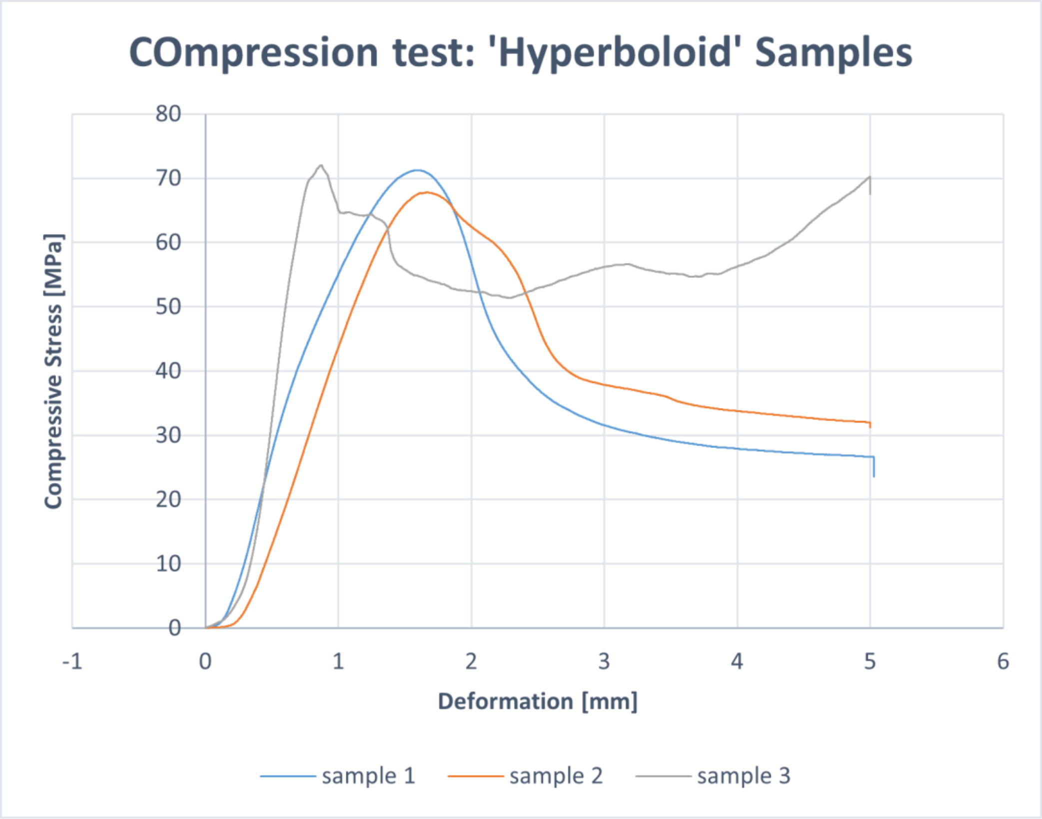
Figure 66: The discontinuous mandrel is prepared with wooden beads on a string as shown

Figure 67: Pre tensioning applied to the resin soaked braided cordage, compacted against the discontinuous mandrel

Figure 68: Section of the composite with the discontinuous mandrel.

Results:

Based on the cross-section area, the following compression strength values are obtained:



sample	max compressive stress [MPa]
1	71.22238498
2	67.79407552
3	72.01468099
average	**70.3**

Observations and Inferences:

- Though the hyperboloid creates a slight inward curvature, this appears to create a significant but acceptable reduction to the compressive strength (compared to Series 3), with a drop of about 10% (from 77 MPa to 70 Mpa).
- In fact, the failure once again is a flare-out micro-buckling which happens at the portion abutting the beaded insert, creating a convex curvature in the composite's fibres

Fabrication of the Joint:

The ability to make a joint hinges on the idea that the beads of the discontinuous mandrel can be slid around inside the braided cordage. This allows the fabricator to 'vacate' a portion of the cordage to have a hollow sock-like portion, which can then be wrapped by hand around the tensioned chord. Naturally, this is required in order to be able to negotiate the tight curvature of the chord member.

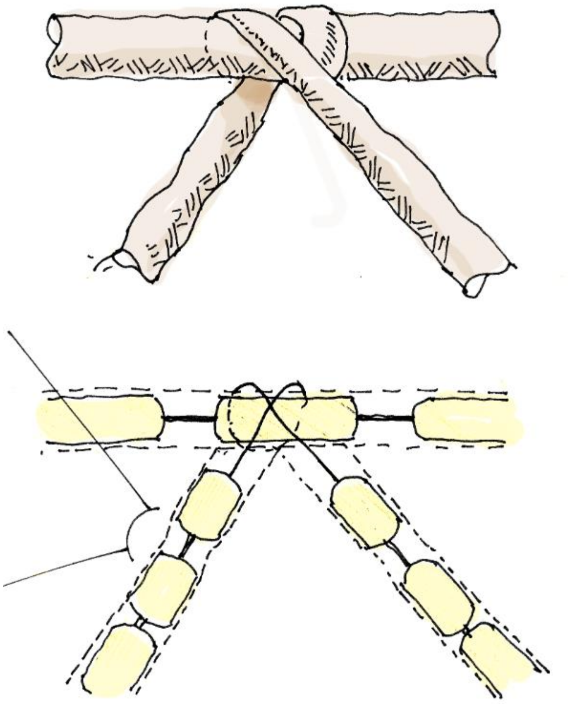


Figure 69: Joint prepared as a 'hollow' sock, wound at least fully once around the chord member

An advantage of this hand wound method is that the fabricator can wind more than once around the chord, maximising the contact surface between the strut and chord textiles, thereby increasing the strength of the joint from the point of view of shear slippage. IN the case of the robotically filament wound methods of the wraptor truss, this is naturally not possible, and the contact area is limited. Consequently, in the failure modes of the load tested specimens, the failure of the joint occurred through interfacial shear.

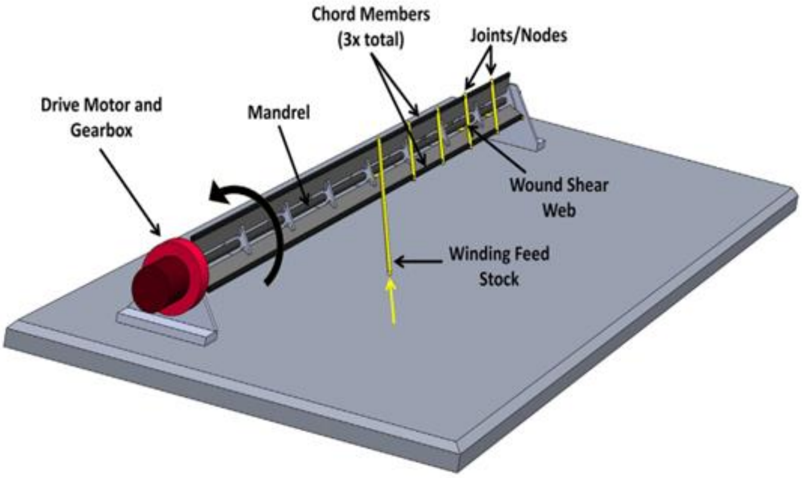


Figure 70: Schematic of the robotic filament winding process of the 'WrapToR truss'. (Hunt, Wisnom, & Woods, 2019)

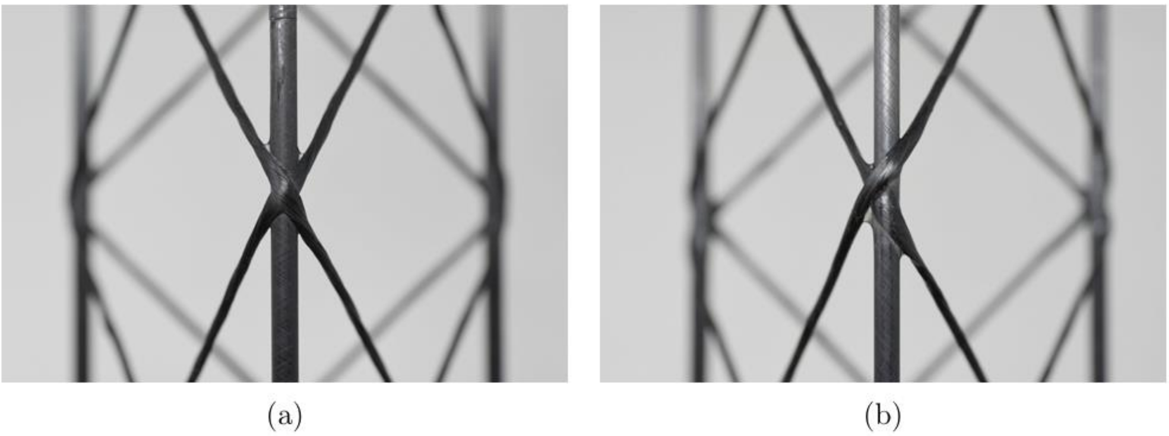


Figure 71: Joint slippage occurring during the curing process of the WrapTor Truss Fabrication (Hunt C. J., 2021)

To make the joitn, a test setup was prepared, whereby a smapp portion of the joint could be fabricated with the braided flax cordage, and then tensioned to the required force of 45kg, as established in Part A. A nut and bolt system was used to apply the tension, and a spring of known stiffness was used to measure the force applied.

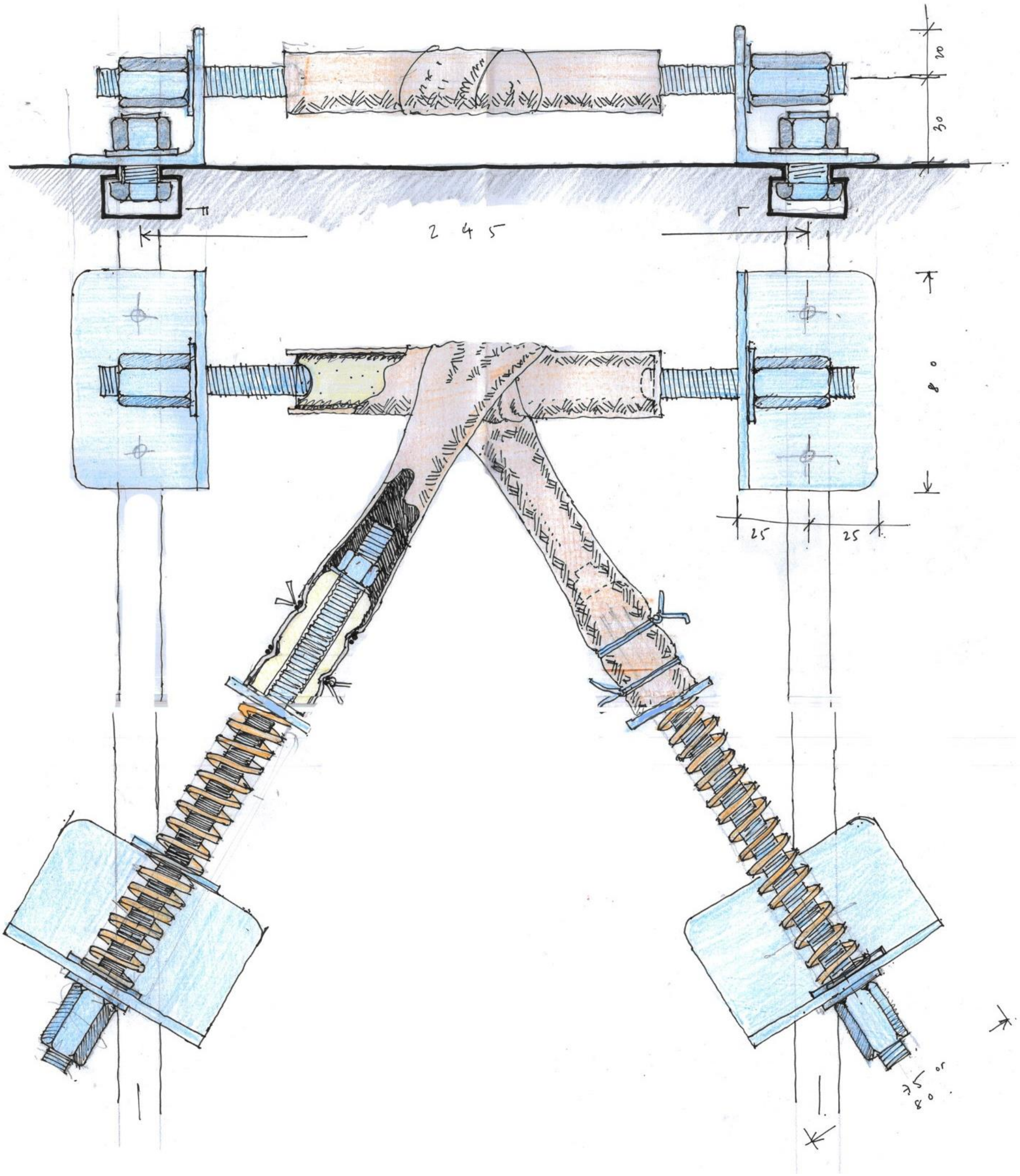


Figure 72: Shop Drawing of the joint fabrication setup, showing the nut and bolt system to apply the tension and the springs to measure the force

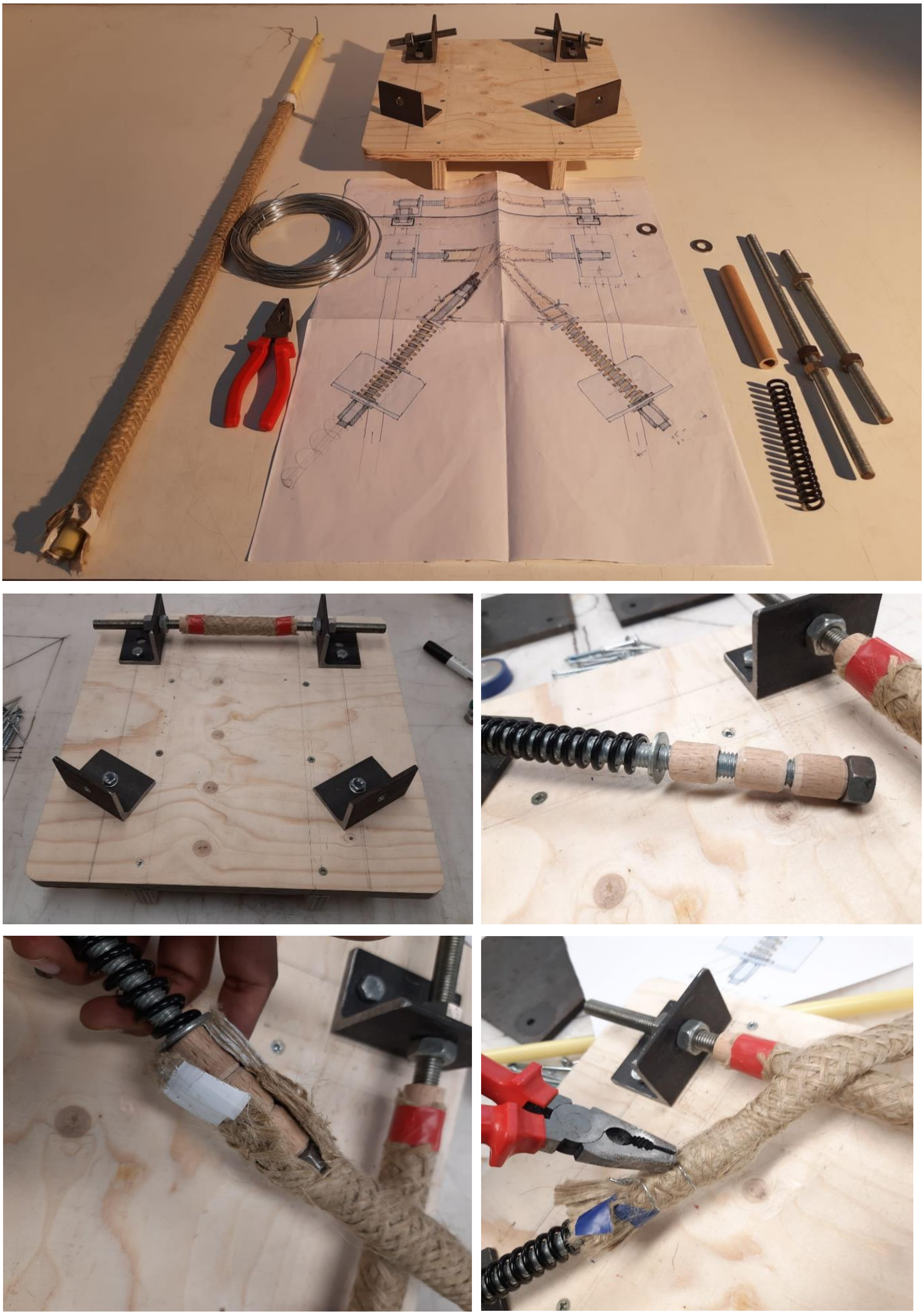


Figure 73: Sequence of joint fabrication- A montage/ 1. Required materials 2. Setup of the chord section on the jig, 3. Preparation of the clamping insert for the strut. 4. Insertion of the clamping block in the strut sleeve, 5. Tightening of the strut sock over the braid sleeve.

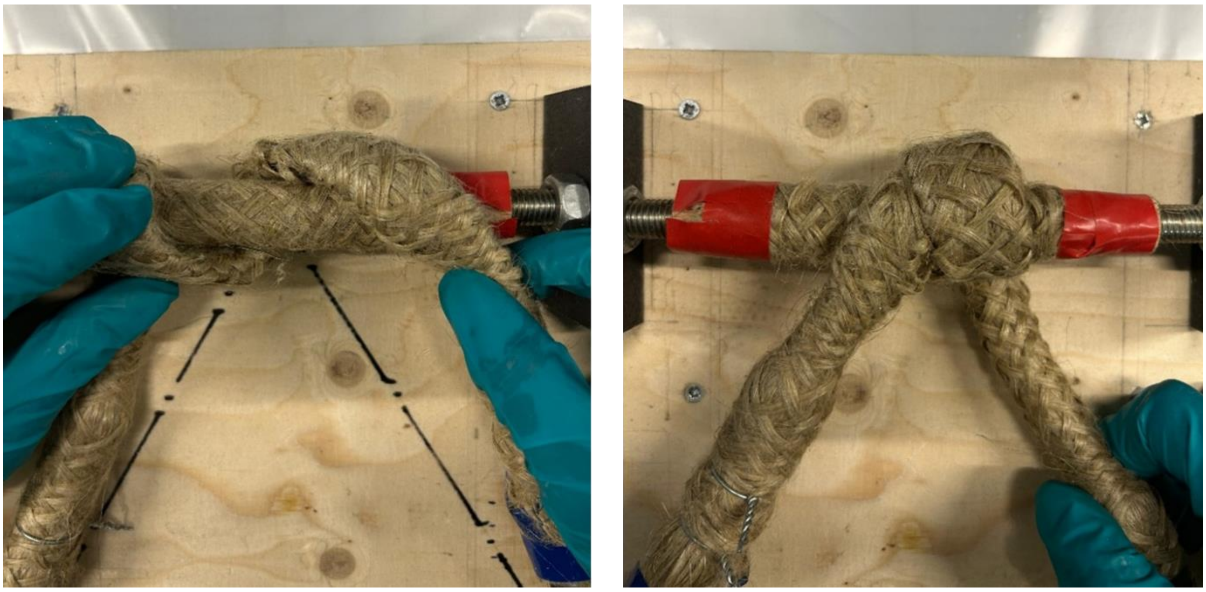
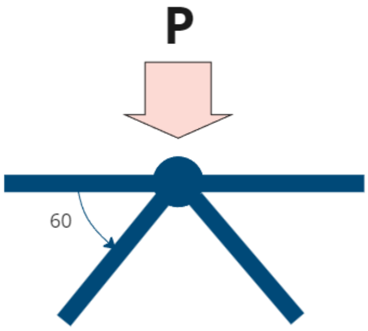


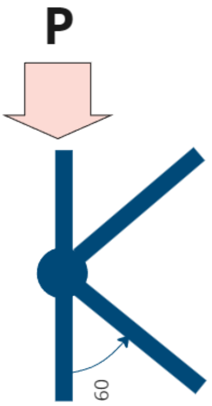
Figure 74: Sequence of joint preparation of the hollow strut 'sock' over the chord section.

Figure 75: The joint section after resin application and pre-tensioning. The tension force fractures the timber in the chord section, compromising the joint geometry, but the tension is maintained. The final product is shown on the joint.

Experimental testing of the joint:

To assess the strength of the joint, there were two load ditrection options, as shown in the figure below.





Whereas the first option mimics the load pattern on a purlin on a chord, the second is indicative of an internal unbalanced force in the strut that must be resisted by the joint. The magnitude of tnternal forces that develop in the struts are typicall larger than the tributary loads received from the purlin (due to the overall proportions of most trusses, the moment resisting internal forces are greater than vertical loads from the supported structure). Due to the limited research time, it was decided to lest in the second pattern only.

Test design and fabrication:

A design was made to encase the cured joint in a block of epoxy and coarse aggregate. This block would then be slid into a custom-made jig that could be loaded onto the Zwick Z10 Universal Test Machine.

Due to the inaccuracy of the casting and the fabrication of the jig, the sample could not be inserted into the jig, and required to be clamped to the front of the jig instead. Furthermore, the joint performance exceeded the 10 KN capacity of the Z10, and the experiment then had to be moved to the z100. The base plate of the jig was not compatible with the bed of the z100, however, and makeshift measures were used to restrain it in place, using steel channel sections and clamps.

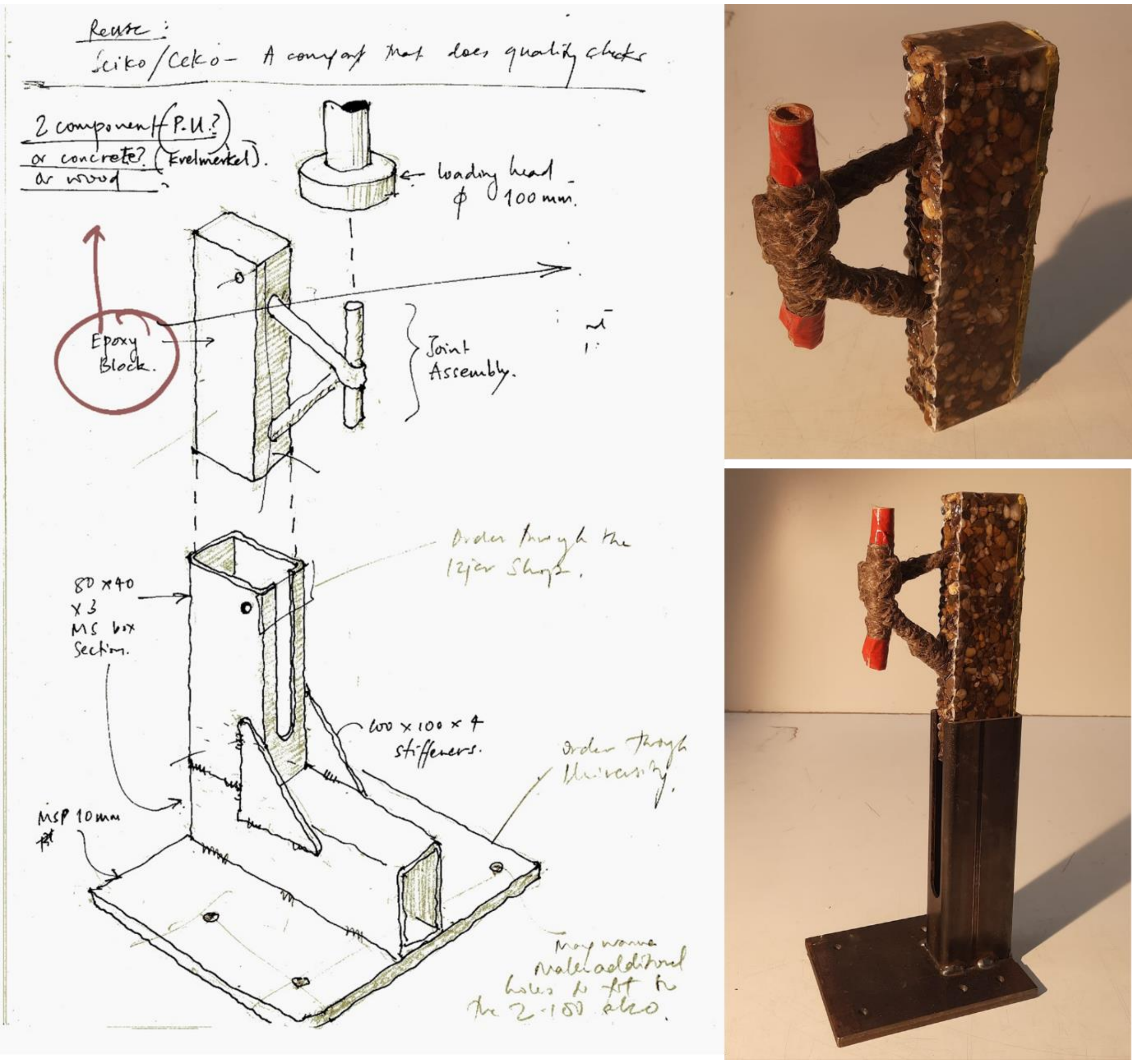
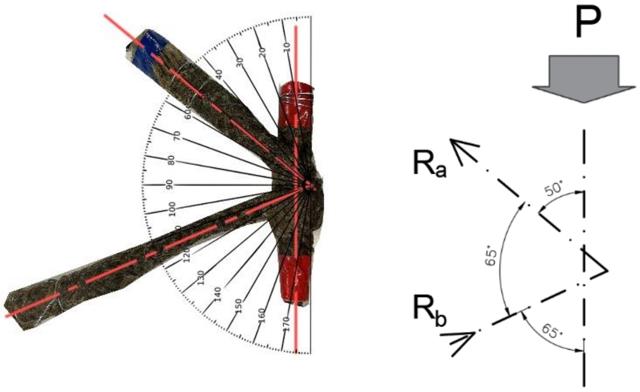


Figure 76: Proposal for joitn testing. a. Sketch showing the fitting of the epoxy encased joint into the custom fabricated jig. b. Photographs of the specimen. The jont encasement did not fit inside the jig, and was later clamped to the front of the box section for the load test.

Test results:

The failure of the specimen was expected to happen in one of three ways;

1. Failure at the node by crumpling/shearing of the composite
2. (if the node is stronger than the struts) Failure of the compressive strut by microbuckling
3. (if the node is stronger than the struts) Failure of the tensile strut by fracture.
   Due to the breakage of the jig during the fabrication, the angle between the struts and chord was slightly disturbed. This was photographed and measured to establish the new geometry. With this, the internal loads in the struts were calculated as a function of the load recorded by the test machine.



$R_b \cos 45° = R_a \cos 40°$

$R_b \sin 25° + R_a \sin 40° = P$

$R_b = P / 1.183$

Figure 77: Expression of internal forces at the joint as a function of applied load.

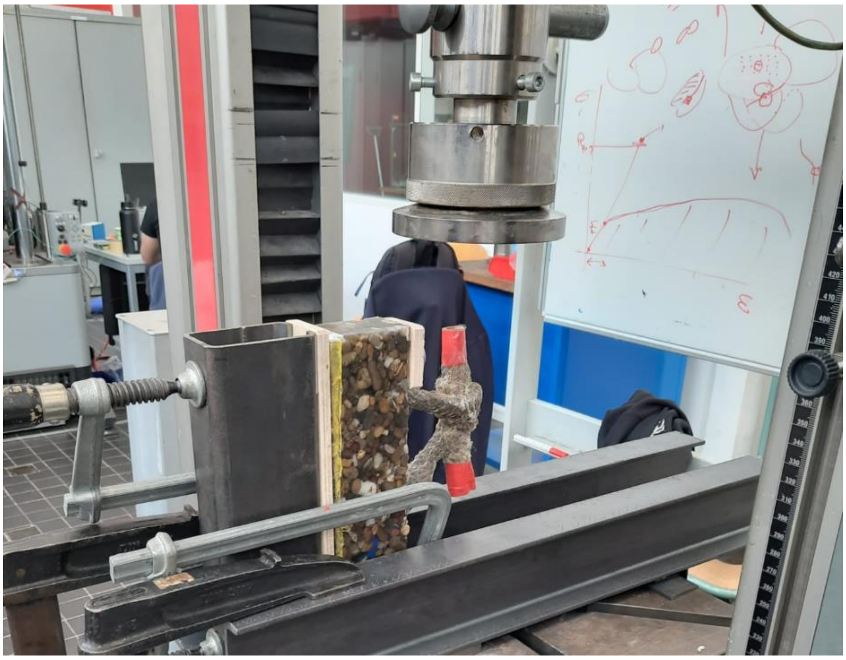
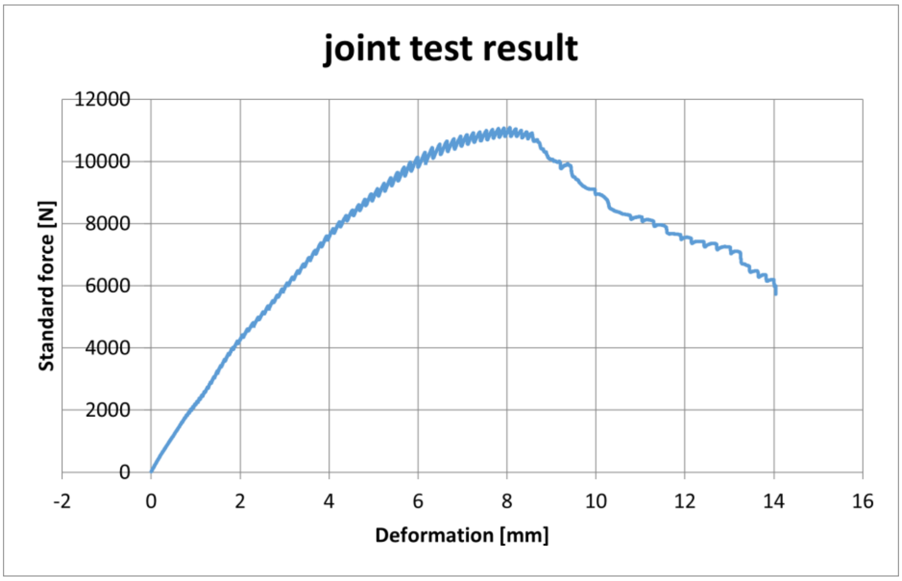


Figure 78: Test setup for the joint test. The epoxy block was clamped to the front of the fabricated jig- a method that proved sufficiently effective

Test Results:

The joint load test failed with compressive failure of the lower strut. The force in the strut at the time of compressive failure was approximately 11kN.



Cross sectional area of strut= 215mm^2
Force in compressive strut = P/1.18 (see Fig 77)
Compressive stress in strut at time of failure= 11000/215 **= 60.37 MPa**

Discussion:
The compressive stress in the strut is lower than the 75 MPa that was estimated in Part A. This is because there was a vulnerability in the compressive strut caused by the bulge from the embedded M12 bolt. This resulted in premature failure of the joint.

It however appears that there is substantial strength in the joint, although it is not possible to know whether the joint is in fact stronger than the strut members, as they did not reach full capacity.

Further, substantial deflection in the joint was observed during the loading cycle, and is reported in the graph (8mm before compressive failure of strut). This is partially due to the flexure of the cantilever steel jig, and the remainder must be attributed to the stiffness of the joint. This may be explained by the reported Youngs modulus of Flax-Epoxy composites of about 30 GPa (SIngh & Bala, 2022)((Saadati, 2020) which is lower than what is seen in steel or aluminium.

Chapter Summary:

1. To ensure the flexibility of the product, a rigid core could not be allowed in the braided cordage. However, to apply the method of consolidation using pre tensioning of the cordage, there is a need for some form of internal mandrel.
2. The idea of a 'Discontinuous Mandrel' was proposed- a flexible core that is made of rigid beads on a string.
3. The beads can slide along the length of the string. With the application of axial tension, the braided tube constricts about this chain of beads and achieves compaction against the surface of the beads. The portion of the braid that spans in between the beads does not, but is tensioned nonetheless, to a lower degree. The hollow void also causes this portion of the braided tube to deform slightly, into a hyperboloid shape. However, with a 15-degree braid angle, the deformation seen was not substantial.
4. Compressive test was conducted on the hyperboloid segments to assess the extent of loss of capacity due to the geometrical irregularity. It was determined to be about 10%.
5. The sliding beads on the string also allow for sections of the cordages core to be 'vacated' allowing the strut cordage to be tightly wrapped once, or more than once, about the chords, to prepare the joint.
6. The integrity and mechanical strength of the joint was tested with a load applied on the chord. The failure occurred at the strut in compression, although only 80% of the strut's capacity was achieved due to an imperfection in its structure (at 60Mpa).

Conclusions:

1. The idea of an internal mandrel seems feasible in terms of ensuring flexible cordage that can be spooled and compactly carried, as well as offering sufficient resistance for a tensioning-based consolidation.
2. There is a compromise in the compressive capacity in this method, which must be taken as the design value.
3. The joint showed good strength- at least 80% of the member strength, but the stiffness is likely lower that what could be expected in a truss with metallic members and nodes.

3.4 The Site Fabrication Proposal

Having approximately estimated the mechanical properties of both the planar joint of the truss and the compressive capacity of the strut when prepared with the discontinuous mandrel, the exact site fabrication workflow is to be established, in order to understand the required site preparation, equipment and labour processes involved.

Need for a Jig

The pre-tensioning consolidation method for the truss manufacture requires the application of a force in the order of 400N on the impregnated textile cordage. Naturally, this requires a jig-like arrangement to hold the joints firmly in place before the tension is applied.

Revisiting the fantasy vision introduced in 2.1 Objective and Research Question, **this means that the idea of 'weaving lattice structures in space' is not possible**, as the tensioning cannot be applied in a void, and to erect a falsework with 'anchor points' for each joint is likely elaborate, expensive, and defeats the intention to keep the fabrication workflow simple and efficient.

The jig is an indispensable part of the equipment required to facilitate an onsite fabrication of Truss-to-Go, and will have to be transported to the construction site. Such an effort is made economical by the repeated reuse of the jig. This means that, among other requirements, it must adaptable to some range of two dimensional truss geometries.

Requirements of a jig

For the jig to be realistic and feasible as part of the required infrastructure, it must be reusable and versatile. Similar to cast-concrete formwork, its economy would lie in its reusability. Thus the following key attributes required are:

- Offer Geometric Freedom and Scalability: For multiple reuses of the same Jig, it is desirable that several geometries of trusses or girders can be built on it. This allows a given project to have multiple truss designs, and also allows for the Jig to be used across multiple projects.

- Durability/Robustness: To withstand the rough use of a construction site, the design must be sturdy and hardy.
- Economical: Naturally, the cost of both its purchase and its maintenance must be reasonable. TO keep the design as simple as possible is important.
- Portability: The weight and dimensioning of the Jig must allow for a convenient transport method
- Geometrical Stability: Construction sites have a variety of topography and soil conditions, and the fabrication of the truss is a geometrically precise operation. The jig should be stiff and able to negotiate uneven contour etc.

The 'Bread-board':

Based on the above requirements, the Jig is conceived as a stiff, modular board that can be chained together. The truss shall be built upon this.

- The top board is stiff and hard **polyethylene**. Its low surface energy and relative chemical inertness against many resins helps in the required application.
- The board has a set of identical 30mm dia holes, much like a carpenter's clamping table. Its resemblance to an electronic breadboard gives it its name. These holes are used for the pegs and tensioning devices.
- For stiffness, the bottom of the Breadboard is a 200mm deep aluminium spaceframe. Aluminium is chosen for its corrosion resistance, and acceptable strength, hardness and impact resistance.
- The Bread-board is dimensioned at 1200 x 2200mm such that it fits in a shipping container and can be compactly stacked. A 20 foot shipping container will allow the storage of up to 50 breadboards. This inventory allows, for example, for a combination of 5 arrays of almost 12 metre length.
- The long ends of the breadboard are reinforced with 100x 100 box section made of aluminium. These sections also serve to 'chain' several breadboards together, as shown in *Figure 80*, to create the array upon which the truss is fabricated.

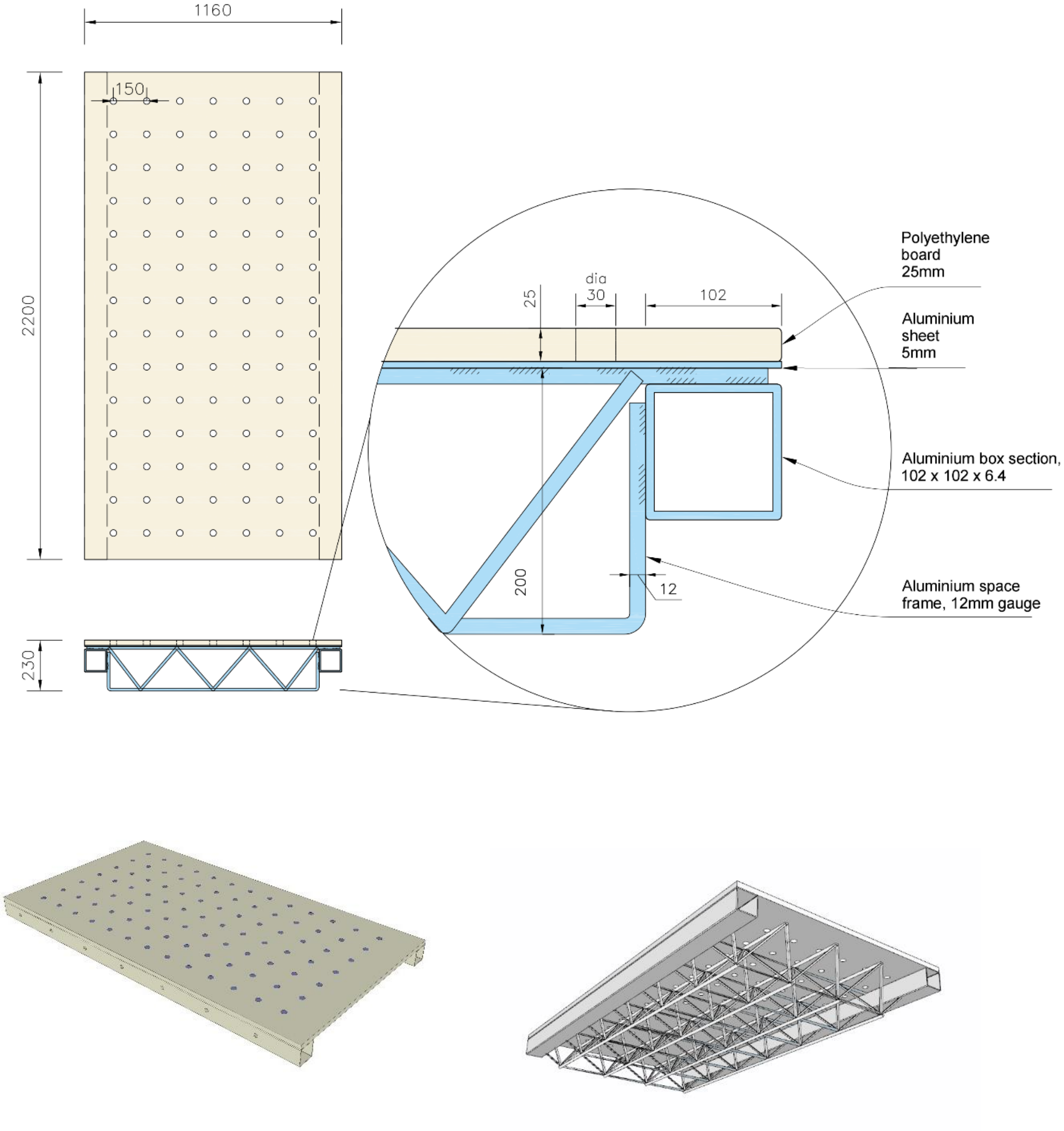


Figure 79: Breadboard Design Drawing and Views.

There are smaller devices to be fitted on the breadboard. **These serve the purposes of pre tensioning and joint anchorage.**

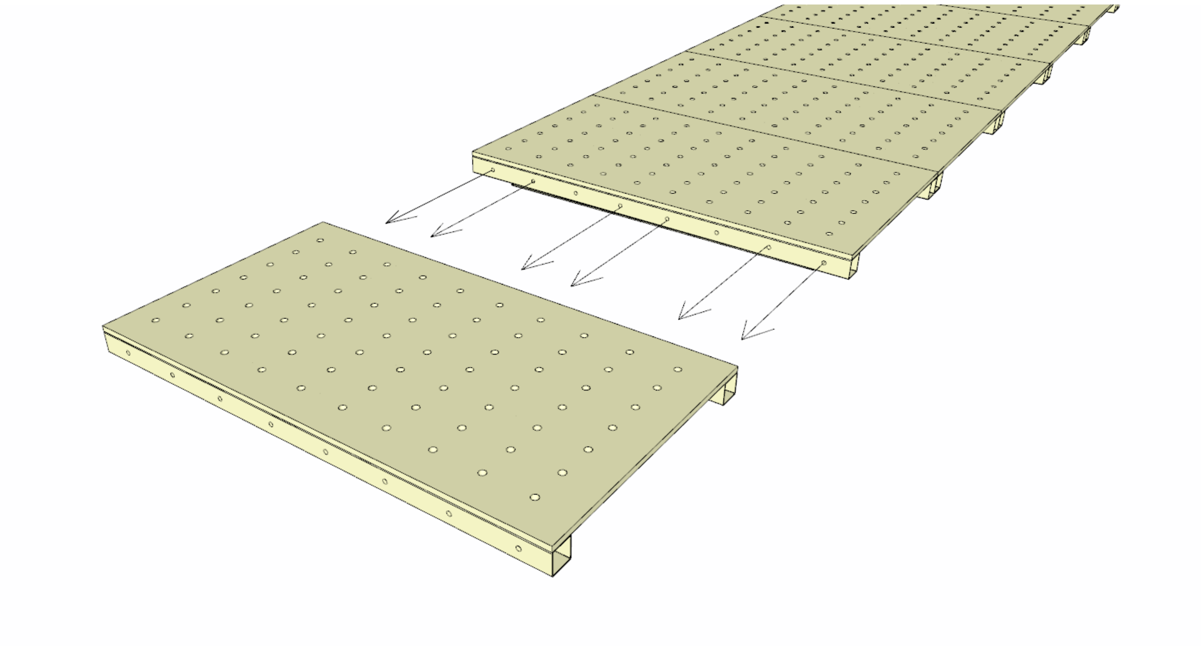


Figure 80: Breadboards may be 'chained' together by bolting the box sections together using M16 bolt nut combinations. This is how an 'array' may be created.

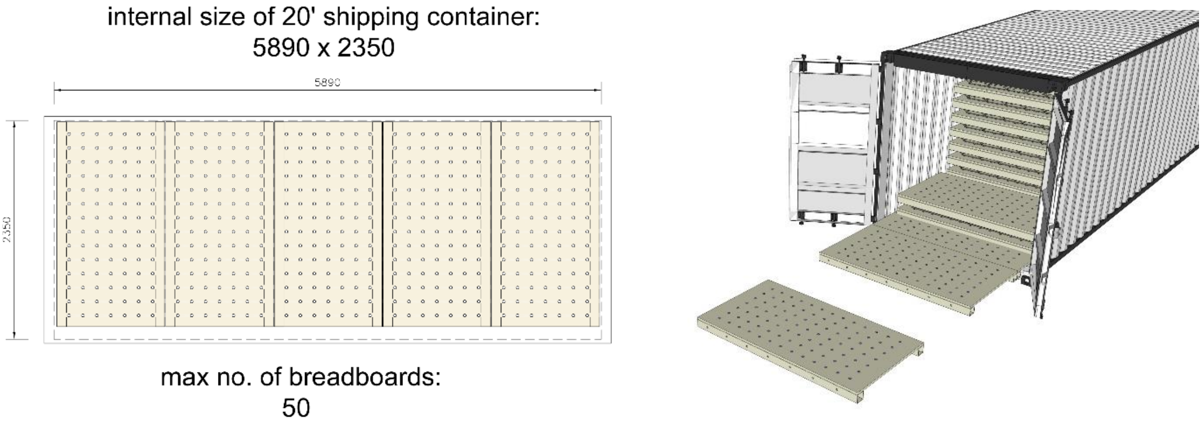


Figure 81: The Breadboard is dimensioned for compact fitting in shipping containers. 50 Breadboards can be fitted into a 20' shipping container.

Assembly workflow:

As described in Section 3.3.2, the tying of the truss itself is a 3 or 4-step process (depending whether the resin application is an In-situ process, or the cordage is a pre-preg) (*Figure 82*).

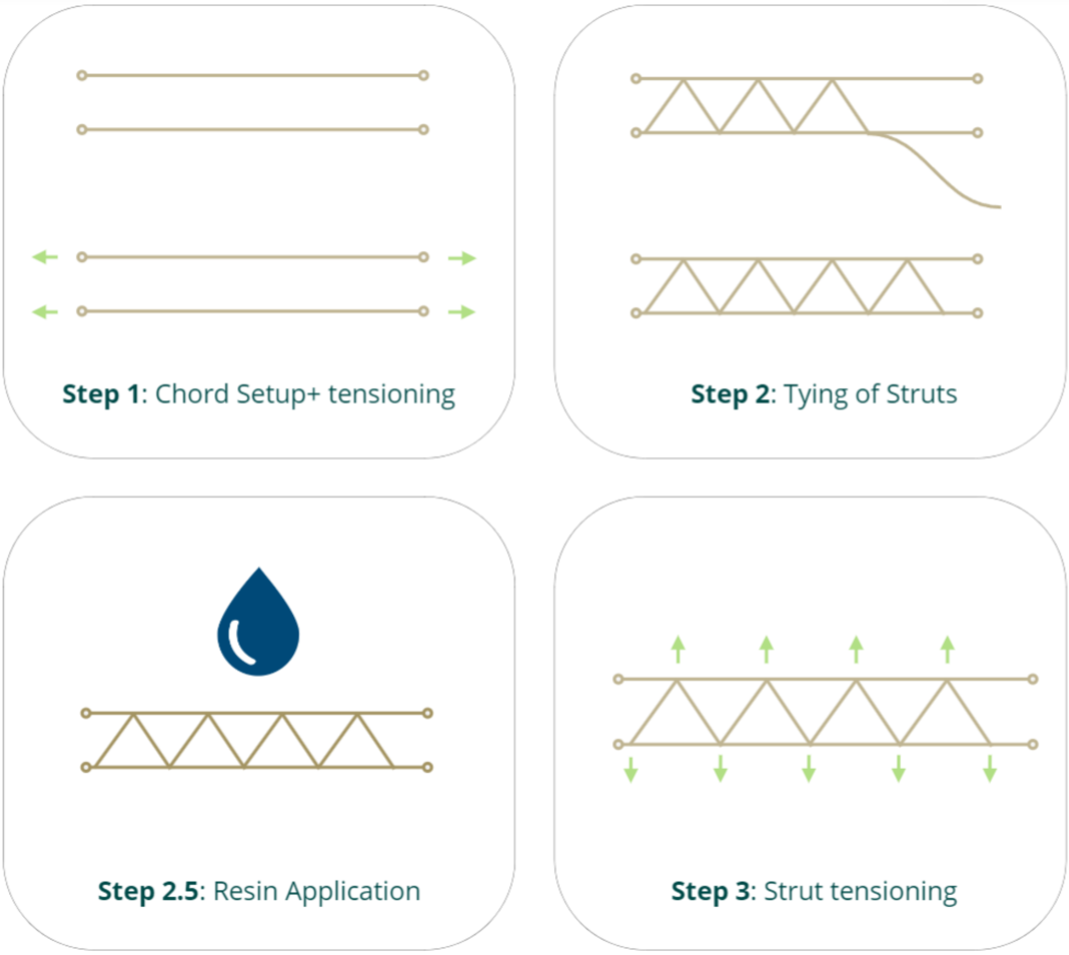


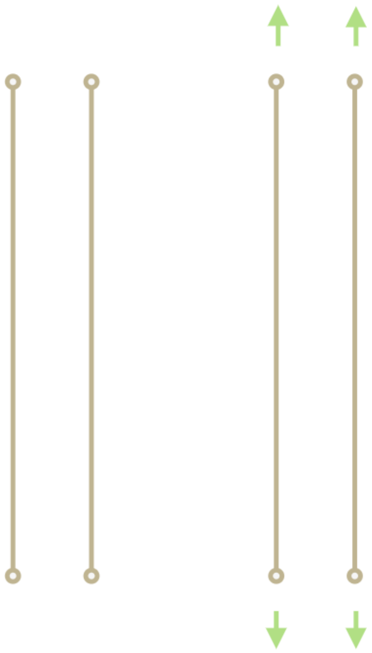
Figure 82: The step-by step schematic of the truss fabrication

There are attachments designed for the application of the chord tension and strut tension.

Chord tensioning:

This is achieved by a combination of aluminium gable units that are bolted to the ends of the array, as shown in Figure 83

The fixed unit is simply a stiff plate with a braided constrictor to clamp onto the flax cordage. It works exactly like the Constrictor clutches mentioned in Section 3.1.6.



The tensioning unit consists of an acme threaded bolt that is manually rotated with handles. This drives the Sleeve Pipe, which also has a braided constrictor to grip the flax cordage. When the sleeve pipe is driven back, the chord may be tensioned.

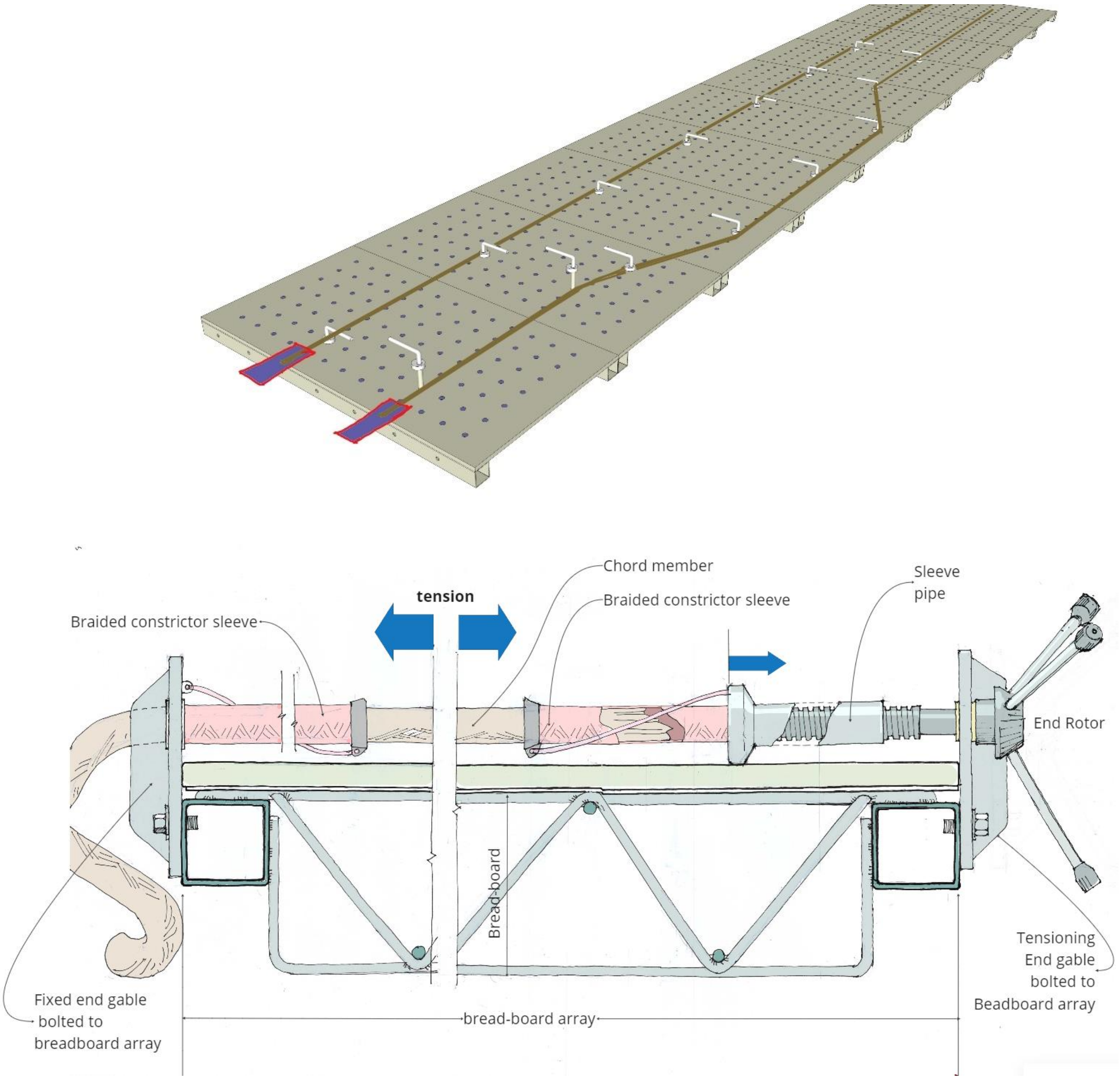


Figure 83:
a. View of breadboard array showing the location of the tensioning units. The exact shape of the chord may be controlled by inserting simple pegs into the breadboard.
b. Section- Gable ends of the breadboard array showing the fixed and tensioning gable units. The aluminium units are bolted onto the box sections of the end breadboards.

Strut tensioning:

This is achieved by an aluminium joint-tensioning unit that can be pinned into the breadboards holes. This allows for tensioning by ‘pulling’ the chords apart. The unit can be set up at a variety of positions, allowing for freedom of joint position as well.

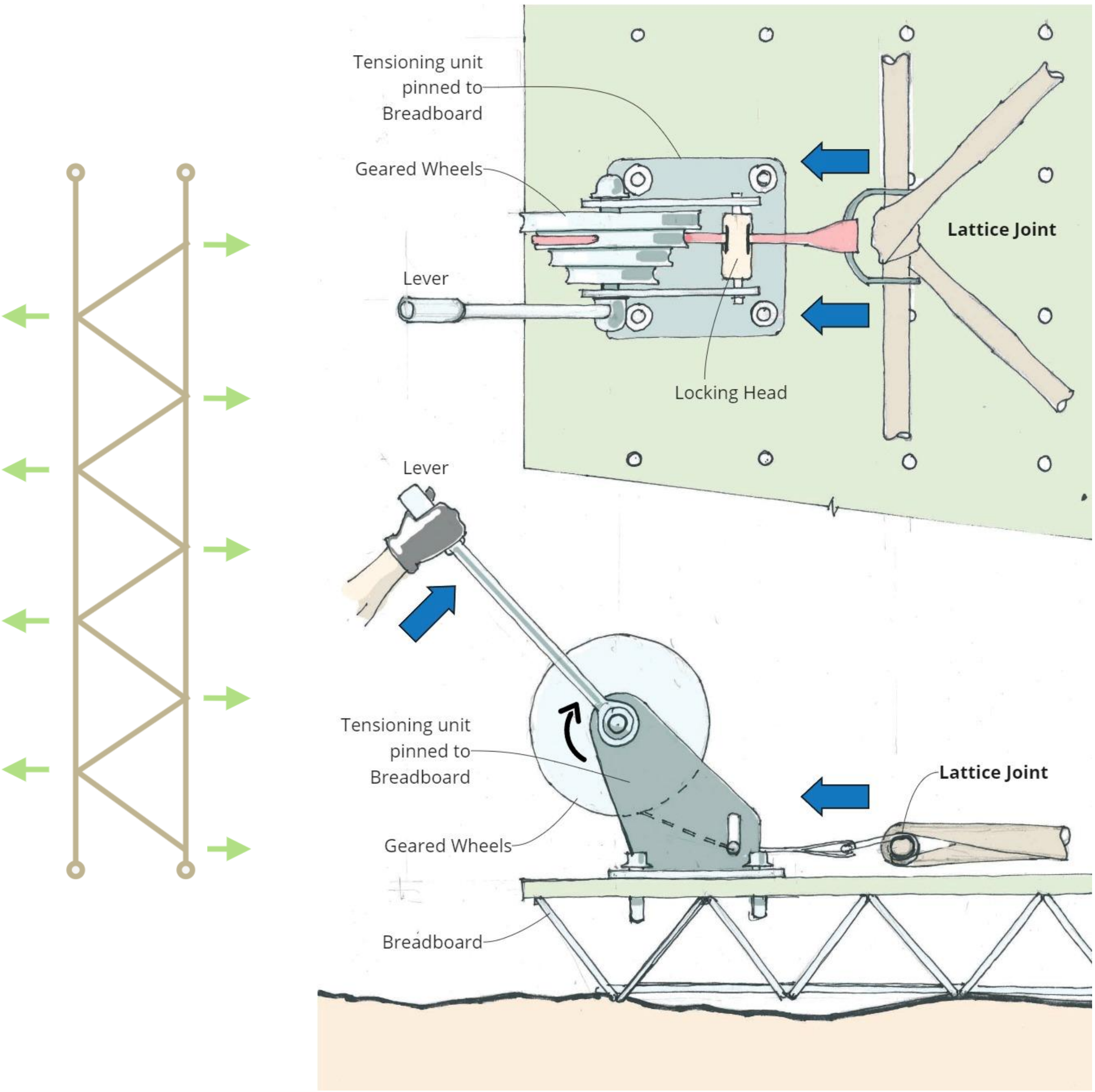


Figure 84: The joint tensioning mechanism.

In the initial design development, it was considered to use the pegs as the tensioning mechanism, by building an eccentric die into the peg (Figure 85). When the peg is rotated, the joint is automatically moved.

This idea was rejected, as the traverse that is achieved by such a mechanism is limited. Further, the eccentric die-flax joint interface would have to be virtually frictionless on order to avoid traction between the textile and the peg that could displace the joint.

Finally, if the size of the eccentric die was increased (to achieve greater pull), it interfered with the truss members centreline concurrence at the joint.

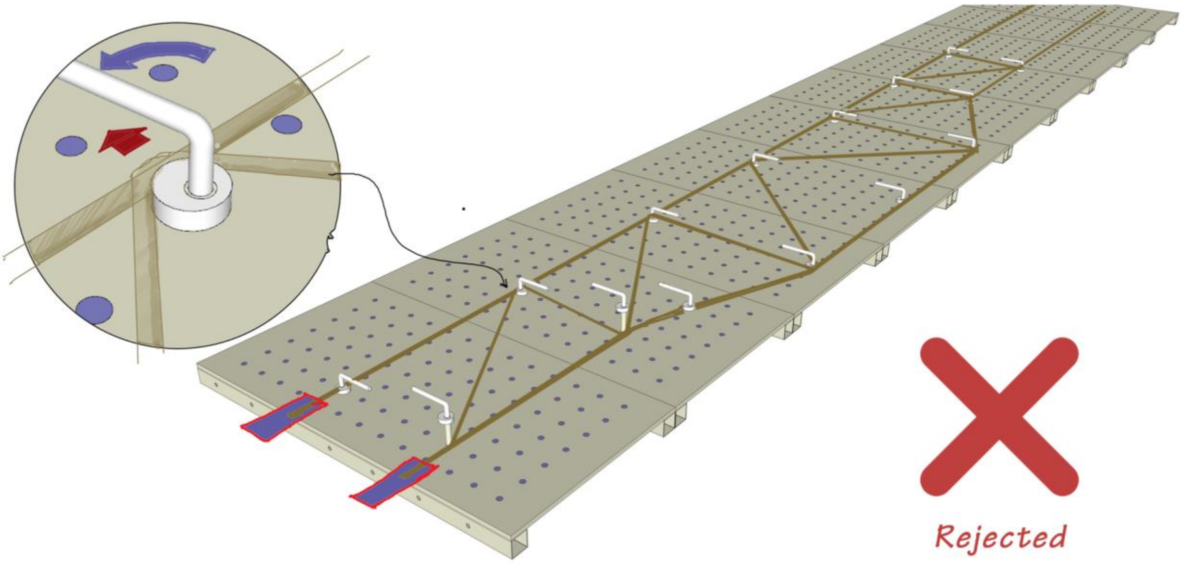


Figure 85: The peg-with-eccentric-die model for the lateral tensioning, eventually rejected.

Construction Possibilities:

The Breadboard design allows effectively for the construction of 2D lattice structures of a maximum depth of approximately 1350mm. Theoretically, the breadboards can be chained into a infinitely long array, but there are likely to be **practical issues** with over-long lattices.

- The relatively stiff array will, over large enough lengths, begin to sag and hog with the terrain, affecting the planarity of the fabricated lattices.
- The depth limitation of 1350mm suggests **a maximum recommended length of around 25m (**Figure 86**)**, at which point the aspect ratio is unfavourable for the truss, possibly resulting in unacceptable deflection under load or even failure.

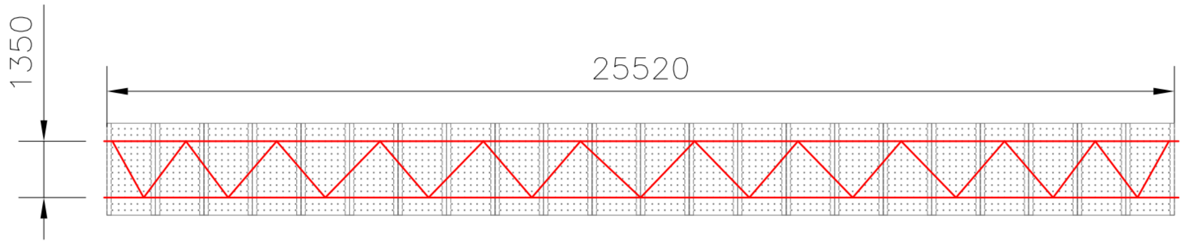


*Figure 86: The depth of girders is limited to about **1350mm** in order to accommodate the joint tensioning units. This suggests a maximum truss length of about **25m**, keeping to a span-depth ratio of 20.*

The design of the Jig allows for **some variations and freedom in the geometry** (Figure 87)of the lattice because the nodal positions can be freely chosen within the resolution of the Breadboard.

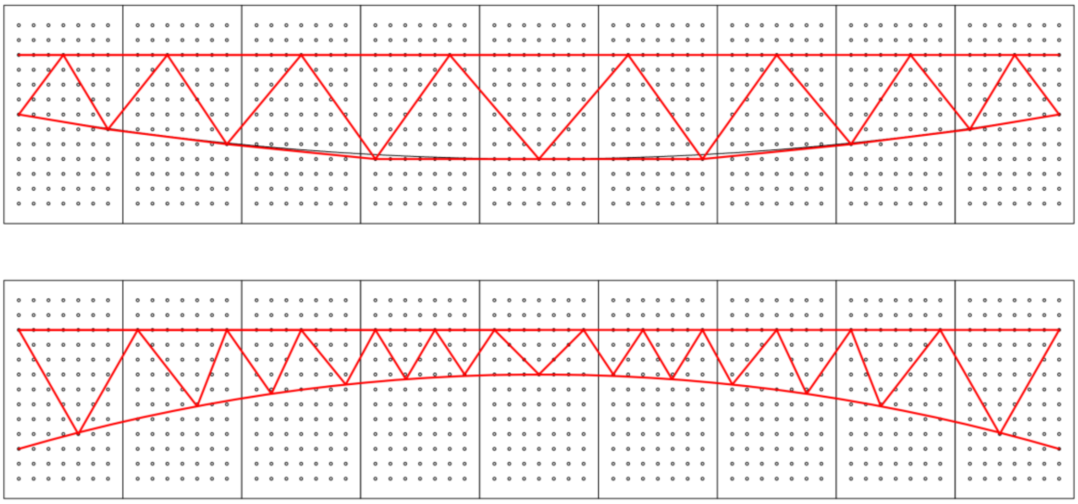


Figure 87: Within the depth limit of 1350mm, there is some geometric freedom in choosing truss geometries.

The 'Scale Prototype':

To better understand the proposal for the site fabrication method, a 1:5 scale version of the process was conducted, with some simplifications to the design. The purpose of the prototype was to study the convenience of the fabrication process proposed and suggest improvements. The prototype is not intended for structural load testing.

The breadboards were made from plywood and solid timber cross sections, to the size of 240mm x 440mm.

Since the prototype required several metres of cordage, hand braiding was not attempted, and a regular rope was purchased instead from Hornbach Bouwmarkt. This was considered acceptable, as the structural properties were not the focus of the prototype, and the fiber angle etc. were therefore not of concern and a rope from the market served the purpose.

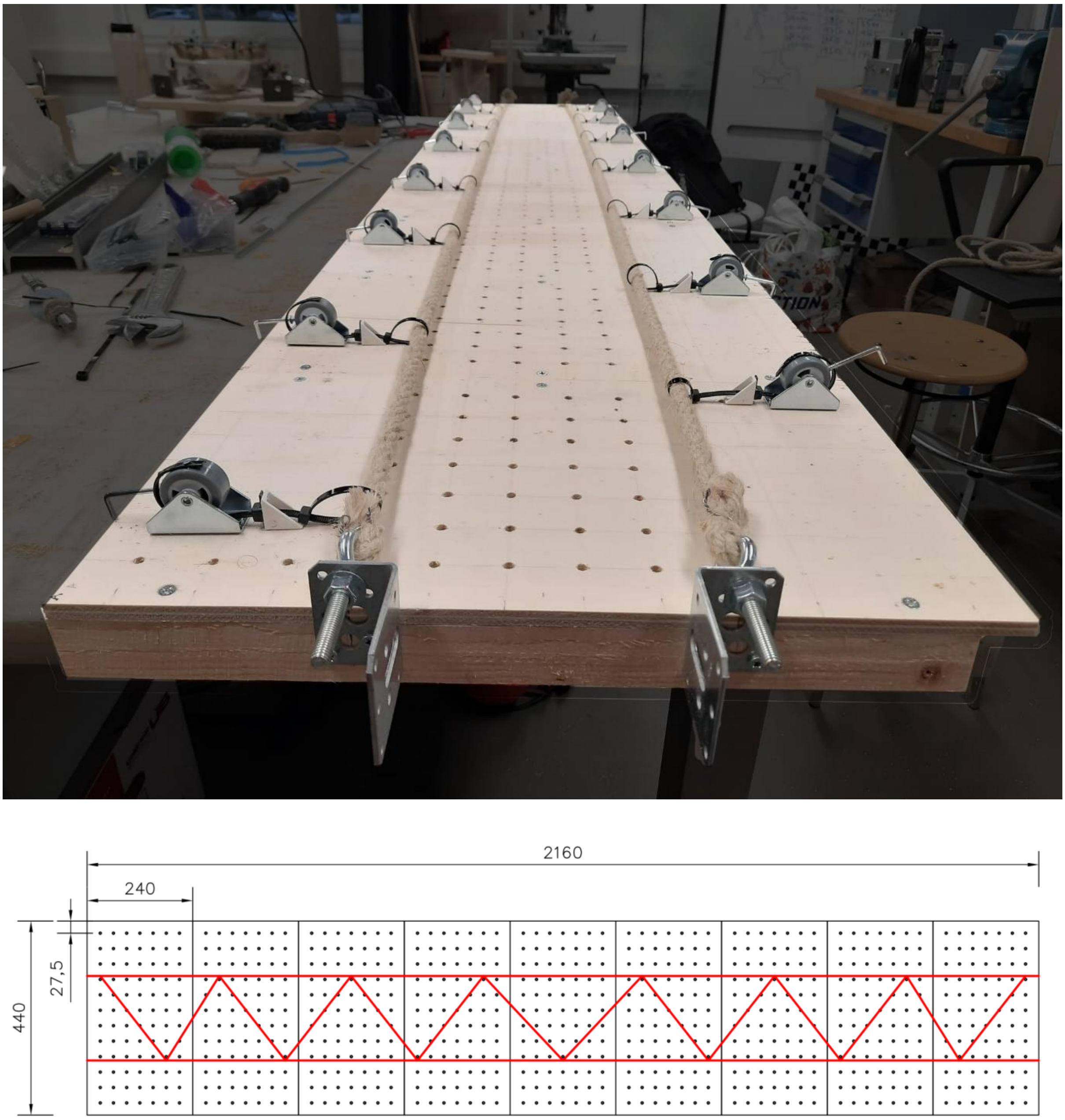


Figure 88: a. Prototype- Breadboard array of 9 breadboards for the construction of a simple 2D Warren Girder. The figure shows the chords already in position ready for axial tension, along with the devices for lateral tensioning at the joint positions. b. Drawing of the girder design to be manufactured. The simplest geometry was chosen for the first attempt.

Miniaturization of tensioning mechanisms:

An important part of testing the prototype was to assess the behaviour of the tensioning mechanisms as an approach to the truss manufacture. So, the devices proposed in the previous section were simplified and miniaturized as shown in Figure 89.

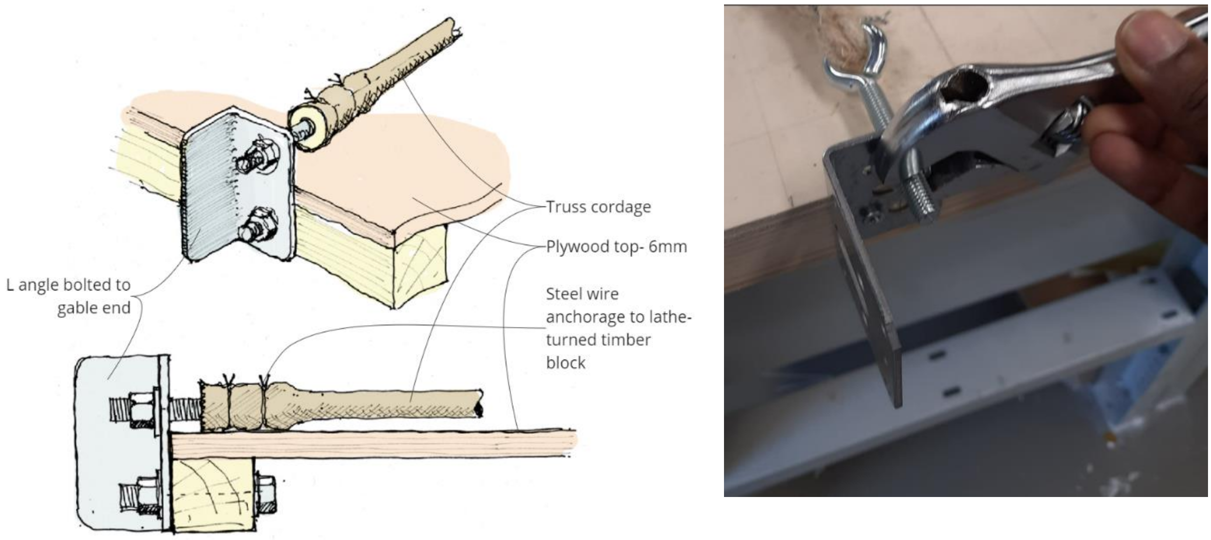


Figure 89: a. Initial sketches for the simplified design of the axial tensioning mechanism as proposed in Figure 83. b. The final simplified design using a hoop bolt. The cordage is simply looped through it and arrested with steel wire. This avoids the need for any lathe turned wood parts etc.

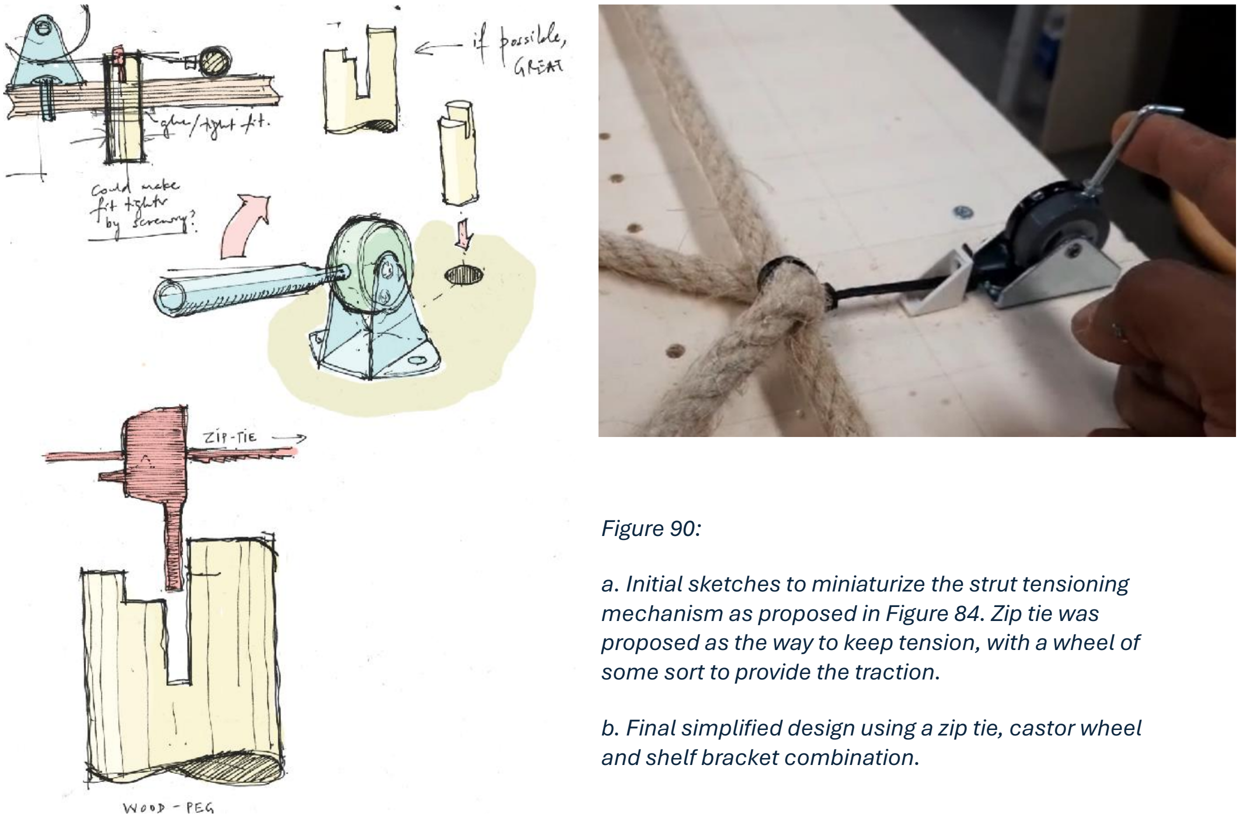


Figure 90:

a. Initial sketches to miniaturize the strut tensioning mechanism as proposed in Figure 84. Zip tie was proposed as the way to keep tension, with a wheel of some sort to provide the traction.

b. Final simplified design using a zip tie, castor wheel and shelf bracket combination.

The fabrication of the girder was done in the same sequence as proposed for on site construction:

1. Set up of chords and axial tensioning
2. Placement of lateral tensioning units (zip tie arrangement)
3. Winding of strut cordage, secured with the zip tie arrangement
4. Resin application
5. Lateral tensioning

Overall, the fabrication workflow was proven to be a successful and feasible method to prepare the lattice girder, at least in the 1:5 scale. However, this does not assess the structural soundness of the product.

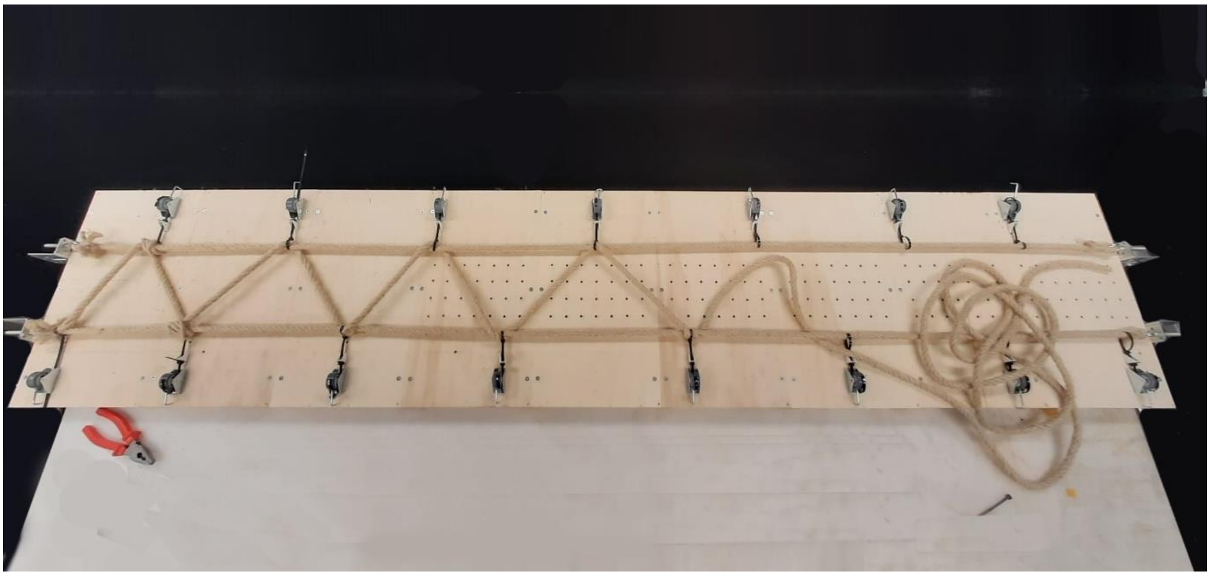


Figure 91: A 1:5 scale demonstration of the truss fabrication workflow

The **recommended next steps** for the research into fabrication workflow are:

1. A small-scale fabrication using the correct technical textile with the discontinuous mandrel and appropriate braid topology, followed by a load test of the prepared structure.
2. (Should 1. provide an acceptable product) A true to size field test of the proposed fabrication method.

Limitations of the proposed fabrication model:

- **The need for joint symmetry:** The tensioning of the struts is achieved through applying force at the joint perpendicular to the chord. Further, based on the experiments there is a target of 400-450N tension to be achieved in the strut to achieve the consolidation effect.

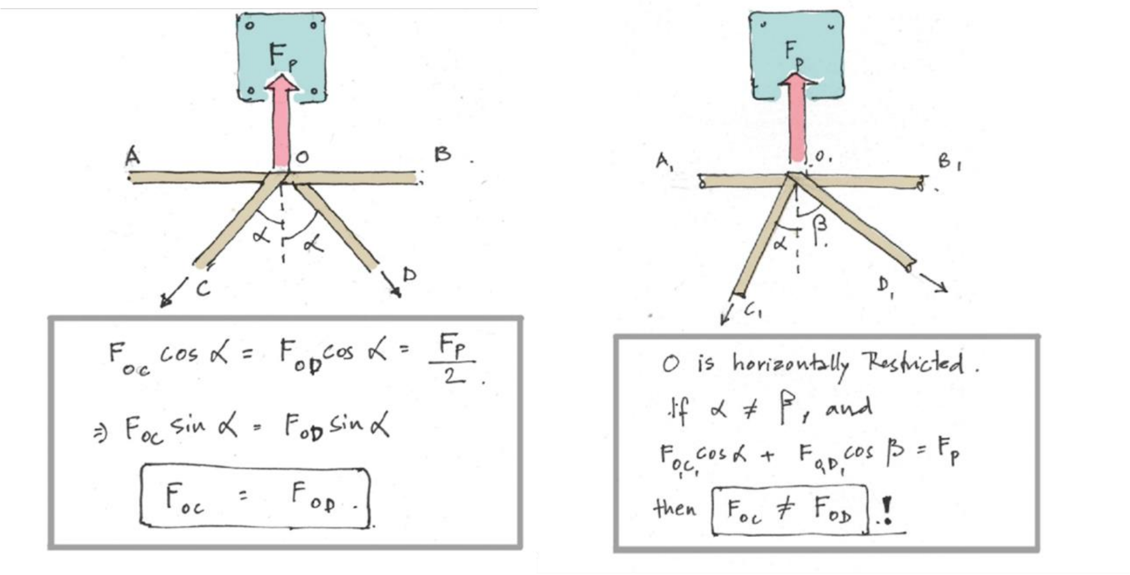


Figure 92: In the case of a symmetric joint, the internal pre-tension developed in the struts are equal. b. In asymmetric nodes, this cannot be achieved when the joint is distended orthogonally.

These conditions require that the geometry of struts at the joint is fairly symmetric. If not, the internal tension achieved in the joints is not the same (**Error! Reference source not found.**). Further, the imbalance could create a lateral force that rotates the strut tensioning unit.

- **Odd number of members not preferable:** Since the preparation of the joint involves the winding of a continuous length of cordage, and this is also what makes it sufficiently convenient (as opposed to each strut being a distinct segment of rope that needs to be knotted onto the chords), this means that only an even number of members can form a joint. TO have an extra member, the fabricator is forced to tie a short segment of rope. Further, the mechanical strength of such a joint is unknown,

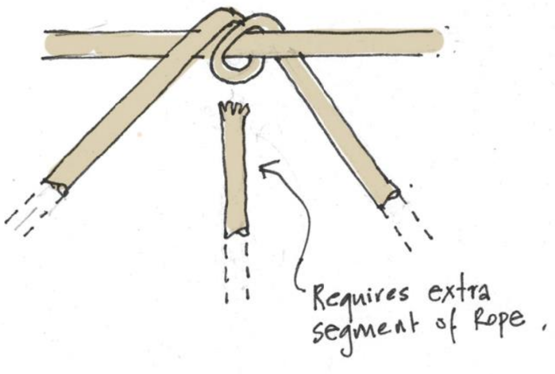


Figure 93: An odd number of members meeting at the node creates a continuity problem, requiring short segments of rope that have to be knotted as end termination. Such joints make the fabrication process slow and cumbersome.

- **Unclear whether non-girder type configurations are possible:** The proposed fabrication workflow involves two bounding chords that are drawn apart to create tension in the struts in order to achieve consolidation. This allows so far only girder type lattices to be fabricated. It cannot be said how the system works if other kinds of planar trusses are attempted.

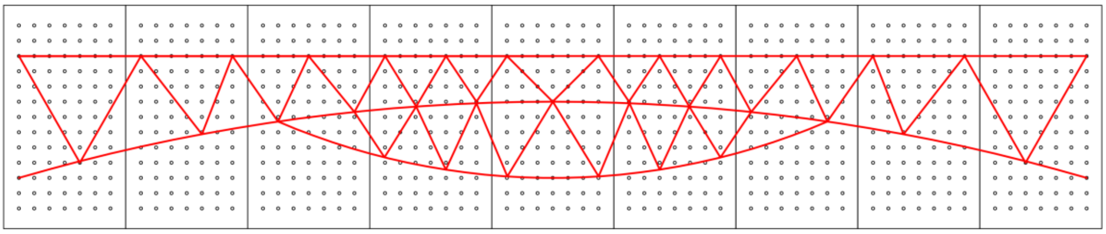


Figure 94: Unlike a girder with two parallel chords, the midsection of the truss shown above has a complication, as it is not clear how to achieve the strut tensions about the 'floating' middle chord.

Untested Construction Possibilities for future exploration:

1. **The possibility of portal frames:** The fabrication of a single girder alone still leaves the question of how the connection to the next load bearing element is handled, for effective load transfer. Unlike in metal trusses where the lattice can be borne on the supporting column by a welded or bolted connection, or a timber truss where it can be borne by gusset plates or simple fastener connections, the problem of connections in composite materials arises once again. Although it is not within the scope of the thesis to address this issue, there is a definite advantage *if the girder and bearing columns can all be fabricated as one continuous portal.*

   This would be very favourable for construction, as only the foundations and base connections have to be developed in a compatible way with the lattice structure.

It **may** be possible to construct whole lattice portal frames with the appropriate arrangement of Breadboards, as shown in Figure 95. However, this would require an adaptation to the breadboards such that they can be chained on the short side as well. The need to keep joints symmetric is of particular importance in this case, to achieve adequate consolidation tension in the struts.

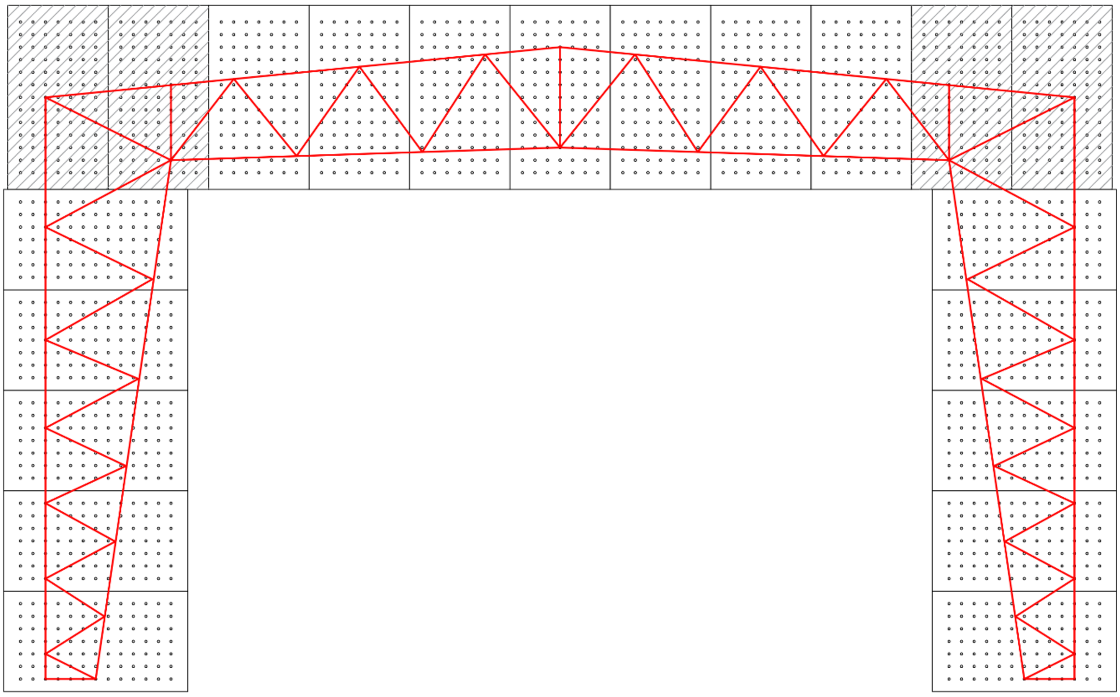


Figure 95: A possible setup for the manufacture of entire portal frames in a continuous process. This required the adaptation of the corner breadboards (shown as hatched in the figure) for long-side connection to perpendicular arrays.

2. **The possibility of 3D (or 2.5D) lattice girders**: A major drawback of lightweight 2d lattices is the lack of out-of-plane stiffness. This could result in compression buckling (when the lattice is a vertical load bearing element) or Lateral Torsional Buckling (when the lattice is a spanning load bearing element). A girder with a prismoid cross section is advantageous in this context.
   It could be that a prismoid girder can be 'built-up' by assembling a set of planar lattices that are prepared sequentially. However, this would require weaving 'wet' or uncured cordage onto the members of the preceding cured lattice. The interface of the dry and wet composite would create joints of different characteristics, and their behaviour and mechanical performance would then have to be determined.

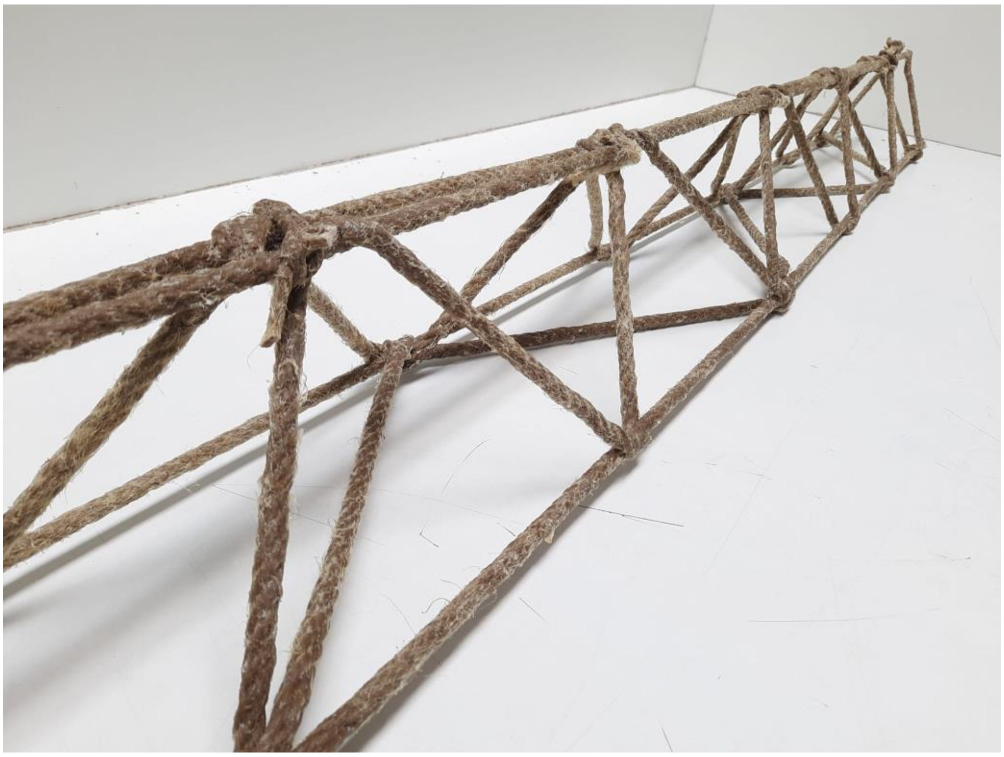


Figure 96: A prismoid portal frame constructed on the breadboard as a series of 3 tying cycles for each of the planes.

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Conclusions

1. With a well detailed and feasible ‘site construction manual’, it appears that the proposed technology can be used for the fabrication of in situ trusses
2. However, against a benchmark steel structure, it does not compare favourably in a strength to volume sense, in that it has failure values in the vicinity of 70 MPa (compared to steel in the 250-300 MPa range)
3. However, it may still compare favourably in the strength to weight sense, as although it is 4 times weaker than steel, it is about 6 times lighter (steel: 7800kg/m3, flax composite 1200-1300 kg/m3)
4. Cost and eco impact need yet to be assessed.
5. The next steps for the exploration of the construction method should be a small-scale fabrication using the correct technical textile with the discontinuous mandrel and appropriate braid topology, followed by a load test of the prepared structure.
6. Should this prove acceptable, a full-scale prototype may be attempted as a field test of the proposed fabrication method.
7. There are exciting possibilities for other fabrications, such as prismoidal girders, which will have much better resistance to Lateral torsional Buckling, but also for the fabrication of entire girder portals, which could be used for construction in future.

3.5 **The Big Picture**

In the preceding chapters, the following have been established:

- The choice of fibre (and substitute polymer) for the composite.
- The design and method of manufacturing cordage in such a way that it can be woven into a lattice as proposed.
- The mechanical performance of isolated elements (strut/chord and joint) when loaded in patterns to be expected as internal forces in a loaded lattice.
- A workflow and setup for the actual fabrication- weaving the cordage into the form of the lattice.

Due to key areas of research being excluded from the scope of this thesis, important parameters of this structural product remain unknown, such as creep and fatigue behaviours, thermal behaviour, resistance to weathering etc. These are subjects for future research.

If, however, this technology is realized in its existing form, it remains to assess this from the point of view of Economy and Ecological implication. A comparison with typical lattice fabrication materials like steel and wood is attempted, to provide perspective.

Structural Design- A hypothetical problem

With the quantified mechanical strength of the Flax truss cordage and joints, it is possible to use them as values to propose a member sizing for a lattice girder that shall be designed for a hypothetical structural problem.

The problem is prepared as shown below:

Propose a design for a lattice girder across a span of 10 metre. The depth of the lattice is 1m, and the ends are simply supported- taking only the bottom chord ends as pin jointed. Consider a dead load (from the roof sheet and purlins) of 0.25kN/m2 and a wind load of 1kN/m2.

Prepare a design in steel, wood, and the novel flax technology:

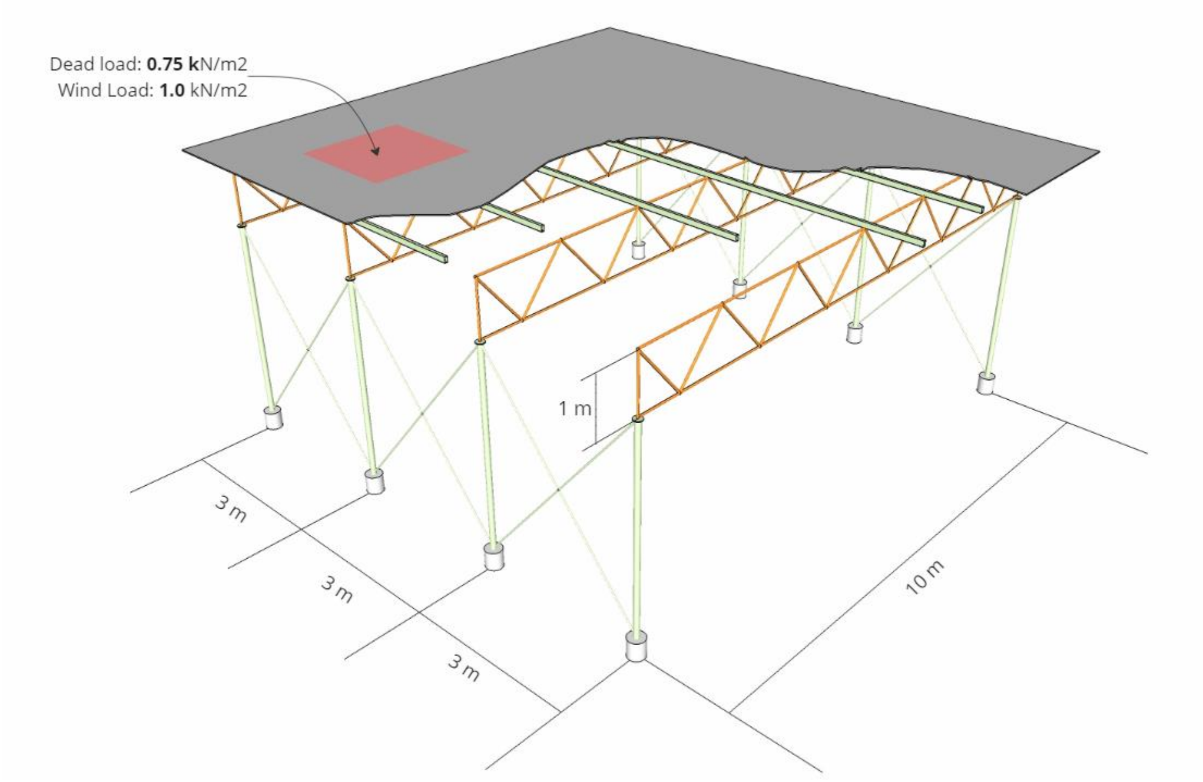


Figure 97: The hypothetical Design problem for the truss

The first step is to determine the forces in the members, which were determined to be as shown in Fig, using a Karamba analysis, and cross checked by some hand calculations.

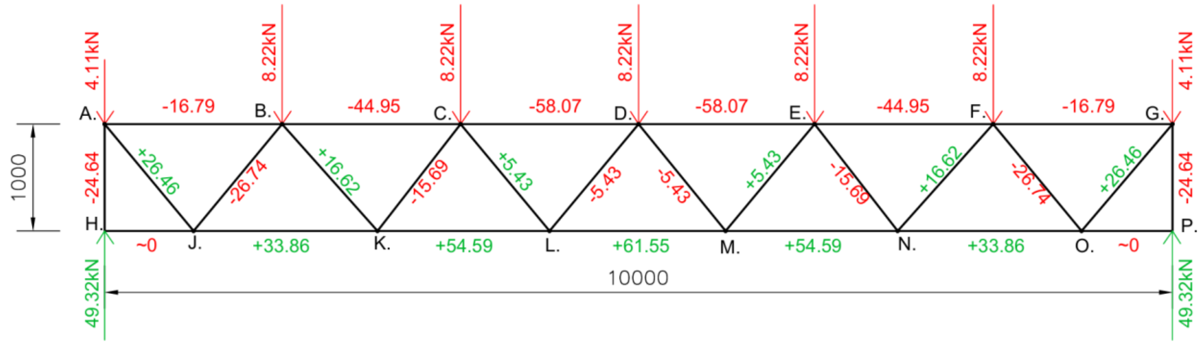


Figure 98: Truss analysis for the load problem in Figure 97.

Design in Steel:

For the steel design, tubular pipe sections manufactured according to the standard EN 10219:2006, are considered, with a tensile failure strength of 345 MPa.

The joints are considered to be fully welded- a reasonable assumption, as fabricators often do this to weatherproof and dust-proof the joints by closing off all seams.

Assumptions made for the design to follow are:

1. All member joints are pin-joints (conservative assumption, as the welded connections have significant fixity, and also reduce effective bucking lengths of struts in actuality).

2. Lateral Torsional Buckling of the whole girder is restrained.

Calculation method:

The **member sizing** was done accounting for compression buckling based on strut capacity curves. The calculations were done based on a Grasshopper script for efficiency, and checked with hand calculations. Based on these, the set on theoretical member sizes were prepared for each member.

Since it is typically impractical fabrication effort to have a single line chord made of a number of different cross sections (see top chord), the design is rationalized such that the thickest diameter is used as a single bar through the length of the truss (the truss is 10m long, and it is assumed that is built with a 6m + 4m stock combination with a butt weld joint).

The **weld lengths** were simple calculated based on the circumference of the pipes, and the assumed fabrication method that all struts are segments cutoff from stock and welded onto continuous chord sections.

The data is summarized in Table 3: Member sizing, steel design.

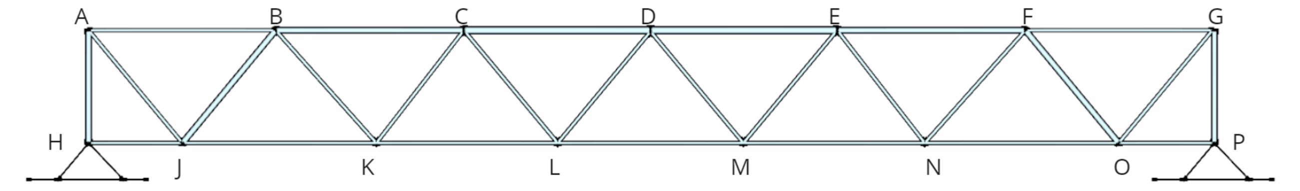


Figure 99: Theoretical cross section design, using steel pipes (see table for member sizes)

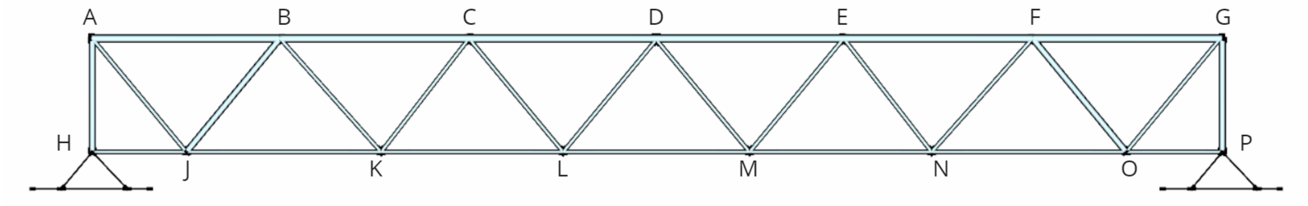


Figure 100: Fabrication-Rationalized design, where the top chord is a single cross section with only 1 joint.

Table 3: Member sizing, steel design

STEEL TUBES- Member Sizing									Strut Welding	
		Theoretical		Rationalized						
Member	Length (m)	Section dia (mm)	Thickness (mm)	Section dia (mm)	Thickness (mm)	CS area mm2	Volume		Outer circum-ference (mm)	Approx Weld Length (mm)
AB	1.66	26.9	2.5	**60**	**3.2**	574	**952.84**		188.4	376.8
BC	1.66	48.3	3.2	**60**	**3.2**	574	**952.84**		188.4	376.8
CD	1.66	60	3.2	**60**	**3.2**	574	**952.84**		188.4	376.8
DE	1.66	60	3.2	**60**	**3.2**	574	**952.84**		188.4	376.8
EF	1.66	48.3	3.2	**60**	**3.2**	574	**952.84**		188.4	376.8
FG	1.66	26.9	2.5	**60**	**3.2**	574	**952.84**		188.4	376.8
HJ	0.83	26.9	2.5	**26.9**	**2.5**	192	**159.36**		84.466	168.932
JK	1.66	26.9	2.5	**26.9**	**2.5**	192	**318.72**		84.466	168.932
KL	1.66	26.9	2.5	**26.9**	**2.5**	192	**318.72**		84.466	168.932
LM	1.66	26.9	2.5	**26.9**	**2.5**	192	**318.72**		84.466	168.932
MN	1.66	26.9	2.5	**26.9**	**2.5**	192	**318.72**		84.466	168.932
NO	1.66	26.9	2.5	**26.9**	**2.5**	192	**318.72**		84.466	168.932
OP	0.83	26.9	2.5	**26.9**	**2.5**	192	**159.36**		84.466	168.932
AJ	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
JB	1.3	48.3	3.2	**48.3**	**3.2**	453	**588.9**		151.662	303.324
BK	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
KC	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
CL	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
LD	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
DM	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
ME	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
EN	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
NF	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
FO	1.3	48.3	3.2	**48.3**	**3.2**	453	**588.9**		151.662	303.324
OG	1.3	26.9	2.5	**26.9**	**2.5**	192	**249.6**		84.466	168.932
AH	1	48.3	3.2	**48.3**	**3.2**	453	**453**		151.662	303.324
GP	1	48.3	3.2	**48.3**	**3.2**	453	**453**		151.662	303.324

total volume	**12209.16**	cm2
total weight	**95.23145**	kg

6345.94 mm
total weld length

Design in Timber:

For the timber option, a design is prepared using C24 softwood timber, using values taken from EN 338– Coniferous Species and Poplar. The design values taken are:

Compressive strength $f_{c,0}$ = **21 MPa**, tensile strength $f_{t,0}$ = **14 Mpa**, Tensile Modulus $E_{0,mean}$= **11 GPa.,** density = **420 kg/m3**

The building is assumed to be of Service class 2, and with Long Term load duration of <10 years. (k_{mod}= 0.7)

Based on these values, a member sizing is prepared, as shown in the table below.

C24 TIMBER SECTIONS- Member Sizing

member	length (m)	Theoretical		Rationalized		CS area cm2	Volume (cm2)
		section width	section depth	section width	section depth		
AB	1.66	100	75	**100**	**75**	75	**12450**
BC	1.66	100	100	**100**	**100**	100	**16600**
CD	1.66	100	100	**100**	**100**	100	**16600**
DE	1.66	100	100	**100**	**100**	100	**16600**
EF	1.66	100	100	**100**	**100**	100	**16600**
FG	1.66	100	75	**100**	**75**	75	**12450**
HJ	0.83	100	50	**100**	**50**	50	**4150**
JK	1.66	100	50	**100**	**50**	50	**8300**
KL	1.66	100	75	**100**	**75**	75	**12450**
LM	1.66	100	100	**100**	**100**	100	**16600**
MN	1.66	100	75	**100**	**75**	75	**12450**
NO	1.66	100	50	**100**	**50**	50	**8300**
OP	0.83	100	50	**100**	**50**	50	**4150**
AJ	1.3	100	50	**100**	**50**	50	**6500**
JB	1.3	100	75	**100**	**75**	75	**9750**
BK	1.3	100	50	**100**	**50**	50	**6500**
KC	1.3	100	50	**100**	**50**	50	**6500**
CL	1.3	100	50	**100**	**50**	50	**6500**
LD	1.3	100	50	**100**	**50**	50	**6500**
DM	1.3	100	50	**100**	**50**	50	**6500**
ME	1.3	100	50	**100**	**50**	50	**6500**
EN	1.3	100	50	**100**	**50**	50	**6500**
NF	1.3	100	50	**100**	**50**	50	**6500**
FO	1.3	100	75	**100**	**75**	75	**9750**
OG	1.3	100	50	**100**	**50**	50	**6500**
AH	1	100	75	**100**	**75**	75	**7500**
GP	1	100	75	**100**	**75**	75	**7500**

total volume	**257200**	cm2
total weight	**102.88**	kg

For the connections, light-gauge galvanized steel plates are considered, and assumed to be laser-cut to size. The details for the same are shown below.

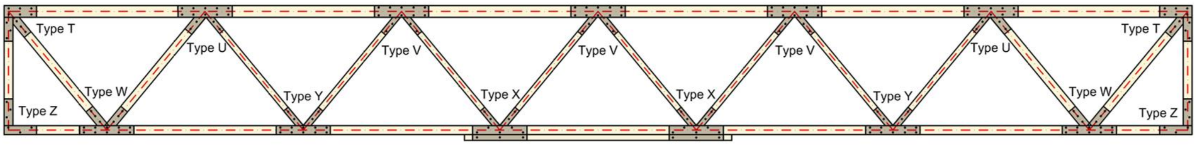
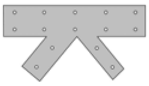
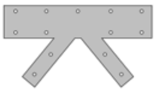
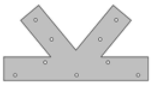
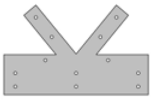
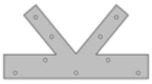
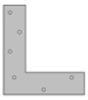


Figure 101: Timber truss design with C24 solid sections and Light Gauge GI connector plates.

Plate	Fig	Thick-ness (mm)	Nos.	Area (cm2)	Weight (g)	Lasercut Length /pc	Total
Type T		2	4	540	3369.6	1800	7200
Type U		2	4	645	4024.8	2135	8540
Type V		2	6	625	5850	2230	13380
Type W		2	4	600	3744	2180	8720
Type X		2	4	747	4661.3	2240	8960
Type Y		2	4	516	3219.8	2165	8660
Type Z		2	4	370	2308.8	1330	5320
			total weight		27178	total lasercut	**60780**

The weights of the bolts and fasteners are neglected.

Design with Truss to GO technology:

For this method of fabrication, the idea is that 2 lengths of cordage are are strung up and tensioned on the array of breadboards to act as chords, and a continuous length of cordage is woven between them by hand to form the struts.

The design is done is 3 steps:

- Calculate cordage cross section for bottom chord (tension)
- Calculate cordage cross section for top chord (compression). Strut capacity curves are unknown bvut euler buckling can be checked with the E value.
- Calculate the load on **the most heavily loaded strut**. Since it is a continuous piece of ‘rope’, this is the governing factor that determines the cordage for the entire ‘strut-chain’.
- Apply a **Joint Weakening Factor of 0.8.** Since it was discovered from the load test of the joint that the joint failed at 80% of the struts true load bearing capacity
- Calculate the cross section of cordage that forms the ‘strut-chain’, for the *factored load*.

Bottom Chord Design:

The bottom chord is in tension. The calculated tensile capacity of the product is 75MPa.

Max Tensile stress in bottom chord occurs at L-M , = 61.55 kN.

The cross-section demand is therefore:

$\frac{61.55\ kN}{75\ MPa}$= **820mm^2**

A cross section of **76mm dia, 4mm thickness** (area= 904mm^2) will suffice.

Top Chord Design:

This chord is in compression so it is important to check Euler Buckling. For this, we require the E modulus of the composite.

In the literature on flax epoxy composites, the E modulus has been reported as approx. 30GPa. However the flax and the epoxy were different.

For Truss to GO, the equivalent E value of the composite can be calculated using the Rule of Mixtures, since the E moduli of the Flax alone, the resin alone, and the Fiber Volume Fractions are known.

E_{eff} = E_{flax}(FVF) + E_{epoxy}(1-FVF) = (0.25 x 60 GPa)+ (0.75 x 2.9 GPa) = **17.175 GPa**

Using the Euler buckling formula,

$P_{cr} = \frac{\pi 2.\mathrm{EI}}{l\hat{}2}$.

For a load of 58 kN compressively (the max load that occurs at CD), we must calculate the cross section

Try diameter **76.1mm, thickness 4mm**

P_{cr}= $\frac{\pi 2.\mathrm{EI}}{l\hat{}2}$ = $\frac{\pi 2.(17.2\mathrm{GPa})(59.06\mathrm{cm}^4)}{(1.66m)\hat{}2}$ = 60.3kN > 58 kN

Sufficient.

Similarly, for the strut design:

the factored load is **26.46 KN** (highest compressive force) / **0.8** (Joint Weakening Factor) = **33.075 kN**

Try CS diameter **76.1mm, thickness 2.0mm**

P_{cr}= $\frac{\pi 2.\mathrm{EI}}{l\hat{}2}$ = $\frac{\pi 2.(17.2\mathrm{GPa})(31.98\mathrm{cm}^4)}{(1.66m)\hat{}2}$ = 39 kN > 33 kN

Sufficient.

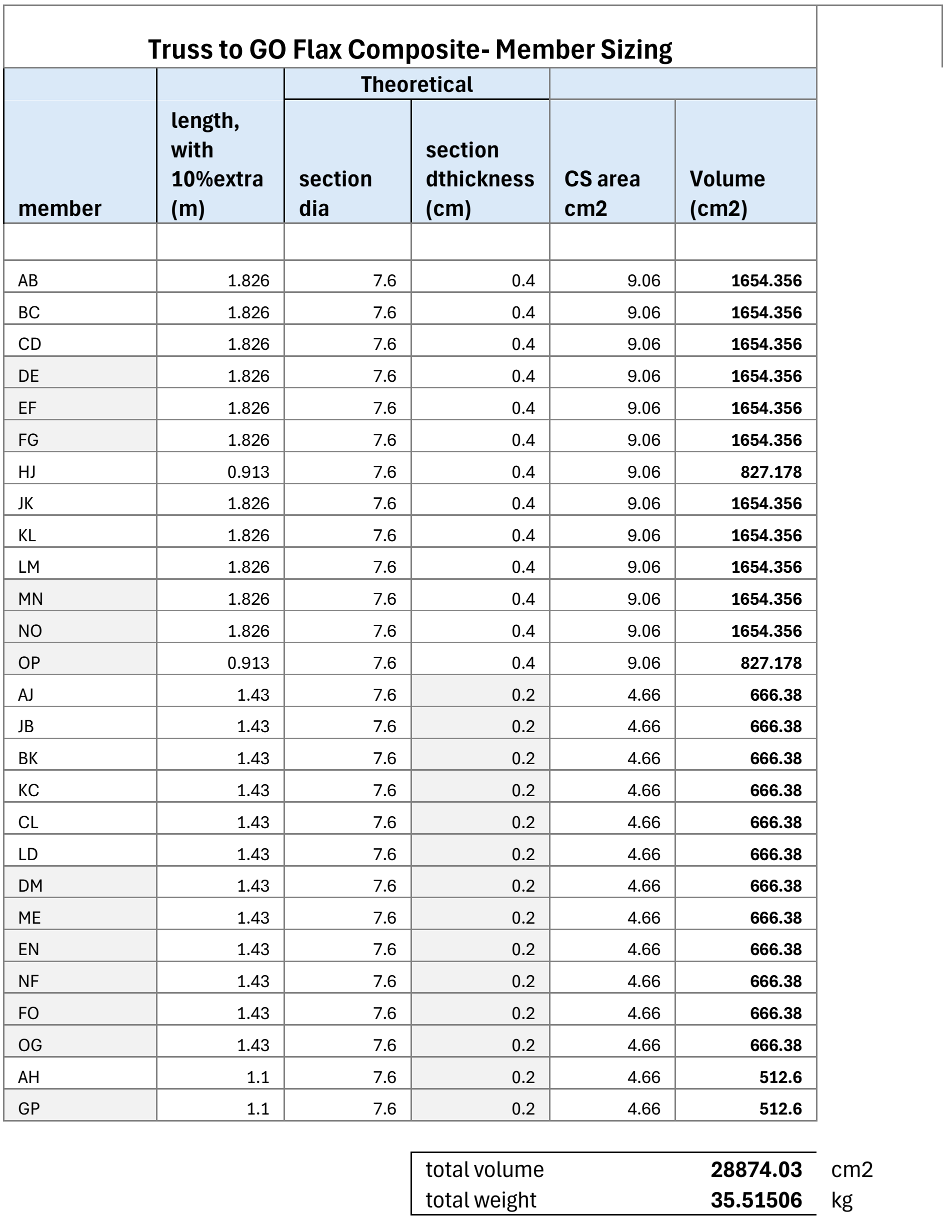
TO summarize, the member sizes are as follows:

Top chord: 76.1mm, 4.0mm

Bottom chord: 76.1mm, 4.0mm

Strut: 76.1mm, 4.0mm

The quantities are expressed in the following table:



Truss to GO Flax Composite- Member Sizing

		Theoretical			
member	length, with 10%extra (m)	section dia	section dthickness (cm)	CS area cm2	Volume (cm2)
AB	1.826	7.6	0.4	9.06	**1654.356**
BC	1.826	7.6	0.4	9.06	**1654.356**
CD	1.826	7.6	0.4	9.06	**1654.356**
DE	1.826	7.6	0.4	9.06	**1654.356**
EF	1.826	7.6	0.4	9.06	**1654.356**
FG	1.826	7.6	0.4	9.06	**1654.356**
HJ	0.913	7.6	0.4	9.06	**827.178**
JK	1.826	7.6	0.4	9.06	**1654.356**
KL	1.826	7.6	0.4	9.06	**1654.356**
LM	1.826	7.6	0.4	9.06	**1654.356**
MN	1.826	7.6	0.4	9.06	**1654.356**
NO	1.826	7.6	0.4	9.06	**1654.356**
OP	0.913	7.6	0.4	9.06	**827.178**
AJ	1.43	7.6	0.2	4.66	**666.38**
JB	1.43	7.6	0.2	4.66	**666.38**
BK	1.43	7.6	0.2	4.66	**666.38**
KC	1.43	7.6	0.2	4.66	**666.38**
CL	1.43	7.6	0.2	4.66	**666.38**
LD	1.43	7.6	0.2	4.66	**666.38**
DM	1.43	7.6	0.2	4.66	**666.38**
ME	1.43	7.6	0.2	4.66	**666.38**
EN	1.43	7.6	0.2	4.66	**666.38**
NF	1.43	7.6	0.2	4.66	**666.38**
FO	1.43	7.6	0.2	4.66	**666.38**
OG	1.43	7.6	0.2	4.66	**666.38**
AH	1.1	7.6	0.2	4.66	**512.6**
GP	1.1	7.6	0.2	4.66	**512.6**

total volume	**28874.03**	cm2
total weight	**35.51506**	kg

Mandrel material:

The chord mandrel beads are taken as 10cm long, 7cm dia, and at 400mm c/c on average.

Over 20m of chord, this gives us 50 blocks of 385 cm^3 = 19230 cm^3

For an approximate timber weight of 0.4g/cm3, this amounts to **7.6kg**

The strut mandrel beads are taken 5cm long and 7cm dia, and at 200mm c/c on average

Over 17.6m, this gives us 88 blocks of 192 cm^3 = 16896 cm^3

For an approximate timber weight of 0.4g/cm3, this amounts to **6.7 kg**

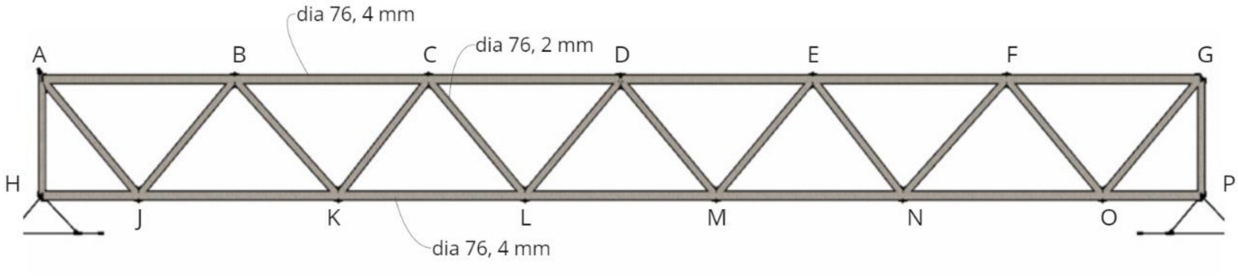


Figure 102: Truss to GO design with calculated member sizes

Comparison against the Usual Suspects

It is now possible to make a fairly simple quantitative comparison between the three technologies of truss construction for given problem. Most values are taken from Granta Edupack, and some others have been calculated as follows:

The Embodied energy and CO2 of Fillet welds with Shielded Metal Arc Welding (SMAW):

SMAW is versatile and fairly low power consuming, with a consumption of 1500-6000watts (Source: https://weldmart.com.my). Consider an average of **3700 watts.**

For a weld size of 6-8mm, the welding speed is about 10cm/45 seconds. This is also known from the author's experience.

This means that the electrical energy demand for a unit length of welding is :

45 seconds x 3700 J/s ÷ 10cm = ***16.65 kJ/cm electrical energy***

With the primary production efficiency for the generation of electricity- a factor of 0.4 can be applied

Therefore, the **embodied energy** for welding is= 16.65 / 0.4 = **41.625 kJ/cm of weld.**

As per the KEV 2019 in NTA8800:2019, the embodied carbon for electrical production is 0.3 kg/kWh, or 0.083kg/MJ.

Therefore, the **embodied carbon** for welding is **= 0.0035 kg/cm of weld.**

The Embodied Energy and CO2 of Fiber-Laser Laser Cuts:

Fiber Lasers are considered one of the more efficient laser cutting technologies.

The *energy efficiency* of Fiber lasers are reported as 30-50% (Source: Kimla.pl). Consider an average of **40%**

The cutting speed of steel for a 6kW machine (6kW is typical) = 472 inch/min = 12m/min

The electrical energy demand for a 3mm cutting job is therefore:

6 kJ/s ÷ 0.4(efficiency) x 60 seconds ÷ 12m = **75kJ/m electrical energy**

With the primary production efficiency for the generation of electricity- a factor of 0.4 can be applied

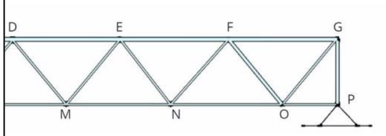
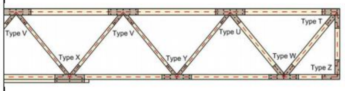
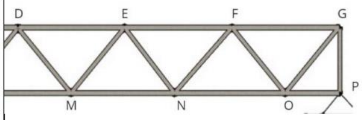
Therefore, the **embodied energy** for welding is= 75 / 0.4 = **187.5 kJ/cm of lasercut.**

As per the KEV 2019 in NTA8800:2019, the embodied carbon for electrical production is 0.3 kg/kWh, or 0.083kg/MJ.

Therefore, the **embodied carbon** for lasercutting is **= 0.015 kg/cm of lasercut.**

The Table below shows a comparative study between the resources of the three technologies.

Table 4: A comparative audit of the Truss built with three different technologies- welded steel pipes, solid timber sections, and the Truss to Go technology

Truss Design	Product Weight (kg)	embodied energy					embodied CO2			
		material/ process	**qty**	**unit**	**MJ/unit**	**total (MJ)**	**qty**	**unit**	**kg CO2/unit**	**total (kg)**
 **Design in Steel Tubes**	**95.23**	primary: low	95.23	kg	31.7	3018.791	95.23	kg	2.3	219.029
		roll forming	95.23	kg	2.9	276.167	95.23	kg	0.21	19.9983
		welding	672	cm	0.041	27.552	672	cm	0.0035	2.352
		cutting	neglected		0	0	0		0	
		total				***3322.51***				***241.379***
 **Design in C24 Softwood**	**129.98**	**Timber sections**								
		primary pro	102.88	kg	11	1131.68	102.88	kg	0.36	37.0368
		coarse mac	20	kg	1.3	26	20	kg	0.1	2
		Connection Plates (50% waste)								
		primary pro	40.77	kg	31.7	1292.409	40.77	kg	2.3	93.771
		roll forming	40.77	kg	2.9	118.233	40.77	kg	0.21	8.5617
		laser cutting	607.8	cm	0.1875	113.9625	607.8	cm	0.015	9.117
		total				***2682.28***				***150.487***
 **Design in Truss to GO**	**49.96**	**cordage (flax)**								
		primary pro	8.87	kg	2.75*	*24.3925*	8.87	kg	0.46	4.0802
		cordage (epoxy)								
		primary pro	26.6	kg	120	3192	26.6	kg	5.9	156.94
		cordage (manufacture)								
		production	49.9	kg	**unknown**		49.9	kg	**unknown**	
		timber blocks								
		primary pro	14.5	kg	11	159.5	14.5	kg	0.36	5.22
		fine machin	14.5	kg	10	145	14.5	kg	0.65	9.425
		total				***3520.89***				***175.665***

*Cristaldi, G., Latteri, A., Recca, G., & Cicala, G. (n.d.). Composites based on natural fibre fabrics. In University of Catania – Department of Physical and Chemical Methodologies for Engineering. Catania, Italy.

Oberservations, Limitations and Conclusions

Observations:

- In terms of weight**, the truss to go technology is the lightest possible solution** for the design at about 50kg. It is twice as light as the steel tube option, and 2.5 times lighter than a softwood timber solution.
- In terms of embodied energy, however, it is clear that the truss to go technology **does not compare favourably** against the conventional technologies, being 5% and 23% more intensive than steel and timber options.
  It must be observed that the **epoxy is the most energy intensive material** in this product, amount to **about 90% of the entire system's energy**.

  It is worth noting that in the timber option, the solid wood by itself embodies less than half the energy of the entire timber system, the rest being attributed to the somewhat 'easy' connector plate solution. It can be concluded that a 'pure timber' solution with traditional joinery etc, will likely have a significantly lower E value still.
- IN embodied carbon, **Truss to GO compares favourably against the steel option**, embodying only 60 percent of the CO2 as a steel option. **The timber option, however, is still better than Truss to GO** by about 16%.
  These results may be due to the fuel intensive process of steel production and refining which requires the combustion of fuels like coal.
  Once again, in the Truss to Go technology**, 85%** of the embodied carbon is contributed by the **epoxy** component.

The need for better polymer technology: Based on these results described above, it is clear that whereas the Truss to Go solution is perhaps favourable in terms of its strength to weight ratio, the material chemistry requires more advancement for this technology to have a favourable environmental impact.

Ease of fabrication: Another possible advantage of the Truss to Go technology may be the ease of fabrication

Limitations:

Emb energy of cordage manufacture are unknown: The energy required to manufacture the cordage from the flax and epoxy has been neglected in the audit presented above, because it was difficult to collect data on the operational energy on the braiding and polymer impregnation of the yarn without a better understanding of the exact industry manufacturing process. It may be, however, that the energy demand is relatively low, as braiding is knows to be a very efficient process that is not particularly power intensive. Unlike in the manufacture of steel or epoxy, there is no requirement for high temperatures etc, which is usually quite energy expensive.

Transport and other logistics are ignored: This audit is presented without context or location. IN reality, the transport logistics should be considered while accounting for the embodied energy and

For the electricity requirements as well, the Coefficient of Performance of primary production for the EU has been taken, but his could vary from country to country, especially outside Europe.

'Ease of Fabrication' is not understood quantitatively: It is not easy to quantify the 'ease of fabrication' which was an important Key Performance Indicator for the evaluation of the Truss to GO technology. Only a qualitative commentary can be offered based on the experience of the prototype fabrication, which reveals that the fabrication method is quite easy and fast, and is likely possible with a team of two. How exactly it compares against the labour effort of constructing a timber or Steel truss are not known in terms of man-hours etc.

IT may be concluded however, that the truss to go can be fabricated without an electricity supply.

Steel trusses with welded connections are most commonly shop fabricated. Bolted connections may be attempted on site. However, if the entire process of cutting and fastening and welding is accounted for (at site or at shop), it may be that truss to GO is fabricated faster.

Conclusions:

It is clear based on the audit that the Truss to GO technology presents a design solutions that is acceptable in terms of material demand and fabrication effort.

However, it is clear that the biggest impact on the improvement of the product lies in **advancement on the resin (matrix) technology**, which offers the possibility of better mechanical performance, but also a much better eco prognosis, as at the moment, the stand in resin (not to be used on the actual product) accounts for 85-95% of the embodied carbon and energy of the technology. There is increasing work being conducted in this field of chemical engineering, with better biobased and biodegradable resins being developed. Some of these are discusses in the next chapter.

3.6 Conclusion and Future Recommendations

The research into the proposed Truss-to-GO technology is now concluded.

To answer the research question,

Can a Novel Bio-Based FRP technology be designed and developed for the in- situ construction of Lattice Structures for Building Industry applications?

The answer is affirmative. Flax has proven to be a competitive fiber for the purpose of a lattice fabrication. Braiding has also proven to be a promising approach to create the textile and fiber architecture for the struts and chords of a lattice structure.

The proposed method of pre-tension-based consolidation for composite quality was explored and it was discovered that it is not as effective as vacuum bag, but still is able to produce composites of a quality that may be useful for the proposed structural application.

A site fabrication workflow is proposed, along with the design of the necessary fabrication jigs to be able to prepare these lattices on construction sites.

However, there are several limitations, some of which were out of scope of this research, and others that were discovered during the research period, that must be addressed in time to come. Some key ones are discussed below.

Limitations- Truss to GO

1. **The Composite Material Technology is Incomplete:**
   There does not exist **in the market,** the resin with the properties that could allow the preparation of a composite on site. The reviewed biobased resins require high temperatures for curing, and the atmospherically curing resins have an environmental cost to manufacture. We must wait for this technology to be developed, but the promising research into chemistry and material science of composite polymers may yield a solution to the problem.

2. **The product is mechanically inferior to structural metal alloys:**
   Although composites, particularly those of carbon fiber, can be superior to many metal alloys in mechanical properties, this is not achieved with Flax fiber composites. The advantages to this technology lie in environmental arguments, as natural fibres are undoubtedly better for the environment from the point of end of life as well as embodied energy. It must be said, however, that the end of life of natural fibres is quite different from the end of life of flax fiber-based composites, where fiber polymer separation, and the quality of the polymer itself come into the picture.

3. **Buckling behaviour is unknown:**
   The presence of tension and compression is crucial to the versatility of trusses as a construction and structural vocabulary. Without this, the ultra-efficient structural vocabulary is restricted to tensile structures. The thesis did not explore slender struts in compression. Whereas an Euler curve can be plotted based on the materials elastic modulus, the real capacity curve is also a function of the materials imperfections. With a manufacture method that involves the lay up of fibres, the homogeneity and anisotropy could present serious challenges to the buckling capacity of the compression members. This needs to be better understood.

4. **Effects of imperfections, workmanship of joints, geometric distortions need to be accounted for:**

   Whereas the tests on the individual aspects of truss to show showed good agreement and a narrow statistical dispersion between the results, the properties of the truss as a whole may not show such a narrow scatter. The effect of workmanship variability with the fabrication of the truss, especially considering that it is a handicraft, is important to understand.

   With this, **we may be able to develop some Partial Safety Factors** for this technology, and we must then reassess the comparative efficiency of this technology once again against the Usual Suspects.

   A broad scatter of strength or stiffness, for example, would have to be compensated with a very conservative partial safety factor, resulting in much higher material requirements.

5. **Three-dimensional Lattice Structures are yet to be explored for Truss to GO:**
   The investigation of this thesis was limited to planar structures due to the time and resource constraints. However, the product undoubtedly benefits from being applied in 3D configuration, as this provides stiffness to the structure in multiple directions.
   Further, the relatively low stiffness of the material makes it particularly vulnerable to buckling, meaning that planar lattices are much more vulnerable to lateral torsional effects and the effect of imperfections. These aspects are yet to be investigated.

6. **Aspects of Fatigue, Creep, and resistance to weather and thermal events need to be investigated**:
   The reduction of the mechanical properties of natural fibres due to moisture is well known. Can the technology be made suitably weatherproof in order to resist the conditions of construction sites as well as the operational use of the building?
   The creep and fatigue behaviour are naturally also important for any structure that is of Service Class 2 or 3.

7. **Building construction and assembly are to be investigated**: This proposal has not covered the strategy for how to build with the truss once it has been fabricated. How is it erected on a column? If it is prepared as a portal, how is it mounted on a foundation? How are roof elements connected to it? Composites are complex materials, and mechanical connections and interface behaviour is an involved topic that also needs full resolution before the technology can be useful. From many sources it is known that making joints in composites is notoriously difficult.

The Proof of the Pudding is in the Eating: A most significant limitation to the technology is the nature of its incompleteness itself. The product hasn't been prototyped or tested in any real-world way. This means that there are possibly many **'unknown unknowns'** that need to be discovered. Testing a strut or a joint or a construction method in isolation, although understandable in an academic setting, presents a 'Ship of Theseus' problem: The value of the sum of the parts are unknown.

During the course of this research, many interesting ideas also emerged, that could be interesting subjects for future research, in addition to the above mentioned mandatory topics

Interesting Ideas for the Future

1. *Advances in Bio-Based/Natural Polymers for composites:*
   The possibility of a bio-based resin is very interesting for several reasons: It represents a **potentially** more sustainable manufacture process. If it is biodegradable, it also creates the opportunity for east end of life management, where there is no hazard in landfilling or even composting the material, as described in the fantasy in the start of this thesis research.

   However, there are interesting advances in biobased resins that are processed from natural oils. Triglyceride oils synthesised from plant products have been used to make chemicals capable of polymerization, and have also been used for making composites for structural applications (Wool & Khot, 2001). The unsaturated oils extracted from soybean, linseed (flax), and cashew shells, have shown some potential in this regard.

Acrylated Epoxidized Soybean Oil (AESO) is formed by reacting acrylic acid with Epoxidized soybean oil, and with further chemical modifications such as blending with styrenes, structural polymers with a range of properties can be manufactured. They can have a tensile strength of 6- 21 MPa with a Young's modulus of 0.4 GPa.

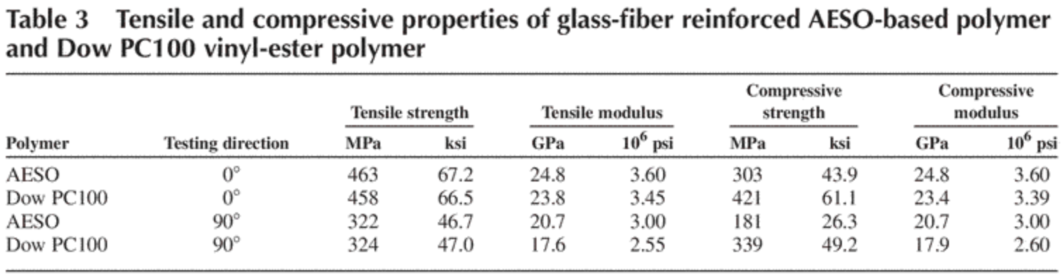


Table 3 Tensile and compressive properties of glass-fiber reinforced AESO-based polymer and Dow PC100 vinyl-ester polymer

		Tensile strength		Tensile modulus		Compressive strength		Compressive modulus	
Polymer	Testing direction	MPa	ksi	GPa	10^6 psi	MPa	ksi	GPa	10^6 psi
AESO	0°	463	67.2	24.8	3.60	303	43.9	24.8	3.60
Dow PC100	0°	458	66.5	23.8	3.45	421	61.1	23.4	3.39
AESO	90°	322	46.7	20.7	3.00	181	26.3	20.7	3.00
Dow PC100	90°	324	47.0	17.6	2.55	339	49.2	17.9	2.60

Figure 103: Tensile and compressive properties of glass fiber reinforced with AESO and DOW PC100 vinylester ((Williams & Wool, 2000)

Cardanol based bio-epoxies may also be a potential opportunity for high performance biobased resins. Cardanol is an aggressive oil extracted from cashew shells that has been traditionally used for surface treatments, including the anti-termite of wood in indigenous Indian cultures. Hu et al (2023) have reported two biobased monomers that form into vitrimers that have high mechanical properties, thermal stability, and are also weldable. Maffezzol et al (2004) have also reported cardanol based biocoposites reinforced with natural fibres Hemp, Ramie and Flax, reporting composite Flexural strengths between 5 to 20 MPa, even with a low FVF's of 13 to 15%.

2. *In-Situ Polymer Curing Mechanism, Proposal 1- Resistive Heating:*

Many technical composite polymers require high temperatures (100-250 deg) for the curing reaction as reported in the literature review. This is often a challenge in on-site conditions. However, with a continuous cordage approach like proposed in Truss to Go, there may be an opportunity to integrate a heating mechanism.

It may be possible, in the manufacture of the cordage, to integrate a non-structural filament for the purpose of Resistive Heating, such as a Nichrome wire. Since the truss is made from a few segments of continuous cordage, there is a continuous circuit for electric heating, which could be used to heat the bulk of the cordage to achieve polymerization temperature. The cordage could then be manufactured as a pre-preg with the nichrome braided into it.

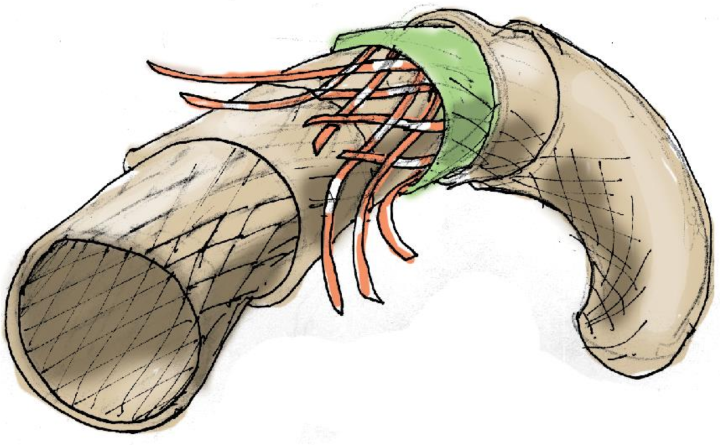


Figure 104: An impression of a hybrid cordage with resistive wiring integrated into the braid layers.

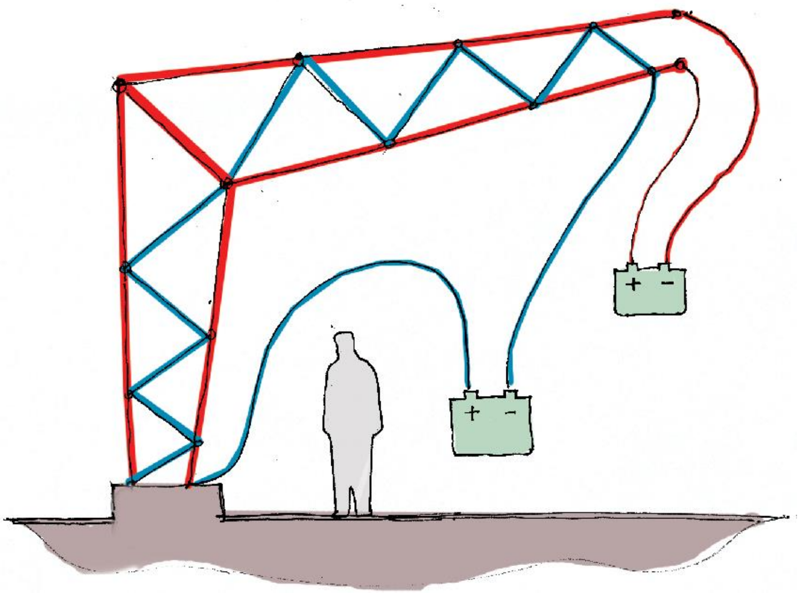


Figure 105: schematic of the circuit paths in a truss for a heating-based curing mechanism

Potential Advantages:

- Could increase the options for thermoset polymers that can be used for the composite matrix.
- Could even make possible the use of thermoplastic matrices. This has many advantages, as thermoplastics have 'infinite' shelf life making for convenient cordage, and the operation of Thermoplastic Welding is integrated into a one-step process (for the joints).
- The temperature may be controlled with the current value supplied, so the same cordage can be prepregged with a range of matrices to create composites with different technical performances.

Potential Disadvantages:

- The system now requires electricity, a resource that is not required in a Truss to GO style proposal. Electricity as a resource is not always available in construction sites, particularly in challenging situations like remote locations or disaster relief scenarios where power supply is lost.
- The system is also slightly more Hi-tech than the Truss to Go proposal, as the requirements of resistive heating now must be built into the product manufacture and on-site fabrication infrastructure.

3. *In-Situ Polymer Curing Mechanism 2- Frontal Polymerization (FP):*

Simply put, frontal polymerization is an alternative mechanism to the polymer curing of some thermosets that are designed for this mechanism. It is an out of autoclave process, where the polymerization is sustained by the heat generated from an exothermic chain reaction that is initiated at one or more ‘fronts’. This not only avoids the autoclave, but also reduces cure time dramatically, as demonstrated by research from Sangermano et al (2018), Sangermano et al (2019), Robertson et al (2018), Cheol et al (1995) and others.

Figure 106: A corrugated carbon FRPC part fabricated by FROMP using vacuum-assisted resin-transfer moulding (Robertson, et al., 2018)

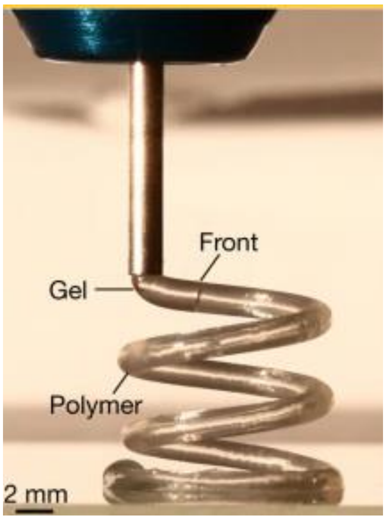


Figure 107: 3D printing of gel DCPD solution that is solidified by FROMP immediately following extrusion from the print head (Robertson, et al., 2018)

Potential Advantages:

- This form of polymerization could solve the autoclave and high temperature requirements, making in situ composite manufacture within grasp.
- In some cases, the catalyst is not radical based, but rather through UV excitation. It may be possible to provide the catalysis through a simple UV lamp, or even through the exposure to sunlight (if the fabrication is performed in the dark with artificial light etc)

Potential disadvantages

- Typically, the frontal polymerization is an aggressively exothermic process with temperatures that may exceed 200 degrees. This mechanism is then incompatible with natural fibres which will deteriorate at such temperatures. The technology may still be applied to glass fiber and carbon fiber technologies for in-situ manufacture.

4. 'Quasi-Triaxial' Braiding:

The axial mechanical properties of a cordage-based composite would benefit greatly from fibres oriented with a 0 degree bias, where the fibres are parallel to the member itself.

This can be achieved in principle with a triaxial braid, where a series of yarns are woven axially into the braid layer. Such a braid method is possible and established. The reason this was not attempted in the Truss to GO system is that such a fiber layup then becomes linearly stiff, i.e. it can no longer be tensioned into lateral constriction, and is therefore incompatible with the proposed consolidation method in Truss to GO.

It is conceivable that a special textile design is manufactured- one that is a triaxial braid, however, the axial yarns are not continuous, as shown in the figure below.

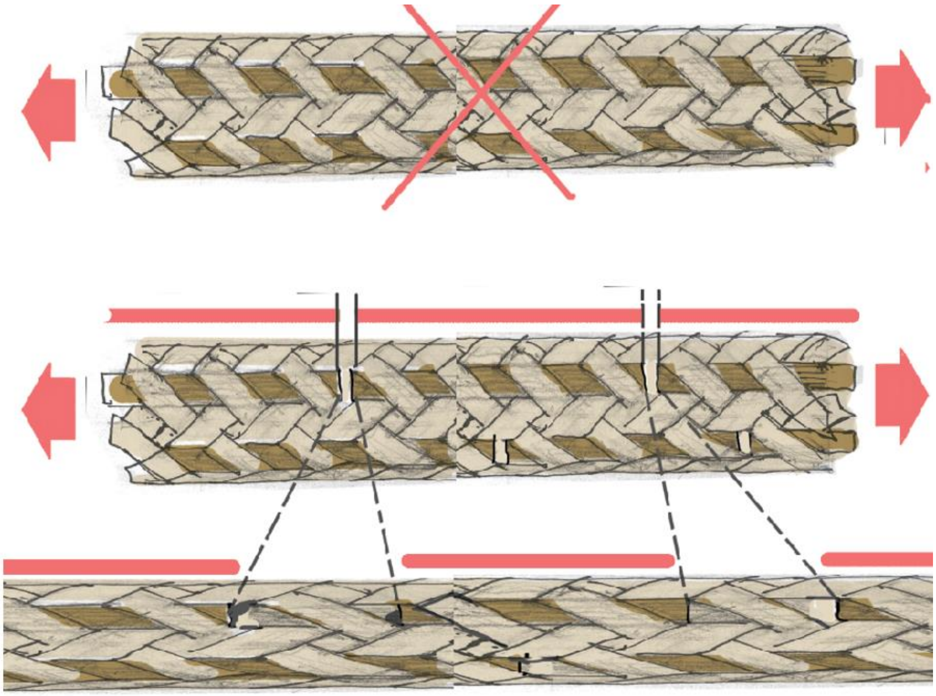


Figure 108: Whereas a conventional triaxial braid cannot be extended, it may be possible that shorter segments of axial yarns still allow for extension

Such a braid architecture is not known at the moment but may be possible.

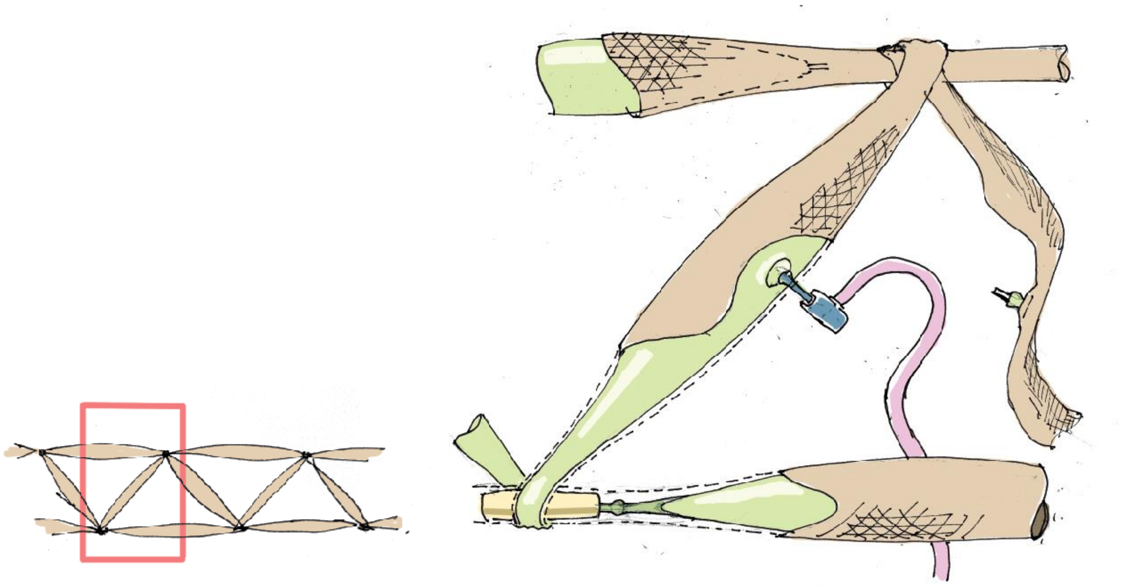
In this setup, the post tensioning method could still be accommodated- as the braid constricts, the axial yarns are shifted about their axis. When the composite is cured, it still possesses a percentage of yarns in the favourable alignment for axial loading.

It is not clear, however, whether such a fiber architecture is possible. Further, it must be determined what the optimal length of the axial segments shall be- very short segments are not effective for axial load transfer and approach a 'chopped fiber' type architecture. Very long segments may not allow for the proper axial elongation (and thus lateral constriction) of the braid, due the friction between the axial and angular yarns, that work to resist the displacement of the axial segments.

5. ***Inflatables Technology*** *as a method to achieve consolidation*

This proposal is an inversion of the vacuum bag method to achieve pressure- The idea is to braid the composite around a collapsed inflatable bladder. ON site, this bladder may be inflated on a strut-by-strut basis to generate the consolidation pressure from the inside of the braided core. After the matrix resin is cured, the bladder serves no purpose and the air can be released. In that sense, it is not like an inflatable tent or blimp, which is vulnerable to punctures through its operational life. Here the action of the air is for the duration of the cure cycle only.

This method has the added advantage that **large diameter cross sections** are possible at the struts**, greatly increasing the Euler buckling capacity** of the member- a particularly desirable geometry for materials that have low stiffness, like the flax epoxy composite proposed (E~ 30 GPa).



It can be argued however that such methods are becoming increasingly more hi-tech and the simplicity of the fabrication is lost. In a sense, this idea resembles that of an inflatable braided stent that is used to clear arterial blockages in Surgery, which is hardly low-tech, after all.

3.7 Reflection

"What is the relation between your graduation project topic, your master's track (Ar, Ur, BT, LA, MBE), and your master's programme (MSc AUBS)?"

The Thesis topic was a preliminary investigation into a somewhat unconventional idea- using Bio fiber-based technology to weave trusses in-situ in a low tech, simple way.

The relation to Building Technology Track:

- ***Material Science investigation***: Part A of the thesis and some aspects of Part B were entirely an exercise in Fiber Reinforced composite Engineering and Innovation, which is relevant to the Building Products and Innovation section of the Track. It explored the possibility to take knowledge fields in composites that are *typically the domains of automotive and aerospace and apply it to Building Products*. Though technical composites are gaining traction in the building industry, finding applications even in structural elements, they still remain an emerging trend
- ***Structural Performance:*** One of the key parameters in the evaluation of this idea was an assessment of its structural performance, characterized by members and joints. This was an application of the Structures and Mechanics discipline. The methods of truss analysis and loading were applied in the course of this research.
- ***Design of Construction workflow and strategy****:* The Building Technology department is also interested in the questions of how to actually build the designs and schemes that are imagined on paper or a code processor. These are explored in the fields of Design Informatics and Building Products and Innovation. Part B of the 'Truss-to-Go' Thesis was concerned with these aspects- the actual site workflow and construction design.
- ***Eco Audit****:* The final part of the thesis deals with the environmental impact of the materials and processes in such a technology, and how it compares to typical construction. This falls squarely within the agenda of the Sustainable Structures division, where energy and ecology concerns in our present world conditions drive the research.

The relation to MSc AUBS:

The relation to the overall AUBS track can be understood in the broader perspective of today's concerns with building in our environment. This is elaborated more in Question 4: Societal Impact, but broadly speaking it can be summarized in these ideas:

- Addressing the need for efficient and accessible construction

- Taking an existing idea and making it ‘low tech’ and ‘bio based’
- Chasing a solution for remote and low infrastructure construction.

“How did your research influence your design/recommendations, and how did the design/ recommendations influence your research?”

The Prior research was crucial to entering this research, because the engineering of composites is not covered in the Building Technology course as of now. Whereas in the timeframe of the Graduation it was not possible to study this entire field, the research on similar fabrication ideas, like the IsoTruss, and the increasing literature on flax fiber FRPs gave me clues on where the ‘meat’ (or ‘tofu’, depending on which Department you’re from) of the matter might lie, and what the limiting factors are.

This is elaborated in question 3, but here are some examples of the ‘**research influencing design recommendations’:**

- ***The Resin Problem***- attending the JEC Composites Forum (Paris 2024) and speaking to the leading polymer manufacture companies there revealed that there **does not exist** (in the market, at least) a resin with all the properties that are demanded by this technology. This finality clarified that the **resin should be removed from the scope of the research**, and work should proceed with a typical high performance ‘stand in’ resin, and other aspects be researched, while we wait for the industry to develop the required resin, so to speak. This is also addressed in the chapter ‘Discussion’.
- ***Braiding as the cordage choice***- as explained in Part A of design, the decision to go with braiding was informed from the start by knowledge of the fiber angles as a KPI for composite performance. Research into braiding methods and braid machines also showed that it is possible to prepare simple equipment to manufacture braids and control braid angles and yarn counts. The thesis could not have been initiated without this reassurance, which was initially a serious concern, when I looked to partner (unsuccessfully) with companies who made braided composites.
- ***Joint vulnerability***- prior research into previous works on robotically manufactured filament-wound trusses showed that joints were particularly vulnerable to failure, as described in part B. This guided the design of a manually wound joint, with the hypothesis of increase in contact area to make stronger joints.
-

Instances of the ‘**design recommendations influencing research’** are too many to elaborate, but briefly listed, are:

- The braiding hypothesis demanding research on the compressive strength of braided composites
- The performance of flax fibres in compression
- Investigations into the compatibility of hydrophilic fibres with hydrophobic resins
- The experimental research into compressive strength of funicular braids

- The possibility of vacuum bag-free FRP compaction using braid constriction as an alternative
- The joint strength evaluation of a manually wound flax cordage.

Since the thesis started with a fantasy-like design idea which was then pursued to realize, the entire thesis report is perhaps an answer to the question of 'design recommendations influencing research'.

"How do you assess the value of your way of working (your approach, your used methods, used methodology)?"

Top-Down Research Approach:

One way to classify research is into a. a '**Bottom-Up**' approach and b. '**Top-Down** approach'.

I usually see the Bottom-Up approach in academic research, where the researcher identifies a facet of a problem and investigates it thoroughly, and then reflects on the implications of it in the various 'bigger-picture' instances. The result of this knowledge is deep and narrow- we learn a lot about a very specific focused topic. Such research demands high scientific rigor and exhaustive exploration within the niche.

My research was with a 'top down' approach, which started with the 'crazy fantasy'. Initially having no idea how to achieve it, I broke it down to smaller pieces to investigate. I found the closest technologies (from various inspirations) to solve said individual 'sub-problems', applied them to the problem at hand. The aim and priority in this was to visit as many of the sub topics as possible, to have a 'well-rounded' understanding of whether the Fantasy is worth further research. As a result, I was only able to explore each one to the bare minimum depth to assess if it had potential. With the limited time at hand, it was also necessary to almost 'cheat', and find the quickest way to investigate an idea, trading definitive precision for speed and thrift. The fabrications and test setups designed were only just about good enough (hopefully) to discover the approximate results and, to qualifty whether each little idea was 'good or not'. This results in a shallow but broad understanding of several technicalities.

The top-down approach for me was the only right answer, and it reveals a list of 'good and bad' tricks to solve the design problem. This means the work is far from industry adoption, but any value lies in revealing more questions and areas of potential, which I hope is useful to any future researcher who wants to pursue this topic.

To summarize, my observations about this approach:

- *Less precise than bottom-up approach:* Usually when there is no time, money or technical knowledge for precise investigation
- *More creative than a bottom-up approach*: The bottom-up approach is about understanding something. It usually chases one right answer. The Top-Down approach is about solving a problem. There are probably many ways to get there. This is an opportunity for creative work.

My learnings and recommendations about a Top-Down research approach:

- *Works better in teams*: This thesis combined several different fields of knowledge, and an individual researcher usually does not have it all. This should be kept in mind by anyone attempting a student thesis. There are answers I discovered with the right conversation with an expert, after weeks of chasing dead ends due to lack of knowledge.
- *May have to accept imperfect solutions*- In essence, a top-down approach is an attempt to solve a problem in a new way. Any kind of improvement over the norm solution is a successful result. However, it could also create new problems. Comparison with benchmarks is key.
- *Have no expectations:* We do not know if the hypothesis is true or not. Especially if the design problem is difficult and unconventional. A lot of my consternation during the research was because I grew attached to the Vision I dreamt, and began 'hoping' for a certain kind of result.

"How do you assess your graduation project's academic and societal value, scope and implication, including ethical aspects?"

Academic Value:

I think that the following aspects in my work are scientifically interesting and could warrant further research:

- The research of flax fiber composites for building structure applications.
- Suggesting the potential of site prepared FRP trusses, if further pursued
- Highlighting the need for a polymer for the above application, and what the required parameters are.
- Analysis on novel FRP in situ fabrication techniques, and the idea of braid compaction and discontinuous mandrels.
- A comparison with benchmark of simillar structures conventionally built.

By exploring a previously untrodden path, "Truss-to-go" holds significant academic value. It not only introduces flax fiber composites as a potential building material but also identifies key research gaps that could lead to advancements in bio-based resins, in-situ fabrication techniques, and comparative analysis. The project's novelty and potential for further research make it a valuable contribution to the field of sustainable building materials and construction methods.

Societal Value:

- ***Addressing the need for Efficient and Accessible Construction- Taking an idea and making it low-tech***: From my perspective, it often appears that some of the cutting-edge building technology developed today is often not accessible to the scenarios of Developing and Underdeveloped countries (one of which I come from). This is usually because the tech requires high costs (materials, resources), high levels of instrumentation (e.g.: robotic fabrication, 3d printing), or high levels of skilled labour.

  This thesis is an attempt to take existing technologies in FRP manufacturing and deliberately making it as 'low tech' as possible, under the belief that good design is 'dumb simple'. Further, the attempt to use biobased materials was part of this spirit, addressing not only ecology and the usual planet concerns, but also the high costs of carbon fiber and the growing research in natural fiber based FRPs, which are available in various forms throughout the world. In the EU it is flax, but in other continents, jute, hemp, ramie etc can also be explored.

One of the reasons carbon fiber FRP products are so expensive is that they are made by hand and require high levels of skill. This is expensive in the case of 'mass production' of the same product- like a bicycle frame or a tennis racquet, but for 'mass customization', and in parts of the world where labour is more affordable, this could be a convenient asset.

- ***Chasing a solution for Remote Sites and Low infrastructure Construction:*** If the Truss to Go technology is fully developed, it offers an attractive solution to the problem of building in areas poorly developed or equipped to support conventional construction, which typically requires the following resources in good supply: water (soaking, curing etc), electricity (power tools, welding etc) in addition to a host of building materials and tools that need to be transported to site. With truss to go, the requirements are comparatively lower, ie: the setup for the fabrication rig, and the spools of rope themselves. If an in-situ resin application is opted for, then the resin and resin application (by bath or brush on application) is also required. This might allow for a lot of fabrication material and planning capacity transported in few truck-loads. This might be favorable for construction in remote areas (army camps, site workshops), but also for relief camps in disaster affected areas (drought, earthquake struck areas etc.) where resources are cut off and rapid construction is desired. These situations *demand* simple low tech construction solutions.

Scope

For an overview of the scope, readers are directed to the report chapter Scope and Focus.

My reflection on the scope is that it was a necessary set of decisions in order to manage time and expectations but is not really enough to 'put my money' behind the technology yet. It is not reasonable to invent an entire technology during the scope and time-period of a Master Thesis and comprehensively address all issues and make it industry ready. But I hope that the work can interest other researchers to further explore the idea and the necessary sub-topics to more detail.

"How do you assess the value of the transferability of your project results?"

Transfer to other materials:

This research commits to flax and traditional bisphenol-type epoxy resins based on the scope. However, there may be potential to explore other materials of fibers that have strong mechanical properties as shown in the Material Research Chapter.

IN terms of fibres, I think it is important to make the technology more site specific. Flax fibres are a good option for the EU as the major producers, but in other countries, other natural fibres, particularly bast fibres like Jute, Hemp, Ramie and kenaf can also be explored.

IN terms of polymers, as mentioned earlier, the ideal polymer is yet to be developed. Further, there is a need to explore thermoplastics (for high recyclability and lower manufacture energy) and natural/bio based resins, that are not derived from petroleum, like most bisphenol based resins. This would make the whole proposal much stronger. There is promising work already in this discipline, particularly in the aerospace industry, where composites form a large fraction of their material use, and the need is felt to develop environmentally more responsible materials.

New manufacture Processes:

If braid constriction is deemed a suitable way to achieve compaction pressure, this may have applications in composite manufacturing in general, for the industry production of braided composites. This is also interesting because braids do not necessarily need to have a uniform cross section.

I think, however, that a lot more work is needed to design the finer mechanics of braid constriction.

Ubiquity of Trusses:

The application of truss-like lattice structures is not restricted to building techniques. However, the idea of in situ truss weaving has its strength mostly in mass customization applications, where one-off products need to be made. I envision the building industry, furniture industry and some art-and-craft type applications for this, but I do not see that it will really be used to make a bicycle frame or car chassis. These are better prepared on a jig in a factory with a robot arm welding the joints, since it is a repetitive task and there ideally shouldn’t be variations in quality or build.

Perhaps it can compete with other carbon fiber manufacturing methods, however. A carbon fiber bike is also made, quite laboriously, by hand. To be able to weave a continuous cordage over a jig could be more efficient, but at the moment, the robot filament winding methods do not prepare a joint in the same way as proposed in ‘truss-to-go’, as shown in the literature. The weaving by hand, is also only a part of the idea. There are clearly also advantages to building with robots (e.g.: high precision, working in hostile environments). The general cordage technology could still be relevant in that setting, without the hand labour aspects.

I bear in mind also that sometimes the implications and applications of a technology can, over time, exceed the vision of the developer/scientist. The thesis work did not quite reach the level and vision of the fantasy that inspired it, but the pure idea, to me, sounds undeniably exciting and quite powerful with the applications we might eventually find for it. A truss that can be delivered on a compact spool could be an interesting idea for the construction of a space station, or even a colony on a different planet.

I think we’ll get there someday soon.

Appendix:

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