Designing the lightest Solarboat hull using Flax Fibre - Sealander 3

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Middelburg, 2021

Duurzame Technologische Innovatie op het Water

UNIVERSITY OF APPLIED SCIENCES HZ

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1 - Introduction

1.1 - Background Information

Solar Boat, the project was born in 2009 by a group of enthusiastic students of mixed educational backgrounds who wanted to fill their free composition course points in a special, more meaningful way. They came in contact with DTIW and established an agreement of what they could offer each other, eventually settling on the idea of a solar powered boat to take part in scientific research and races.

DTIW has more than just Solar Boat going on though, Sensor boat is also a project just as esteemed and driven by similar origins. The solar boat project in particular though, was rekindled in 2019 after having been retired in 2011. The team of 2019 had a first goal; picking up the project and redefining the boat so that it is ready to race again.

The goal of the solar boat project is to give students a chance to explore their inventive mind and develop new techniques on the basis of Green energy and alternative to conventional methods. Furthermore, it is important to have direct involvement in the growth of a project, of course also learning about vital project points such as logistics, budgeting and general management.

Currently the heads of the Solar Boat project are W. Haak and Ronald Eijlers.

The Hull currently used was designed in collaboration with a reputable boat manufacturer of the Netherlands, DAMEN.

1.2 - Problem Statement

Ideally, the boat should be able to withstand all critical situations comfortably without overcompensating in any aspect as this is a form of inefficiency. It is to compete in all races and events, meeting all requirements for entry and do so at its best possible performance.

In designing the boat, the ideal hull shape for function was provided but there was one critical element missing; Thickness of the hull with use of Flax Fibre composite. With no specified thickness provided the sealander 2 was constructed very conservatively, airing on the side of rather safe than sorry.

Having a very thick hull has its benefits of being comfortable that the structure will hold in all experienced situations. It does, however, also increase the weight unnecessarily and cost more to produce. As a racing boat, it will be pitched against others and needs to be as competitive everywhere possible, weight being a vital category.

Given that this is a project funded by the university, there is a limit on the budget. This is not to say that the team is constantly restricted but reduction in material costs for hull construction could free up space in other sectors which may need it, or just give them a bit more leeway. The exact amount by which costs will be decreased is not yet known but will be discovered along the course of this research.

1.3 - Research Question

Given the current state of build, it was decided that the next iteration of the boat should have weight and general material efficiency accounted for. Through discussion the following research question was defined:

"How to create the lightest boat hull possible using flax fibre?"

This research question directly falls in line with objectives of the Solarboat team and should ultimately benefit it in performance and material efficiency. Additional sub questions would include:
What is the ideal fibre orientation?
What is the ideal hull thickness?
What should the balance between strength vs weight be?

2 - Theoretical Framework

2.1 - Boat Construction

One of the biggest revolutions in boat construction was the shift from wood to fibre reinforced composites. A second, arguably as important but understandably more subtly shift in the science was the adoption of alternative materials to Fibreglass which served as the core material for a vast majority of boats. Conceptually, most of the methods remain the same all that needs to be done is readjustments to the new selected materials properties.

Basal cores have played a vital role in the field for centuries, first used as hull stiffeners, boat builders laid long planks of balsa along and across hulls, there was an issue with this though which was it led to rot and structural failure when water would seep in through the plank. Regardless, modern balsa remains a widely accepted coring material in boats. One solution to the water seepage issue was slicing through the grain, turning it on edge, to create a checkerboard pattern of end-grain pieces that no longer transmit water as damagingly. Depending on size and function of the boat in design, basal cores can be used or not. With an appropriately designed hull, basal cores can be left out which would simplify the construction process and make it cheaper.

Fig. 59
The above example shows a boat made entirely of fibreglass. Instead of utilising a basal core for stiffness, other elements were incorporated that five just as good a result. Around the hull rim is a cover whose shape already adds significant stiffness, that in addition to connecting both sides with strips provides a sound structure, with the benefit of more floor space.

2.2 - Fibre-Reinforced Composites

The acceptance of composites as a distinct classification of materials began in the mid 1900's with manufacturing of deliberately designed and engineered multiphase composites such fibre-glass reinforced pol;ymers. Although multiphase materials such as wood and bricks made from straw- reinforced clay, seashells and alloys like steel had been known for millennia, the recognition of this novel concept led to the identification of composites as a new class different to how it was known in history. The concept of combining dissimilar materials opens the engineering space for exciting new opportunities for unprecedented varieties of materials with property combinations, unmatched by monolithic conventional metal alloys, ceramics and polymeric materials.

Although there are numerous variations of composites, technologically, the most important(arguably) composites are those of a fibre dispersion phase. Fibre- Reinforced composites often include high strength and/or stiffness relative to their weight. The incorporation of this technology implies that it is possible to orient fibres in a manner that would most efficiently manage any designated function. Composites of this sort have been produced with exceptionally high specific strengths and moduli have been produced that use low-density fibre and matrix materials.

The use of synthetic fibres has indeed provided engineers with vast flexibility and unmatched physical properties. The use of natural fibres does not *yet* offer standards high as their synthetic counterparts, however, they provide the outlook of a more harmonious future in construction. Manufacturing of synthetic fibres does however come with a cost, a carbon footprint significantly higher than those of more natural origin. Virgin Carbon Fibre for example can produce over 29 tonnes of CO_2 per tonne of fibre whereas natural fibres dance in the range of 0.3-0.5 tonnes per tonne. This can increase due to the fact that natural fibres may require more processing depending on application but remains a mere fraction compared to Carbon, and just below half that of Glass Fibre.

2.2.1 - Flax Fibre

Flax fibres, Like the majority of natural fibres, are being considered as an environmentally friendlier alternative of synthetic fibres composites. A common feature of natural fibres is that they have a much higher variability of mechanical properties due to natural imperfections. This necessitates study of the flax fibre strength distribution and efficient experimental methods for its determination.

Plant or vegetable fibres are generally used to reinforce plastics. The main constituents involved in the composition of plant fibres are polymers themselves: cellulose, hemicelluloses, lignin and pectin. Consider the fibre in focus, flax, to understand the intricate structure of plant fibres. The ~1 metre long "technical fibres"(as they are called) are isolated from the flax plant for use in the textile industry. These technical fibres consist of elementary fibres with lengths generally between 2 and 5 cm, and diameters between 10 and 25 Pm. The elementary fibres are glued together by a pectin interface. They are not circular but a polyhedron with 5 to 7 sides, this improves packing efficiency in the technical fibre.

As the fibres are naturally grown, it is near impossible to have identically formed filaments, resulting in variations of physical characteristics. Due to this, the tensile strength of (elementary)flax fibres was found to range between 1500 MPa and 1800 MPa.

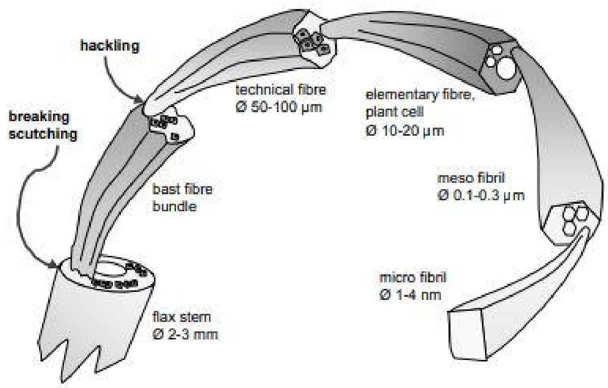


Fig. 1

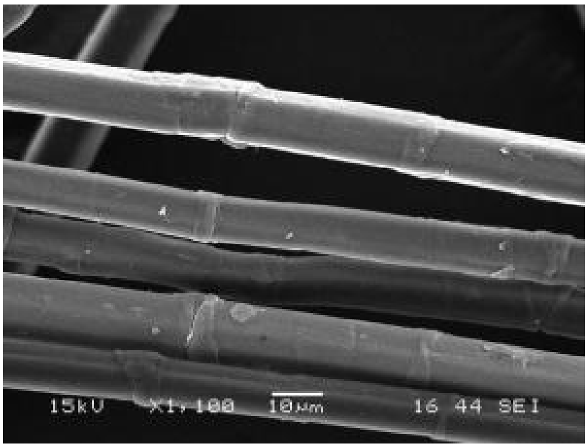


Fig. 2

2.2.2 - Glass Fibre

Glass fibre is a material that consists of numerous extremely fine fibres of glass.

Throughout history, glassmakers have attempted several experiments with glass fibre, but wide scale manufacture of the material was only made possible with the invention of finer machine tooling.

The material is formed when thin strands of silica-based or other formulation glass are extruded into fibres of small diameter appropriate for textile fabrication. This technique of heating and drawing glass into fibres has been known for millennia. Before the recent use of these fibres for textile applications, all glass fibre had been manufactured as *staple*.

Staple refers to textile fibres of varying length. Alternatively there are filament fibres, which come in continuous lengths.

More common than any other glass fibre used inis E-glass, alumino-borosilicate glass, mostly used for glass-reinforced plastics. Other types include A-glass (Alkali-lime glass), E-CR-glass (Electrical/Chemical Resistance, with high acid resistance), C-glass (alkali-lime glass with high boron oxide content), D-glass (named for its low Dielectric constant), R-glass (with high mechanical requirements as reinforcement), and S-glass (with high tensile strength).

The manufacture of Glass Fibres is now a well known science and yields minimal variation in physical properties, meaning consistent mechanical abilities. The tensile strength of glass fibre is 3445MPa.

This number falls in line with the advice gotten from fibre composites expert Warren Penalver, who stated that flax generally tends to be about twice as thick as glass for equal physical application.

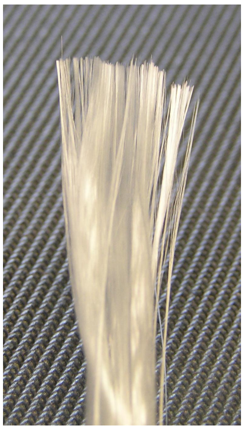


Fig. 3

Fig. 4

2.3 - Calculations

2.3.1 - Situations

Sealander 3 will be exposed to infinitely complex situations as the waters are unpredictable and ever changing. It is impossible to account for each of them, so as is common practice in engineering and design, realistic critical situations will be calculated for.
The motivation behind this approach is that if the designed product can withstand the most severe situations it will encounter there is nothing else it would be at risk of failing to.

2.3.2 - Manual Calculations

2.3.2.1 - Acting forces

Acting forces are those exerted by the boat onto the water. Components location and weight are what will determine the total force. As a first step, it is then important to explicitly identify all acting forces. They will be categorised into point and distributed loads despite the fact that in reality all forces are distributed, this is for simplicity.

2.3.2.2 - Technosoft

Technosoft Raamwerken focuses on the fast and efficient design of portals and trusses. The coupling of alphanumeric input tables with graphical input screens is unique, providing users with very helpful analysis tools. This is where Raamwerken proves its greatest strength. Technosoft Raamwerken standard includes:

- non-linear beds.
- non-linear supports.
- tensile and compression beams.
- temperature loads.
- prescribed displacements
- expiring profiles

2.4 Models & Finite Element Methods

In order to simulate the forces that will be complexly distributed across SeaLanders hull, it is imperative to conduct a FEM analysis. In this FEM analysis, the regions of highest stress will be highlighted and their exact values of stress too. This coupled with the results from practical experimentation(next subchapter) will allow for the designing of a hull capable of withstanding expected stresses.

In order to properly conduct a FEM analysis, 3d models of the boat need to be created as accurately as possible. The exact thickness is what needs to be defined by the end of this project and so there will be models of varying thickness. Initially there will be 3, 4mm, 6mm and 8mm, from the results, an interpolation will be performed to identify the optimal thickness, and with that the amount of layers.

Using the different planes it is possible to detect that kinds of forces are present in what directions, this will aid in the fibre orientation process & optimization.

To make it possible to run these simulations in FEM, the boat needs to be divided in 2 parts. Ideally, the division point should be at the point of maximum deflection which has been determined from the Technosoft analysis.

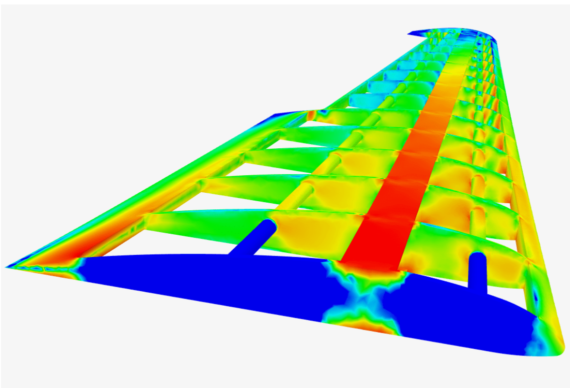


Fig. 5

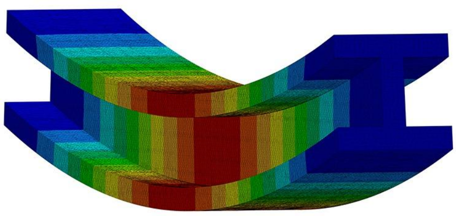


Fig.6

2.5 - Experiments

2.5.2 - Digitised Experiments

To get the material properties required for the design of SeaLander, the marital in focus needs to be put to the test. Flax fibre will be experimented on in practice then the procedure will be replicated in the softwares technosoft and Autodesk Inventor to approximate what distributed values of stress bring the material to its yielding point.

2.5.2 - Building Block Approach

When it comes to composites material testing, the *building block approach* is a step-by-step series of mechanical tests/experiments with each phase increasing subject component complexity, coupled with analyses performed at each step, that serves as a guideline for designing composite structures. Although the large majority of references to the building block approach for composites design focus on the aviation industry(where it was introduced), the general approach is followed in numerous other end markets served by the industry. Unsurprisingly, the amount and types of composites testing varies greatly, and is dependent on both the application and the complexity of the composite structure.

An example of a building block pyramid, illustrating the levels of testing performed, is shown below. In a building block approach, the levels which we call "blocks" each serve a specific purpose and are approached in order, starting most simple from the bottom. Testing associated with each level is described by the level of complexity of test samples as well as usage of the test results.

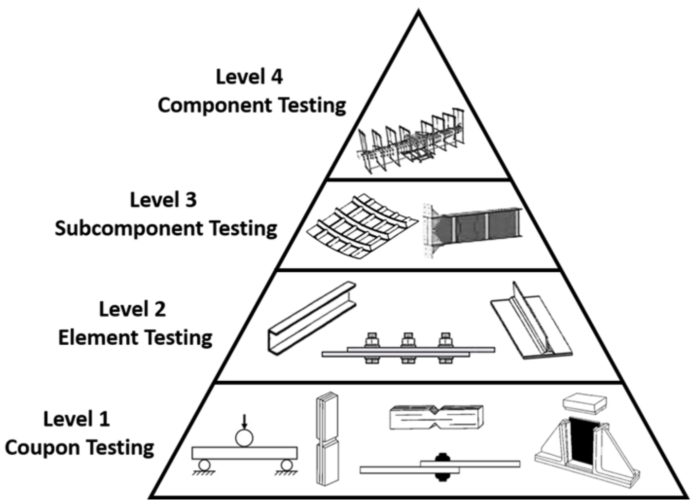


Fig. 7

2.5.3 - Analogue Experimentation

An alternative to the primary option of digitised experimentation would be analogue. For this kind of experimentation, samples would be exposed to predetermined or measured loads until yielding point. The information would then, just like with digitisation, be transferred to FEM software where the proceeding calculations would be done.
Pros for this method would be that it is simpler, requires less equipment and can arguably be more engaging/fun because it has a higher likelihood of requiring a partner in execution than digitised.
Cons are first and foremost a reduction result in accuracy, Requirement of larger pieces uses more resources and is more time consuming overall.
Description of how an analogue experiment would be carried out:

1. A 2 layer sample of dimensions 40x150mm would be supported on the 2 farthest ends, with 10mm excess on each side to allow for elasticity.
2. A string would be tied around the centre of the sample.
3. Weights would gradually be added onto the hanging string causing the sample to flex until it breaks.
4. The whole experiment would be filmed, possibly even in slow potion for rewatching and further analysis of material behaviour and accuracy.

With the availability of digitised experimentation for the research, it will be the path of choice although if there is time analogue experiments will also be done for sake of comparison. The HZ UoAS provides a dual column hydraulic press that can load upto 250kN on our samples, far more than we would ever need given the scale.
The setup selected for experiments is dual support centre point load flexion test till failure.

3 - Methodology

3.1 - Research design

The final product of this research is a boat hull design and in order to provide it there are clear steps which need to be taken, decided before even beginning. The steps taken with explanation as to why are listed below:

1 - Gathering of relevant information

Having had minimal to no experience with fibre composites in the past privately or academically, it was important to properly develop an understanding of the materials at hand. This meant reading up on literature of composites in general and flax in specific too. This gives a good general understanding of what is being worked with and how it behaves allowing for more confident design on multiple layers from strength to thermal resistance and availability.

2 - Creating 3D Models

The necessity of 3d models is not present at this early stage into research but once again due to minimal prior experience with 3D Design and that of boats especially the decision was made to begin early. Having taken this approach, it means when the time comes to use the models they will already be there or easily made. A week was dedicated purely to developing the skills, studying the chosen software(Autodesk Inventor) and taking exact measurements of the boat, getting closer with each iteration until both the client and myself were satisfied.

3 - Calculations

Calculations somewhat move from this point in the research until the end but the first vital ones that set everything in motion are those identifying the acting and reacting forces. This basically means the objects on the boat acting by gravity and the reacting force by water. Next is the calculation for pitch equilibrium, balancing forces along the length of the boat to ensure it sits flat for best efficiency.

4 - Experimentation

Experiments are used to find the material properties, strength in particular for this research. A series of experiments will be conducted and then replicated in a 3d software to accurately understand the breaking point of Flax as accurately as possible.

5 - Final Optimised Design

Once the maximum conditions for the material are understood, it is possible for us to ascribe limits on the 3D boat model. The derivatives of this final step will tell the reader how much flax is needed where and in what orientation.

3.2 - 3D Models

The Models created are as close as possible to the boat given the attainable measurements. The models are split across the section at which SeaLander displays the greatest deflection(obtained from secondary calculation series, can be found in calculation method)

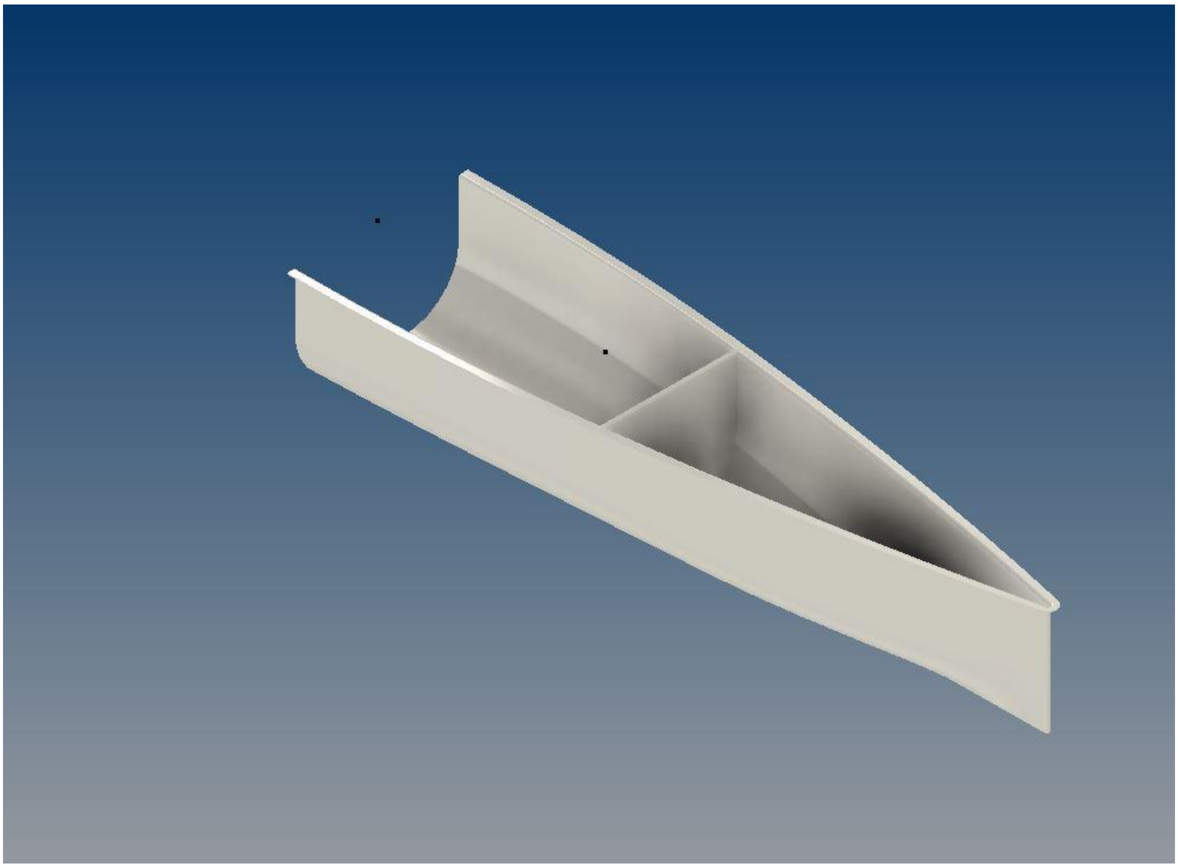


Fig. 8

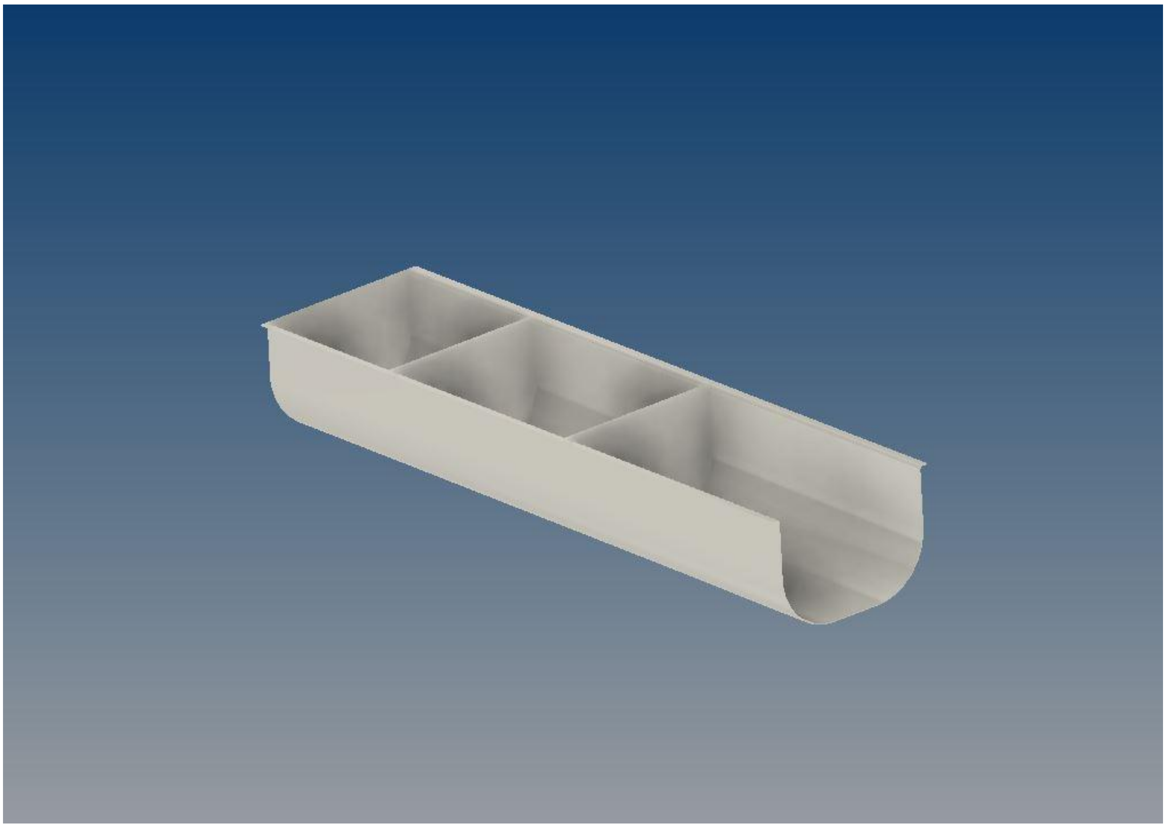


Fig. 9

There are also 3D models of the samples experimented on, one per sample type. They will be put under the exact same load at which they each yielded to give us a result of force at all areas, in specific, the critical areas.

2.5mm & 4.5mm samples (Phase I)

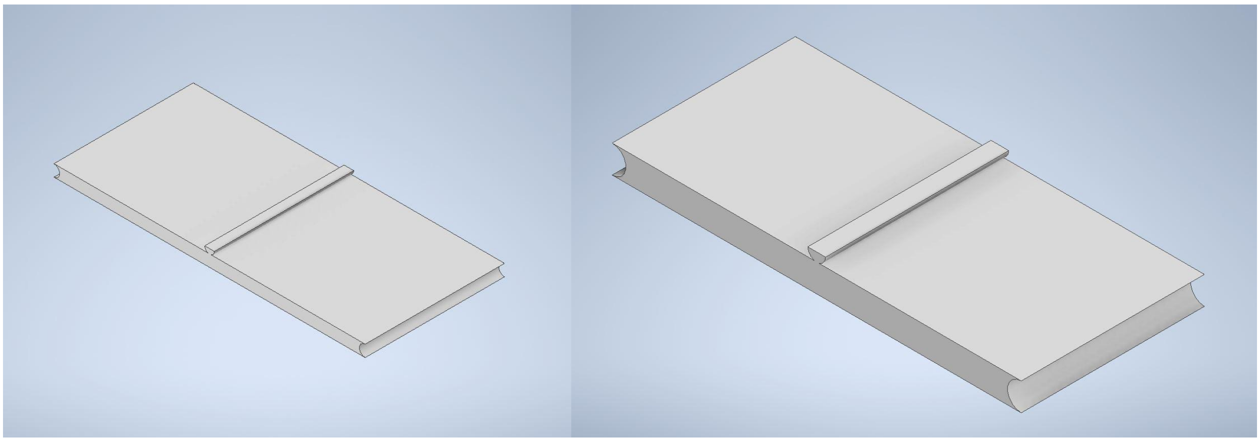


Fig. 10

2.5mm Semi Round and L sections(Phase II)

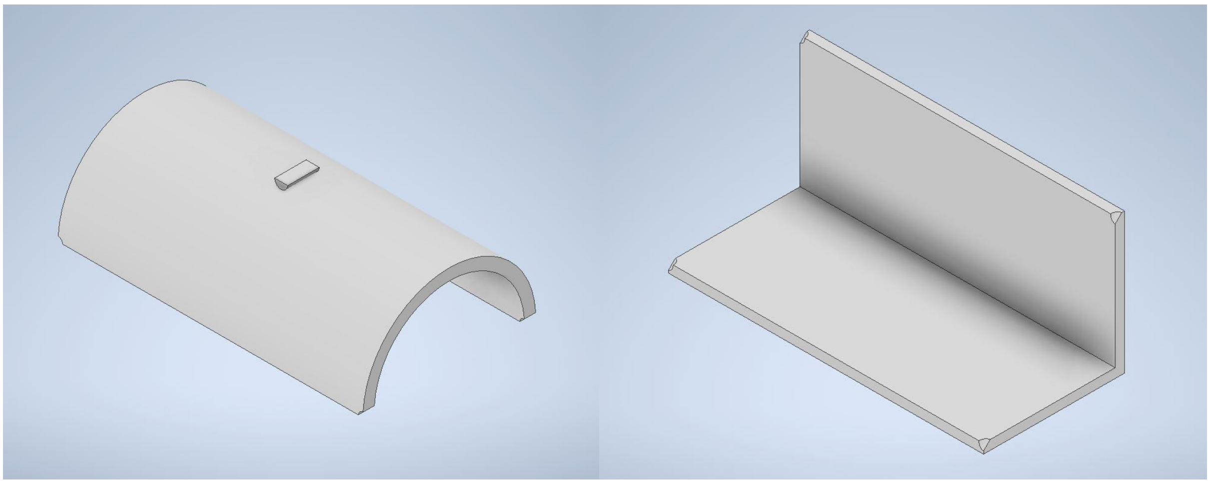


Fig. 11

2.5mm Fully Closed Sections(Phase III)

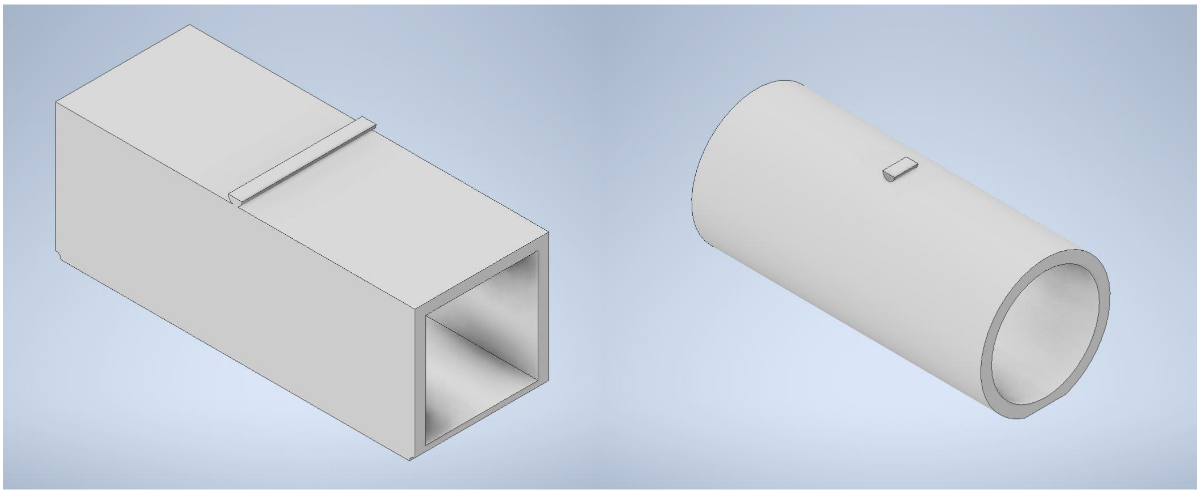


Fig. 12

Looking at the designed samples, one will notice 2 continuous features, round cutouts at parts of the ends of all samples and nodes of varyingly different shapes at the longitudinal centre point.

The purpose of these features are to give the software locations at which it can apply loads and support reactions. For all experiment replications, a pin support was used which best represents the experiments executed.

3.3 - Calculations

3.3.1 - Acting Forces

Baseline forces acting and reacting on the boat hull need to be established, when these are acquired, those for critical situations will be attained. The reason for doing baseline ideal condition calculations is for an extra layer of precaution. It is possible, however unlikely, that critical situations may leave certain aspects unaccounted for due to the fact that they are dependent on physical positioning of the boat, changing all orientation of force distribution.

The first step of calculations is acting forces, all acting forces are identified below alongside their magnitude and type:

Identification	Force(N)	Type
Pilot	2000	Point
Solar Panels	1000(split in 3)	Distributed
Battery	150	Point
Motor	100	Point
Hull Self Weight	500	Distributed

Fig. 13

The forces are all placed along the longitudinal line of symmetry of the hull meaning it is already equilibrium in the roll axis. The Pitch axis, however, requires some adjustment to ensure the boat sits flat. This will all be determined from the calculations executed manually and by aid of the software Technosoft Raamwerken V6.

3.3.2 - Reacting Forces

The reacting force present is Water. Water will be pressing evenly across the bottom surface of SeaLander 3. The total pressure exerted is equivalent to sum of the aforementioned acting forces;

2000+1000+150+100+500= 3.75kN

This is the total force(3.75kN) distributed across the bottom of the hull. Next step is to identify the pressure in n/mm^2. To do this the hull surface area in contact with water is taken. divide the total force by it and that is the reacting pressure.
It is rather complicated as the hull has a curved slipstream shape, so to simplify the manual calculations the rear half of the hull is considered to be rectangular and the front a combination of rectangle+triangle, refer to images below.

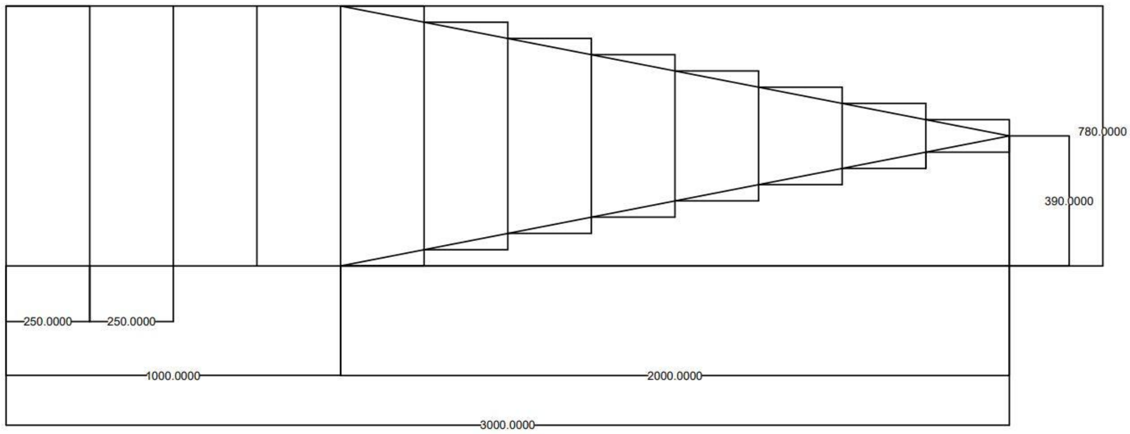


Fig. 14

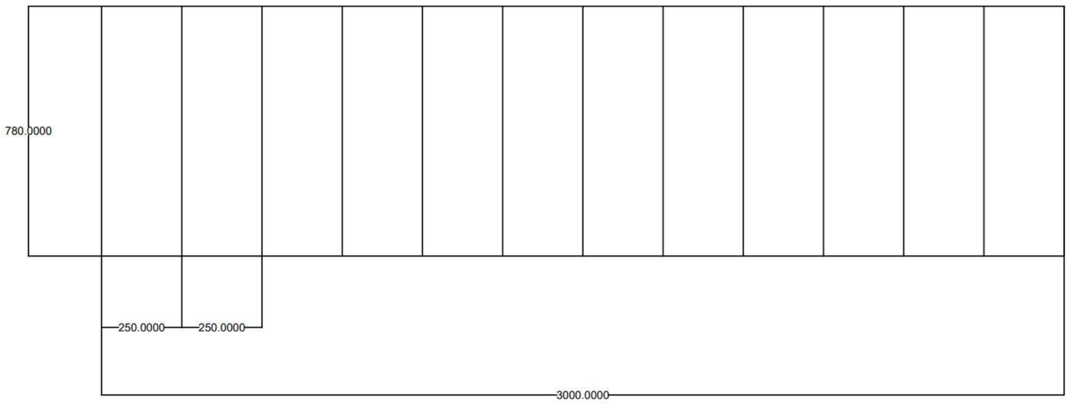
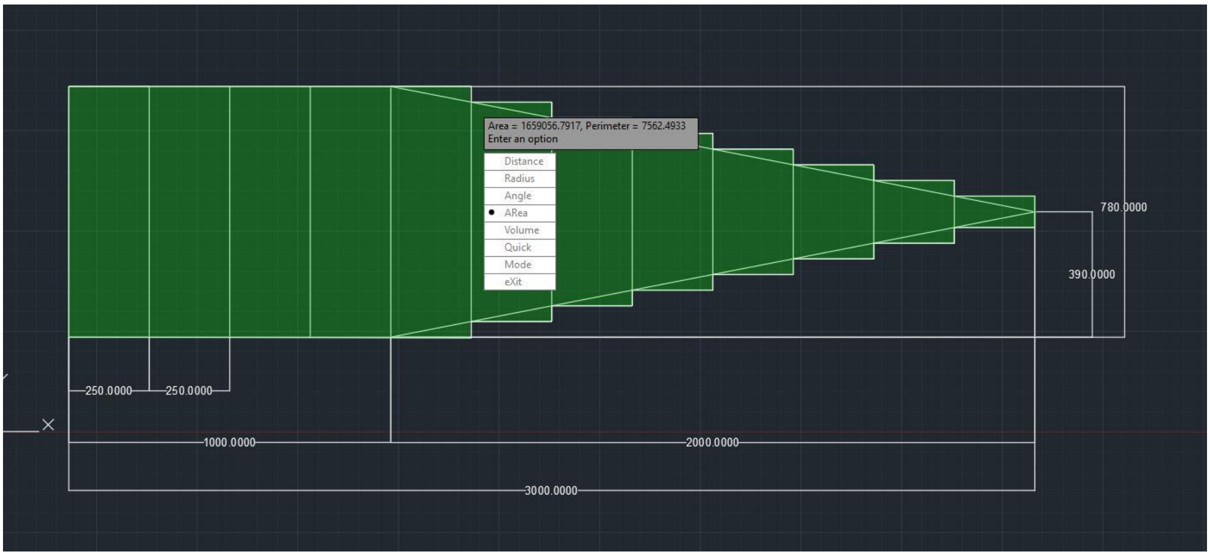


Fig. 15

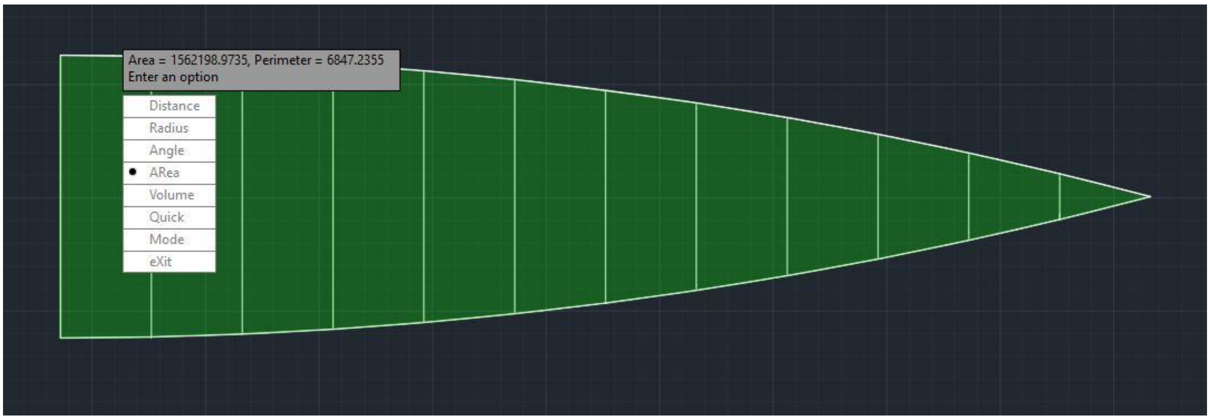
From here, we now divide the hull laterally into 250mm wide strips. The strip lengths are then added up tip to tip, to give a total length of **15404mm.** Total sum of the forces(**3750N**) is then divided by this total length to give us a value of **0.243N/1x250mm** strip, or **0.00097N/mm^2.**

This was the process for manual calculations, with the aid of AutoCAD though, we are able to much more quickly and accurately solve this calculation and even get the area of more complex shapes including curves. Below is a comparison of the two possibilities.



Area: 1,660,000mm^2

Fig. 16



Area: 1,560,000mm^2

Fig. 17

These are the two varying nose section possibilities, the tail section remains the same as we don't consider its complex geometry for calculations(yet). The two methods produce a very similar result, but we will use the curved geometry variant for superior accuracy. Total nose half area is then added to that of the tail half(2,340,000mm^2) giving a total of 3.9m mm^2. Dividing the force by area then gives us a pressure of 0.00096N/mm^2, a 0.00001N/mm^2 difference to the alternative.
A rounded pressure of <u>0.001N/mm^2</u> will be used.

3.3.3 - Technosoft

There are 3 main analyses that will be executed for SeaLander 3's calculations using Technosoft. First for **longitudinal equilibrium**, second determination of maximum deflection point and third for **compressive and tensile loads** across different regions. 3D poinload experiments will also be replicated to identify what kinds of forces are subjected to the samples, as this would too offer further insight. To begin with, we consider the standard boat conditions, in which it is subjected to all loads on still water. See diagram:

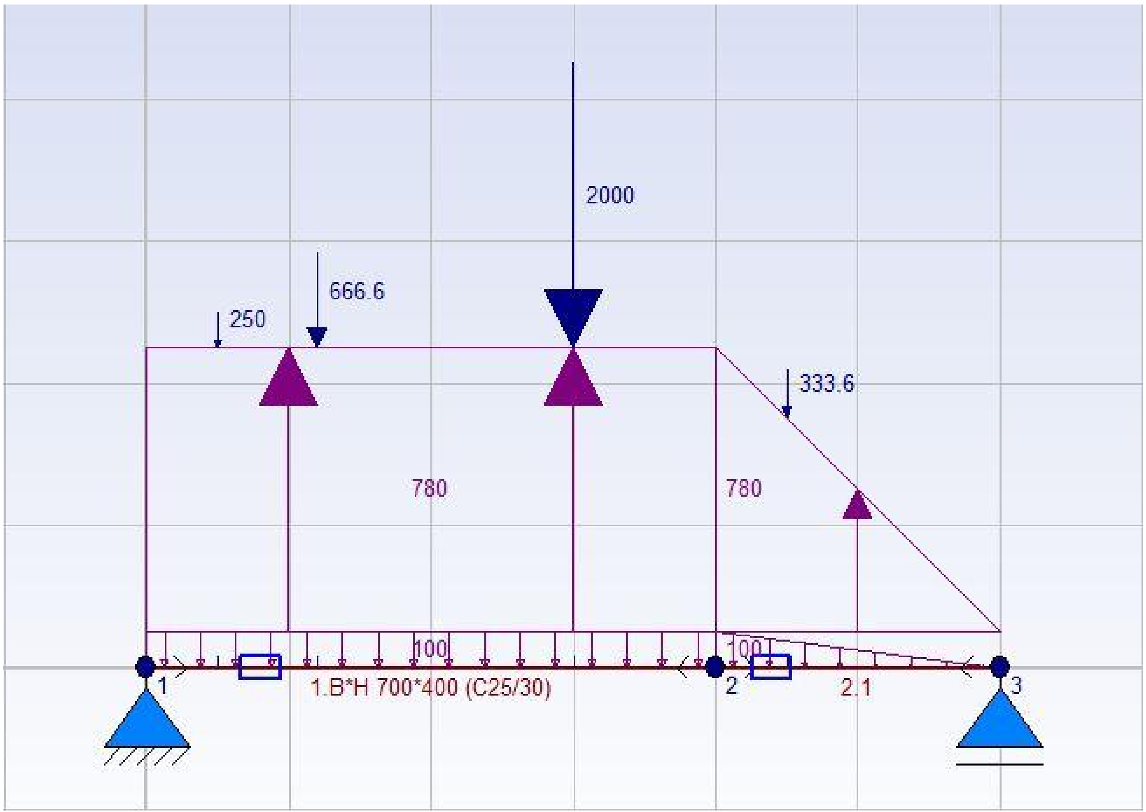


Fig. 18

This free body diagram represents the boat and all forces applied to it. And explanation to clarify:

- Beam - The boat, accurately spanning a length of 6m
- Distributed load(100N/m) - Boat hull self weight
- Distributed load(780N/m) - Water pressure on hull
- Point load(2000N) - Pilot

- Point Load(250) - Motor & Battery
- Point load(666.6 & 333.3) - Solar Panels, totalling weight of 1000N

In this scheme with the help of technosoft, we are able to determine the ideal locations of components so that the boat floats with horizontal equilibrium. We know we have reached that point when the support reactions are lowest as they can be and more importantly of about equal magnitude.

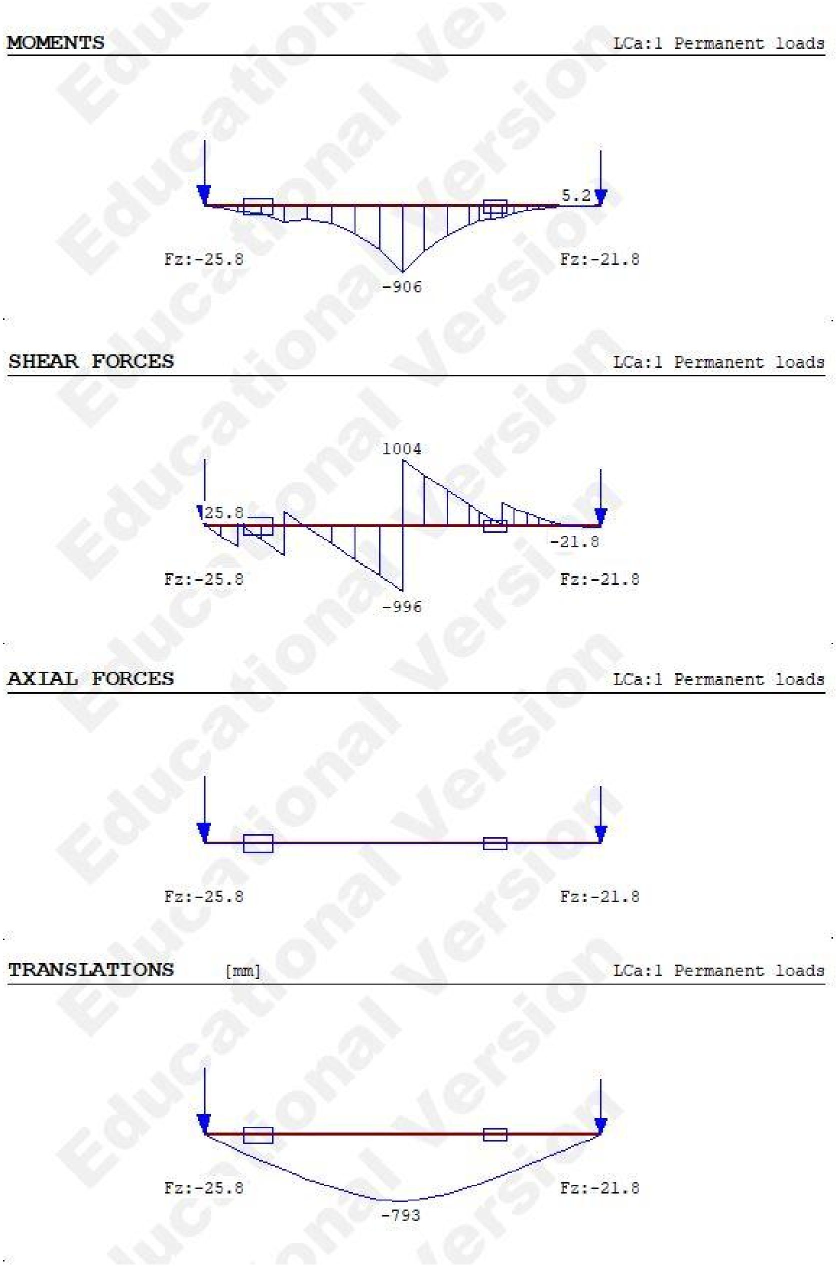


Fig. 19

We can see from the results of the technosoft analysis that with the proposed placement of components Sealander 3 will be in pitch equilibrium, sitting flat on the water's surface.

From the same analysis, the deflection values were extracted. The deflection values taken from technosoft do not represent the sealanders situation to scale but will tell us the maximum points regardless.

INTERMEDIATE POINT TRANSLATIONS — LCa:1 Permanent loads

			Global [mm]		Local [mm]			[kN/m²]
Bar	Nd.	Pos.	Displ-X	Displ-Z	Displ-X	Displ-Z	Rotation	Gr.press.
1	1		0.00	0.00	0.00	0.00	0.36432	
1		0.400	0.00	-145.51	0.00	-145.51	0.36180	
1		0.800	0.00	-287.66	0.00	-287.66	0.34782	
1		1.200	0.00	-422.00	0.00	-422.00	0.31993	
1		1.600	0.00	-542.50	0.00	-542.50	0.28377	
1		2.000	0.00	-648.55	0.00	-648.55	0.24412	
1		2.400	0.00	-734.51	0.00	-734.51	0.17984	
1		2.800	0.00	-786.31	0.00	-786.31	0.06980	
1		3.200	0.00	-782.73	0.00	-782.73	-0.08768	
1		3.600	0.00	-723.87	0.00	-723.87	-0.19716	
1	2		0.00	-631.17	0.00	-631.17	-0.26034	
2	2		0.00	-631.17	0.00	-631.17	-0.26034	
2		0.200	0.00	-576.94	0.00	-576.94	-0.28116	
2		0.400	0.00	-518.96	0.00	-518.96	-0.29818	
2		0.600	0.00	-457.80	0.00	-457.80	-0.31282	
2		0.800	0.00	-394.21	0.00	-394.21	-0.32221	
2		1.000	0.00	-329.21	0.00	-329.21	-0.32725	
2		1.200	0.00	-263.50	0.00	-263.50	-0.32939	
2		1.400	0.00	-197.56	0.00	-197.56	-0.32983	
2		1.600	0.00	-131.62	0.00	-131.62	-0.32948	
2		1.800	0.00	-65.78	0.00	-65.78	-0.32901	
2	3		0.00	0.00	0.00	0.00	-0.32881	

Fig. 20

From the table above, it is observable that the maximum deflection(referred to as Displ-Z, column 5&7) occurs at 2.8m inwards of Bar 1(meaning from the back of the boat), which is 0.2m behind the centre of the boat. Rotation is the alternative characteristic one could look to for a max deflection point, and it too has its lowest value at 2.8m inwards of Bar 1.

The maximum deflection point is necessary because it lets us know the best point at which to create the back and from sections of the 3d models for simulation. Since the softwares used cannot simulate an entire situation in which water and the forces would be acting, we need to rely on free body diagrams for some calculations which can only be used if the boat is sectioned in 2, and the best point for this sectioning is at the maximum deflection as its where rotation is Zero and we can consider it a fixed end beam situation.

3.4 - Critical Situations

In order to provide a fully accounted for design solution, before calculations begin, it is necessary to make a decision on what the critical situations would be. Two decided upon critical situations are stated below in no order of priority:

1. *Wave lifting Nose or tail, by simplification causing the boat to be supported from only 2 points leaving the rest suspended*

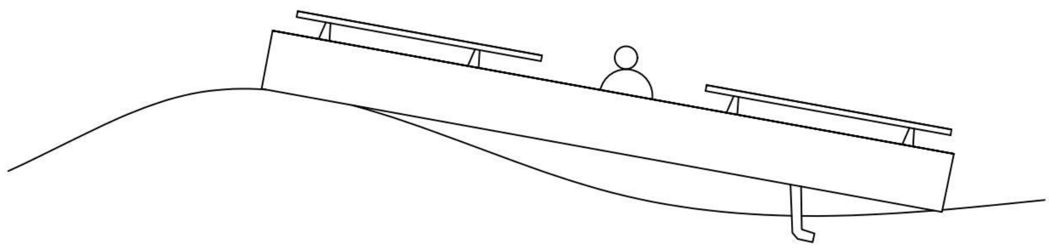


Fig. 21

2. *Wave directly under the centre of the boat, causing both the nose and/or tail to be suspended.*

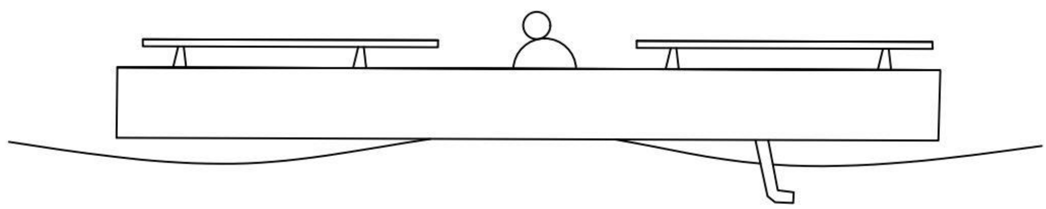


Fig. 22

Prior to this though, for baseline calculations we consider the boat to be at rest in calm waters. This will give us the pressure we need to resist and when we reach the point of critical calculations all necessary reinforcements will be added.

3.4 - Experiments

For experimentation the building block approach has been chosen. The building block approach consists of multiple phases of experiments going from very simple elements to more complex ones eventually resembling the subject(the boat for this project) in the final phase. Four phases will be executed in this project, starting with simple coupon samples eventually leading up to a shape which closely resembles SeaLander 2 although not exact. The reason it wont be exact is because it does not need to be, the experimentation is simply to gather information about the marital so it is possible to advance with the computed calculations. Creating an exact replica would yield no benefit and cost a hefty amount in time.
The elements created will be put into a flexion test, 2 pivoting supports and a point load in the centre. Graphs will be produced showing deformation relative to force until yielding point, any further data is irrelevant to the research.

Below is a display of the samples per phase:

Phase 1

2 layer 30x100mm coupon(x2)

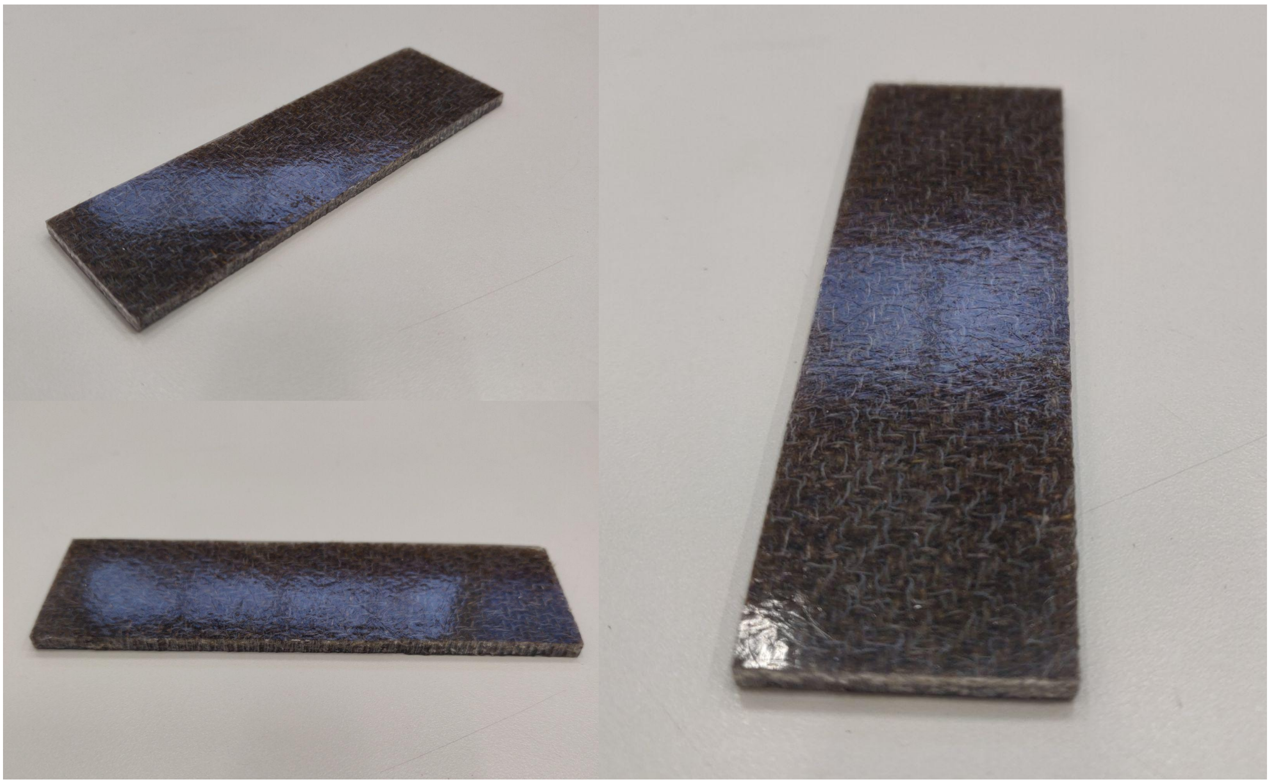


Fig. 23

4 layer 30x100mm coupon(x2)

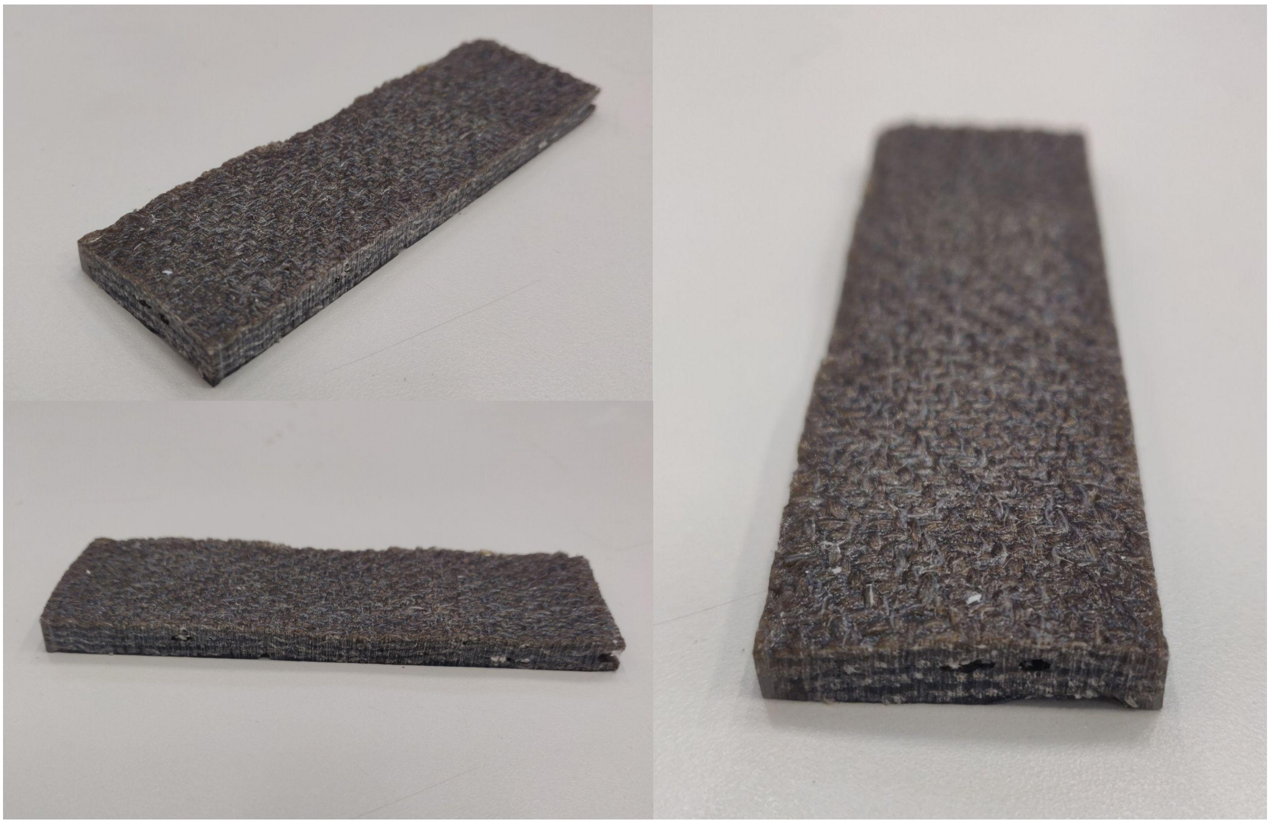


Fig. 24

Phase 2

2 layer L-shape section 30x30x100mm(x2)

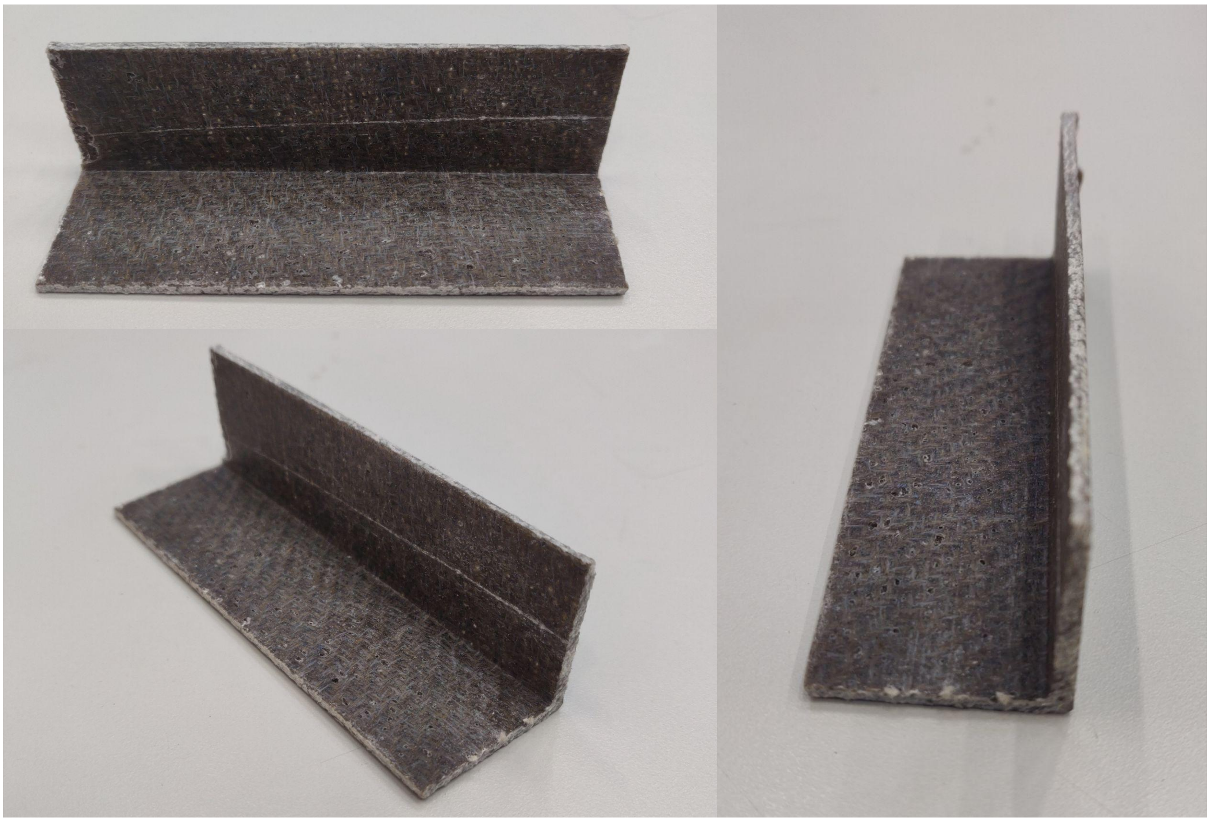


Fig. 25

2 layer semi circle section 38(diameter)x100mm(x2)

Fig. 26

Phase 3

2 layer round section 30(diameter)*100mm(x2)

Fig. 27

2 layer square section 25x25x100mm(x2)

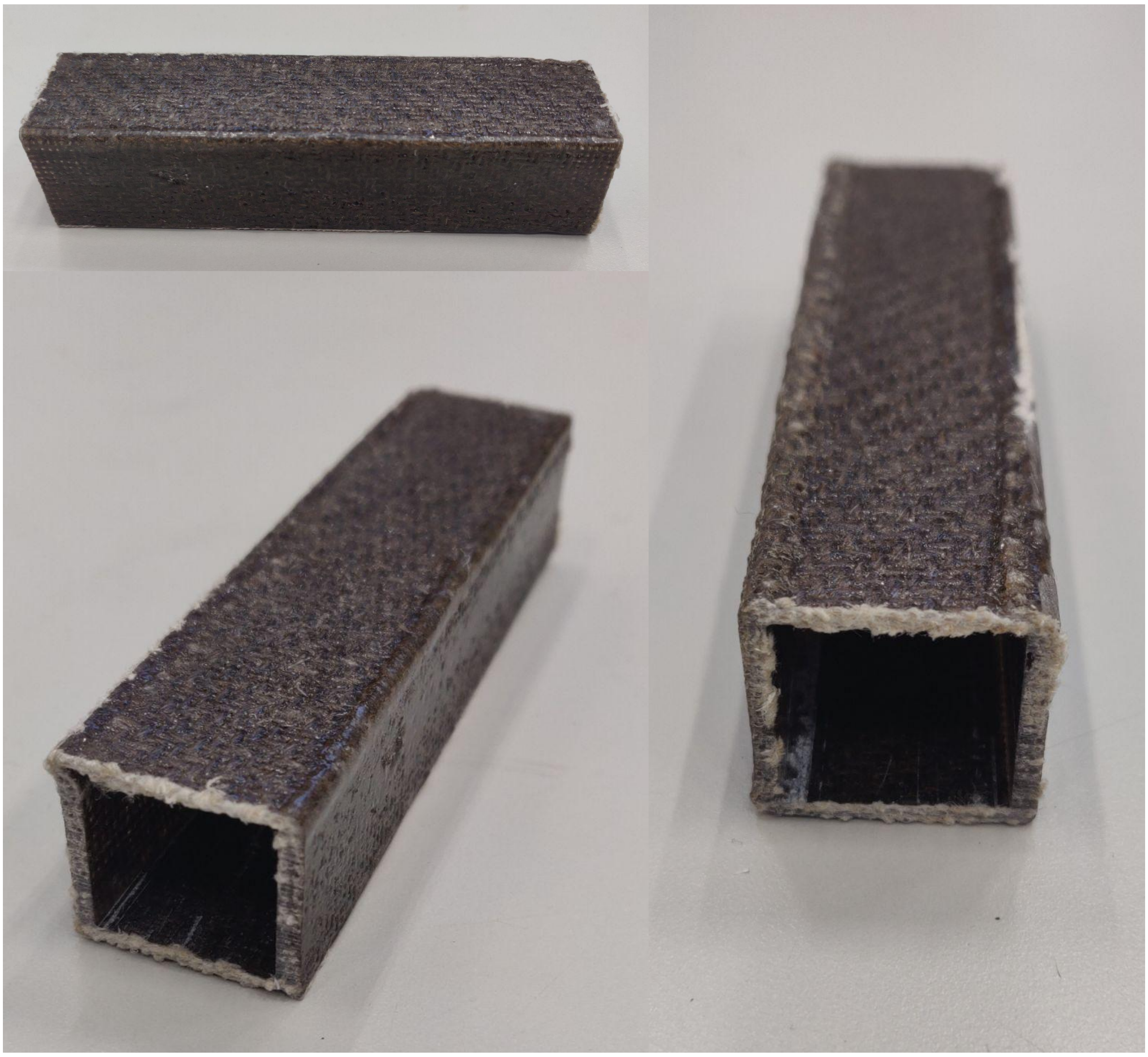


Fig. 28

Phase 4

2 layer U-shape section with flat and pointed ends(x2)

(DUE TO MULTIPLE REASONS, IT WAS DECIDED PHASE 4 BE EXCLUDED FROM EXPERIMENTS AS IT WOULD NOT GIVE MORE THAN IS ALREADY KNOWN AND REQUIRE UNJUSTIFIED EFFORT IN ADDITION TO CORONA RESTRICTIONS)

—---

The gap between supports during experimentation was 67mm. There is no particular reason for this gap related to experiment processes. The hydraulic press was simply set to this by previous users and it presented no problem for the research so work proceeded as intended.

3.5.1 - Post Experiment status vs simulation

Two experiments were conducted per sample, this was to minimise inaccuracy caused by imperfections of sample manufacturing as they were all created with limited experience and resource access. The average of the two experiments is then calculated and taken as the value for the sample type.

The varying shapes also meant force response was different, some shapes offered high stiffness until snapping point whilst others began deforming irreversibly(plastic) though still able to bear high loads. The exact situations will be discussed with graphs and pictures to accompany. Videos are available for all experiments and can be found in the appendix.

The experiment graphs display deformation on the X-Axis and applied Load on the Y-Axis, this is the standard for composite material testing.

2 Layer - Coupon - 2.5mm

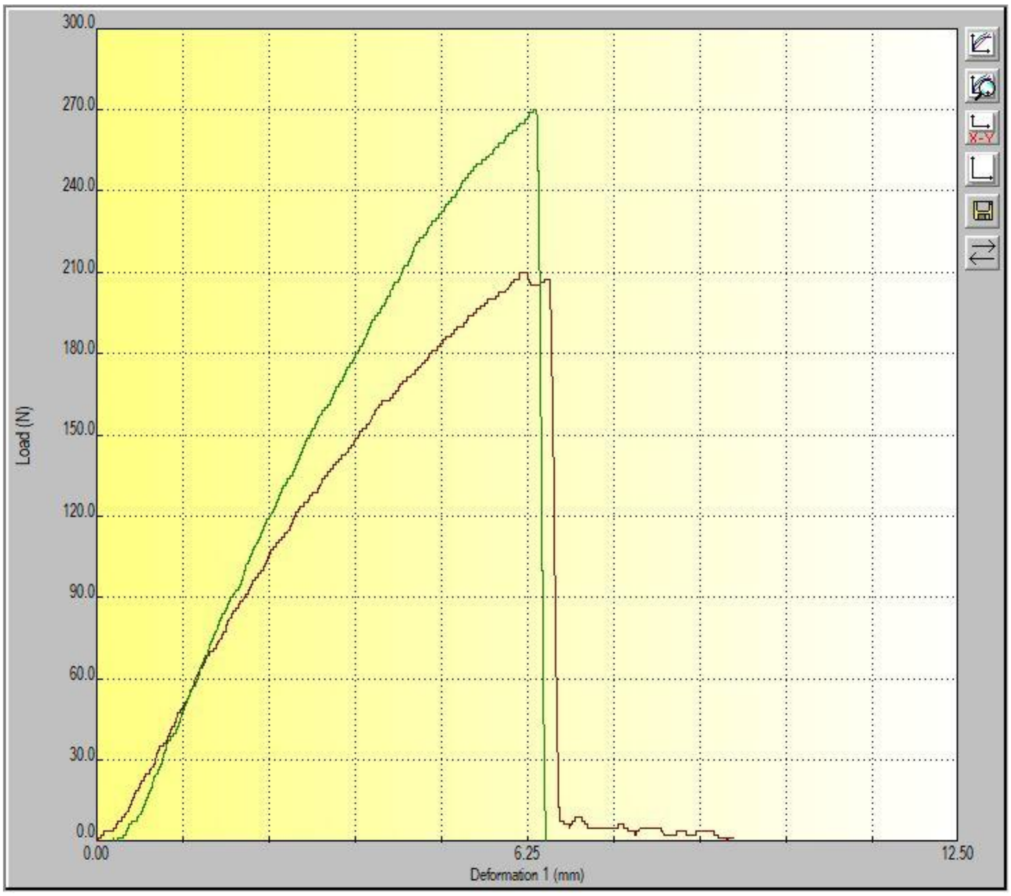


Fig. 29

Peaks: 270N & 210N

Average: 240N

FEM Result(stress, stress)

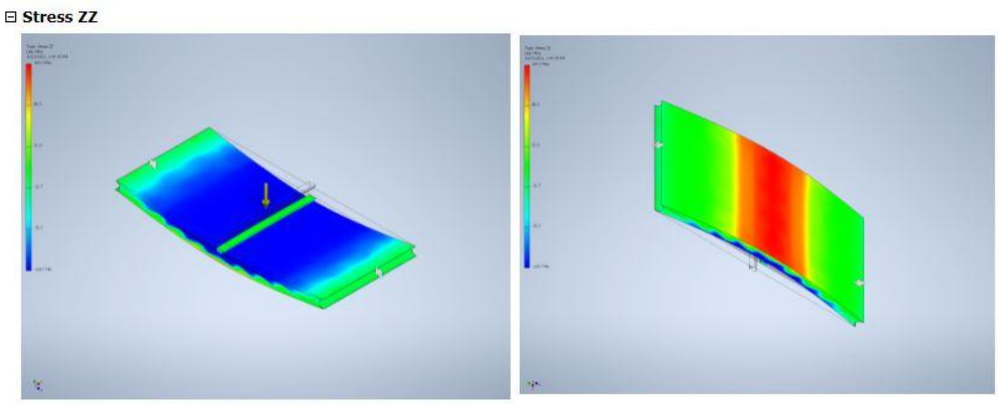


Fig. 30

Name	Maximum
Stress ZZ	140.266 MPa

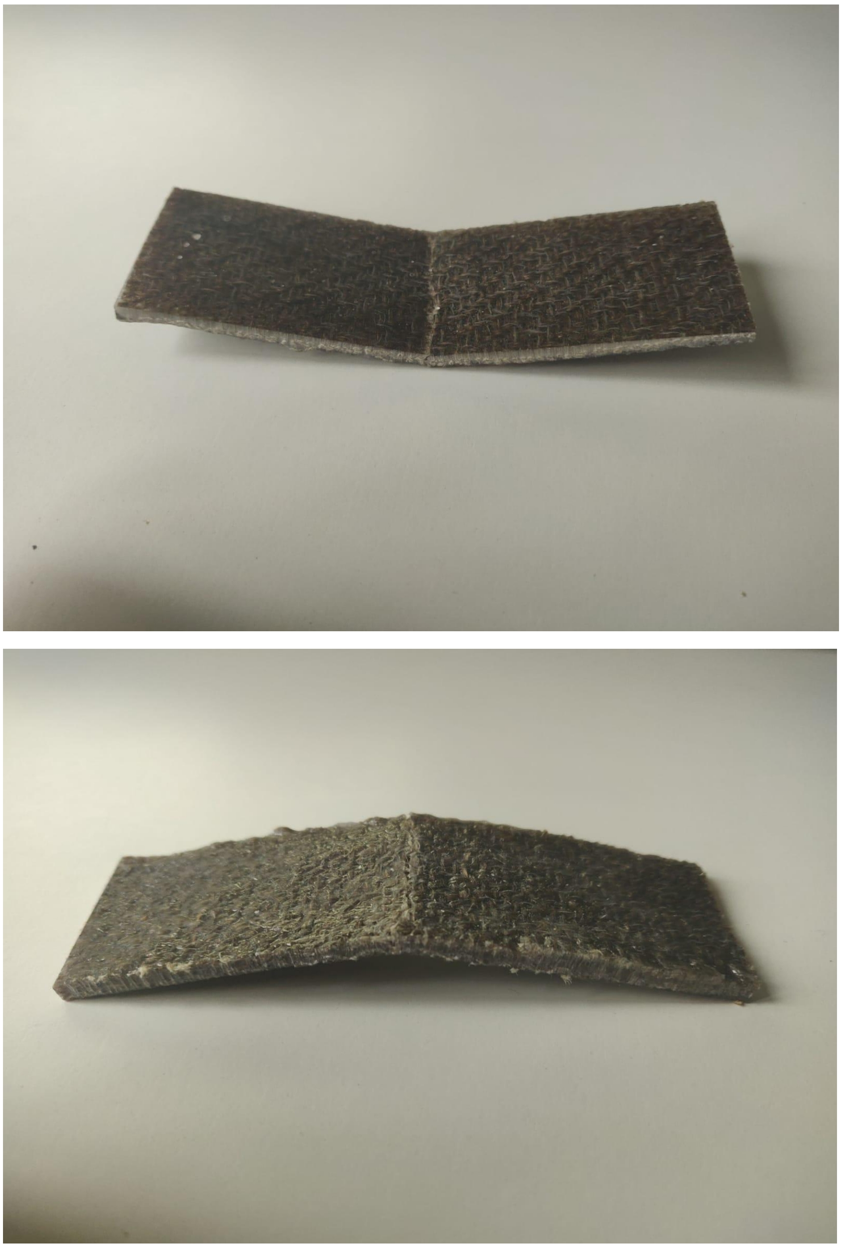


Fig. 31

Failure: Tensile capacity exceeded

Observation: The resin on the inner side of the break shows no signs of compressive failure and flax fibres on the tensile side all snapped.

4 Layer - Coupon - 4.5mm

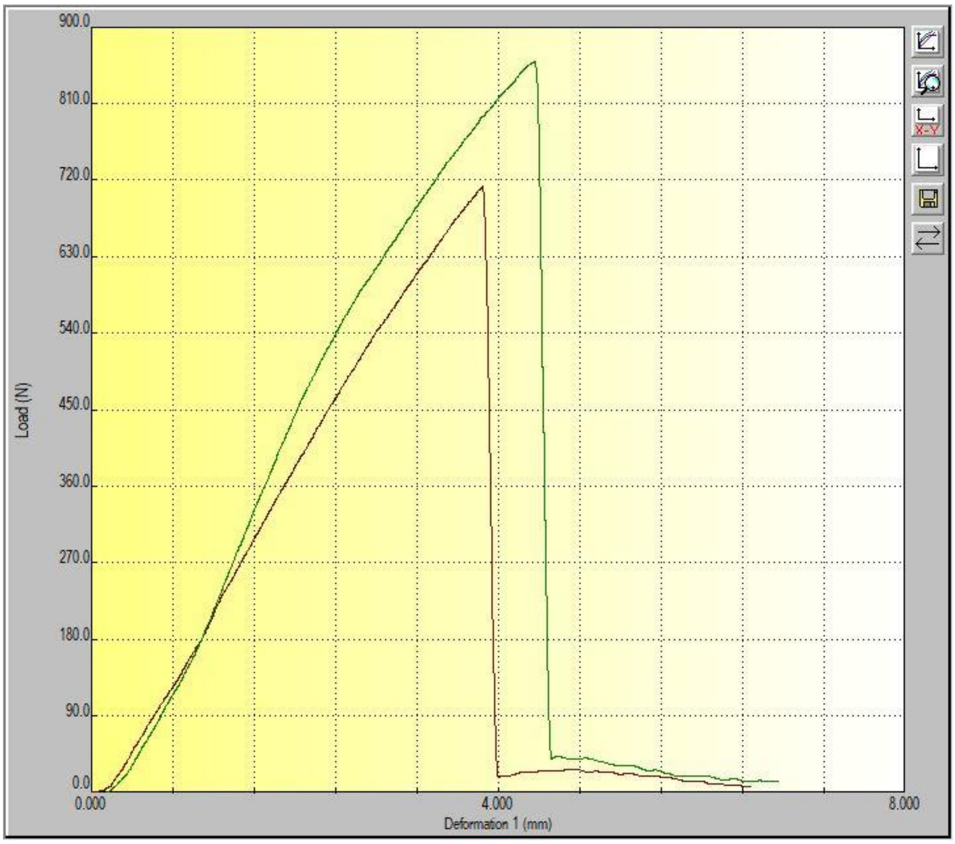


Fig. 32

Peaks: 715N & 850N

Average: 782N

FEM Result(stress, displacement)

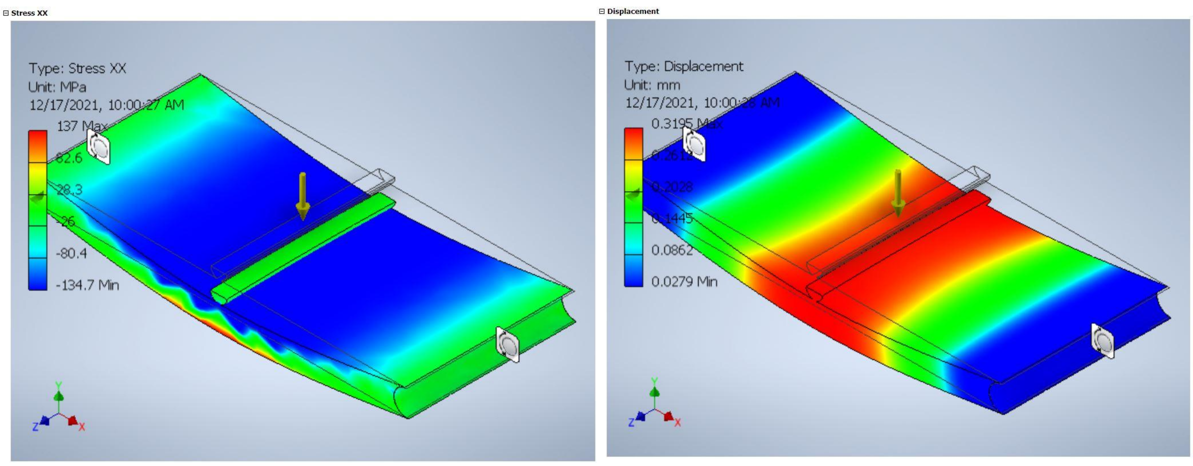


Fig. 33

Name	Maximum
Stress XX	136.972 MPa

Fig. 34

Failure: Tensile Capacity Exceeded

Observation: as its thinner variant, the resin on the inner side of the break shows no signs of compressive failure and flax fibres on the tensile side all snapped.

2 Layer - Semi Pipe

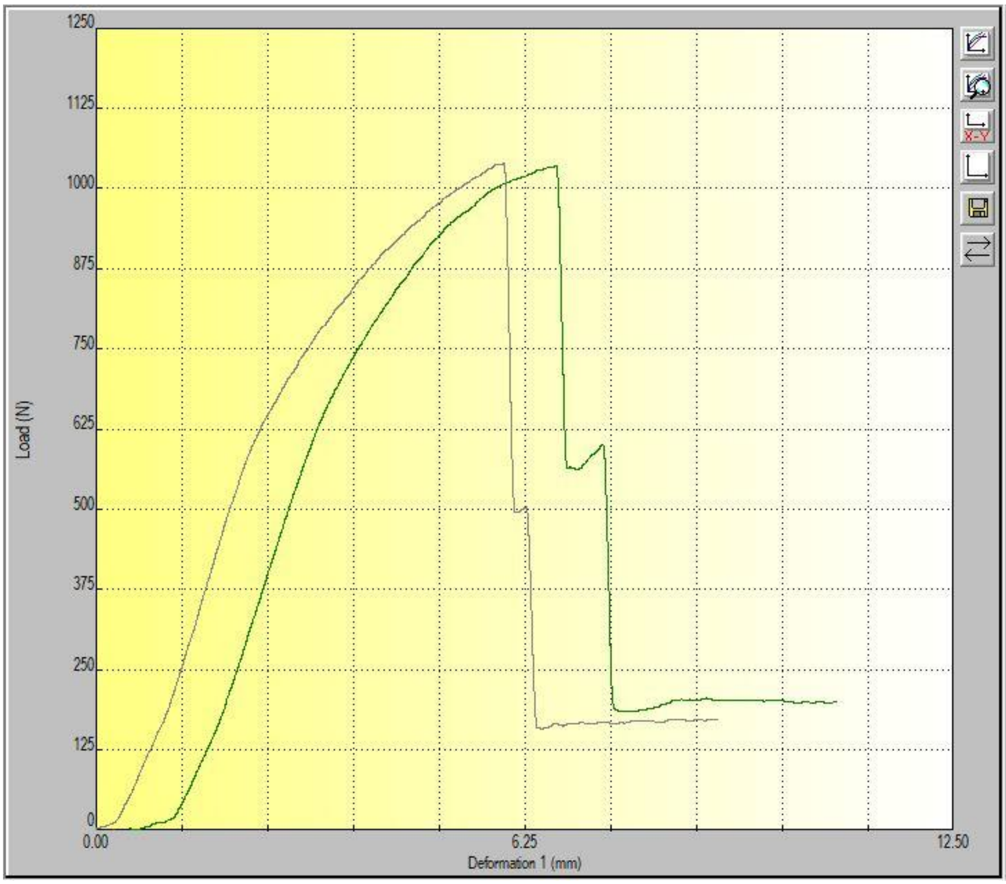


Fig. 35

Peaks: 1030N & 1030N

Average: 1030N

FEM Result(stress, displacement)

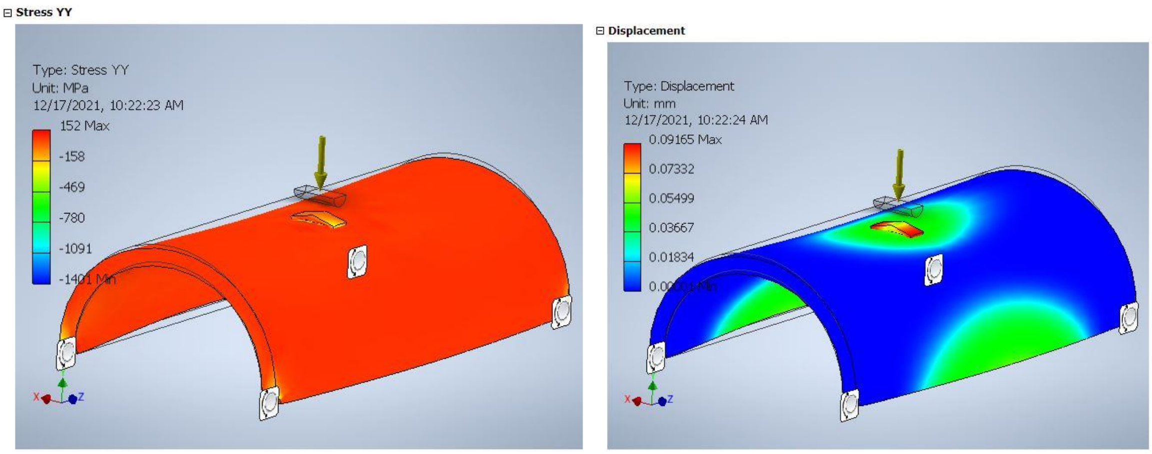


Fig. 36 (minimum can be ignored, it's compression in the node representing hydraulic head)

Name	Maximum
Stress YY	152.327 MPa

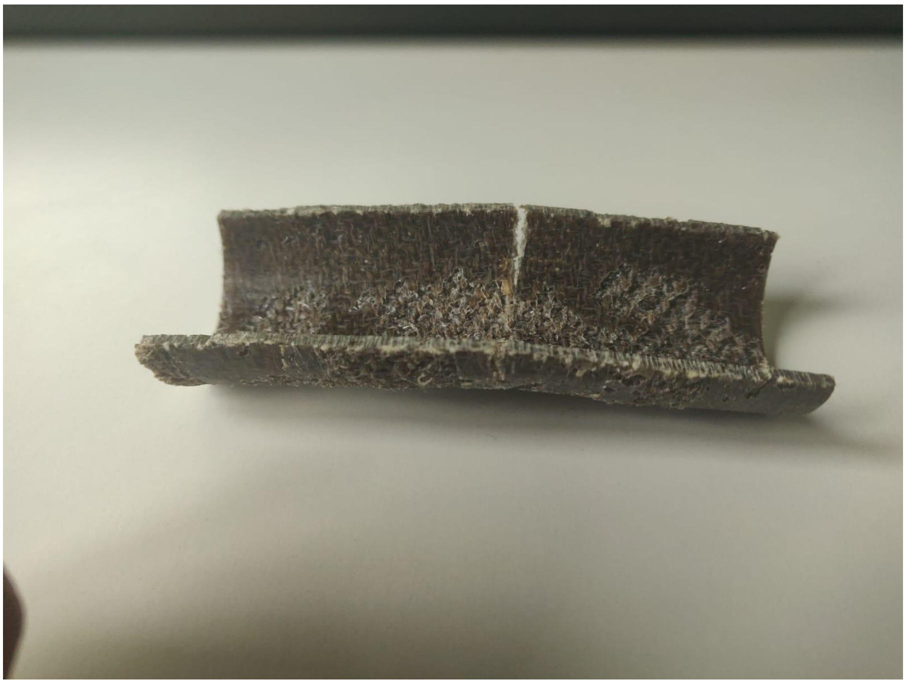
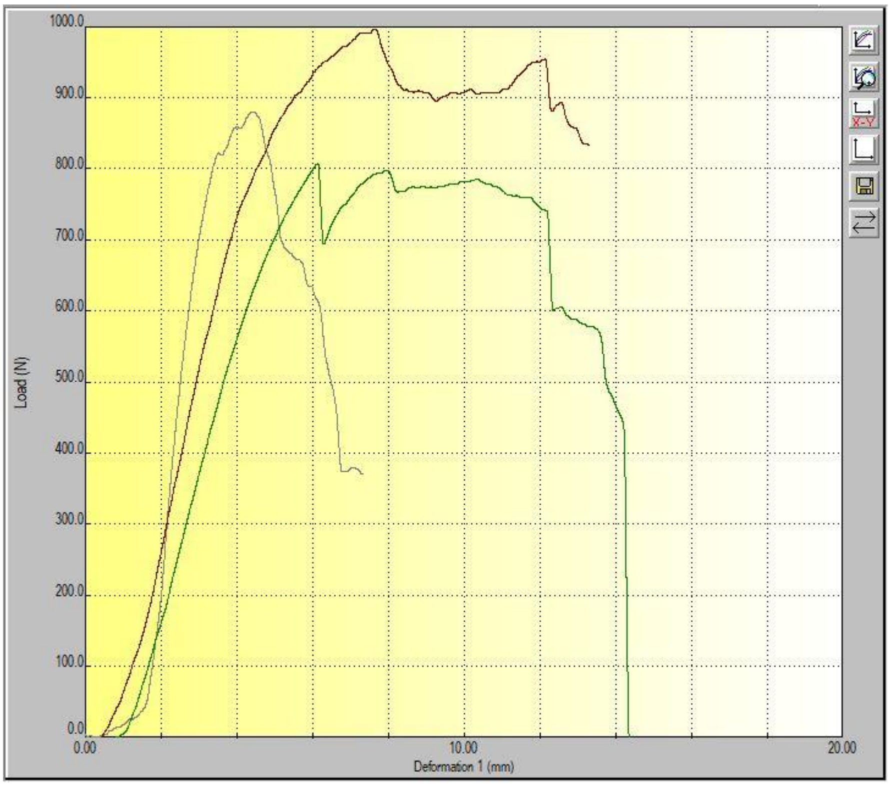


Fig. 37

Failure: Tensile capacity Exceeded

Observation: break occurred on tensile side where most deformation occurred, failure was a result of fibres relatively inadequate max capacity. The experiment showed an initial failure bringing bearing load down to about half of peak shortly after followed by a second break, These were the two down facing edges of the semi circle failing at different times.

2 Layer - L Shape



Standard experiment: Brown & Green lines *Fig. 38*

Additional experiment: Grey line

FEM result(stress, displacement)

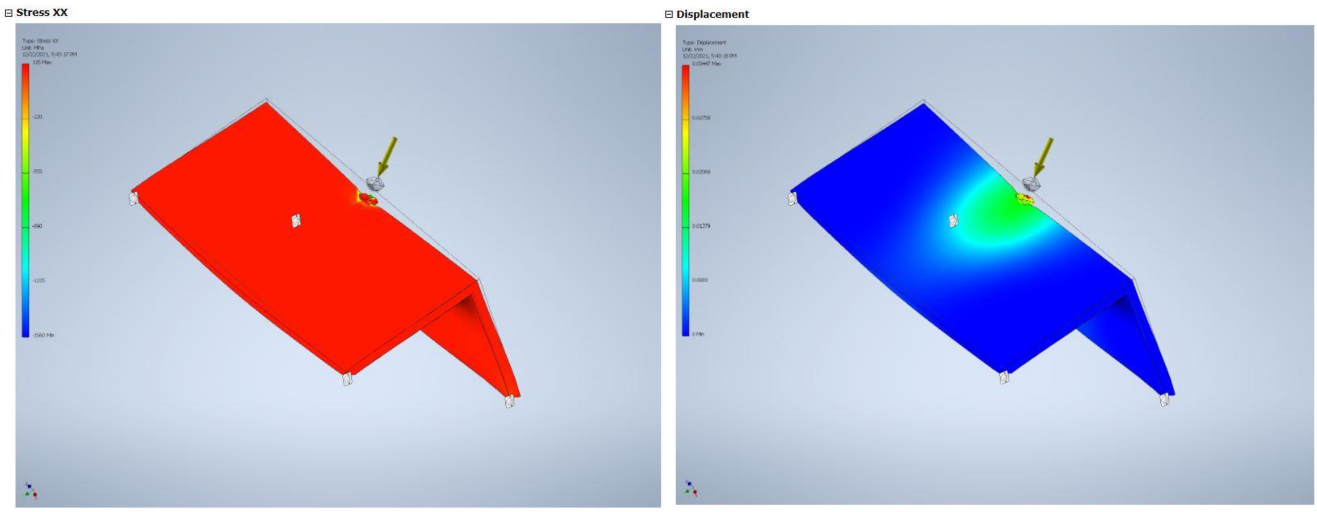


Fig. 39 For this experiment, there was excessive deformation due to experiment style. For that reason, instead of the peak, an approximation of the first inflection point of the lines are considered. The values are 550N & 500N. Average: 525

Name	Maximum
Stress YY	119.766 MPa

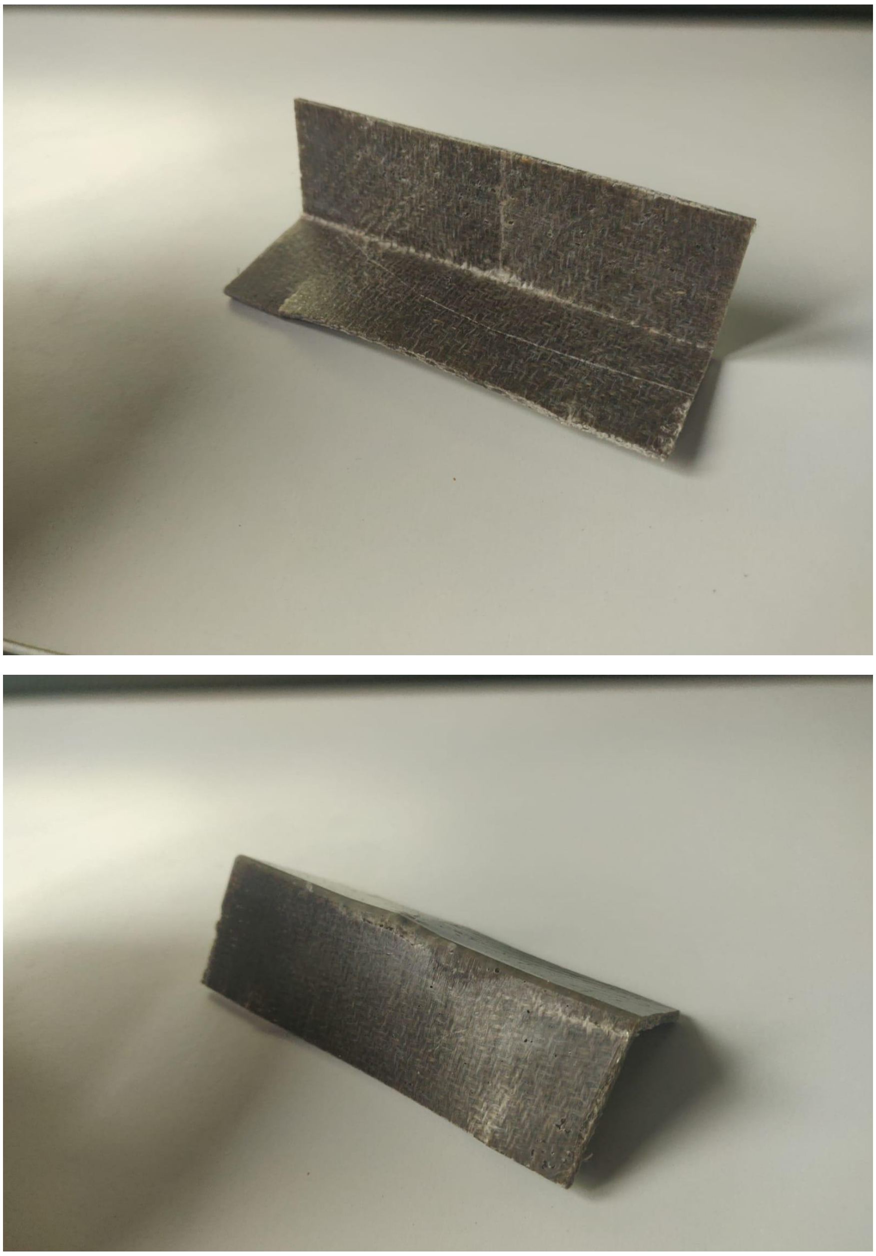


Fig. 40

Failure: Excess deformation

Observation: This sample behaved very differently compared to the others, and predictably so. Given its shape and the layout of the experiment, it began to flatten, sliding outwards on its steel supports which resulted in no abrupt failure, but a deformation exceeding 12mm. The experiment was short as it was not behaving as intended, but when finished the sample almost completely reverted to its original shape.

2 Layer - Square Section

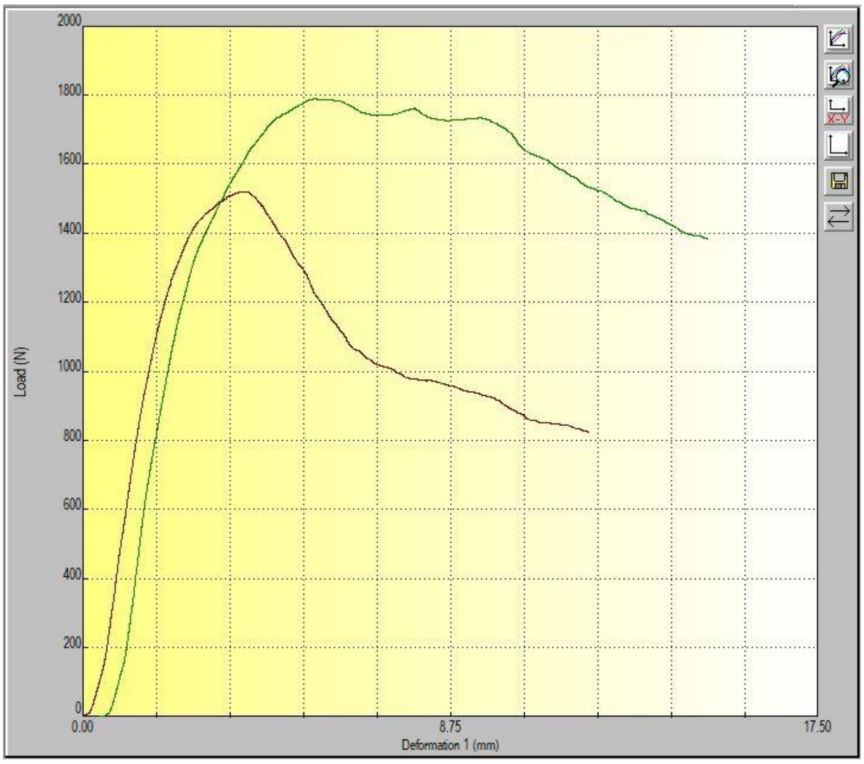


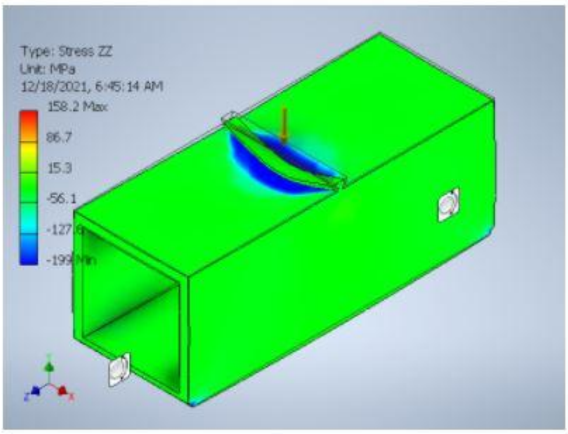
Fig. 41

Peak: 1700N & 1500N

Average: 1600N

FEM Result(stress, stress)

⊟ Stress ZZ



⊟ Stress YY

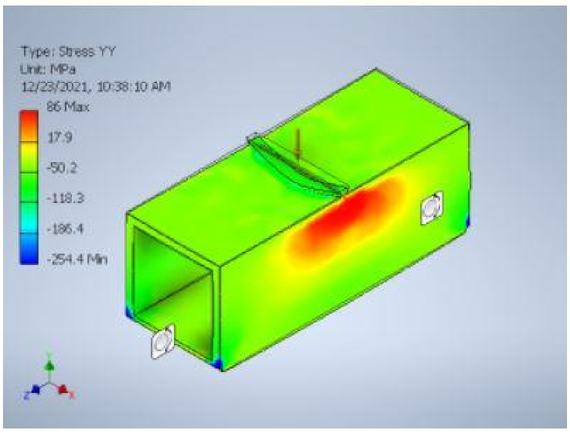


Fig. 42

Name	Maximum
Stress XX	166.811 MPa
Stress YY	85.9879 MPa
Stress ZZ	158.176 MPa

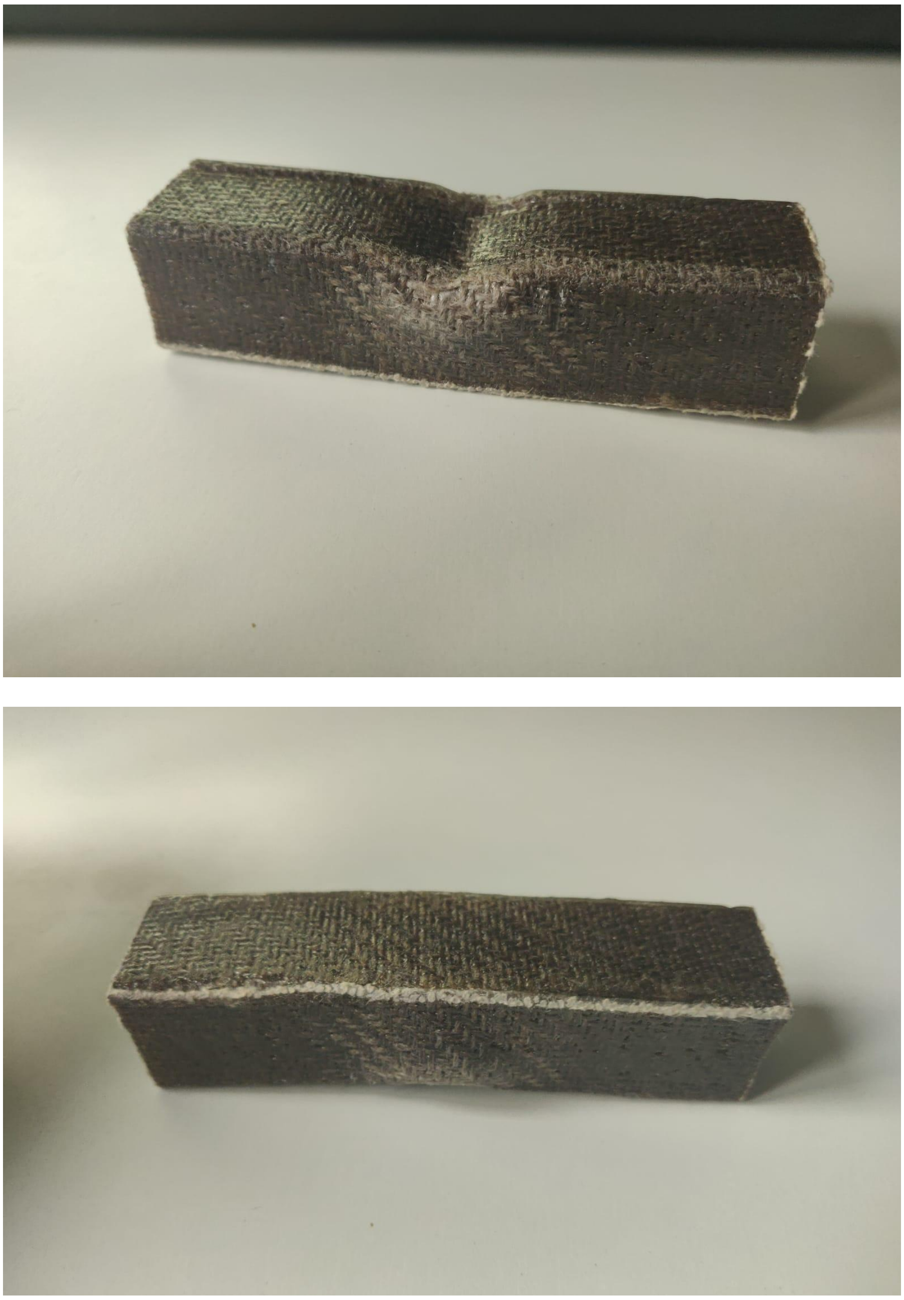


Fig. 43

Failure: Excess deformation + Tensile capacity exceeded

Observation: This sample has significantly more material than all others, that and its complementary shape contributes to its high bearing capacity. The most apparent exterior sign of failure is visible on the outer corner but it's hard to determine if this is valid because there was an imperfection when creating its edges. The inner upper section, however, performed exactly as predicted according to the previously obtained results, tensile failure at ~140MPa. The experiment was taken beyond initial failure out of curiosity to behaviour.

2 Layer - Pipe Section

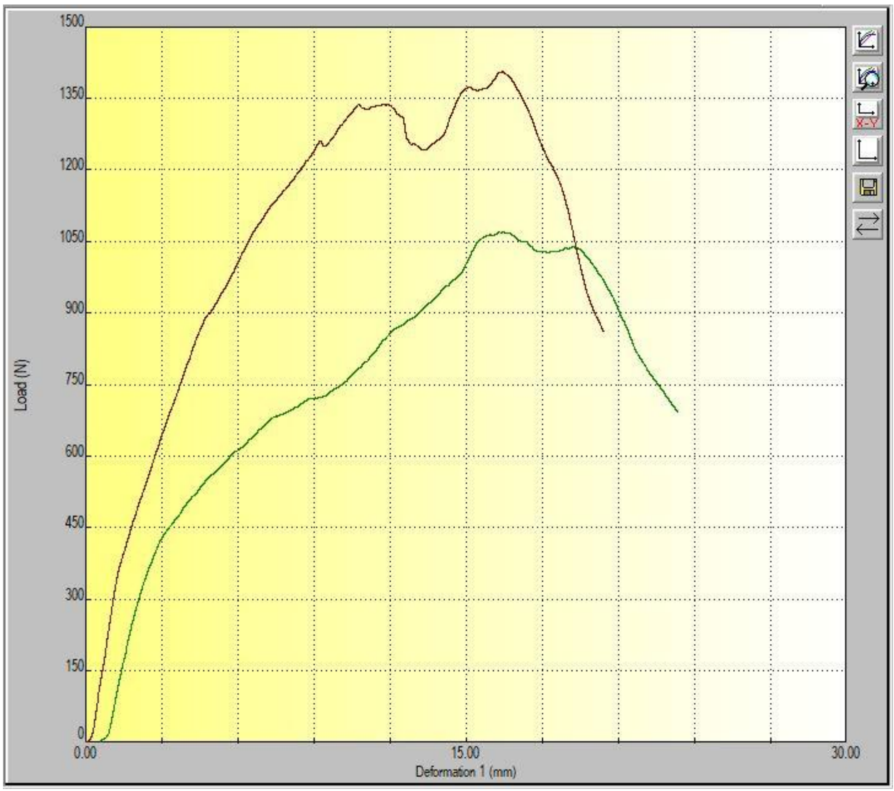


Fig. 44

The pipe section too displayed excessive deformation after the first major failure, therefore, only the first peaks are to be considered giving values of 1070N & 1300N. Average: 1185N

FEM Result(stress, stress)

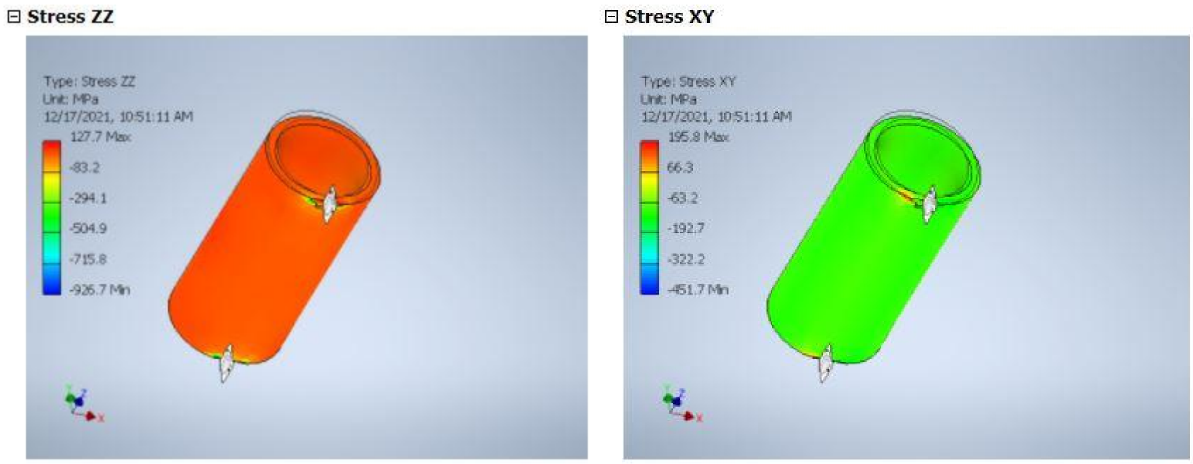


Fig. 45

Name	Maximum
Stress XY	195.832 MPa
Stress ZZ	127.704 MPa

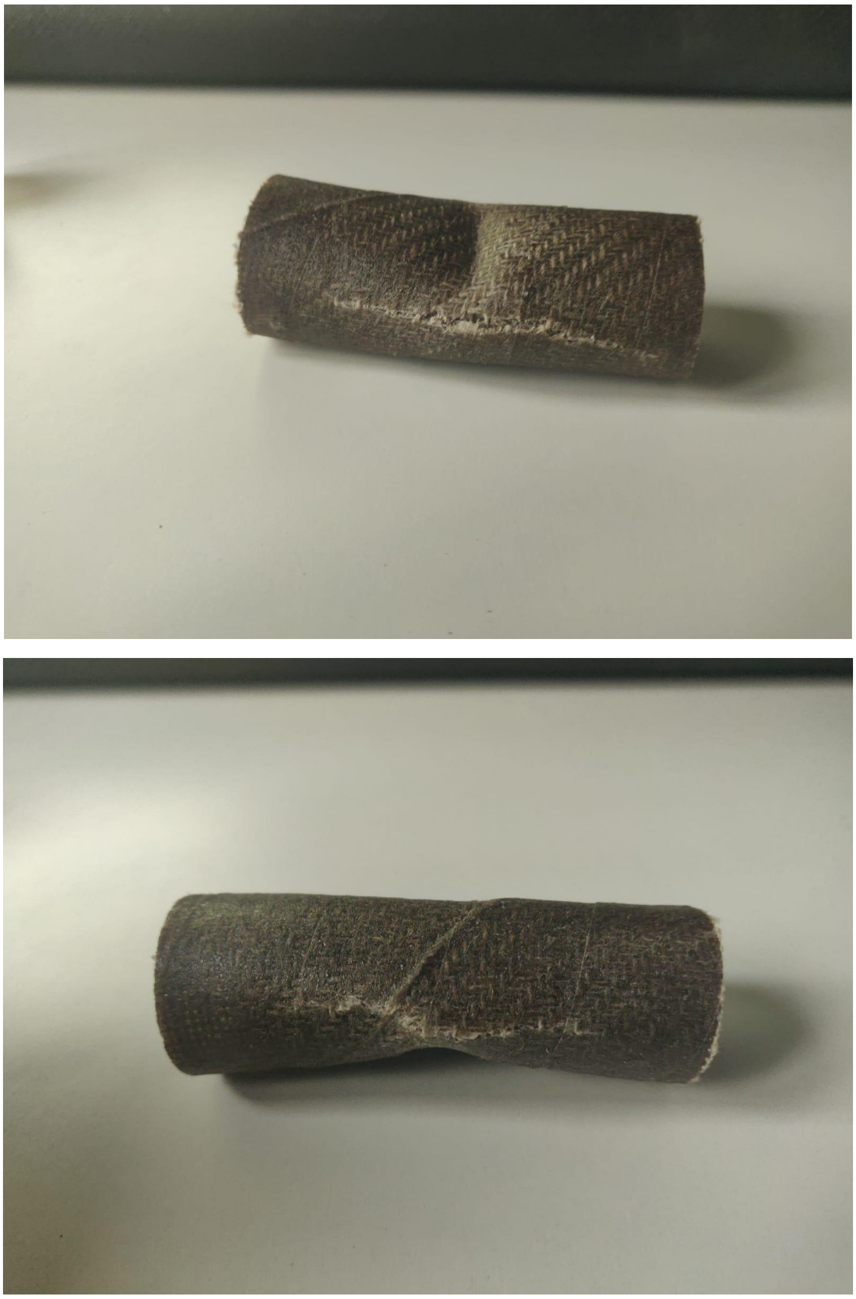


Fig. 46

Failure: Excess deformation + Tensile capacity exceeded

Observation: This sample had equal material volume as the squared section but its shape led to lower ultimate bearing capacity. During the experiment, the sample failed quite a bit before it reached the ultimate bearing capacity, this was because due to its shape, the more it deformed the more material was shifted into position in which it positively contributed to the load conditions. Like the one before it, the experiment was dragged longer out of curiosity of behaviour.

3.5.2 - Experiment Conclusion

Core purpose of the experiments was to develop an understanding of flax fibres limits and in specific the limits in a composite format situation.
Flax fibre in a composite situation has a complementary relationship when it comes to dealing with stresses, similar to that of concrete and steel reinforcement. The fibres have high tensile strength but arguably no compressive resistance longitudinally to a strand, and the resin matrix a high compressive resistance but lacks in resistance to tensile stress. Knowing this, when analysing the experiment results, we are able to determine what failed first of the matrix and dispersion phase.
Analysing the samples after experimentation, it is noticeable that the limiting factor was almost always fibres tensile strength. The resin matrix rarely showed any signs of compressive failure.
The average failure point of all samples was at **142.8MPa**. For the imperfect experiments approximations were made by estimation that most make sense. For design of the hull, that doesn't mean loads are allowed to reach this point, an important consideration is cyclic load. When designing with steel, a rule of thumb for cyclic load is to create components in a way that they reach only one third the yielding point of that respective steel. In general, fibre-reinforced composites perform well in cyclic loading and have better resistance to fatigue than metals. Fatigue failures in metal are related to crack propagation which is ultimately tied back to the grain structure and initial imperfections in the metal. Fibre-reinforced composites do not have a grain structure like metals do, so cracks do not propagate through them the same way as metals. Composites can have a range of imperfections, but it is usually the resin matrix or bond lines that are prone to cracking. Therefore, it can be considered that the metal limit of ⅓ max stress is even a safe margin. For this research, since there is no settled upon consensus for the topic especially with the variance in manufacturing, **50MPa** will be the limit for cyclically loaded components and sections of the hull.

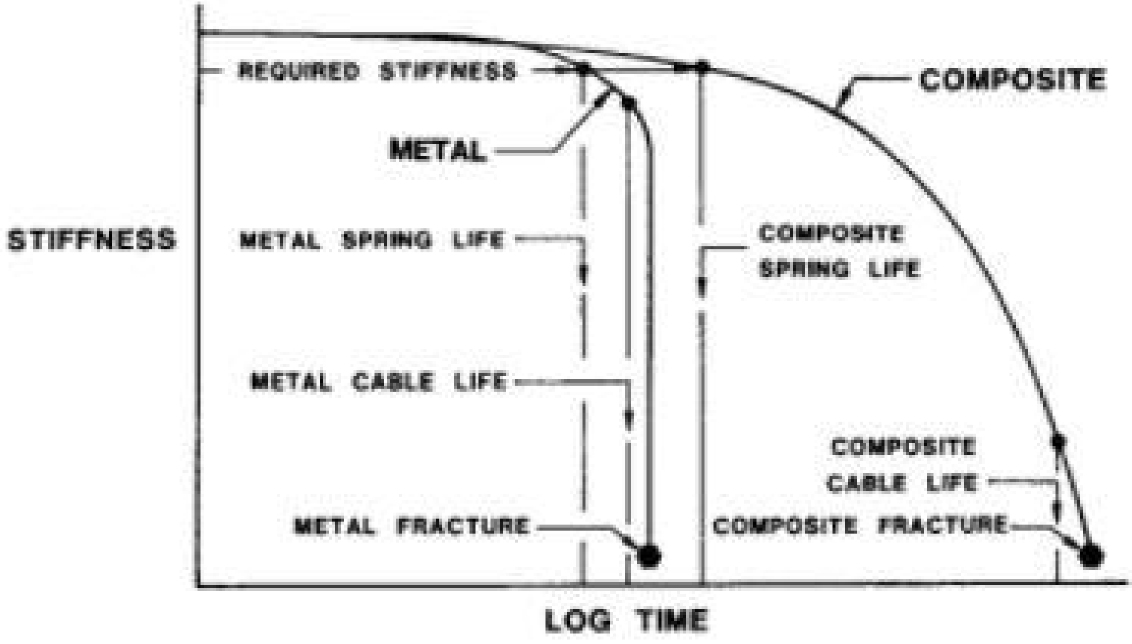


Fig. 47

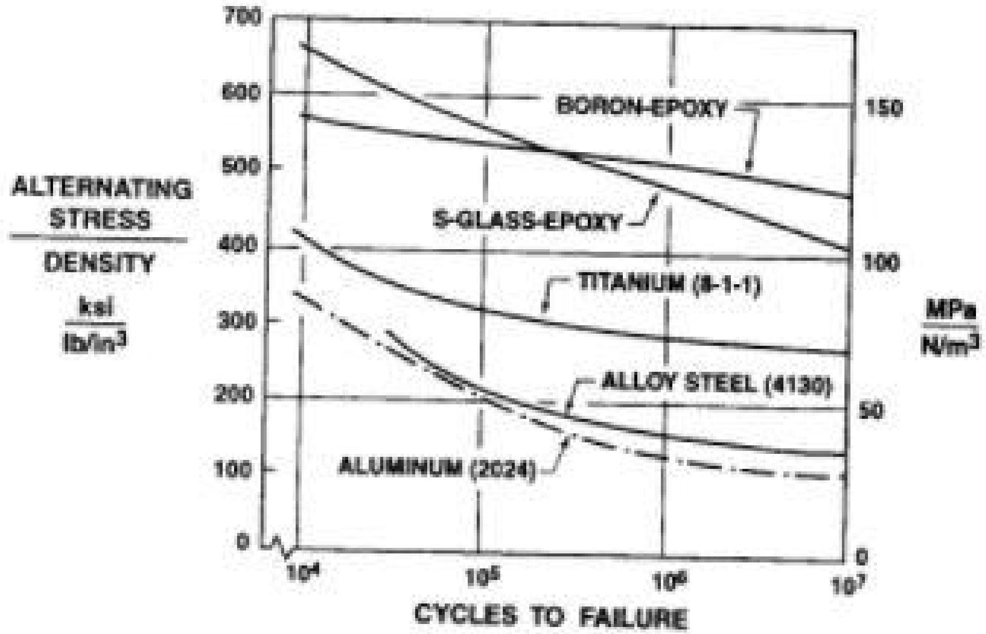


Fig. 48

These two graphs from the book *Mechanics of Composite Materials* by *Robert M. Jones* somewhat demonstrate the comparison between metals and composites, exact reference available in the references section(#21).

4 - Results

With the results from experimentation in, we are able to interpret the 3D simulations created for all conditions. Having tested varied thicknesses and shapes, a good understanding of the material has been developed. This means it is now possible to determine how much flax will be needed at all sections of the boat and in what orientation.

4.1 - Selected Hull Design

The Final design for the hull, it was determined that a general 2 layer(2.5mm thickness) with 6 layer(7.5mm thickness) in the cockpit area will suffice for all standard use and will even comfortably withstand all critical situations with one exception. The one exception is if someone were to step on the hull whilst it is upside down. With the addition of a third layer though, stepping on the hull even for a fairly heavy individual would be bearable. General durability would be increased with a third layer so for example impacts would be less of an issue.
This decision will be left to the client, depending on what they believe will best suit their preferences.
For fibre orientation, a plain weave pattern aligned with the boat across the entirety of the boat will work best as those are the axes along which most stress is ever experienced.
Flanges should be of length 42-45mm with the base thickness of 2.5mm

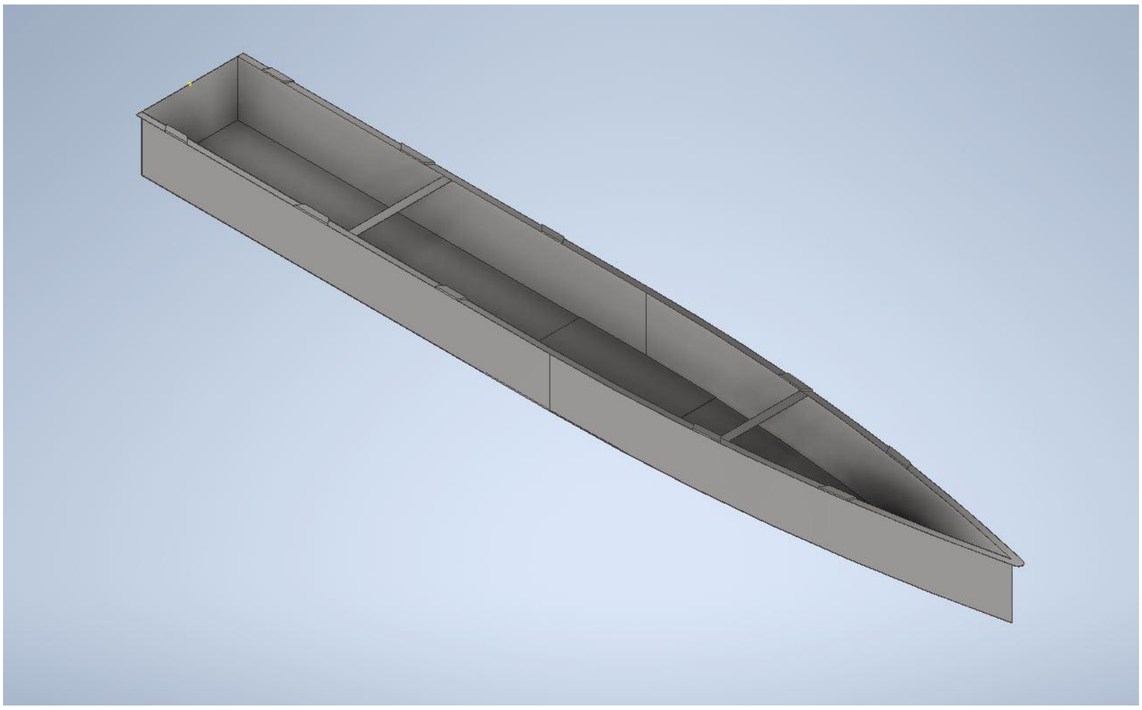


Fig. 49

4.2 - Critical Situations

The selected hull design was put through a series of virtual simulations which made it possible to verify that it would withstand all conditions. Below are the different selected situation simulations from Autodesk inventor with an explanation and interpretation of the relevant extractable information. What is important is to make sure our stress values don't reach the selected limit of 50MPa. Full stress analysis reports are all available in the appendix.

Nose + Tail Suspended

The nose and tail suspension is meant to represent a situation in which a wave is directly under the centre of the boat, bringing the nose and tail out of the water. The greatest tensile experienced in this simulation is 5MPa, meaning it is well within safe limits.

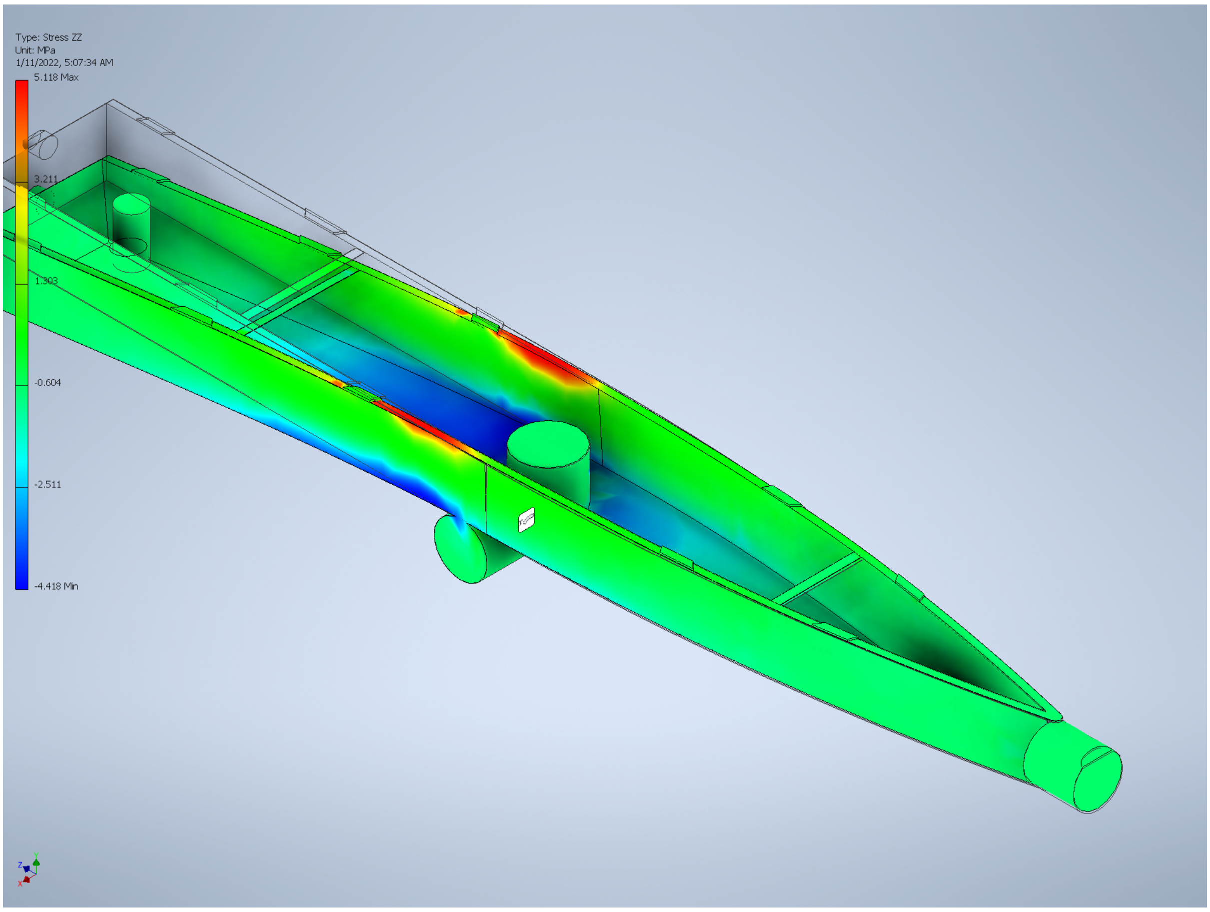


Fig. 50

Mid Suspension

In this simulation, the nose and tail are both lifted by waves, causing the boat to almost act like a 2 point suspended beam with all loads acting on it. The way it was approached was to create 2 pin constraints at the front and back of the boat, this best simulates the situation. As can be seen from the results, this is no issue handling this situation with the design. There was a maximum *valid(the maximum on 27 is at support point which does not have continuity with reality of situation)* tensile stress hovering around the 5MPa and maximum compressive of 27MPa.

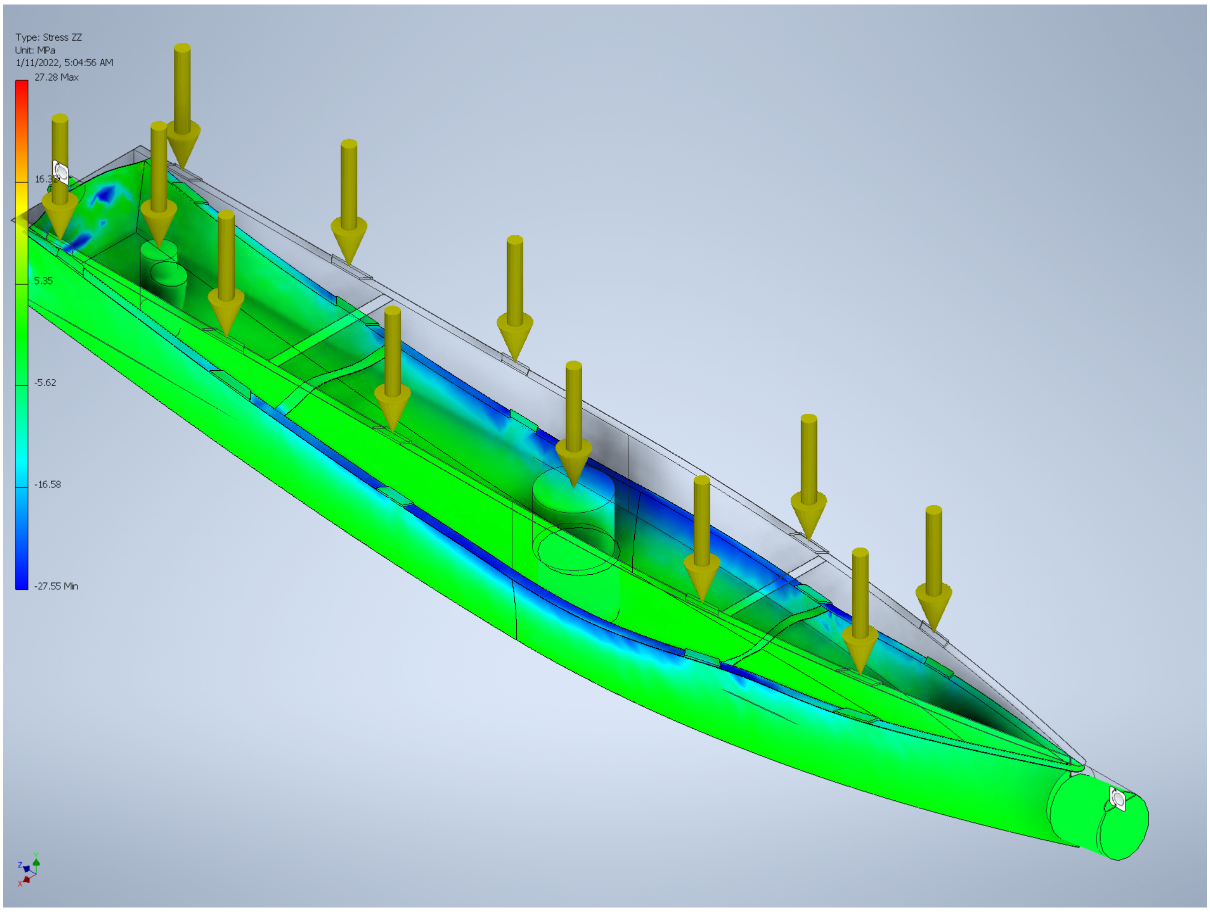


Fig. 51

Wave Collision

This simulation is meant to replicate a situation in which the boat hits a wave head on moving at 20km/h, temporarily bringing it to a halt. By executing a simple conservation of energy calculation we can find out the force at impact:
Weight: 375kg
Speed at impact: 5.56m/s
Distance to halt: 0.3m

(375*5.56)/0.3
=6950N.

The boat has no support points in reality, but since we need them for this virtual simulation, the decided support point was the Pilot. This was done because the pilot has the most weight of all objects in the boat, so they will also carry most resisting inertia when the boat comes to a stop or more accurately; an immediate speed reduction.
Looking at the results, we once again see that the boat has no problem resisting the situation. The maximum tensile force experienced is 14MPa on the front support strip.

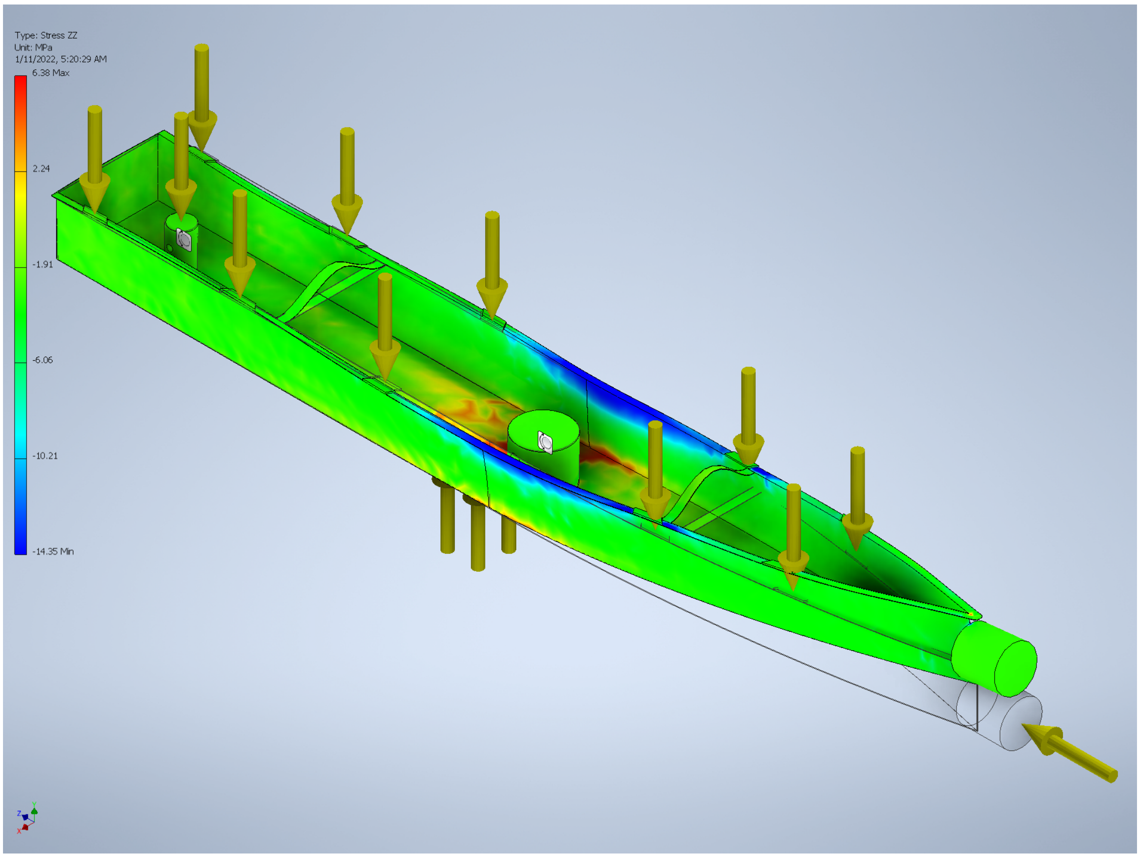


Fig. 52

Jump in Cockpit

The foot surface area for an adult is approximately 100cm^2, there are two situations which need to be accounted for in this category, for a standard step on the hull surface and for the impact of someone jumping onto the surface. The jump will be particularly useful for someone entering the cockpit irresponsibly. For these simulations, the subject will have a body weight of 90kg and be landing on one foot.
Starting with the cockpit situation, we use the same conservation of energy calculation as before, someone of stated weight jumping into the hull from a height of 30cm. The result of this calculation is 5297N on impact. Below is the virtual simulation of the situation.

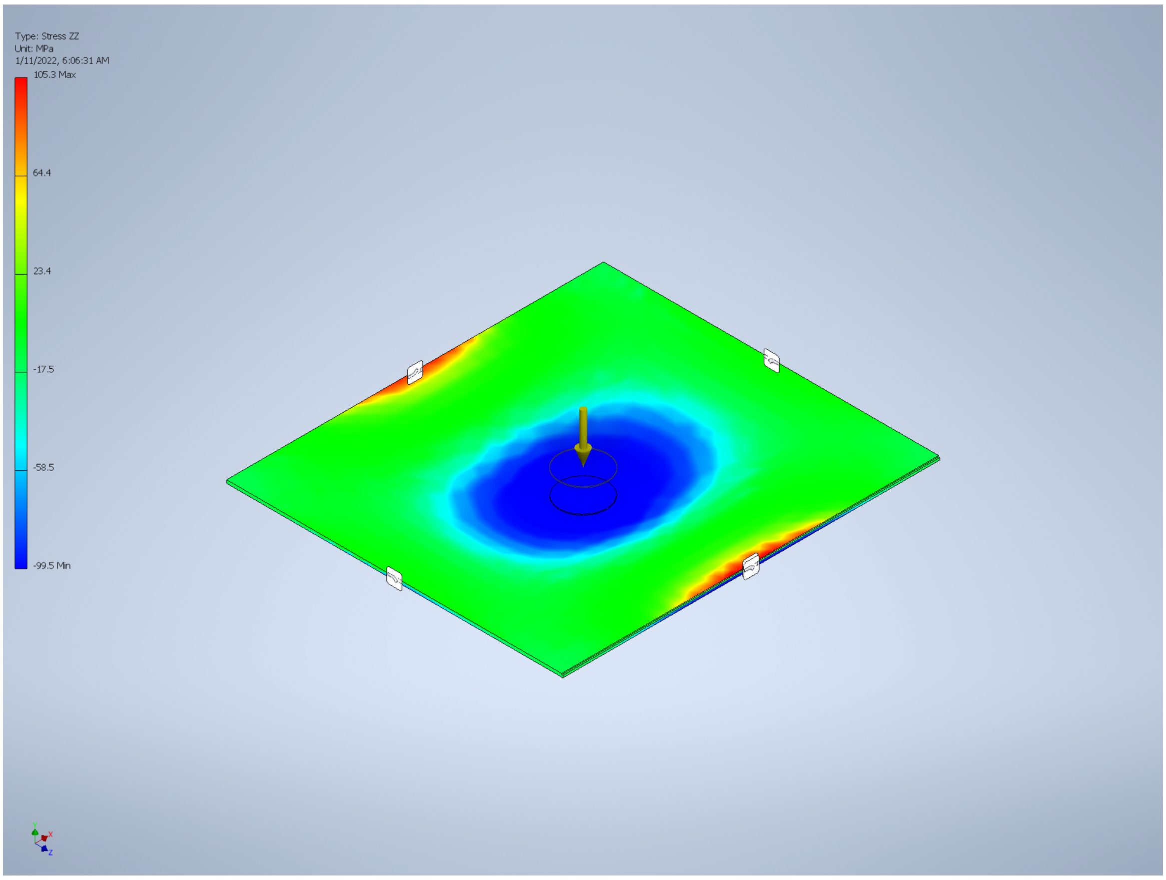


Fig. 53

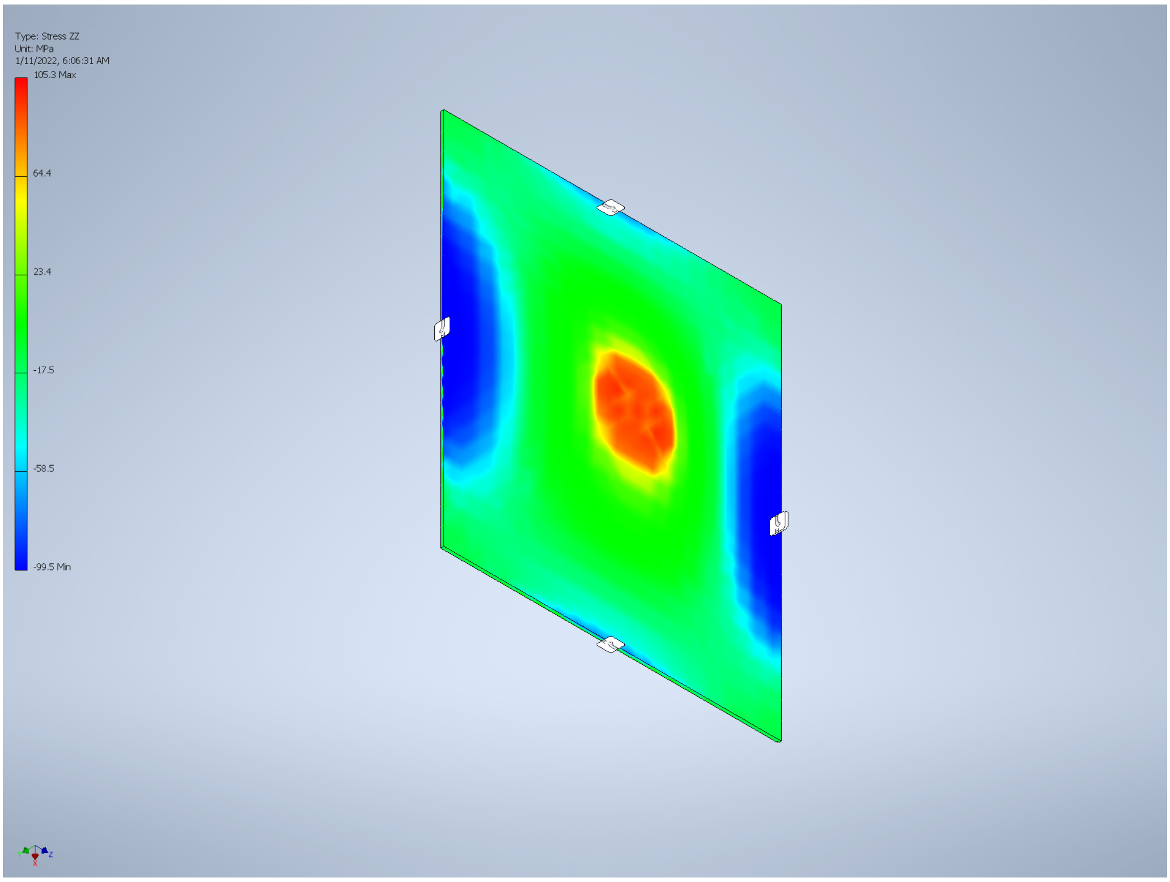


Fig. 54

With a thickness of 7.5mm or 6 layers of flax fibre, the cockpit will be able to resist a jump impact but just make it. Therefore, it would be highly recommended not to jump into the boat and rather enter carefully. If it were to happen though, the design will be able to withstand its impact, generating a max of 105MPa in tensile and since it's not meant to be a common occurrence it doesnt need to fall within the cyclic load parameter.

Step on hull

Having a person step on the hull is not something the boat is required to do and so the design is not catered for. Regardless, an analysis will be executed to understand what exactly would occur were it to happen.
With a Hull thickness of 2.5mm(2 layers), if someone were to step on the hull it would likely break especially if their weight exceeds 80kg. The maximum tensile stress reached in this simulation was 198MPa for a 90kg single foot step.

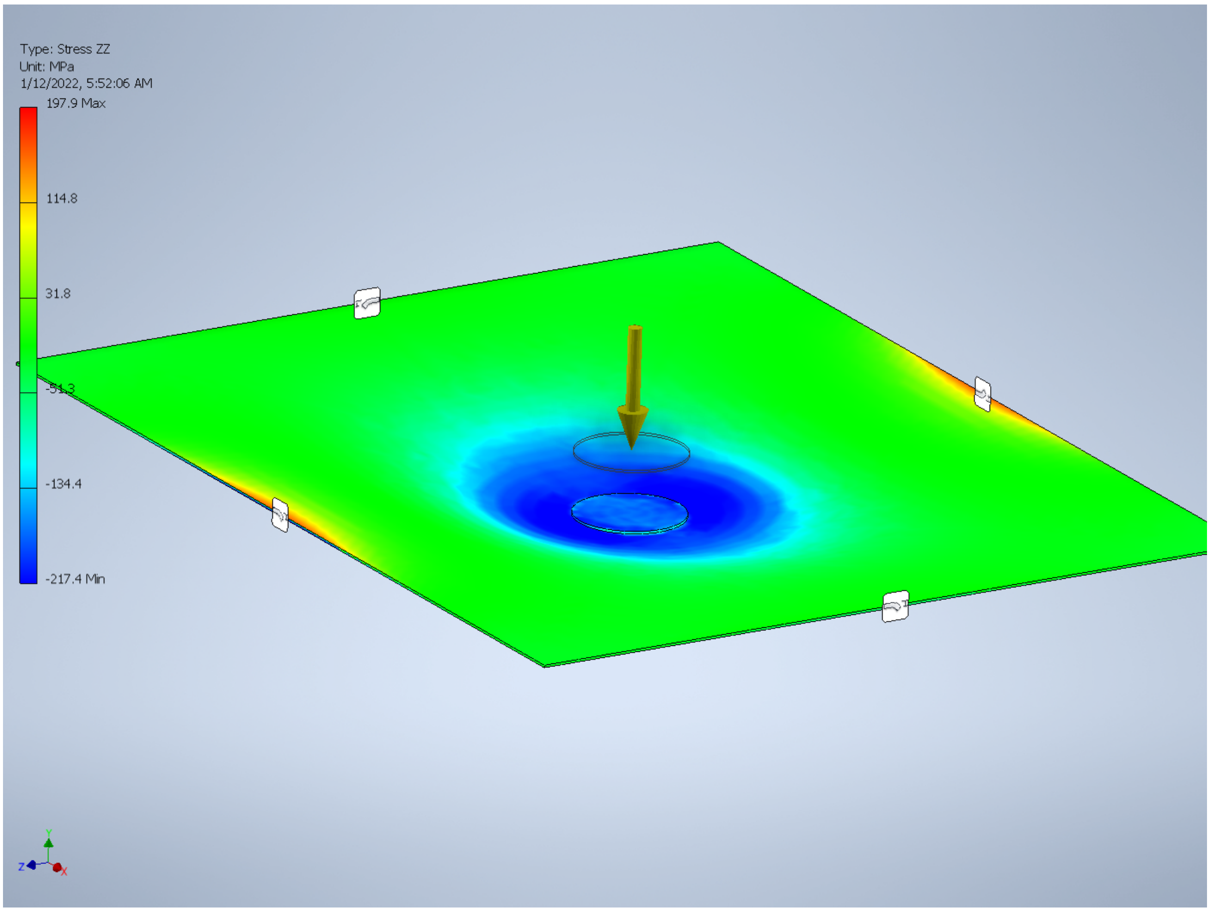


Fig. 55

The situation changes when a 3.73mm(3 layers) hull is used. The maximum stress is greatly reduced to only 74MPa, which the hull would be able to bear although it would still not be recommended.

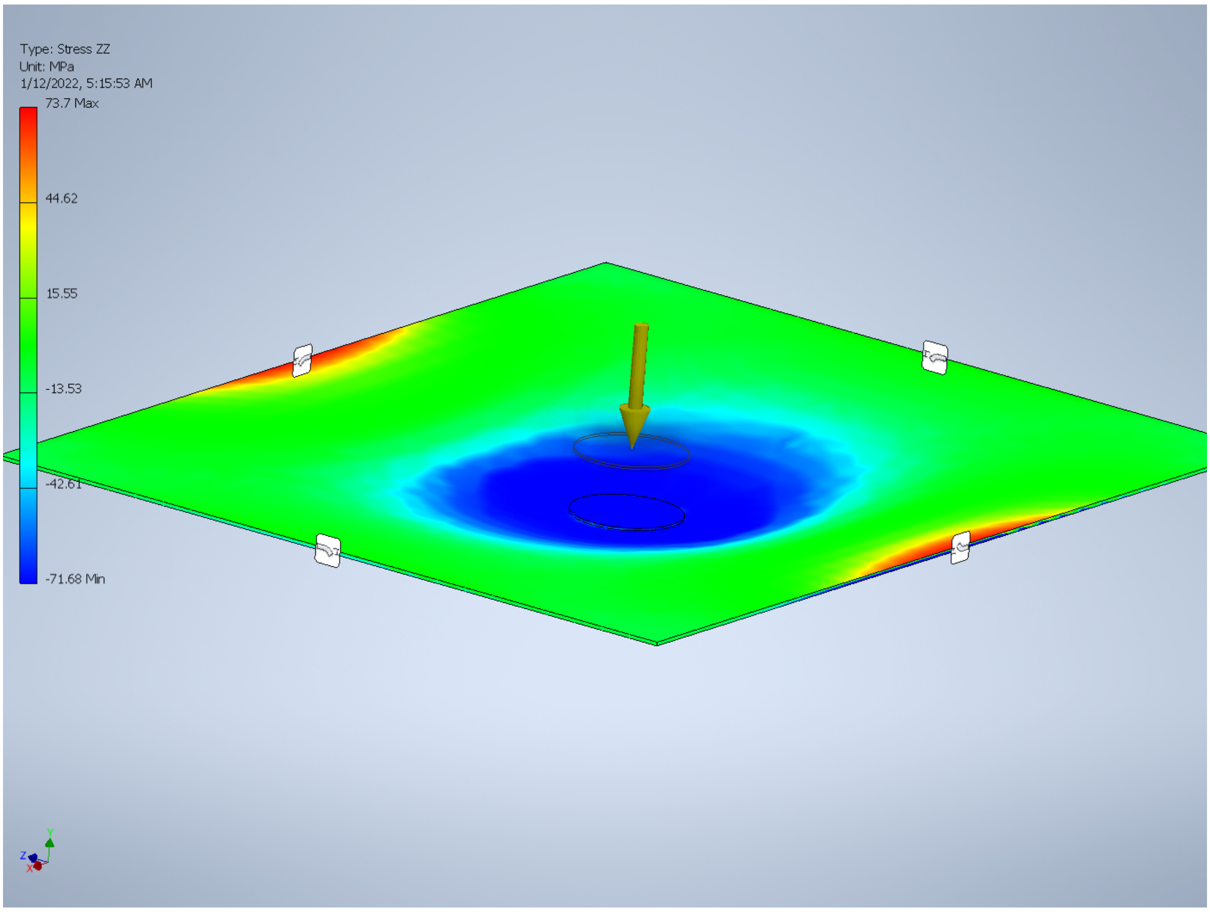


Fig. 56

Person on Solar Panel

It is likely that at some point in the boat's life people will step on the solar panel platforms. For this situation, the weight of two adults, each 200kg(total 400kg), is added to the portions on which the solar panels exert their force. Due to complexities faced with FEM, the constraint selected was the entirety of the bottom of the boat that would normally be in contact with water.
This simulation gave a maximum of 5MPa, well within the predetermined safe limits.

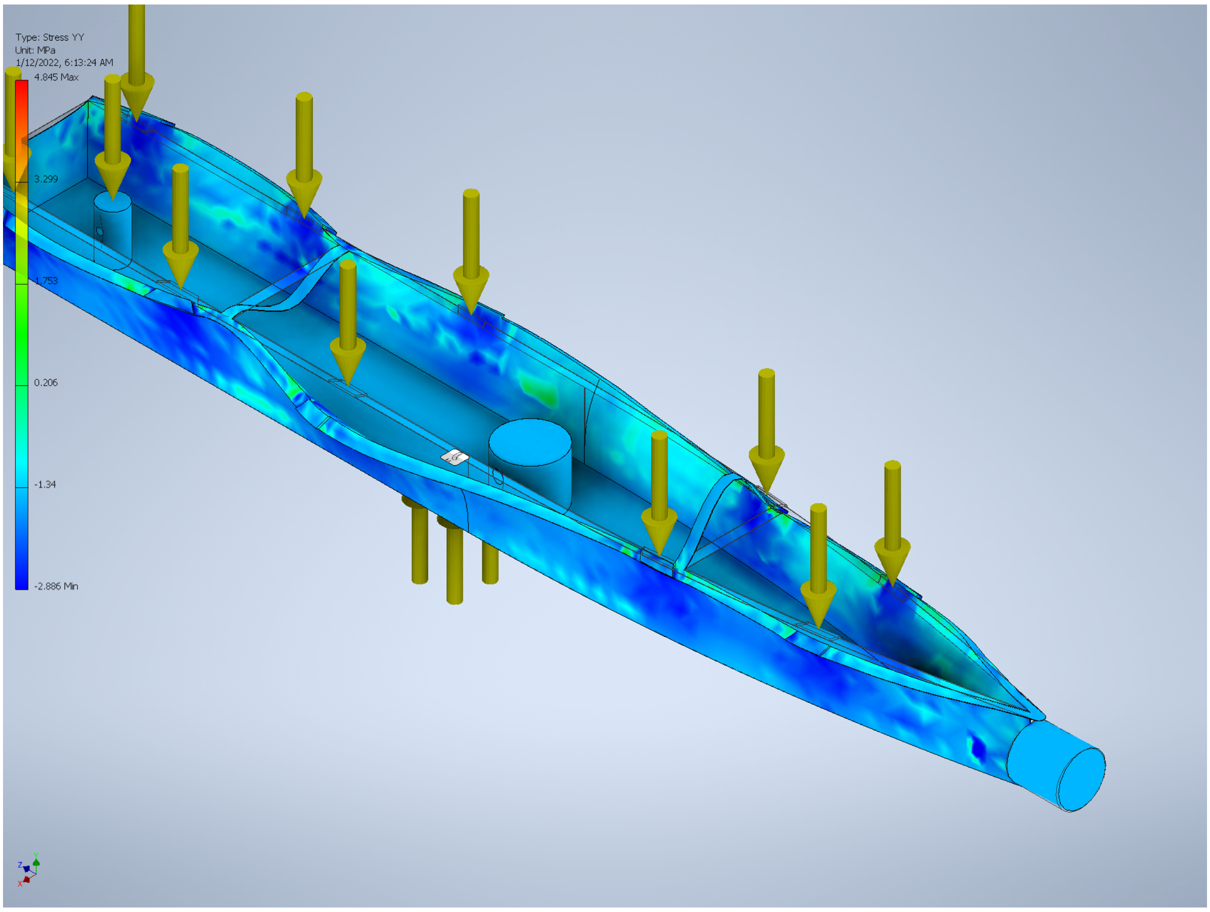


Fig 57

5 - Discussion

This chapter will conclude the thesis by summarising key research findings in relation to the research aims and questions, discussing their value and contribution. It will also review the limitations faced and propose opportunities for future research.

5.1 - Limitations

Experiment sample creation was imperfect. This was due to 2 things, 1 being lack of experience and the other is not having access to high accuracy measures of production. This meant samples were created in the simplest way possible, cutting required fabric and adequately coating them in resin on a tray or whatever mould respective to the sample.
The effect of this was apparent in how differently the two samples of the same kind would react to applied forces in terms of deformation and amount of resistance provided.
Samples were also left to cure in a non vacuum environment on top of indoor radiators. This resulted in increased cure times extending to 3 days.
The current iteration of Sealander doesn't have much documented information in terms of material composition. It is known that an excessive amount of Flax Fibre was used but not exactly how much. This information could have been helpful in the initial phases when getting an overview of the current situation. Creating 3D models would have also been facilitated with this knowledge as the exact value for thickness would not have to just be estimated.
For the most accurate final result, more time would have always been a benefit. Things like creating more experiment samples, refining calculations and applying more simulations could have all been possible to yield a superior result had there been more time. The research can reach much further grounds of complexity but given the limitation the current results were agreed and settled upon. Additionally, I was unable to dedicate my time entirely to the research as I work a job for sustenance which consumes a significant portion of my time.

5.2 - Recommendations

Were the entire research to be either extended or replicated something highly suggested would be creation of sample moulds. This can be done using high quality polystyrene and to prevent resin from fuding with mould a layer of pliable plastic be placed in between additional to the standard procedural wax coat. This would result in much more consistent and reliable results from experiments. The creation of moulds would be a simple process and yield notable benefits, also it would be an inexpensive addition.
Having 3 samples per type rather than 2 would also give more confidence in results.
Perhaps the most influential and interesting addition one could make to the research is use of topology optimization. Topology optimization is a tool of 3d models and simulation. The way it works is very similar to the FEM analysis executed in this research. But rather than just giving the total stress distribution, it excludes the most irrelevant sections of material giving a final render as seen below:

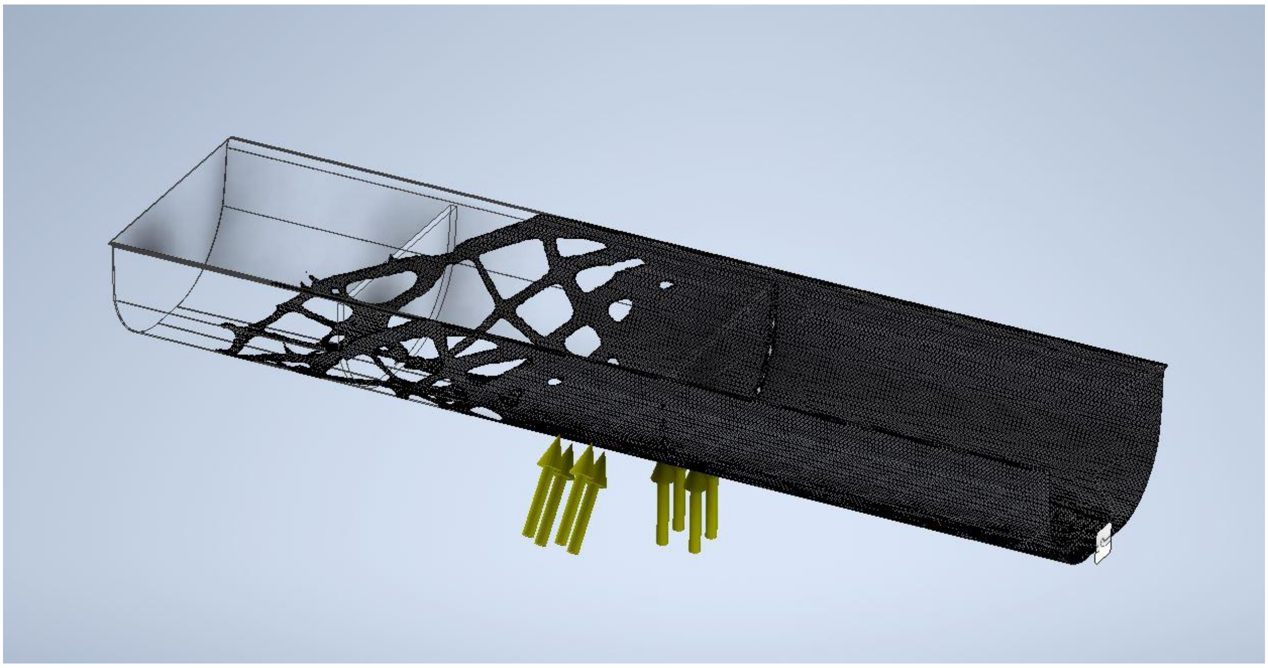


Fig. 58

This render can then be taken and considered as the structural skeleton of the, bearing all the load transferred to it naturally. The rest of the hull can then potentially be manufactured with less even material than currently proposed, though this would have to be tested and proven first. This would require extensive plotting of fibre orientation that would consume more time than was currently available but was interesting enough to be dabbled in a bit.
The use of helicoid fibre layering could also be used to a reasonable limit in the case of multi directional force.

Given there are electronics in the hull of sealander, it would be advisable to use some sort of thermal protection in case of general electronic heating or even electric failure from shorting for example. Flax fibre begins to discolour at 120C which is the first step of failure, not difficult to reach in a worst case scenario. Having the boat on fire is already bad, even worse would be on fire and sinking.
Another point of interest is that during experimentation there was a consistent trend of the samples breaking due to maximum tensile capacity being reached. Perhaps doing more experiments each time using less resin until there is a more equal balance between tensile and compressive capacity, the efficiency would be improved even further. Currently the focus was on the actual linen used which was helpful indeed but other components would bring great benefit to the material efficiency of Sealander.

5.3 - Conclusion

Over the course of the research, there were minor changes that occurred relative to the initial plan but I am proud that in the end, all pieces fell into place as intended. The product was delivered with strong recommendations for the next steps.
In construction of Sealander 3, the team will have a choice of two options when it comes to the construction of the hull. With that, they will also have all stress analysis reports which allow them to understand and justify the choices they make.
A rundown of the key findings in this research includes the following:

- Flax Fibre composite material has a maximum tensile stress capacity of ~MPa142.8. Compressive capacity is dependent on the resin used and in my recommendation should be explored by those who will carry on the torch.
- The boat hull is well capable of carrying its loads even through critical situations at 2.5mm, perhaps even 1.25, with a good skeletal structure. The biggest limitation is impact force, with a thickness of 1.25mm(1 layer), the boat would be significantly lighter but risks getting damaged at even slow speed collisions with hard surfaces. Once again something which can be discussed with the future teams and easily testable given the foundation laid in this research.
- Cyclic load of Composite materials exceeds that of metals due to the differences in grain structure. Metal has an inescapable trait of imperfections in grain structure which result in more frequent crack propagation. Composites aren't perfect, but the structure of the resin once cured does not allow cracks to propagate as they do in metals. The topic is however ever in discussion and very relative to the different mixtures in use.

Looking at the main research question and its accompanying subquestions, lets see how the research has brought us to answering them.

"How to create the lightest boat hull possible using flax fibre?"

From what we have learned, we know what methods, materials we need to use in order to create the lightest boat hull by the limitations of Flax Fibre.

What is the ideal fibre orientation?

The boat faces plenty of dynamic forces, but the most critical conditions generally affect the boat in 2 directions, along its axis and across it, meaning that a plain weave fabric in alignment with the boat will suit the function best. In the application of a single layer hull, however, the skeletal structure will likely need more complexly aligned fibres. A study for the future.

What is the ideal hull thickness?

There are two proposed thicknesses, 2.5&3.75mm, the client will decide which of the two they opt for when construction comes in, they are both strong choices. There is an exception for the cockpit area where thickness is suggested to be 7.5mm as that area is at risk of experiencing high impact situations.

What should the balance between strength vs weight be?

As explained in the previous answer, that will have to be decided by the clients at project inception. What is important however is that the hull is able to withstand all critical conditions, no strength was compromised there.

And with that we can conclude the research was successfully carried out.

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Appendix

Videos of experiments:

https://www.youtube.com/watch?v=4Oj-PQw0ohk

FEM analysis reports of sealander:

https://www.dropbox.com/sh/rsmy9slq730lfqq/AABG1-AonCGAXbgdmzHtRycea?dl=0

FEM analysis reports of experiments:

https://www.dropbox.com/sh/q59bhvc0zihi9dr/AAC4cb9Psq5VXZdg6aIVFxJea?dl=0

All contents of appendix can be accessed on line or be found in accompanying folder

A special thanks to

W. Haak

M. Gatto

G. Scuderi

A. Repko

R. Karl

W. Penalver

For guidance and help provided in the making of this thesis and all the steps leading up to it, despite these tumultuous times we currently face.