Bachelor's thesis

Zoran Gavric
Vegard Leistad

Investigation of flax fibre in cross country ski structure

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og byggteknikk

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Sammendrag:
Hvordan lage bærekraftige ski? Nedbrytbar biobasert epoxy, PMMA og petroleumsbasert epoxy ble testet med linfiber for å se om dette kunne erstatte dagens glassfiberarmerte petroleumsbasert epoxy i skiproduksjon hos Madshus. Prøvestykkene ble testet i trepunktsbøying og strekkprøvetesting. Videre ble en livsløpseffektanalyse gjennomført for å tydeliggjøre miljøinngrep for et par ski, og for å kunne redegjøre for hvor stor miljøbesparelsen er ved å endre fibertype. Andre komponenter av skistrukturen ble også undersøkt for deres miljøinngrep ved hjelp av livsløpseffektvurdering.

Livssyklusanalysens resultater viste en marginal gevinst av å gå over til linfiber fra glassfiber, samt at det største miljøinngrepet ligger i petroleumsbasert epoxy. PMMA matrix ble vurdert som en god erstatning for petroleumsbasert epoxy. Glassfiberarmert petroleumsbasert epoxy hadde bedre mekaniske egenskaper på både trepunktsbøying og strekkprøvetesting, enn linfiberarmerte kompositter med biobasert epoxy, PMMA og petroleumsbasert epoxy matrix. Naturfiber produsert ved konvensjonelt landbruk ble ikke funnet egnet som erstatning for glassfiber i skistrukturen.

Stikkord:

Kompositt
Naturfiber
Glassfiber
LCIA

Zoran Gavric

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Abstract

The thesis explores the possibility of replacing petroleum-based composite materials with recyclable and potentially more sustainable materials. Synthetic fibers were compared to natural fiber, where flax fiber may be intendent to replace fiberglass in ski production by focusing on the mechanical properties of flax fiber. How competitive is flax fiber compared to fiberglass?

The use of petroleum-based resin in the industry is widespread. Therefore, properties of the various recyclable resin products are examined to enable recycling to be more efficient and less energy intensive, without significantly affecting the mechanical properties of the skis. By analyzing the life cycle and environmental impact of the composite materials, it is possible to determine what combination of materials gives the least environmental impact and compare this with the mechanical properties.

The thesis is a bachelor's thesis written by students at mechanical engineering, Polymer and Composite line at NTNU at Gjøvik. Production and testing of composite have been carried out at the ASEM lab at the university. We extend our gratitude to the dedicated supervisors Sotirios Grammatikos and Angela Daniela La Rosa, as well as Julie Viollet for contributing to the LCA, and Madshus for providing materials and data about the ski structure.

Forord

Oppgaven undersøker muligheten å erstatte petroleumsbaserte komposittmaterialer med resirkulerbare og mulig mer bærekraftige materialer. Syntetiske fiber ble sammenliknet med naturfiber, der linfiber skal prøve å erstatte glassfiber i skiproduksjonen ved å sette søkelys på de mekaniske egenskapene til linfiber. Hvor konkurransedyktig er linfiber i forhold til glassfiber?

Bruk av petroleumsbasert resin i industrien er utbredt. Derfor undersøkes egenskaper til de forskjellige resirkulerbare resin produktene for å muliggjøre resirkulering mer effektiv og mindre energikrevende, uten at dette påvirker mekaniske egenskapene til skiene nevneverdig. Ved å analysere livsløpet og miljøpåvirkning til komposittmaterialene kan man finne ut hvilke material kombinasjoner som gir minst miljøpåvirkning og sammenligne dette med de mekaniske egenskapene.

Oppgaven er en bacheloroppgave skrevet av studenter ved maskiningeniør Plast og Kompositt linjen ved NTNU på Gjøvik. Produksjon og testing av kompositt er gjennomført på ASEM lab ved universitetet. Vi retter en stor takk til engasjerte veiledere Sotirios Grammatikos og Angela Daniela La Rosa, samt Julie Viollet for medvirkning til LCIA/LCCA analyse.

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Term	Explanation
FFRP	Flax fibre reinforced polymer
GFRP	Glass fibre reinforced polymer
RCF	Recycled carbon fibre
Gauge length	Length of measured area exposed for displacement
Normalization for mechanical properties	A mechanical property divided by the volume fraction.
Large deflection	Deflections larger than 0,1 times the span length
Chord modulus	Slope of a line drawn between any two specified points on the stress-strain curve

1 Introduction

UNs 2019 progress for the twelfth goal for sustainability states that “ Urgent action is needed to ensure that current material needs do not lead to the over extraction of resources or to the degradation of environmental resources, and should include policies that improve resource efficiency, reduce waste and mainstream sustainability practices across all sectors of the economy.” (United Nations, 2019). Madshus has shown interest in this transformation and have desired for their ski structure to be evaluated for optimization.

The use of sustainable and environmentally friendly materials in industries is enlarged. Since the 1960 the use of carbon fibre and glass fibre has increased rapidly (Matthews and Rawlings, 1999, p.1) and has been a major part of getting products with excellent mechanical properties, lighter and widespread. The production of the materials and the end of life has a great concern over the past years where non-biodegradable petrochemical's products are widely used.

Increased use of natural fibre in composites may be a possibility for solving problems regarding non-renewability. Natural fibers have a long history of serving in our existence, from approximately the last 7000 years. Fibers are mostly produced from plants and animals, with commonly used fibers today like flax, jute, cotton, silk, wool and hemp.

The word environmentally friendly is large and vague. To get a proper understanding of a products impact on the globe, several methods have been developed. One of these is the Life cycle assessment (LCA). Life cycle assessment (LCA) is defined by the ISO 14040-14044:2006 standards and is a process to analyze impacts of materials and products on the environment over the whole life cycle period, from cradle to grave. It can assist a company with improving the environmental performance, design and marketing. (Standard Norge, 2006).

A Life Cycle Impact Assessment (LCIA) were used to clarify the environmental impact of a pair of Endurace 202 skis from raw material extraction to the manufacturing process, also known as a from cradle to gate analysis. Natural fibre, recycled carbon fibre and glass fibre were compared to get a better understanding of the impacts of potential new fibers in ski production. A polymethyl methacrylate matrix (PMMA) was also investigated for today’s ski structure.

Mechanical properties of unidirectional glass fibre were compared with natural fibre flax to see the possibilities of substituting todays unrecyclable and non-renewable materials with renewable and less environmental impact materials. The mechanical properties for the flax fibre reinforced composite (bio-based epoxy, PMMA and petroleum-based epoxy) were tested by tensile and flexural tests and compared with glass fibre reinforced petroleum-based epoxy.

2 Method

2.1 Materials

Ten types of laminates were produced by different manufacturing methods shown in *Table 1*. FLAXDRY UD 150 from EcoThecnilin was manufactured together with Polar Bear (Recyclamine) bio-based epoxy system from R*consept, SP106 petroleum-based epoxy from Gurit and the liquid thermoplastic Elium® 188XO from Arkema, while glass fibre tape from Madshus were manufactured with Gurit SP106 petroleum-based epoxy. For the Polar Bear bio-based epoxy system, Recyclamine® R101 curing agent was used (making the epoxy system degradable under acetic acid treatment), benzyl peroxide as initiator for Elium® 188XO and Gurit Prime slow hardener for the Gurit 106 SP.

Table 1. Laminates made for testing.

Fibre	Matrix	Mixture ratio of matrix	Manufacturing method	Layers	
				300x250	150x150
Flax	Polar Bear (Recyclamine)	22:100	Hand lay up	4	6
Flax	Gurit SP106	18:100	Hand lay up	4	6
Flax	Gurit SP106	18:100	Vacuum infusion	4	6
Flax	Elium® 188 XO	3:100	Vacuum infusion	4	6
Glass	Gurit SP106	18:100	Vacuum infusion	2	3

The Recyclamine epoxy system exhibited high viscosity which made the manufacturing difficult with vacuum infusion, hand layup was preferred as manufacturing method for this laminate. More visible air bubbles could be observed for the Recyclamine bio-based epoxy system than the Gurit SP 106 petroleum-based epoxy system during production. No clear difference in air bubbles could be seen in comparison of the Gurit SP106 epoxy system and the Elium® 188 XO system.

2.2 Manufacturing

2.2.1 Production

Two different sizes were made for each type of laminate, one with sizes of 150x150 mm^2 and one with 300x250 mm^2 *Figure 1*. The 150x150 laminates were manufactured with 6 layers for unidirectional flax fibre and 3 layers of unidirectional glass fibre tape. For the 300x250 laminates, 2 layers of unidirectional glass fibre tape and 4 layers of unidirectional flax fibre were used, also shown in *Table 1*. To avoid moisture, the Flax fibre was preheated at 150 degrees centigrade for 15 minutes before production of the laminates. For the cutting a Husqvarna TS 60 water cooled saw was used with a 2 mm thick diamond blade. Due to the hydrophilic properties of natural fibre, flax composites were dry cut and glass fibre were wet cut.

Figure 1. Flax fibre composite

2.2.2 Hand lay-up process

The flax fibre and Gurit SP 106 epoxy composite were produced on glass plate. Waxing of glass plate were implemented to ensures easier removal of cured laminate. Impregnation of the fibre layers were performed with a roller. The whole laminate was covered with bleeder/breather to ensure equal distribution of resin. An electric vacuum pump was used to evacuate air under a plastic bag in 15 minutes. After the 15 minutes, the vacuum intake was closed and cured for 24 hours. The finished laminate was prepared by cutting it into test samples with a saw and post curing. Tensile test samples were cut to 250mm length and 15mm width, while flexural samples were cut to 100mm length and 15mm width, respectively. The same procedure was implemented for the flax fibre with Recyclamine resin. Post curing of laminates were performed as described from the manufacturer of the resin, 3 hours at 100℃ for Recyclamine and 5 hours at 80 ℃ for Gurit SP 106.

2.2.3 Vacuum infusion

Composites with Elium® XO 188 matrix and some of the Gurit SP106 epoxy system were produced with vacuum infusion. The setup of the vacuum infusion is shown in *Figure 2*. Breather/bleeder (mesh) were put over the laminate plus 20 mm of each side and 15 mm on each side to secure proper wetting of the whole laminate. A layer of peel ply was placed in between the breather/bleeder and fibers to ensure easier removal of laminate from breather/bleeder layer.

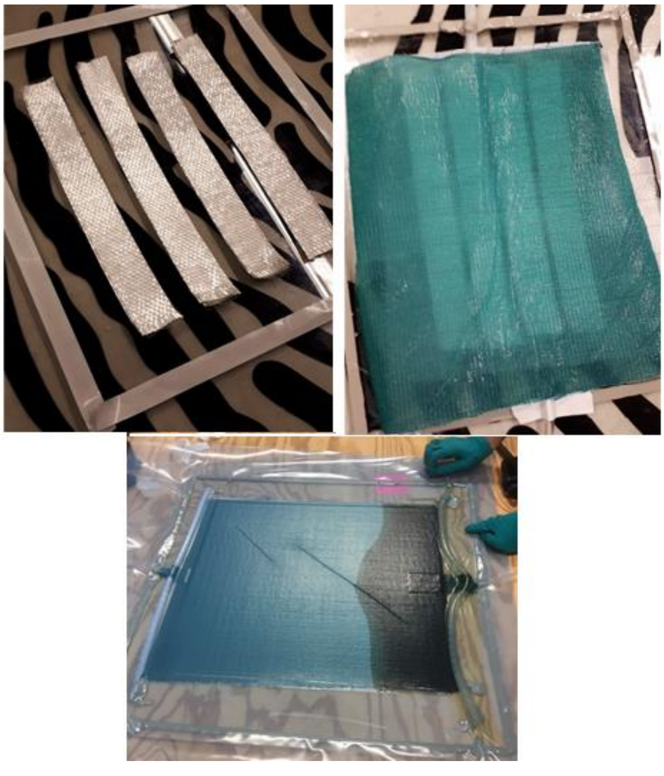

Figure 2. Production steps of vacuum infusion.

The viscosity of the Elium® XO 188 was lower than for the Gurit SP106 epoxy system. Flow restrictions was needed to secure proper wetting. Therefore, the flow speed was paused for 2 minutes for every 100 mm for the big 300x250 laminate, and 2 minutes for every 50 mm for the 150x150 laminate with absolute pressure of 0.50 bar during infusion of resin. The benzyl peroxide went through a strainer before it was mixed with the Elium® XO 188. To avoid agglomerations, the resin mixture was left to rest for 5 minutes for proper dissolving of the benzyl peroxide. Post curing of the Elium® XO 188 laminates was performed at 24 h on 60℃, while the Gurit SP 106 epoxy laminates post curing was performed at 80℃ for 5 hours.

2.3 Testing

The flexural tests were carried out at an Instron 9963 test machine, with a 10 kN load cell. ISO 14125 was followed to ensure valid results, with a speed of the test at 2 mm/min. 5 mm radius support fixtures and upper load member. Dimensions of the specimens were 15 mm wide and 100 mm long, with a support span of 80 mm. Large deflections were used to calculate maximum flexural stress after annex B equation (1). All stress-stress strain curves are calculated with equations (1) and (2), according the ISO 14125 standard (Standard Norge, 1998). Flexural modulus is calculated from equation (3).

$$\sigma_f = \frac{3FL}{2bh^2}\left(1+6\left(\frac{s}{L}\right)^2-3\left(\frac{sh}{L^2}\right)\right) \tag{1}$$

$$\varepsilon = \frac{h}{L}\left(6,00\frac{s}{L}-24,37\left(\frac{s}{L}\right)^3+62,17\left(\frac{s}{L}\right)^5\right) \tag{2}$$

$$E_f = \frac{L^3}{4bh^3}\left(\frac{\Delta F}{\Delta s}\right) \tag{3}$$

The tensile testing *Figure 7* followed the ISO 527-5 standard (Standard Norge, 2009). A test speed of 2 mm/min were applied. The crosshead was used to measure the load/displacement and a gauge length was set to the grip to grip separation. At the start of the test the grip to grip separation was 136 mm and this is used as gauge length to calculate the engineering young’s modulus. A preload of 50 N was set to follow the ISO standard. All stress/strain curves exhibited a non-linear region at the start. Therefore, the modulus could not be calculated between 0,05 % and 0,25 % as stated in the standard. Equation (4) is used for calculation of the chord modulus, from the closest measurements to 0,75 % and 0,95 % strain for the flax fibre tensile specimens, and closest measurements to 1,5 % and 1,75 % strain for the glass fibre tensile specimens.

$$E = \frac{\sigma'' - \sigma'}{\varepsilon'' - \varepsilon'} \tag{4}$$

All specimens were tested inn 22˚C, for flax fibre 30% humidity and for glass fibre 50% humidity.

2.4 Life Cycle Assessment (LCA)

2.4.1 The ski structures

Madshus' ski structures are made up of a sandwich structure of polyurethane core, glass fibre roving, UHMWPE, light polyester foam, glass fibre sleeve, polyester surfacing veil and plexiglass top sheet, with epoxy as binder.

The polyurethane core is the base of the skis. Over and under the core comes glass fibre layers of roving's and unidirectional tape. Light polyester foam is used to transport the epoxy resin during molding. The whole structure is placed in a glass fibre sleeve. A polyester surfacing veil and plexiglass top sheet are placed on the top, and a polyethylene gliding surface on the bottom. High pressures and temperatures are used during the resin transfer molding process with epoxy.

2.4.2 Goal/scope

The goal of this LCA study was to compare the environmental impact of the current sandwich structure used by Madshus in their skis with renewable/recyclable sandwich structure materials. Life cycle assessment (LCA) following the ISO 14044:2006 and 14040:2006 standards and is divided inn four phases: goal/scope, inventory analysis, impact assessment and interpretation. Madshus produces skis in carbon and glass fibre with petroleum-based epoxy, and we have investigated the glass fibre structure. A cradle to gate method were used, calculating the impacts from the raw material extraction to the processing of the materials. LCIA providing an overview over the different impact categories, which further can be divided into end point categories. The methods used were CML-IA baseline and Recipe endpoint. The Recipe endpoint method divides the impact into 18 midpoint categories leading into 3 end point categories. This indicates the damage on human health, eco systems and resources, while CML baseline is a midpoint method linking all stages of life cycle inventory via 11 impact categories: depletion of abiotic resources (minerals—kg Sb eq and fossil fuels—MJ), global warming (kg CO2 eq), ozone layer depletion (kg CFC-11 eq), human toxicity (kg 1,4-DB eq), freshwater aquatic ecotoxicity (kg 1,4-DB eq), marine ecotoxicity (kg 1,4-DB eq), terrestrial ecotoxicity (kg 1,4-DB eq), photochemical oxidation (kg C2H4 eq), acidification (kg SO2 eq), and eutrophication (kg PO4 eq). The Recipe method, midpoint and endpoint categories are shown in *Figure 3*. For this study, software SimaPro, version 8.0.5.13, produced by the Dutch company Pré Consultant, were used according ISO 14040 and ISO 14044. 2006. (Standard Norge, 2006). Impacts from the transport of the materials were neglected due to the procurement and production.

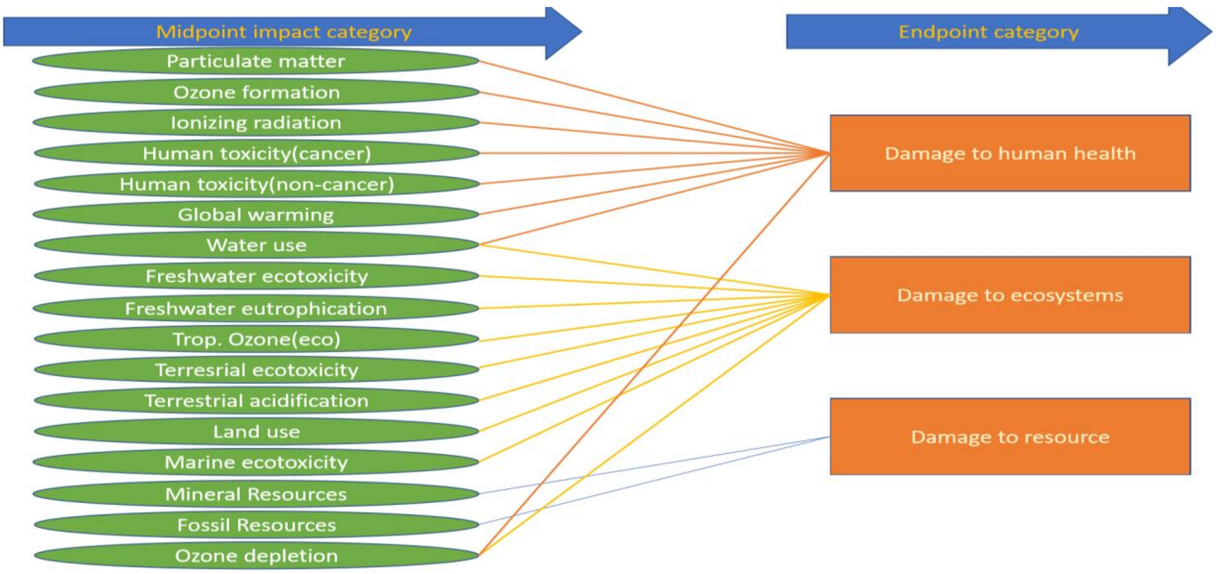

Figure 3. Overview of structure ReCiPe.

In aim to produce recyclable and renewable skis, the study will compare petroleum-based materials as flax fibre (natural) and recycled carbon fibre (recyclable) with glass fibre. Study will also investigate possibility of replacing petroleum-based epoxy with Recyclamine (bio-based) epoxy and Elium® matrix in Madshus skis production.

2.4.3 Inventory analysis

The functional unit was defined as one pair of skis. By assuming a pair of skis containing:

Table 2. List of materials provided by Madshus for the Endurace 202 ski

Material Input	Mass (grams)
Polyurethane Core	500
Glass Rovings	360
Ultra-high-molecular weight polyethylene (UHMWPE)	220
Light Polyester Foam	60
Non-woven Glass fibre	50
Plexiglass Top sheet	120
Epoxy (High Variation)	520
Total	1910

The chosen natural fibre in the SimaPro database was kenaf fibre as flax fibre is not a part of the SimaPro database and the two types of fibres have similar properties. The plexiglass top sheet for surface protection were approximated with PMMA, UHMWPE base material as high-density polyethylene and the light polyester foam as polyurethane flexible foam. Recycled carbon fibre was characterized as the precursor for carbon fibre, polyacrylonitrile (PAN) with avoided use of energy in production. Solvolysis with acetic acid was chosen as recycling method. The Recyclamine epoxy system is not available in the SimaPro database. Therefore, similar compounds were chosen, diethanolamine for Recyclamine® R101 hardener. While Polar Bear resin were characterized as bisphenol type epoxy resin, epoxidized pine oils, benzyl alcohol, and proprietary reactive epoxy diluents.

3 Results

3.1 Flexural testing

The flax fibre showed more inconsistencies in both the thickness and the width than the glass fibre. After the cutting, rough surfaces edges could be observed on the flax fibre. The inconsistencies of the surfaces edges and the flexural testing can be seen in *Figure 4*.

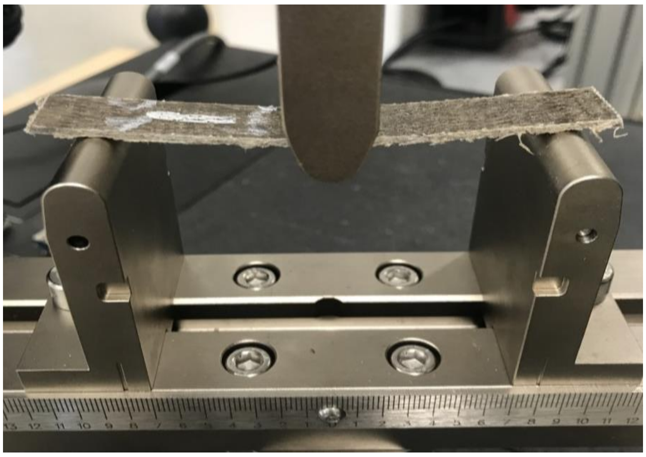

Figure 4. Flexural testing of flax fibre.

Table 3 and *Figure 5* shows the results from the bending tests with bars as standard deviation. Specimens made with vacuum infusion, could withstand higher flexural stresses, while the modulus was almost equal compared with the specimens made from the hand lay-up. With normalization of the results the vacuum infusion specimens would show both greater flexural modulus and strength than the specimens made with hand lay-up. A larger standard deviation for the hand lay-up specimens would be logical due to manufacturing difficulties, due to bending of fiber during applying the matrix and irregular stretching of the fibre. This applied especially for the Recyclamine matrix with higher viscosity than the petroleum-based epoxy resin. The flax Elium® composite and the petroleum-based epoxy laminate made with vacuum infusion exhibited almost similar flexural strength. For the flexural modulus between these two the petroleum-based epoxy from Gurit showed an increase in the modulus. The Recyclamine showed greater flexural strength, but less flexural modulus than the petroleum-based epoxy.

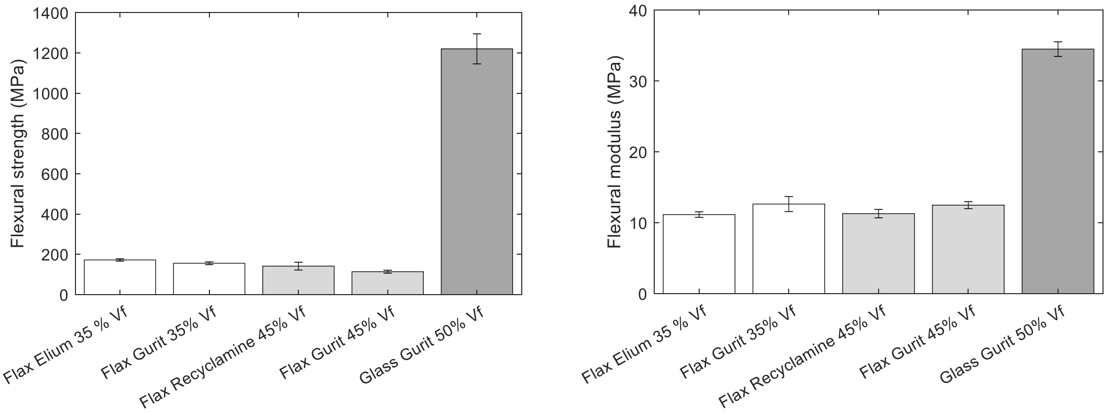

Figure 5. Histogram of flexural testing.

The stress-strain curve for the flexural test is shown in *Figure 6* (glass fibre and the flax fibre Gurit epoxy manufactured with vacuum infusion). The glass fibre observed a linear curve from start till break, ending with compressive failure for all specimens. The flax fibre observed a linear Hookean region at the start before going over to a nonlinear stress-strain behavior with progressive failure. Specimens of flax made with vacuum infusion exhibited mostly tensile failure at the bottom of the specimens, while the specimens made with hand lay-up had mostly compressive failures. Comparing the glass fibre with the flax fibre Gurit epoxy vacuum infusion, larger flexural strength and modulus of ~780% and ~270 % were observed, and for normalized values the glass fibre showed better flexural strength and modulus of ~510 % and ~175 %.

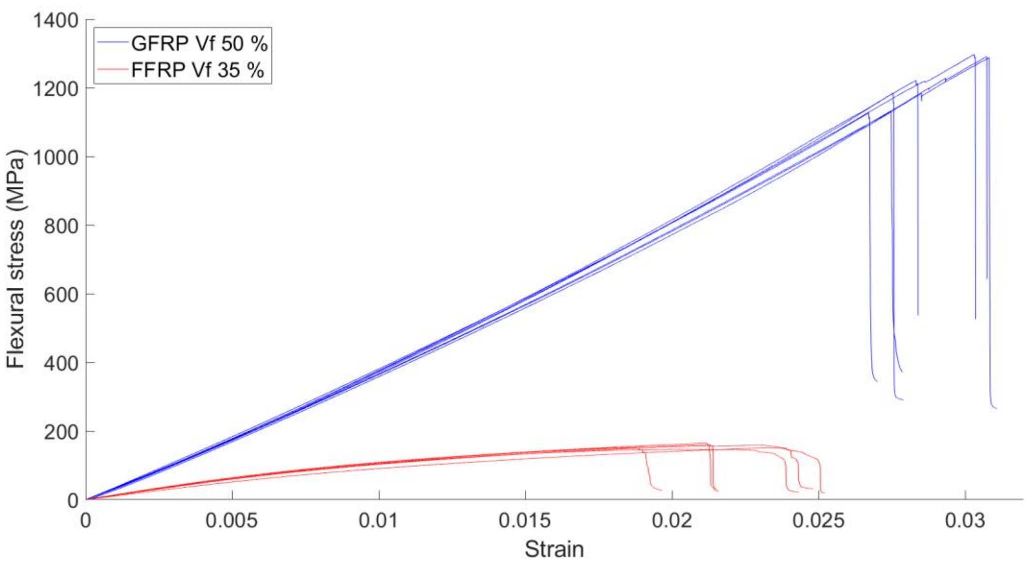

Figure 6. Flexural stress-strain curves of flax- and glass fibre.

Table 3. Properties of the flexural testing.

	Flexural stress (MPa)	Std. Stress	Flexural modulus (GPa)	Std. modulus	Vf. %	Avg. Thickness
Flax Elium® vacuum infusion	172.03	5.80	11.15	0.386	35	1.9
Flax epoxy vacuum infusion	155.52	6.70	12.64	1.058	35	2.0
Flax Recyclamine hand lay up	141.36	19.36	11.28	0.593	45	2.0
Flax epoxy hand lay up	113.57	7.17	12.49	0.494	45	2.0
Glass epoxy vacuum infusion	1220.06	74.63	34.50	1.032	50	2.3

3.2 Tensile testing

The flexural failure for the comparison between GFRP and FFRP showed that the flax fibre had more of a progressive failure, but for the tensile testing, the opposite happened. The GFRP showed a progressive failure starting around ~650 MPa shown in *Figure 10* (bars as standard deviation) and *Table 4,* while the FFRP had brittle failures. The failure modes for the FFRP was what the ASTM D3039 (ASTM International, 2017) defines as a lateral failure, this happening both in the middle of the specimens and close to the grips shown in *Figure* 8. A failure dominant of delamination along the edges and long splitting by the edges occurred mostly in the GFRP shown in *Figure 8*.

Figure 7 Tensile testing flax fibre

Table 4. Properties of tensile tests.

	Tensile stress (MPa)	Std. Stress	Young's-modulus (GPA)	Std. Modulus	Vf. %	Avg. Thickness
Flax Elium® vacuum infusion	192.49	9.40	5.42	0.329	30	1.4
Flax epoxy vacuum infusion	202.00	8.29	5.94	0.218	30	1.4
Flax Recyclamine hand lay up	180.12	22.15	7.41	0.999	45	1.2
Flax epoxy hand lay up	137.03	18.77	6.18	0.699	45	1.4
Glass epoxy vacuum infusion	652.66 842.27	55.63 102.52	14.92	0.700	50	1.6

The stress-strain curve comparing the glass fibre and flax fibre is shown in *Figure 9*. From around 650 MPa, it is possible to see the start of the progressive failure. The average absolute failure for the glass specimens were around ~850 MPa. It was observed at each peak some of the fibers started splitting. The Recyclamine epoxy showed better strength and modulus than the flax specimens made with petroleum-based epoxy. For the specimens made with vacuum infusion a small difference between in strength and modulus could found, but not significantly. Similar results for the tensile testing has previously been shown by (Chilali et al., 2016), where Elium® and petroleum-based epoxy were tested on a flax twill instead of unidirectional flax. Flax fibre shows some variation due to productions method. It is worth noticing the Recyclamine had a smaller thickness than the petroleum-based epoxy.

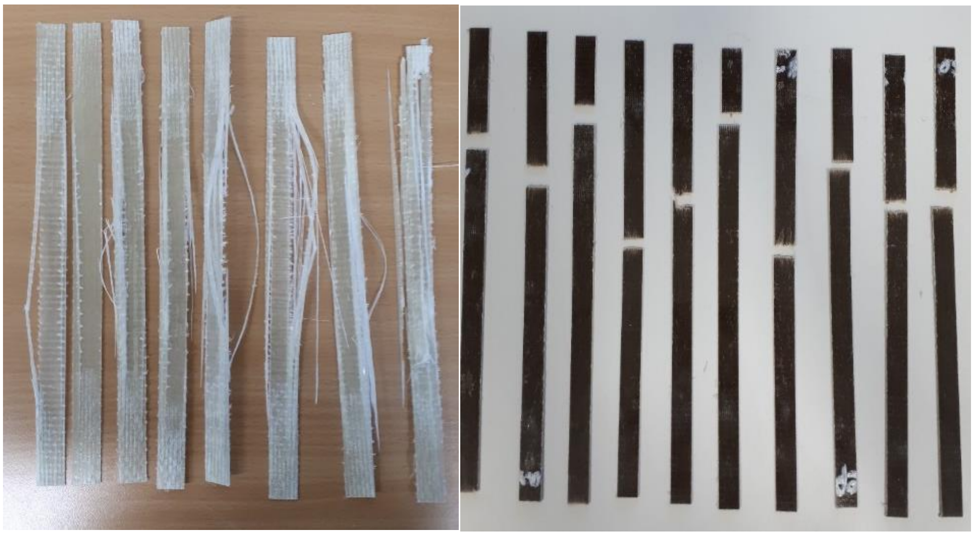

Figure 8. Failure of glass and flax fibre specimens.

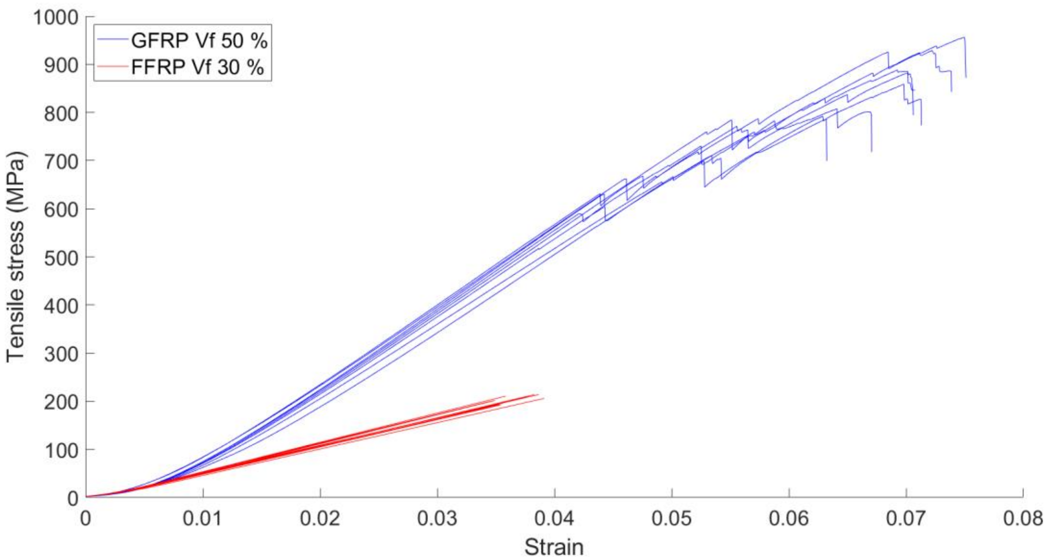

Figure 9. Stress-strain curve for the petroleum-based epoxy reinforced glass and flax fibre.

The tensile strength for all the flax specimens were larger than the flexural strength, which does not correspond to the general expected results. One reason for this may be defects around the surfaces during the production, which may have come from air voids or rough cutting edges.

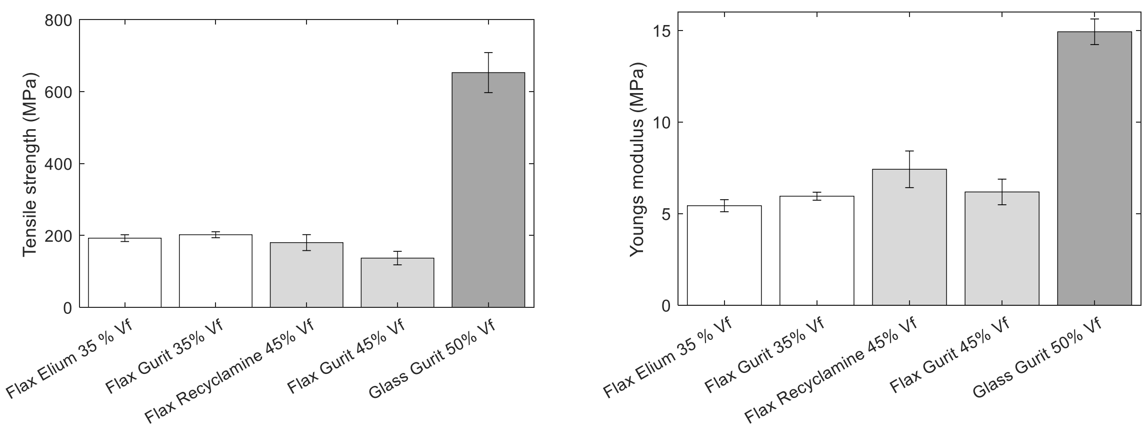

Figure 10. Histogram tensile testing.

Table 3 and *Table 4* shows the volume fractions, they are calculated out from the theoretical datasheets with assuming constant fibre and resin density from weight fraction shown in equation (5). Were the weight fraction is calculated from the numbers of layers, areal density of the fibre, actual weight and actual size of the laminate.

$$v_f = \frac{\rho_m w_f}{\rho_m w_f + \rho_f w_m} \quad (5)$$

3.3 LCA

3.3.1 Current ski impact

Figure 11 shows the impact of the different constituents of the ski, the light blue color is the impact of the epoxy resin and the red color is the impact of the plexiglass top sheet. Most of the impact categories are highly dependent on the epoxy resin, this is also the case for the Global warming potential where the impact is ~45 % of the whole global warming impact. Glass fibre (light green), shows most impact on ozone layer, human toxicity and marine aquatic ecotoxicity.

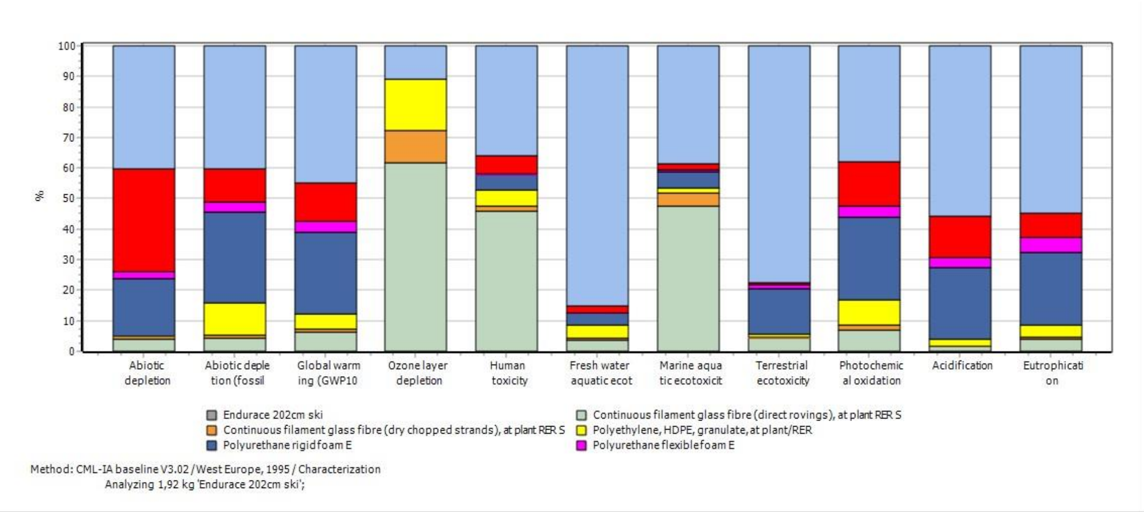

Figure 11. Percentage impact of the different constituents for current ski structure.

Generally, the trend is high impact by two of the constituents. Together the petroleum-based epoxy and polyurethane core have a total GWP impact of 70 % of the ski.

3.3.2 Fibre comparison

The flax fibre shows as expected an advantage over glass fibre under the GWP and ozone layer depletion categories, but shows disadvantages under the abiotic depletion, eutrophication, and fresh water ecotoxicity as well as human toxicity due to agriculture land use, *Figure* 12. Previous studies like La Rosa et.al showed that glass fibre generally have a higher impact compared with organic natural fibre (La Rosa et al., 2014), due to glass and glass fiber production depending mainly on the high electricity consumption.

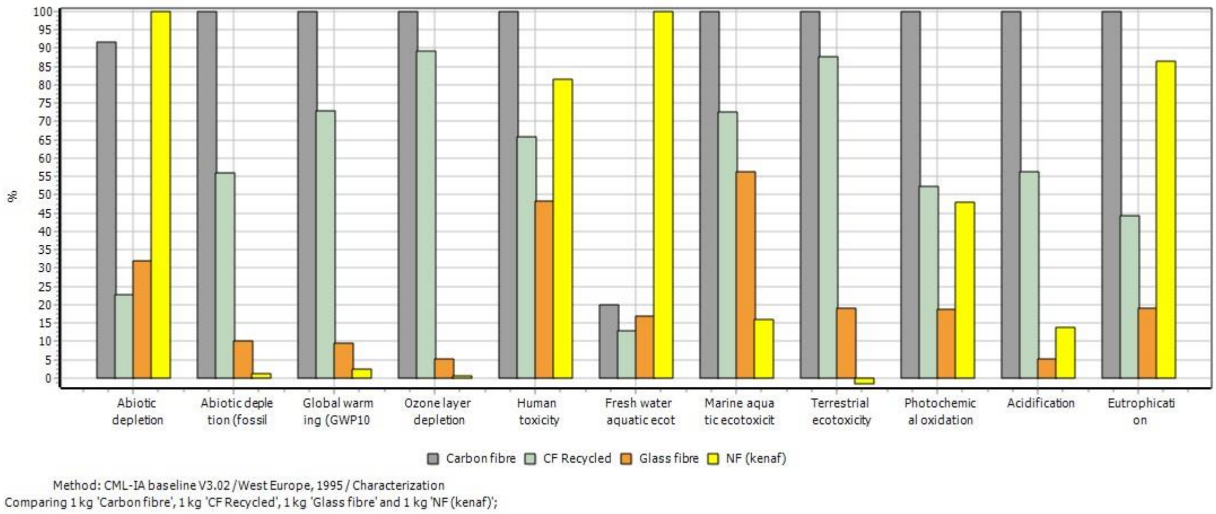

Figure 12. Comparison of 1 kg fibre.

The recycled carbon fibre shows more impact on the GWP and the ozone layer depletion. As expected, virgin carbon fibre have the most environmental impact in all categories except abiotic depletion and freshwater aquatic ecotoxic were natural fibre have highest score. In this LCA study, we assumed the recovered fibers are ready to use, any other impact is avoided, as fossil fuel depletion and electricity. The environmental impact of glass fiber is reasonably lower than carbon fibre (due to the fact that more electricity is required to produce Carbon fibres) and in some categories even comparable with natural fibre e.g:. impact on the global warming potential (GWP)).

3.3.3 Ski combinations

Four different ski combinations were investigated to find the optimal material combination, *Table 5*.

Table 5. Checked material combinations for the LCA.

Matrix	Unidirectional	Roving around core
Petroleumsbased	Natural fibre	Glass fibre sleeve
Elium® (PMMA)	Glass fibre	Glass fibre sleeve
Petroleumbased	Glass fibre	Glass fibre sleeve
Recyclamine	Glass fibre	Recycled carbon fibre

Figure 13 shows the comparison for the different ski combinations. As previous shown in *Figure 12*, the recycled carbon fibre have a large impact on the GWP, ozone layer depletion and abiotic depletion, while the impacts for the flax fibre shows impacts more towards acidification, fresh water aquatic toxicity and eutrophication. When comparing *Figure 12* and *Figure 13*, the differences are much closer for the whole ski structure. This is due to the other constituents of the ski, but especially the epoxy resin having a high impact comparing with the other constituents of the ski.

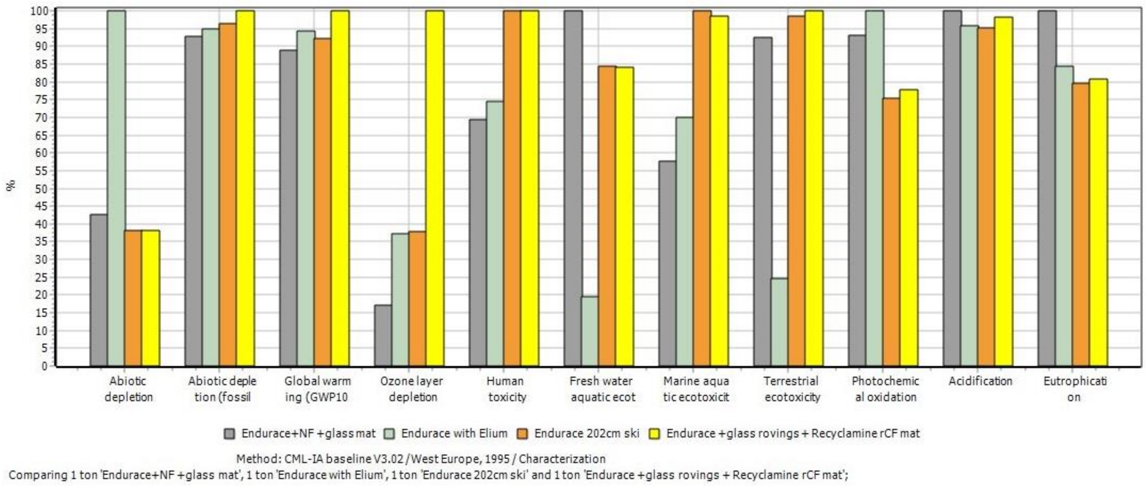

Figure 13. Comparison of the impact for the different ski combinations.

The ISO 14040:2006 standard states the normalization as “calculation of the magnitude of category indicator results relative to reference information” (Standard Norge, 2006). In other words, the normalization is a way of comparing the different impact categories by adjusting what will cause the most severe damages towards the environment, following political objectives for CML method. From the normalization from *Figure 14* the biggest impact is the marine aquatic ecotoxicity and the abiotic depletion, followed up by the GWP and acidification. The CML method shows that the impact on the marine aquatic ecotoxicity is 3 times more severe than the abiotic depletion and in some cases 12 times more severe than the global warming impact, were the todays ski structure and the recycled carbon fibre structure are having the highest impact on the mentioned categories.

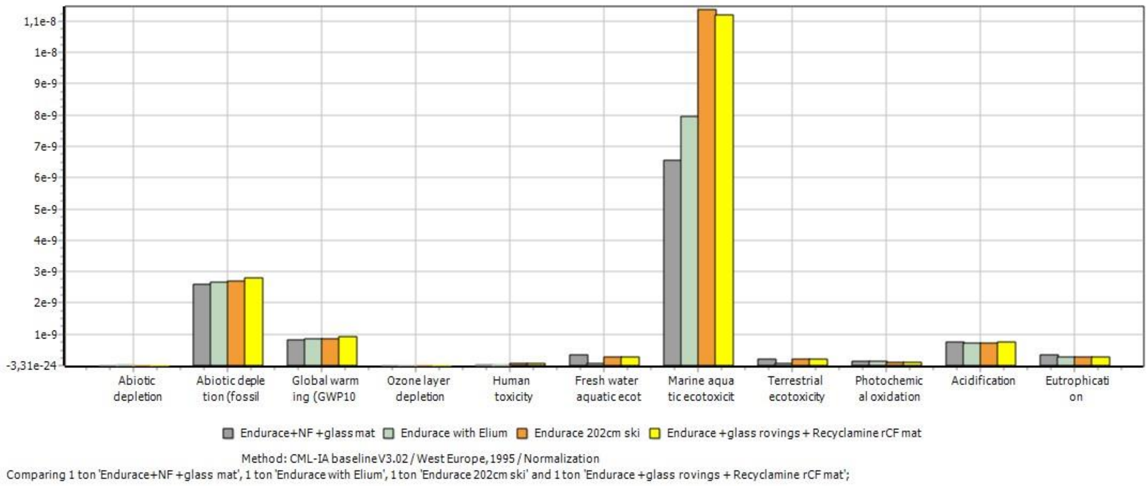

Figure 14. Normalization of the different ski combinations.

4 Discussion

4.1 Mechanical properties

The tensile specimens of the flax composite showed a greater strength than the flexural specimens, which does not correlate with the report of Goutianos (Goutianos et al., 2006) and Weibull theory of brittle materials stated by Wisnom (Wisnom, 1999). Rough surface edges may be the reason for this difference.

Bachmann et. al found that that recycled carbon fibre mats with a maximum length of 25 mm per fibre showed a flexural strength and modulus around 491.5 MPa and 22.795 GPa (Bachmann et al., 2018). Stoeffler found that the recycled carbon fibre they tested had a tensile modulus around ~17 GPa for the 20 % weight fraction and ~30.3 % for the recycled carbon fibre with 40 % weight fraction, for materials from prepreg and finished parts (Stoeffler et al., 2013).

The Recyclamine showed an increase in strength from the petroleum-based epoxy. In *Figure 15* the stress-strain curves for the flax fibre Recyclamine and petroleum-based epoxy is compared. A more brittle failure was observed for the Recyclamine epoxy than for the Gurit epoxy, who exhibited a more progressive failure.

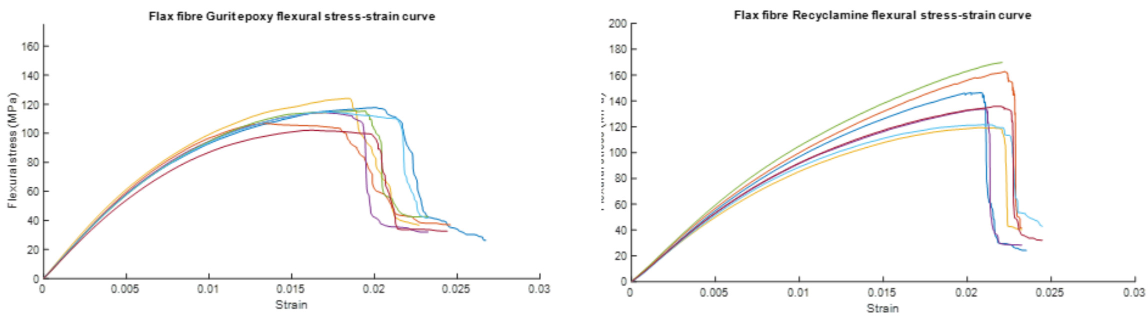

Figure 15. Stress-strain curve, flax fiber with hand lay-up method.

The Elium® and the Gurit epoxy showed similar behaviors, but the epoxy showed larger modulus for both flexural and tensile. The tensile strength of the Gurit epoxy was larger, while the Elium® could withstand a higher flexural stress. This may be due to Elium® having better fracture toughness. The tensile results correspond well with the report of Chilali et. al. (Chilali et al., 2016).

The method of measuring the tensile modulus may be inaccurate due to the use of crosshead and not strain gauges. A tensile machine with spring loaded grips probably led to a substantial decrease in the modulus and increase in the strain measurements. The goal for this thesis was to find a replacement material for the glass fibre, and the glass fibre has been tested in the same way as the flax fibre which lead to an increase of the reliability.

4.2 LCIA

In this LCIA study, the Endurace ski was separated and investigated. At the same time the study was focused on possibilities of replacing fibers as well as matrix to get environmental gain. Endurace is todays ski produced at the Madshus factory. Investigation of contents point out impact categories. As showed in *Figure 16*, most of the GWP impact are linked to epoxy used inn molding production, almost 50% of all impact. Polyurethane core impact is also significant and, with epoxy, representing over 50% of weight in Endurace skies.

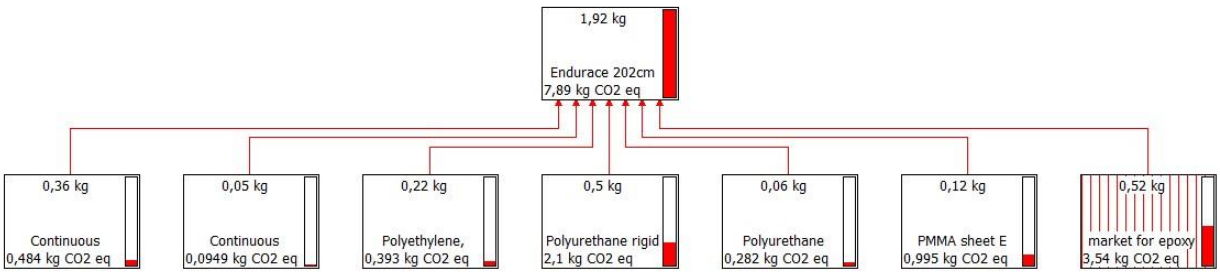

Figure 16. Endurace tree for global warming potential.

Figure 11 representing contents and percent amount for each impact categories. As it is possible to see, epoxy (light blue) has most environmental damage overall.

In the second part of the LCIA study we investigated replacing synthetic fibers with natural fibers and compared environmental damage. *Figure 12* confirms our suspicion. The gain of natural fibers is not so significant due to the use of fertilizers, pesticides and use of land. However, benefits of recycling and disposal are not considered.

Several ski combinations were compared. The Endurace 202cm ski generally have a high impact on most of the impact categories. Replacing petroleum-based epoxy as in Endurace 202cm ski with Elium® impacts like human toxicity, fresh water and marine aquatic ecotoxicity can be reduced. On the other hand, abiotic depletion and GWP is increased. Skies with natural fibers and glass fibre sleeve shows less impact in several categories like abiotic depletion, ozone layer depletion, compared with Endurace 202cm. Endurace with glass roving's, Recyclamine and recycled carbon fibre shows an increase on the impact categories, except marine aquatic ecotoxicity, *Figure 13*.

In *Figure 17*. the ReCiPe endpoint categories are shown. The damage of recycled carbon fibre is generally high on the all the endpoint categories, mostly due to the chosen recycling method. Witik et. al. showed for the pyrolysis process, the recycled carbon fibre can gain an positive effect on the impact categories compared with virgin carbon fibre, but not the glass fibre (Witik et al., 2013), corresponding with the results from the solvolysis process. The glass fibre scores second lowest or lowest on all three end point categories. As one should expect the glass fibre shows higher damage related to resources, while the natural fibre shows most damage towards ecosystem due to non-organic agriculture. Multiple causes can be the reason for this, but the pesticides and the use of fertilizers plays a major part. By choosing organic natural fibre, a benefit on the impact categories of acidifications and eutrophication is likely to happen. Some negative effects could also occur. Less crop per acers and more uncertainties regarding the crop production can be expected.

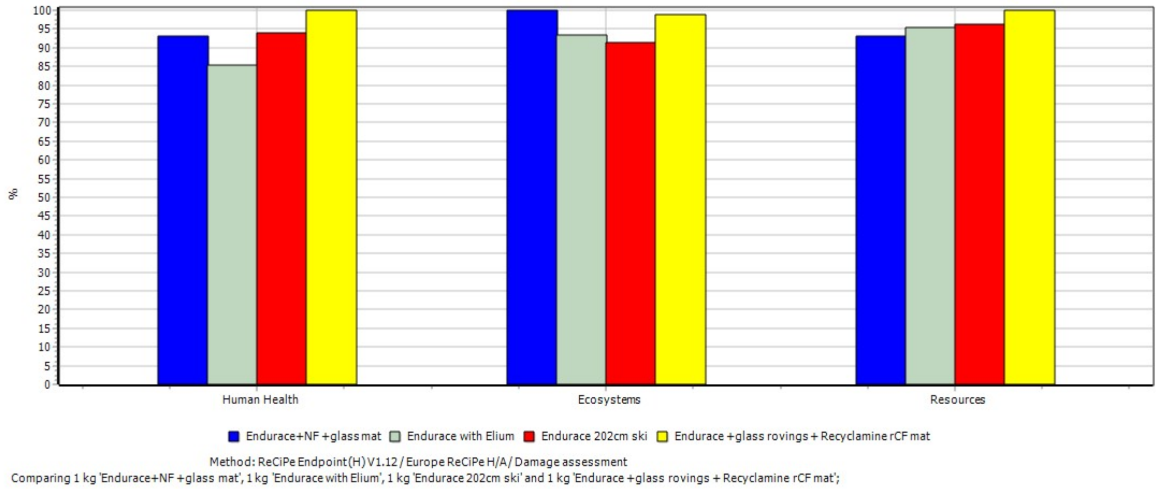

Figure 17. Impact on the endpoint categories/damage.

This study is a cradle to gate study and the end of life assessment is not included in the analysis. Probably the Elium® will show even better results in the LCA since it is a thermoplastic and can easier be reheated, recycled and reused. Recycling of glass fibre could also be a possibility, but with the recycling methods today and for instance the use of acetic acid treatment leading to high impacts, one can expect the environmental gain to be less beneficial.

5 Conclusion

From our testing we can conclude that glass fibre cannot be replaced with the flax fibre if mechanical properties are vital to Madshus skis. The flax fibre showed lower modulus's and strengths, while the gain on the impact categories was rather small. However, mechanical properties are highly depending on their natural origin, geographic area and which part of stem were used in production showed by (Coroller et al., 2013). Importance of origin need to be followed to find fibre with satisfying mechanical properties. Our investigation shows that natural fibre scores better on used resources but got a weaker score on the human toxicity and ecosystem than the glass fibre. The recycled carbon fibre appears not to be environmentally friendly as expected, mostly due energy consumption and methods during recycling. The best way to reduce the impact of today's ski structure would be to reduce the amount of epoxy used and use of ecofriendly core. The core is partially the reason for the large epoxy impact, and it absorbs a large amount of epoxy during the manufacturing process. If the core material were replaced with a lightweight material with equal environmental impact, but who absorbs less amount epoxy, this could lead to great economic and environmental benefit for the ski structure. From our work we cannot find a good reason to replace the glass fibre with natural fibre manufactured from conventional agriculture in the cross-country ski structure.

This LCIA is cradle to gate study, from raw materials to manufacturing. Our assumption was to point out productions and environmental impact of these. We have not investigated the whole life cycle of materials/products. In the end of life, recycling and disposal it may lead to another result. Even though the LCA is a great way to compare materials, the assumptions we do, can never be hundred percent correct.

Further research

It would be interesting to investigate on how the actual sandwich construction would work, both as pure flax laminates and hybrid. Water absorption testing would also have great interest for this project. Torsion stiffness and strength plays a substantial part of the cross-country ski structure and the glass fibre sleeve plays a major part of this properties. Further research on the torsional properties of the glass fibre sleeve and recycled carbon fibre is needed.

LCIA is a part of Life Cycle Assessment. LCA should be completed to get full understanding of production, use and disposal stage. As well a look is needed at Life Cycle Cost Analysis (LCCA).

Acknowledgements

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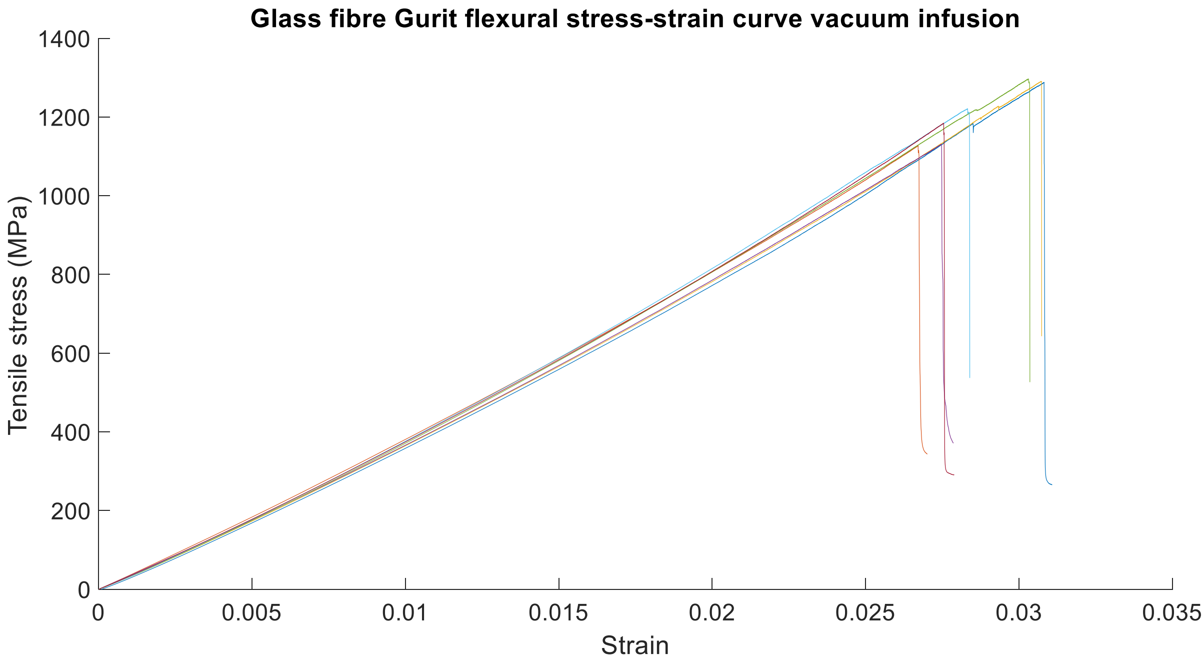
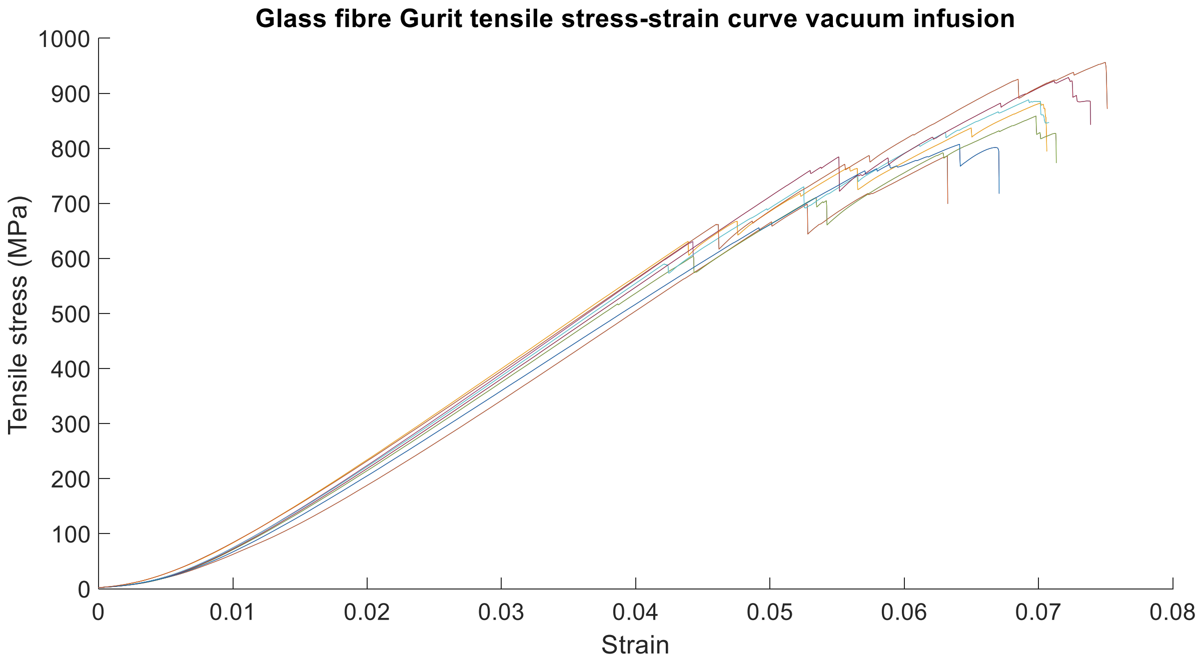
Appendix

Glass fibre Gurit vacuum infusion

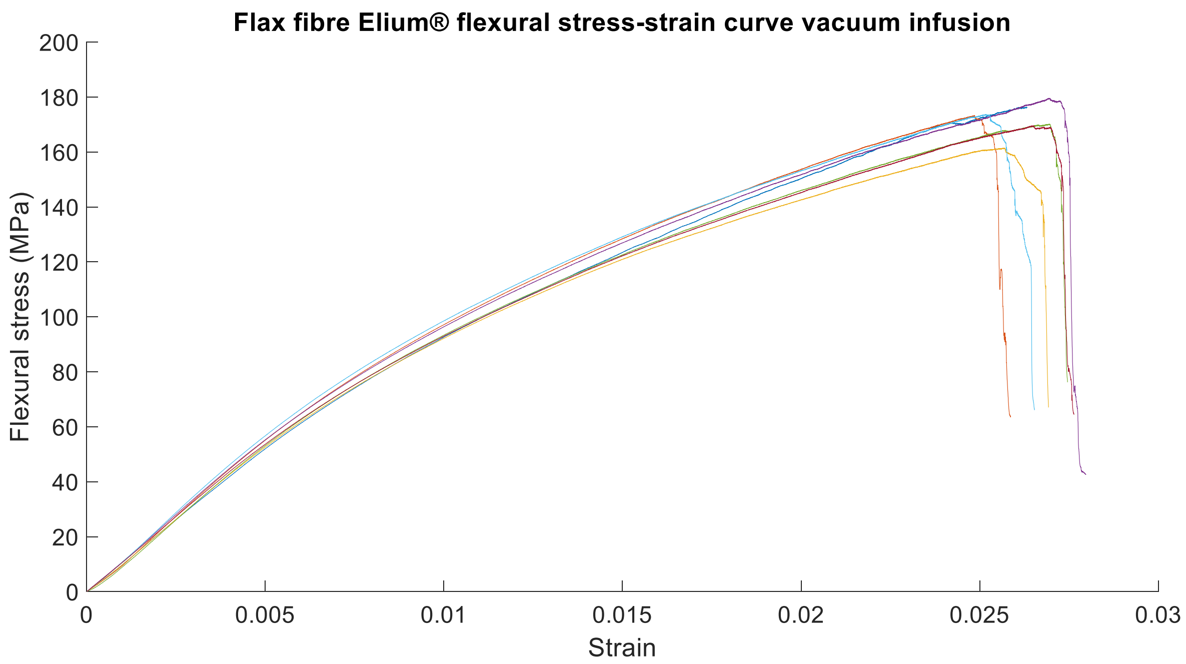


	Specimen	Width	Thickness	Stress	Modulus	Failure
Flexural	Glass fibre Gurit	15.50	2.25	1288.38	33202.29	Compression
Flexural	Glass fibre Gurit	15.00	2.25	1127.16	36333.85	Compression
Flexural	Glass fibre Gurit	15.00	2.25	1290.90	33661.66	Compression
Flexural	Glass fibre Gurit	15.00	2.25	1131.00	34791.15	Compression
Flexural	Glass fibre Gurit	15.50	2.25	1296.97	33910.22	Compression
Flexural	Glass fibre Gurit	15.00	2.25	1221.34	34668.20	Compression
Flexural	Glass fibre Gurit	15.50	2.25	1184.65	34925.84	Compression

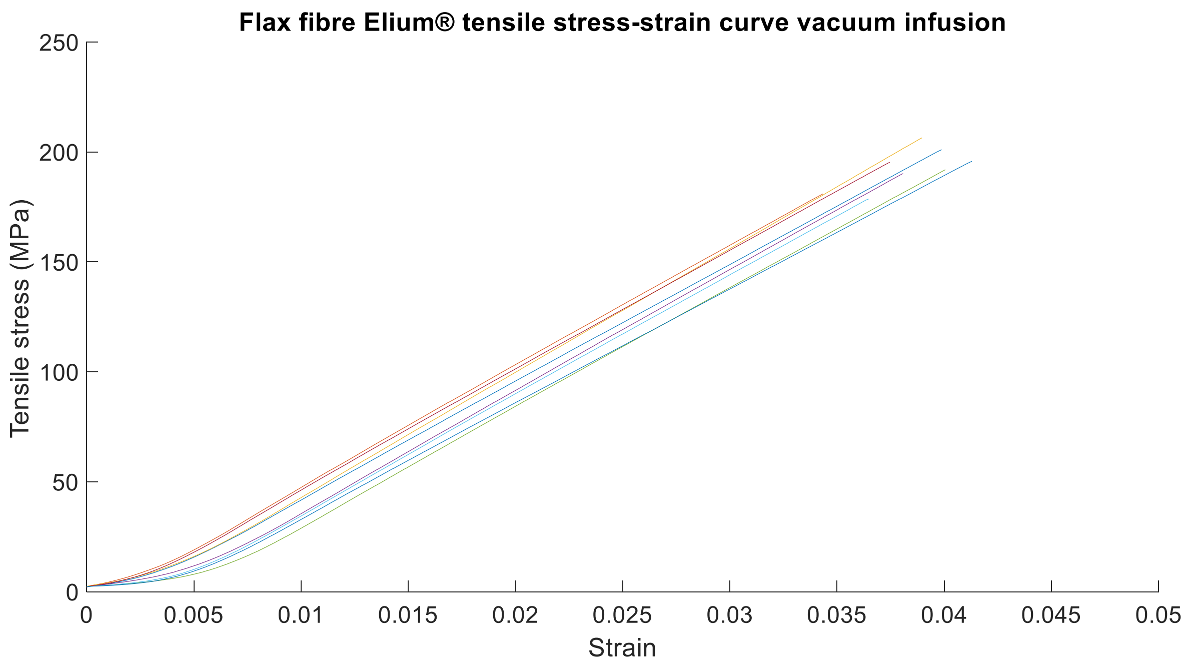


	Specimen	Width	Thickness	Stress	Modulus	Failure
Tensile	Glass fibre Gurit	15.00	1.60	786.01	13419.21	Fibre separation by edges
Tensile	Glass fibre Gurit	15.00	1.60	882.39	15531.97	Fibre separation by edges
Tensile	Glass fibre Gurit	15.10	1.60	630.68	15422.35	Fibre separation by edges
Tensile	Glass fibre Gurit	15.00	1.60	858.69	14885.02	Fibre separation by edges
Tensile	Glass fibre Gurit	14.90	1.60	888.19	15289.15	Fibre separation by edges
Tensile	Glass fibre Gurit	15.30	1.60	928.72	15123.16	Fibre separation by edges
Tensile	Glass fibre Gurit	14.80	1.60	807.41	14434.41	Fibre separation by edges
Tensile	Glass fibre Gurit	15.00	1.60	956.12	15291.33	Fibre separation by edges

Flax fibre Elium® vacuum infusion

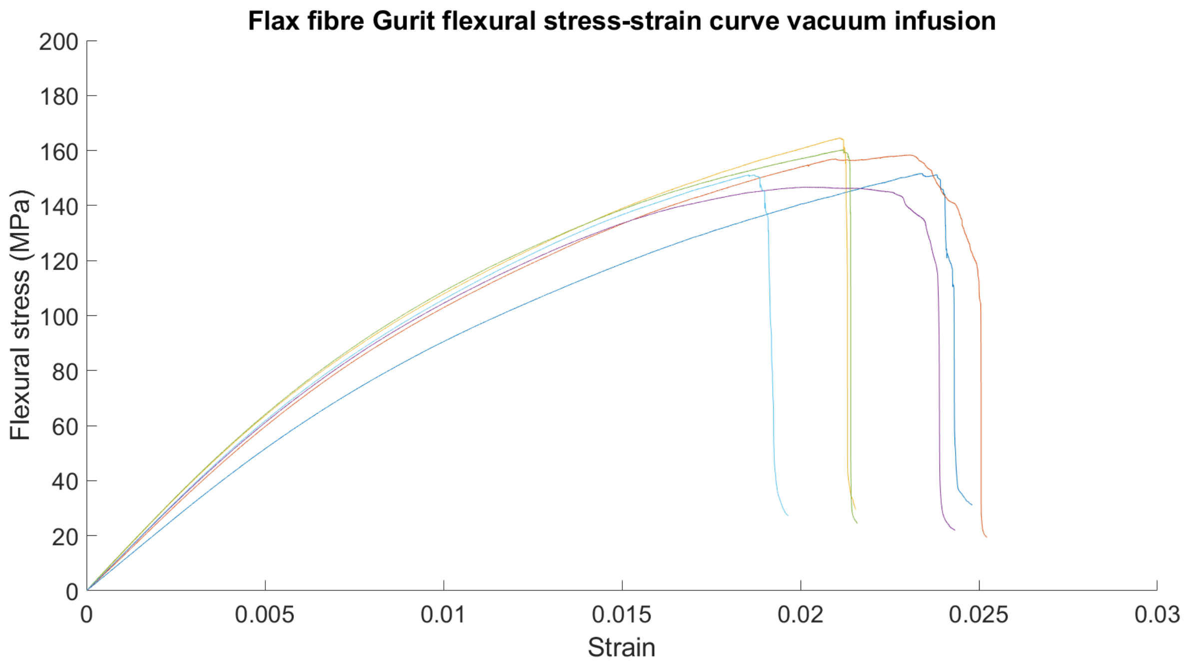


	Specimen	Width	Thickness	Stress	Modulus	Failure
Flexural	Flax fibre Elium	15.00	1.90	176.36	10663.86	Tensile
Flexural	Flax fibre Elium	15.00	1.90	173.31	11448.38	Tensile
Flexural	Flax fibre Elium	15.00	1.90	161.46	10768.25	Tensile
Flexural	Flax fibre Elium	15.00	1.90	179.60	11320.49	Tensile
Flexural	Flax fibre Elium	15.00	1.90	170.17	11079.87	Tensile
Flexural	Flax fibre Elium	15.00	1.90	173.69	11760.53	Tensile
Flexural	Flax fibre Elium	15.00	1.90	169.59	11013.09	Tensile

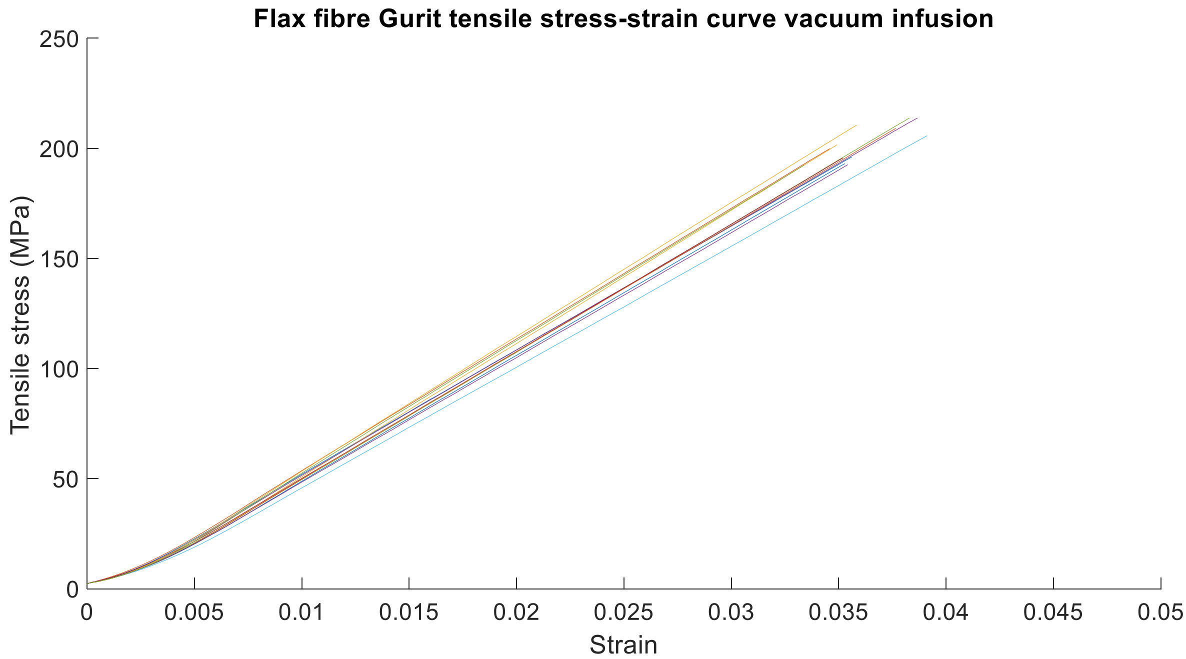


	Specimen	Width	Thickness	Stress	Modulus	Failure
Tensile	Flax fibre Elium	15.00	1.40	200.99	5496.33	20 mm from grips
Tensile	Flax fibre Elium	15.00	1.40	180.88	5790.12	In grips
Tensile	Flax fibre Elium	14.90	1.30	206.40	5739.96	Middle
Tensile	Flax fibre Elium	15.00	1.40	190.08	5243.48	20 mm from grips
Tensile	Flax fibre Elium	14.90	1.40	191.89	4875.38	30 mm from grips
Tensile	Flax fibre Elium	15.00	1.40	178.59	5339.51	By grips
Tensile	Flax fibre Elium	15.00	1.40	195.31	5769.78	By grips
Tensile	Flax fibre Elium	15.00	1.40	195.78	5180.08	10 mm from grips

Flax fibre Gurit vacuum infusion

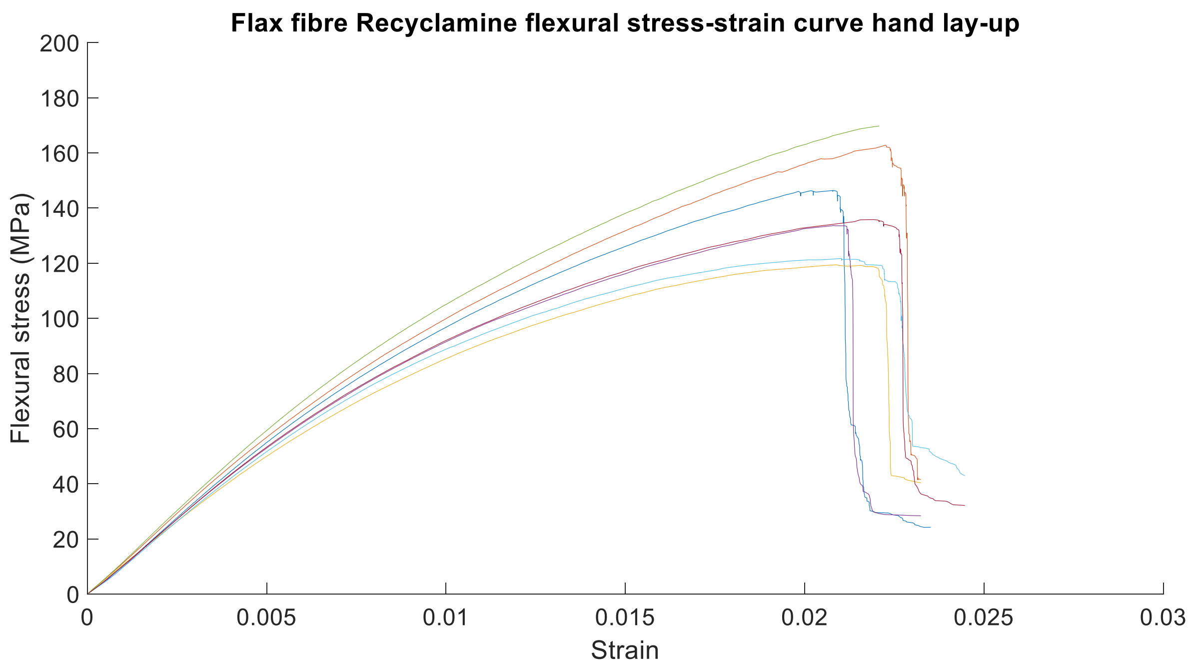


	Specimen	Width	Thickness	Stress	Modulus	Failure
Flexural	Flax fibre Gurit (VARTM)	15.10	2.10	151.74	10649.62	Tensile
Flexural	Flax fibre Gurit (VARTM)	15.00	2.00	158.47	12427.31	Tensile
Flexural	Flax fibre Gurit (VARTM)	15.00	2.00	164.63	13462.16	Tensile
Flexural	Flax fibre Gurit (VARTM)	15.00	2.00	146.77	12874.88	Tensile
Flexural	Flax fibre Gurit (VARTM)	15.10	2.00	160.31	13527.27	Tensile
Flexural	Flax fibre Gurit (VARTM)	15.00	2.00	151.19	12912.18	Tensile

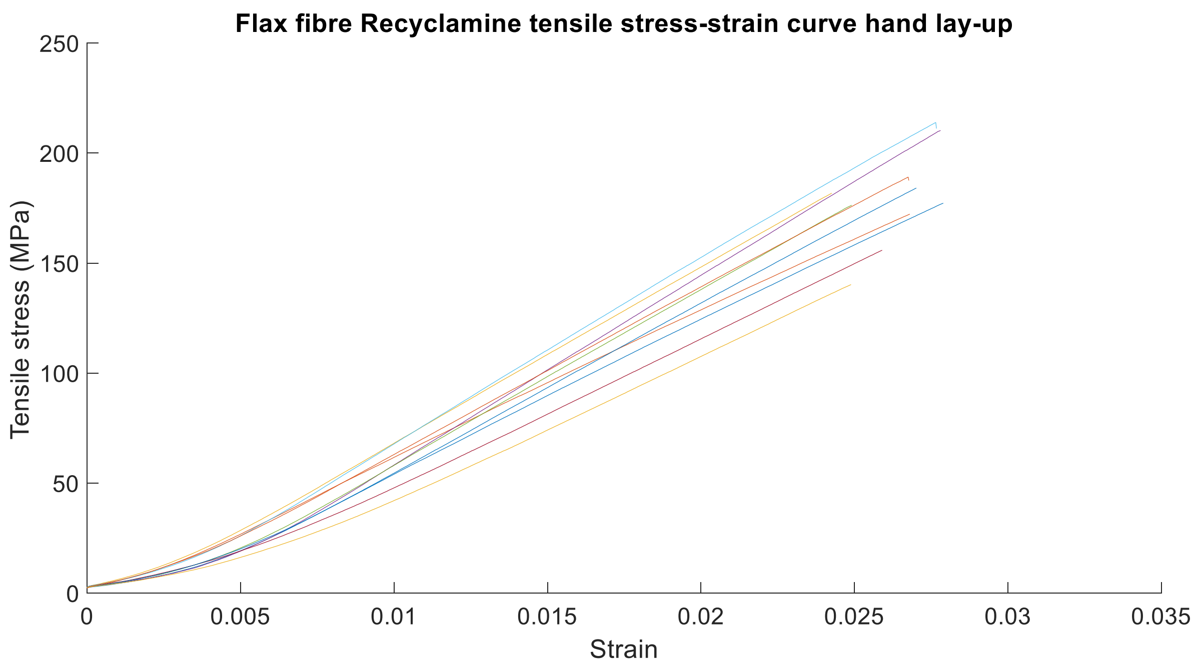


	Specimen	Width	Thickness	Stress	Modulus	Failure
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	196.09	5872.75	By grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	199.86	6124.43	20 mm from grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	201.63	6187.73	By grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	213.77	5931.34	20 mm from grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	213.76	5831.18	By grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	205.73	5582.21	Middle
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	195.63	5815.28	30 mm from grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	193.04	5860.37	By grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	209.07	5961.58	Middle
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	210.51	6260.31	10 mm from grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	192.58	5694.25	20 mm from grips
Tensile	Flax fibre Gurit (VARTM)	15.00	1.40	192.33	6255.40	15 mm from grips

Flax fibre Recyclamine hand lay-up

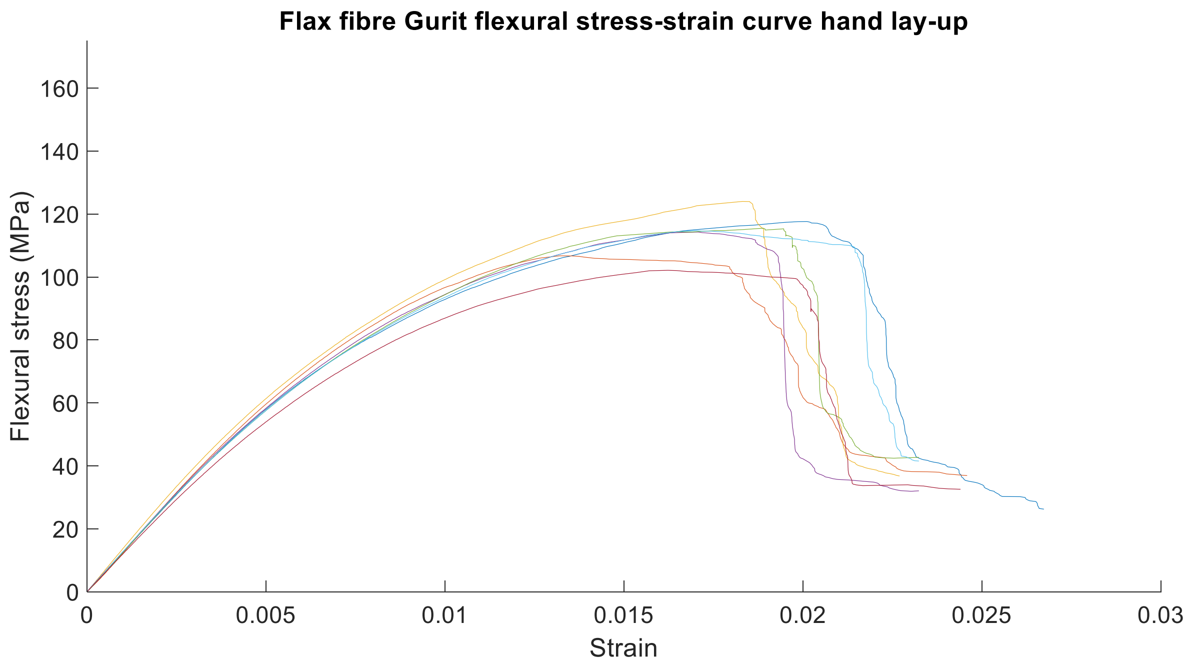


	Specimen	Width	Thickness	Stress	Modulus	Failure
Flexural	Flax fibre Recyclamine	14.90	2.00	146.37	11381.00	Tensile
Flexural	Flax fibre Recyclamine	14.80	2.00	162.80	11773.84	Tensile
Flexural	Flax fibre Recyclamine	14.90	2.00	119.41	10437.27	Compression
Flexural	Flax fibre Recyclamine	14.90	2.00	133.63	11186.54	Compression
Flexural	Flax fibre Recyclamine	14.90	1.90	169.77	12260.73	No fracture
Flexural	Flax fibre Recyclamine	14.90	2.00	121.72	10924.25	Compression
Flexural	Flax fibre Recyclamine	14.90	2.00	135.80	11057.26	Compression

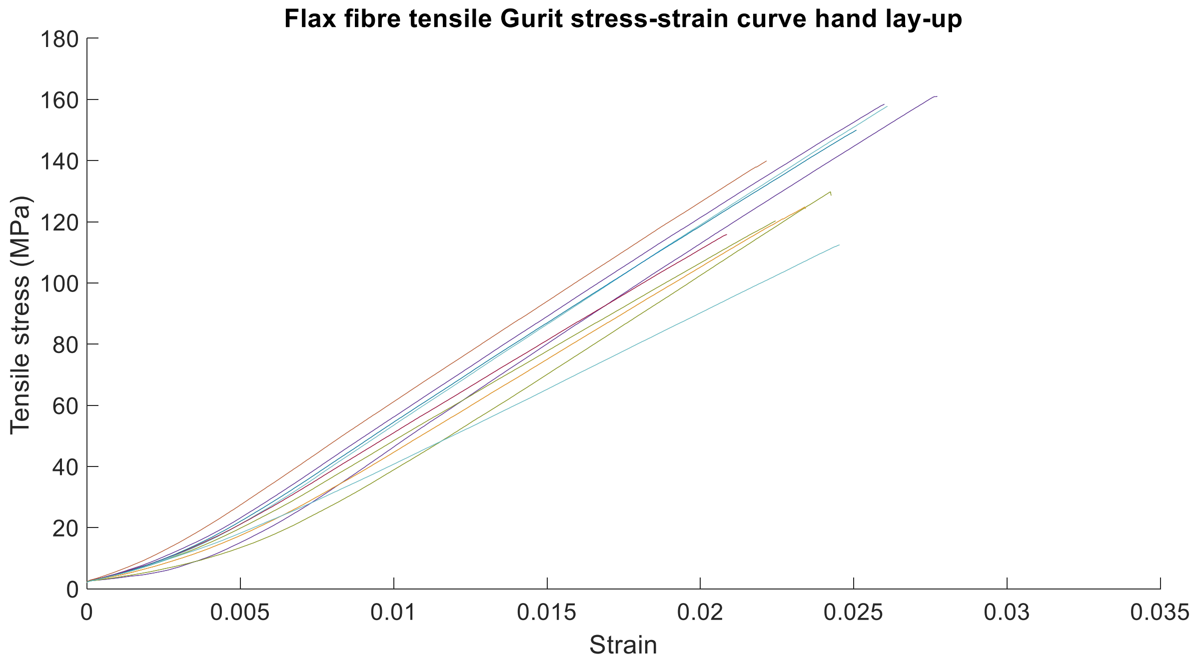


	Specimen	Width	Thickness	Stress	Modulus	Failure
Tensile	Flax fibre Recyclamine	15.00	1.30	177.25	7241.72	Middle
Tensile	Flax fibre Recyclamine	15.00	1.35	172.27	6950.35	20 mm from grips
Tensile	Flax fibre Recyclamine	15.00	1.10	181.80	8131.12	By grips
Tensile	Flax fibre Recyclamine	15.00	1.10	210.32	8512.54	By grips
Tensile	Flax fibre Recyclamine	15.00	1.20	176.32	7962.33	By grips
Tensile	Flax fibre Recyclamine	15.00	1.10	213.89	8618.67	10 mm from grips
Tensile	Flax fibre Recyclamine	15.00	1.20	155.86	6091.69	By grips
Tensile	Flax fibre Recyclamine	15.00	1.20	184.13	7432.13	By grips
Tensile	Flax fibre Recyclamine	15.00	1.20	189.11	7677.92	10 mm from grips
Tensile	Flax fibre Recyclamine	15.00	1.10	140.26	5553.09	By grips

Flax fibre Gurit hand lay-up



	Specimen	Width	Thickness	Stress	Modulus	Failure
Flexural	Flax fibre Gurit (Hand lay-up)	15.10	2.00	117.63	12395.74	Compression
Flexural	Flax fibre Gurit (Hand lay-up)	15.10	2.00	106.73	12845.71	Compression
Flexural	Flax fibre Gurit (Hand lay-up)	15.25	2.00	124.01	13280.14	Compression
Flexural	Flax fibre Gurit (Hand lay-up)	15.10	2.00	114.27	12459.35	Compression
Flexural	Flax fibre Gurit (Hand lay-up)	15.10	2.00	115.50	12433.37	Tension
Flexural	Flax fibre Gurit (Hand lay-up)	15.15	2.00	114.71	12362.14	Compression
Flexural	Flax fibre Gurit (Hand lay-up)	15.15	2.10	102.13	11659.90	Compression



	Specimen	Width	Thickness	Stress	Modulus	Failure
Tensile	Flax fibre Gurit (hand-lay-up)	15.00	1.40	161.02	6784.23	Middle
Tensile	Flax fibre Gurit (hand-lay-up)	15.00	1.40	129.79	5577.95	Close to grips
Tensile	Flax fibre Gurit (hand-lay-up)	15.00	1.40	157.72	6701.50	Middle
Tensile	Flax fibre Gurit (hand-lay-up)	14.90	1.40	115.86	6151.22	Close to grips
Tensile	Flax fibre Gurit (hand-lay-up)	15.00	1.40	149.96	6694.30	10 mm from grips
Tensile	Flax fibre Gurit (hand-lay-up)	14.70	1.40	139.90	6762.55	15 mm from grips
Tensile	Flax fibre Gurit (hand-lay-up)	14.90	1.40	124.83	5757.57	Close to grips
Tensile	Flax fibre Gurit (hand-lay-up)	15.00	1.40	158.46	6731.65	Middle
Tensile	Flax fibre Gurit (hand-lay-up)	15.00	1.40	120.27	5969.32	10 mm from grips
Tensile	Flax fibre Gurit (hand-lay-up)	15.00	1.50	112.46	4672.21	5 mm from grips