Mechanical properties of biaxial carbon fibre laminate

Comparing prepreg, wet lay-up and vacuum infused lamination

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Degree Thesis

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Lärdomsprov

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Uppdragsgivare:

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Sammandrag:

I detta examensarbete kommer vi att försöka fastställa hur lamineringstekniker påverkar de mekaniska egenskaperna hos ett biaxialt kolfiberlaminat. Detta kommer att göras genom att genomföra ett experiment där tre laminat tillverkas med tre olika lamineringstekniker. De tekniker som används för experimentet är prepreg, hand- och vakuumlaminering. Vid handlaminering läggs fiberarmeringslagren ner för hand och epoxin tillsätts med en pensel eller rulle mellan varje lager. Vid vakuumlaminering stakas fiberförstärkningarna och vakuumtryck används för att trycka in hartset i fibern. Prepreg är en halvfärdig produkt, där hartset redan har impregnerats i fibrerna under tillverkningsprocessen, så när man tillverkar en del behöver prepreg bara sättas under vakuum och i en ugn under härdningen. Alla tre laminat kommer att tillverkas av 5 lager kolfibermatta/prepreg. Mattan och prepreggen är 400g/m^2 biaxial som har orienteringen $\pm 45°$. Hand -och vakuumlaminering kommer också att lamineras med samma epoxi medan prepreggen redan har impregnerats med epoxihartsmatris under tillverkningen. Varje laminat skärs till 5 provbitar enligt ISO 14125-standarden och proverna testas med en trepunktsbockningsmaskin enligt samma ISO-standard. Resultaten visade att prepreg och det vakuuminfunderade laminatet har högre böjmodul, fibervolymfraktion och maximal böjhållfasthet, medan våtuppläggning hade den högsta kraften. Detta beror på att prepreg- och vakuumlaminatet var 1 mm tunnare och 3 g lättare när de härdades. Ett materials tjocklek har en betydande inverkan på dess böjhållfasthet, eftersom tjockare material har ett högre tröghetsmoment vilket ger materialet högre motstånd mot böjning. Ett material med högre tröghetsmoment kan uthärda mer kraft. Det är därför som vakuumlamineringen och prepreg har en högre böjmodul än handlamineringen eftersom det finns en skillnad i tjocklek. Vi kan alltså konstatera att vakuumtrycket har haft den tydligaste effekten på de mekaniska egenskaperna.

Nyckelord:

Kolfiber, prepreg, mekaniska egenskaper, trepunktsböjningstest

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Abstract:

In this thesis we will try to narrow down how lamination techniques affect the mechanical properties of a biaxial carbon fibre laminate. This will be done by conducting an experiment where three laminates are produces using three different lamination techniques. The techniques used for the experiment are prepreg, wet lay-up, and vacuum infused lamination. In the wet lay-up technique, the fibre reinforcement layers are put down by hand and the resin is added with a brush or a roller in between each layer. In vacuum infused lamination the fibre reinforcements are staked, and vacuum pressure is used to push the resin into the fibre. Prepreg is a semi-ready product, where the resin is already impregnated into the fibres during the manufacturing process, so when making a part the prepreg just needs to be put under vacuum and in an oven during curing. All three laminates will be made from 5 layers of carbon fibre mat/prepreg. The mat and prepreg is 400g/m^2 biaxial that both has an orientation of $\pm 45°$. The wet lay-up and vacuum infused lamination will also be laminated with the same epoxy while the prepreg is already impregnated with an epoxy resin matrix during its production. The laminates are cut into 5 sample pieces per laminate according to the ISO 14125 standard and the samples are tested with a three-point bending machine according to the same ISO standard. The results showed that the prepreg and the vacuum infused lamination have a higher flexural modulus, fibre volume fraction and maximum flexural strength, while wet lay-up had the maximum force. This is due to the prepreg, and vacuum infused lamination samples were 1 mm thinner and 3 g lighter when cured. A materials thickness has a significant impact on its flexural strength, since thicker materials have a higher moment of inertia which gives them a higher resistant to bending and flexural strength. A material with a higher moment of inertia can endure more force. This is why the vacuum infused lamination and the prepreg have a higher flexural modulus than the wet lay-up since there is a difference in thickness. So, we can see that putting laminates under vacuum has had the most distinct effect on the mechanical properties.

Keywords:

Carbon fibre, prepreg, mechanical properties, three-point bending

Opinnäyte

Malin, Kuikka

Biaksiaali hiilikuitu laminaatin mekaaniset ominaisuudet.

Prepreg, märkälaminaatin ja vakuumi infuusio laminaatin vertailu.

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Tunnistenumero:

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Tiivistelmä:

Tässä tutkielmassa tavoite on selvittää, miten laminointitekniikat vaikuttavat hiilikuitulaminaatin mekaanisiin ominaisuuksiin. Tämä tehdään suorittamalla koe, jossa valmistetaan kolme laminaattia kolmella eri laminointitekniikalla. Kokeessa käytetyt tekniikat ovat prepreg, märkälaminointi ja alipaineinfuusio laminointi. Märkälaminoinnissa kuituvahvikkeet kerrokset asetetaan käsin ja hartsi lisätään harjalla tai telalla kerroksien väliin, tämä toistetaan, kunnes kaikki kerrokset ovat asetettu. Alipaineinfuusio laminoinnissa kuituvahvikkeet asetetaan paikoilleen, ja hartsin työntäminen kuitujen sisään tapahtuu alipaineen avulla. Prepreg on puolivalmis tuote, jossa hartsi on jo kyllästetty kuituihin valmistusprosessin aikana, joten osaa valmistettaessa prepreg tarvitsee vain laittaa alipaineeseen ja uuniin kovettumaan. Kaikki kolme laminaattia valmistetaan viidestä hiilikuitumatto-/prepreg kerroksesta. Matto ja prepreg ovat 400 g/m^2 biaksiaali kuiduista, joiden suuntaus on $\pm 45°$. Märkälaminointi ja infuusiolaminointi laminoidaan samalla epoksilla, kun taas prepreg on jo valmistusvaiheessa kyllästetty epoksihartsilla. Laminaateista leikataan 5 näytekappaletta laminaattia kohti ISO 14125 -standardin mukaisesti, ja näytteet testataan kolmipistetaivutuskoneella saman ISO-standardin mukaisesti. Tulokset osoittivat, että prepregillä ja alipaineinfuusio laminaatilla on korkeampi taivutusmoduuli, kuitujen tilavuusosuus ja suurin taivutuslujuus, kun taas märkälaatoituksella oli suurin voima. Tämä johtuu siitä, että prepreg- ja alipaineinfuusio laminaattinäytteet olivat kovetettuina 1 mm ohuempia ja 3 g kevyempiä. Materiaalin paksuudella on merkittävä vaikutus sen taivutuslujuuteen, koska paksummilla materiaaleilla on suurempi hitausmomentti, mikä antaa niille suuremman taivutuskestävyyden ja taivutuslujuuden. Materiaali, jolla on suurempi hitausmomentti, kestää enemmän voimaa. Tämän vuoksi alipaineinfuusio laminoinnilla ja prepregillä on suurempi taivutusmoduuli kuin märkäasennuksella, koska paksuudessa on eroa. Voimme siis nähdä, että laminaattien asettamisella alipaineeseen on ollut selvin vaikutus mekaanisiin ominaisuuksiin.

Avainsanat:

Hiilikuitu, prepreg, mekaaniset ominaisuudet, kolmepistetaivutustesti

Content

1 Introduction

Carbon fibre, although being a quite new invention, has a fast-growing market and some important sectors are large consumers of carbon fibre. The military, aerospace, and marine industry, and sporting industry all use carbon fibre in great quantities. Carbon fibre is popular due to its strength while being lightweight. This has become a desired property and something that still is being researched in the hopes of improving it. It is still expensive to produce carbon fibre parts and products. (IYRS, 2021)

Carbon fibre has made it possible to innovate many fields and made it possible to meet different demands. Carbon fibre is a durable material so companies can save money in maintenance costs and the adaptability of carbon fibre has made it so that there is a big range of products. There aren't many fields that carbon fibre isn't used in. The aerospace industry is a field that that actively tries to innovate carbon fibre utilising its properties. Carbon fibre has made it possible to innovate different fields in aerospace, commercial aircraft, military aviation, and space exploration. Carbon fibre makes aircrafts both military and commercial lightweight making them fuel efficient and military planes to make them more stealth. In space exploration carbon fibre parts are ideal since they can endure fluctuation in temperature without damaging the structure. Carbon fibre is also used in everyday vehicles to make them more fuel efficient, in sport equipment to make them more durable, and in structural design and infrastructure since carbon fibres is light, strong and resilient to environmental degradation. Advances have also been made with carbon fibre in fields like marine engineering, and carbon fibre is used in medical prosthetics and devices, making it easier to produce tailored prosthetics for individual needs. (Impact Materials, 2024)

The laminates themselves are made up of layers of composites in the form of fibres, weaves, or mats. Laminates are usually named with specifications depending on the lay-up, e.g. unidirectional (UD). (Saarela et al., 2003, Chap.2.4.1)

1.1 Objectives

For this thesis, the lamination technique will be analysed if they influence the mechanical properties of the carbon fibre. This thesis will compare the effect that different lamination techniques have on the mechanical properties of a carbon fibre composite. An experiment will be conducted where three laminates will be produced using different lamination techniques. The laminates will be tested with a three-point bending test. The lamination techniques that will be compared are wet lay-up lamination, vacuum infused lamination, and prepreg lamination. For this experiment, the goal is to produce three laminates that have mechanical differences that are only caused by the lamination techniques.

To eliminate as many as possible other variables similar materials are used in all laminations. All three laminates will be made from five layers of 400g/m^2 biaxial $\pm 45°$ carbon fibre/prepreg. The same epoxy was used for the wet lay-up and the vacuum infused lamination to minimize differences between the two laminates, prepreg is already impregnated with an epoxy resin matrix during its production.

The laminates will be cut into 5 sample pieces according to the ISO 14125 standard and a three-point bending test will be performed according to the same standard. The results from the test will be plotted and compared. The porosity will be tested with the water absorption method. Porosity can indicate the amount of voids the different laminates have.

Prepreg was designed to have an ideal fibre volume fraction, to increase its mechanical properties. So, it is expected that the prepreg sample will endure the highest force before they break. Wet lay-up tends to have a poor fibre volume fraction since the epoxy is put on by hand and therefore will have so much epoxy it weakens the mechanical properties. So, we can expect that the wet lay-up samples will break with the least amount of force.

1.2 Relevance of topic

This thesis is built on the knowledge learned from the degree program. It connects with the course in composite materials, where lamination techniques were studied, and a laminate was made. As well as the course where laminate properties were studied.

This thesis is sponsored by Kevra, in the hopes that it can provide a better understanding of the differences the lamination techniques have on the laminate. With the help of this information, they wish to be able to help their customers make better choices depending on the purpose of the project.

2 Literature Review

2.1 Composite

A composite is a material composed of two or more materials that work together but are not dissolved or blended. A composite is made up from a matrix and reinforcements or fibres. The matrix works as a binder that holds the fibres together, making the two materials into one. These materials are combined with the goal to create a new material with specific properties, like being lighter, stronger, or resilient to the environment or electricity.

2.2 Equations

2.2.1 Young’s Modulus

Young's Modulus is a constant that each material has. The constant gives us the elastic properties in a unidirectional manner during tension or compression.

$$E = \frac{\sigma}{\varepsilon} = \frac{FL_o}{A/L_n - L_o}$$ Equation 1

Where,

E = Young's Modulus

σ = Stress [Pa]

ε = Strain

A = Area [m^2]

F = Force [N]

L_o = Original length [m]

L_n = New length [m]

(Gregersen, 2022)

2.2.2 Flexural stress

$$\sigma_f = \frac{3FL}{2bh^2} \qquad \text{Equation 2}$$

Where,

σ_f = Flexural stress [MPa]

F = Load applied [N]

L = Span length [mm]

b = Width of the specimen [mm]

h = Thickness of the specimen [mm]

(ISO 14125, 1998)

2.2.3 Flexural modulus

$$s' = \frac{\varepsilon_f' L^2}{6h} \text{ and } s'' = \frac{\varepsilon_f'' L^2}{6h} \qquad \text{Equation 3}$$

Where,

$s' and\ s''$ = The beam mid-point deflection, [mm]

ε_f' = 0,0005

ε_f'' = 0,0025

(ISO 14125, 1998)

2.2.4 Flexural modulus of elasticity

Flexural stress can be calculated with either equation 3 or equation 4. The flexural stress will be calculated with both equations to ensure that the result is valid. The flexural stress can also be achieved with Excel. Both the mathematical and the Excel results will be presented.

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

Where,

E_f = Flexural modulus of elasticity [MPa]

Δs = Difference in deflection s'' and s'

ΔF = Difference in load F'' at s'' and F' at s'

(ISO 14125, 1998)

2.2.5 Measurement of fibre volume fraction for laminar composite

Fibre volume fraction gives us what percentage of the composite is made up of fibre. Fibre volume fraction has a direct connection with the laminate's mechanical properties. A higher fibre volume fraction leads to better mechanical properties since the laminate has more reinforcements. Around 80 % is the highest possible theoretical fibre volume fraction, if increased thereafter there will not be enough matrix to keep the laminate from falling apart. Woven materials rarely have a high fibre fraction volume, approximately 40 % per layer at maximum. We use the Rule of Mixtures formula to calculate this. (Saarela, O. *et al.*, 2003)

$$V_f = v_f / v_c$$ Equation 5

Where,

V_f = Fibre volume fraction

v_f = Fibre volume [mm^3]

v_c = Composite volume [mm^3]

(Saarela, O. *et al.*, 2003)

2.3 Voids

Voids are air pockets or gaps within the laminate, leaving a void that has neither resin nor fibres. Voids can affect the material's properties negatively. This is why when making a lamination one must try to minimize the number of voids gained. Voids can lead to cracks and let moisture into the composite. In carbon fibre laminates, a void content of as little as 1-3 % can lead to a reduction of up to 20 % in the laminate’s mechanical properties. (Ritchot, 2022)

Voids occur for different reasons on top and in between layers during the lamination process. Incomplete wetting of the fibres, improper curing, such as wrong temperature or pressure during curing, and air entrapment during lay-up can cause voids. Water and formaldehyde can also be generated from the resin as by-products from condensation, which cause voids. A laminate’s porosity can be calculated to examine the void content. (Ritchot, 2022)

$$\text{Porosity (\%)} = \frac{V_t - V_s}{V_t} \times 100 \qquad \text{Equation 6}$$

Where,

$V_s = Volume\ of\ the\ solid\ [m^3]$

$V_t = Total\ volume\ [m^3]$

(Bai, J., 2013)

Stress concentration occurs around voids when there is a geometrical irregularity in the material. This weakens the material. Voids disrupt the even distribution of stress in a material since stress tends to concentrate around voids. (Bai, J., 2013)

The stress concentration factor is the ratio of the maximum stress at the location of the void to the normal or applied stress. Stress concentration can lead to an increased amount of stress in the localized areas, even so that it surpasses the material’s yield strength. The shape, size, and orientation of the void affect the stress concentration, larger voids usually mean higher stress concentration factors. (Bai, J., 2013)

$K_t = \frac{\sigma_{max}}{\sigma_{normal}}$ Equation 7

Where,

$K_t = Stress\ concentration\ factor$

$\sigma_{max} = Maximum\ stress\ at\ the\ location\ of\ the\ void$

$\sigma_{normal} = Normal\ or\ applied\ stress$

The stress concentration can start the growth of creep-related damages, which happens when a material deforms over time from being subjected to stress and loads which in turn can lead to permanent damages to the materials. Since voids can lead to significant decrease in the material’s mechanical properties, vacuum bagging is used to minimize the chance of voids appearing. (Bai, J., 2013)

2.4 Moment of Inertia

Moment of inertia is a mechanical property that tells us how much a body can resist change. Inertia is affected by the mass of the body, the more mass a body has the greater the inertia. A materials thickness affects its flexural strength and how much force it can take before it breaks. Materials that are thicker have a higher moment of inertia, which makes them more resistant to bending and they have a higher flexural strength.

$I = \frac{bh^3}{12}$ Equation 8

Where,

$I = Moment\ of\ Inertia$

$b = Width$

$h = Thickness$

(Baker, D., 2020)

2.5 Process of wet lay-up lamination

Wet lay-up is the easiest form of lamination method. For wet lay-up, a mould is cleaned from dirt and oils and prepped with a release agent. When the mould is prepped, the fibre is placed down by hand and then resin is added with a roller or brush. More layers can be added to get the desired thickness and look. (Norco, 2019) Fig. 1 shows what a standard wet lay-up process looks like.

Wet lay-up is simple and low in cost but has a high risk of creating voids since a lot of air can be trapped between layers when they are put down by hand. The wet lay-up process also has a risk of leaving dry fibre since the resin is applied by hand, leaving it uneven. This is also why the fibre volume fraction is difficult to control. Wet lay-up can be put under vacuum to minimize the chances of voids, uneven resin, and dry spots. (Norco, 2019) For this experience, the wet lay-up will not be put under vacuum.

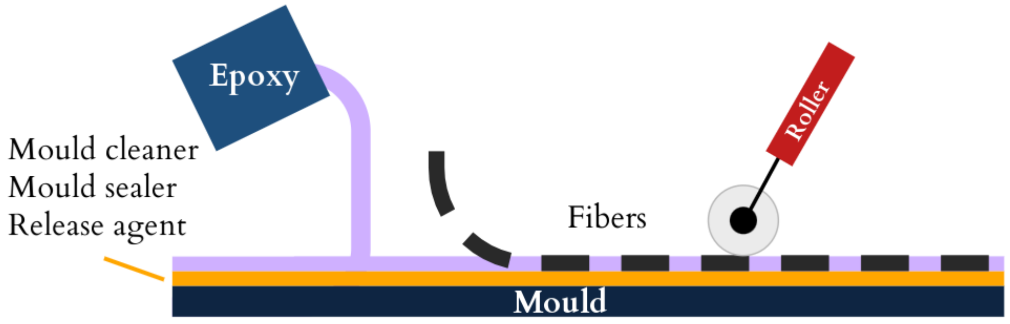

Figure 1 Wet lay-up process. Kuikka, M. (2024)

2.6 Process of vacuum assisted resin infusion

With vacuum assisted resin infusion, vacuum pressure is used to help push the resin into the fibres to get an even distribution. The mould is prepped the same way as in the wet lay-up lamination, then the fibre layers are placed by hand onto the prepped mould. The mould is then covered with a plastic membrane and the edges are sealed. A vacuum channel is attached to the plastic membrane and an entrance channel for the resin. The resin is mixed by hand and a tube is placed in the resin pot that is connected to the entrance channel to the sealed plastic membrane. The vacuum pressure will suck the resin from the pot to the fibres. Since the fibre is so compact due to the vacuum pressure, there is no excess resin. (Norco, 2019) Fig. 2 shows what a standard vacuum assisted resin infusion process looks like.

There are few voids in vacuum laminations and due to even resin distribution, the parts have an even degree of strength. The tools for vacuum laminations can be expensive since the lamination must be enclosed. This may even limit the maximum size of the lamination. (Norco, 2019)

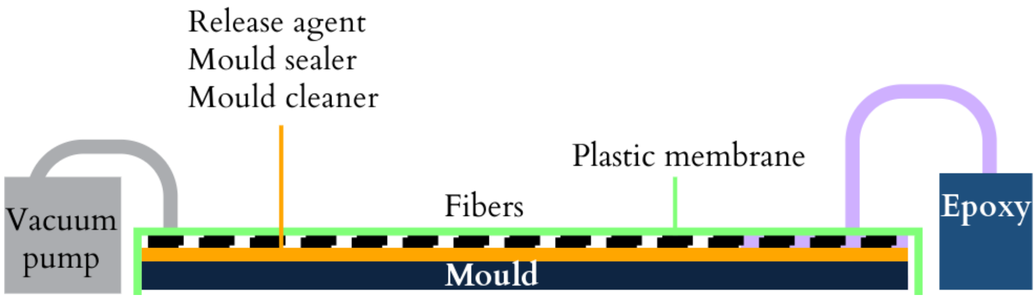

Figure 2 Vacuum infused lamination process. Kuikka, M. (2024)

2.7 Process of vacuum cured prepreg

The name prepreg comes from the term pre-impregnated, which refers to the material's main characteristic. While wet lay-up and vacuum infused lamination are impregnated with resin during the manufacturing of the part/product, prepreg has its fibres impregnated with the resin before the manufacturing. This means prepreg vow is a semi-finished product that can be put into rolls. (Bai, 2013)

When manufacturing the part/product, the manufacturer only needs to cut a piece of prepreg from the roll and lay it in a mould. Prepreg can be stacked in layers to get the desired thickness. (Bai, 2013) The mould is then covered with a plastic vacuum bag and put in an oven with vacuum to cure. The vacuum will help minimize the voids and force excess resin out, making the fibre concentration high and adhesion between the layers better. (Norco, 2019) Fig. 3 shows what a standard vacuum cured prepreg process looks like.

Prepreg tends to have a higher fibre volume content making it more weight efficient. It has a higher mechanical strength and stiffness properties compared to the other lamination techniques. (Bai, 2013) With this technique, the resin/hardener content and resin levels are controlled by the manufacturer of the material. This technique allows for high fibre content and low void content. This technique will bring additional costs to the manufacturing process and storing prepreg can be troublesome. Because prepreg is pre-impregnated with the resin, it must be stored and transported in a cold environment until it is being used. If prepreg is not stored in a cold environment, the resin starts to harden. This in return makes the prepreg unusable. (Norco, 2019)

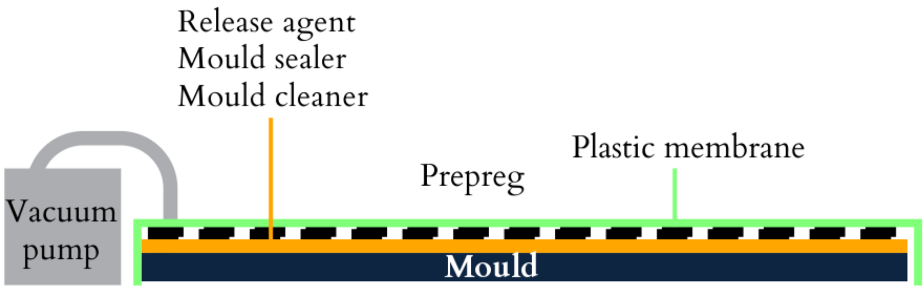

Figure 3 Prepreg lamination process. Kuikka, M. (2024)

3 Method

3.1 Approach

For this thesis the appropriate method to collect data is by doing an experiment, prepare samples and then compare the three lamination techniques. Since the goals is to see the effect different laminations techniques have, the materials used are as similar as possible in each lamination.

3.2 Materials used for laminations

3.2.1 Mold preparation

A sheet of glass is used as the mould for all three laminations and the moulds are prepared in the same manner. For mould cleaning and preparation, the following substances were used. Chemlease mould cleaner EZ is used to clean the moulds. The clean mould will then be coated with Chemlease 15 sealer EZ. Lastly Chemlease 75 EZ mould release agent is put on the mould.

3.2.2 Prepreg

The prepreg that is used in the laminate is HiMax CGL3994, manufactured by Hexcel. It has a fabric weight of 408 $\mathrm{g/m^2} \pm 5\%$ and the ply construction is $\pm 45°$. The prepreg wove is made from 12K fibre (see Appendix B). The prepreg is impregnated with HexPly M79/M79-LT epoxy resin matrix.

3.2.3 Carbon fibre fabric

The carbon fibre fabric that is used in both wet lay-up and vacuum infused laminations is sky 400B2-127P5Z, manufactured by Sky Advanced Materials. It has a fabric weight of 405 $\mathrm{g/m^2}$, with a tolerance between 384 - 426 $\mathrm{g/m^2}$. The ply construction is $\pm 45°$ and the tow is 50K (see Appendix B).

3.2.4 Epoxy

Ampreg 30 Standard by Gurit is used for both wet lay-up and vacuum infused lamination. The mixing ratio for resin to hardener is 100:26. More mechanical properties of the resin can be found in Appendix A.

The volume for the resin used is 827,273 $\mathrm{cm^3}$ and for the hardener 236,342 $\mathrm{cm^3}$. The density of the epoxy use is 1,077 $\mathrm{g/cm^3}$, and for the carbon fibre mat 2,116 $\mathrm{g/cm^3}$.

3.3 Laminating method

3.3.1 Mould preparation

The same glass sheet will be used as the mould for the wet lay-up lamination and the vacuum assisted resin infusion. A glass sheet will also be used for the prepreg lamination, but because of the size of the oven, a different glass sheet needs to be used.

The mould will first be cleaned thoroughly with mould cleaner to remove dirt and oils. When the mould has dried, two coats of sealer will be applied according to the instructions of the manufacturer. Sealer helps to even out any potential bumps or hacks that are in the mould. When the last coat of sealer has dried, 5 coats of release agent will be applied to the mould as instructed by the manufacturer. The release agent will help to release the finished part from the mould.

3.3.2 Wet lay-up

The mould is prepared as described in section 3.3.1. The dimensions of the composites will be 500 mm x 500 mm, and it will be 5 layers thick. The total weight of the carbon fibre layers combined are 529 g. To keep the 100:26 mixing ratio, 910 g of resin was mixed with 236 g of hardener when mixing the epoxy.

A small amount of resin is poured onto the mould and distributed around evenly with a brush. The first carbon fibre layer is put down onto the mould and more resin is poured on and distributed around to wet the fibre. This is repeated until all the layers are placed. When all the layers are placed, the laminate is rolled over with a roller to spread the resin evenly and to eliminate air bubbles. When the residual resin is squeezed out with the help of the roller, the part is left to cure in room temperature. The part is left to cure overnight and is removed from the mould a few days later. The temperature in the room is around 19 degrees Celsius at the time of the lamination. The weight of the finished lamination is 1081 g.

3.3.3 Vacuum infused lamination

The same mould will be used as in the wet lay-up lamination. A new layer of mould release is spread out onto the mould, since the previous is already pre-prepped from the previous lamination. The dimensions of the composites will be 500 mm x 500 mm, and it will be 5 layers thick. The total weight of the carbon fibre layers is 520 g.

The carbon fibre layers are stacked on the mould. On top of the caron fibre, a layer of release film, followed by a layer of peel ply and then by a layer of breather, are added. After this, a plastic vacuum bag is put over the mould. This is then sealed, so that the vacuum will remain when the vacuum pump is turned off. Two channels are attached to the vacuum bag, one for the vacuum pump and the other for the resin input. 982 g of resin is mixed with 255 g of hardener to keep the 100:26 mixing ratio. A tube is put into the epoxy pot and when the vacuum pump is turned on, the force from the vacuum will drag the epoxy through the fibres and wet the mat. The pump is turned off and the vacuum will hold the laminate in place while it cures. The vacuum bag, peel ply, breather and release film are removed after a day of curing.

The final weight of the laminate when it is fully cured is 782 g. Since we know that the weight of the carbon fibre mat is 520 g, we can conclude that the amount of epoxy that went into the laminate is 262 g.

3.3.4 Prepreg

The mould is prepared as described in section 3.3.1. The dimensions of the composites will be 800 mm x 320 mm, and it will be 5 layers thick. The dimensions for the prepreg laminate are different since it was affected by the size of the oven. The total weight of the prepreg layers combined are 741g.

The prepreg layers are stacked onto the mould. On top of the prepreg, a layer of release film, followed by a layer of peel ply and a layer of breather are placed in the same way as in the vacuum assisted resin infusion. Thereafter, a plastic vacuum bag is put over the mould which is then sealed. One channel is attached to the vacuum bag for the vacuum pump. The mould is then put into the oven and the vacuum is initiated. The prepreg will cure in the oven according to the manufacturer's recommendations. The oven will be heated up at the rate of 4 °C/min until it gets to +100 °C. The prepreg will cure for 75 minutes at +100 °C, and then it will be cooled down at the same rate of 4 °C/min.

3.4 Preparing samples

Five samples will be cut from each lamination. The samples will be cut into sample pieces according to the ISO 14125 standard. The dimensions for a three-point bendinvention 100 mm in length with a 10 mm tolerance, and 15 mm in width with a 0,5 mm tolerance. The samples are cut so that the fibres are in a ± 45 degree angle in the direction of the length.

3.5 Three-point bending

The sample will be tested using a three-point bending machine to measure the maximum stress the samples can endure before they crack. The data will also show the maximum deflection of the samples. All the data will be collected in Excel to thereafter be plotted. The test will be done according to the ISO 14125 standard. The outer span for the test specimen is 80 mm.

4 Results

The results for the 15-sample tested for this thesis will be presented with a graph of the samples stress/strain curve, a graph of their flexural modulus and a table showing the following variable that will be mentioned. In table 19 the dimensions of all the samples are presented.

From the test results we will get the deflection, force inflicted, and the flexural modulus. The samples maximum deflection (δ_{max}), maximum force (F_{max}), and maximum flexural modulus (E_f) will be presented for every sample. Flexural modulus will be calculated with equation 3 according to the ISO 14125 standard and the result from the bending test will be presented. Maximum flexural stress ($\sigma_{f\ max}$), maximum strain (ε_{max}) and density (ρ) will be calculated. Mass (m) will be weighed.

4.1 Wet lay-up

4.1.1 Wet lay-up sample 1

The sample has a Flexural Modulus of around 27 GPa, see Fig. 5. The specimen can be seen starting to fracture when the stress is around 520 MPa, and the strain is around 2,7%. The sample breaks completely at a stress around 550 MPa, and the strain is around 3,1 %. This can be seen in Fig. 4.

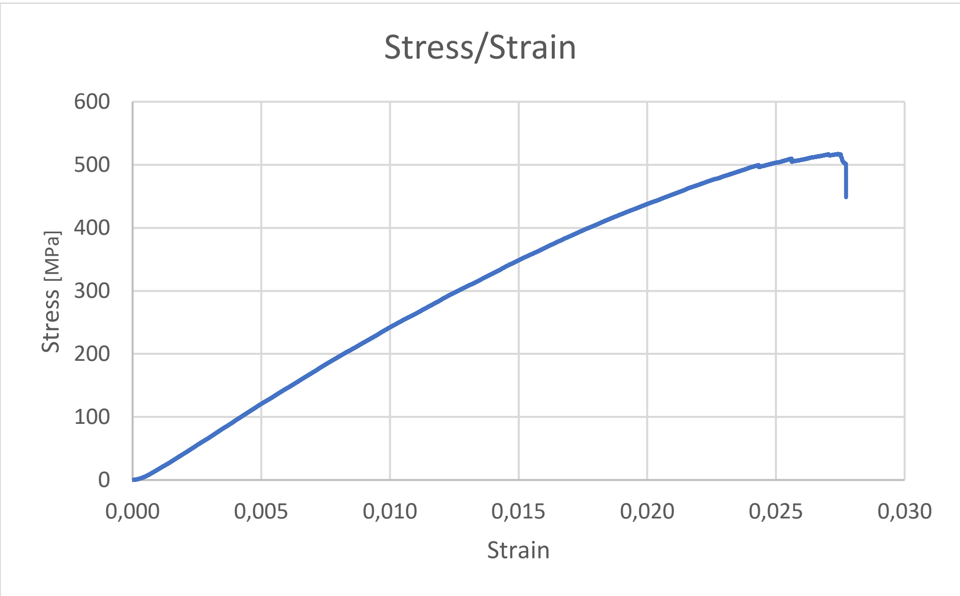

Figure 4 Wet lay-up sample 1 stress/strain curve. Kuikka, M. (2024)

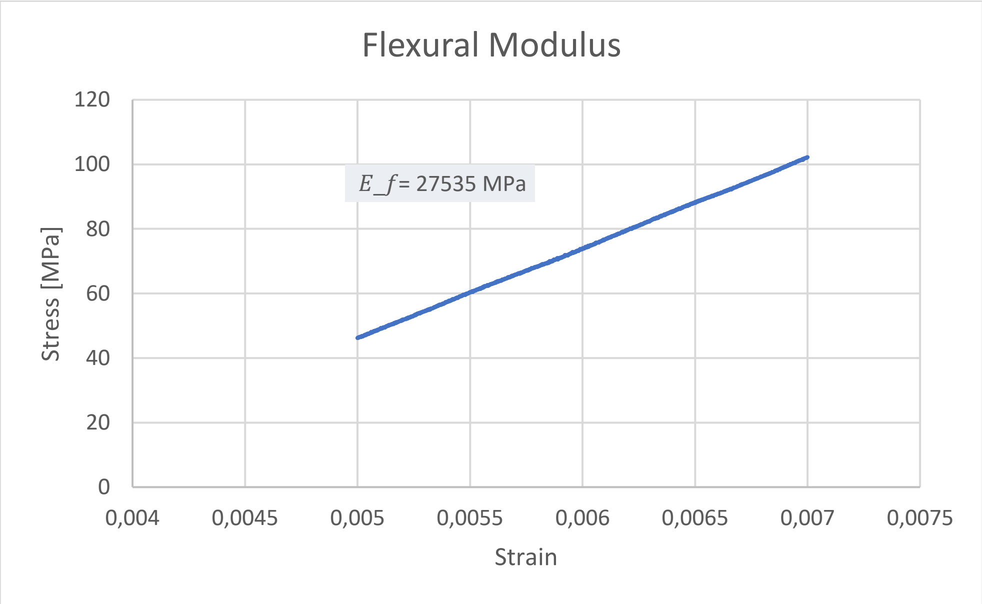

Figure 5 Wet lay-up sample 1 flexural modulus. Kuikka, M. (2024)

Table 1 Wet lay-up sample 1 results. Kuikka, M. (2024)

E_f (numerically)	28000 MPa
E_f (test result)	27535 MPa
$\sigma_{f\ max}$	551,82 MPa
F_{max}	620,80 N
δ_{max}	10,9
ε_{max}	0,03066
m	8 g
ρ	0,001650165g/mm^3

The loading pin was not close enough to the sample, so the stress/strain curve started later than from strain 0, as seen in Fig. 4. Because of this ε_f'= 0,005 and ε_f'' = 0,007.

4.1.2 Wet lay-up sample 2

The sample has a Flexural Modulus of around 25 GPa, see Fig. 7. The specimen can be seen starting to fracture when the stress is around 460 MPa, and the strain is around 2,0 %. The sample breaks completely at a stress around 470 MPa, and the strain is around 2,2 %. This can be seen in Fig. 6.

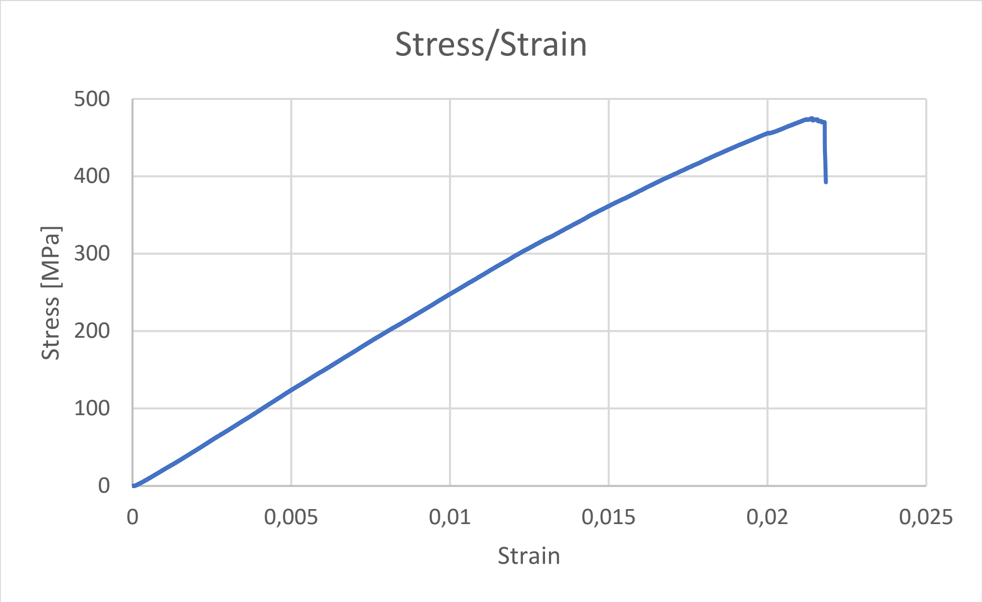

Figure 6 Wet lay-up sample 2 stress/strain curve. Kuikka, M. (2024)

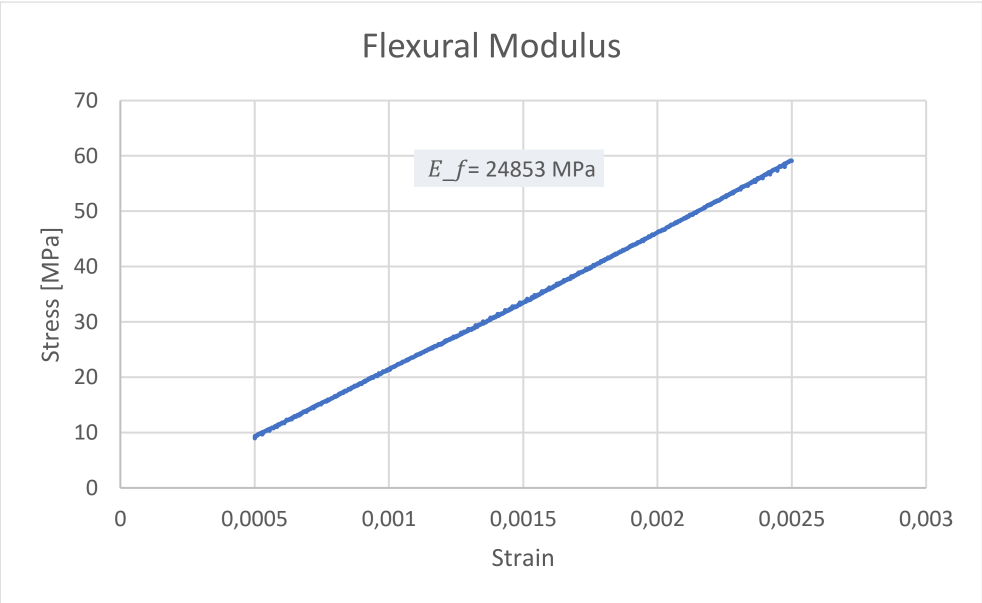

Figure 7 Wet lay-up sample 2 flexural modulus. Kuikka, M. (2024)

Table 2 Wet lay-up sample 2 results. Kuikka, M. (2024)

E_f (numerically)	24916,7 MPa
E_f (test result)	24853 MPa
$\sigma_{f\ max}$	475 MPa
F_{max}	570 N
δ_{max}	7,77
ε_{max}	0,02184
m	8 g
ρ	0,001633987 g/mm^3

4.1.3 Wet lay-up sample 3

The sample has a Flexural Modulus of around 27 GPa, see Fig. 9. The sample breaks at a stress around 540 MPa, and the strain is around 2,5 %. This can be seen in Fig. 8.

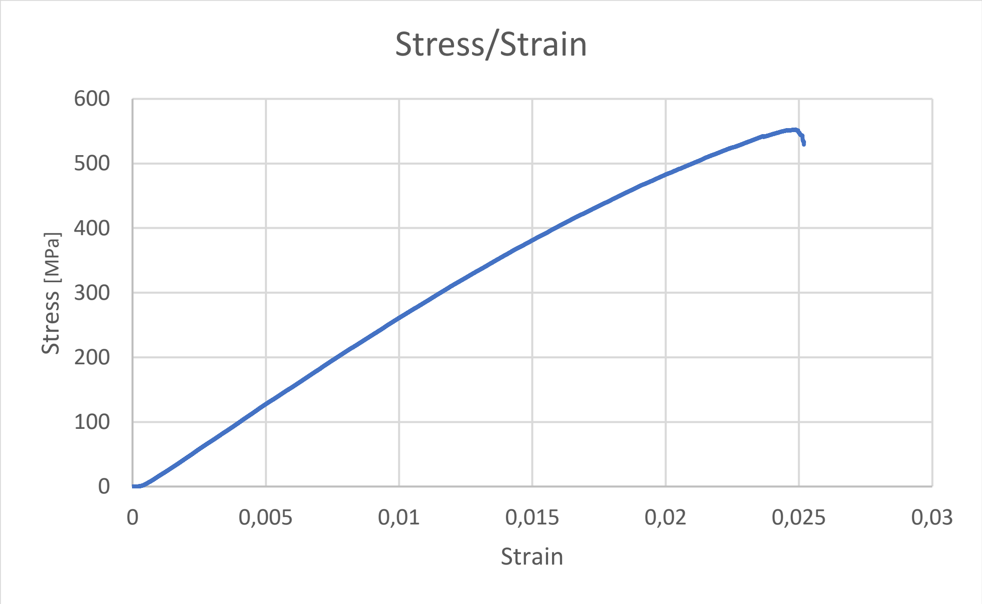

Figure 8 Wet lay-up sample 3 stress/strain curve. Kuikka, M. (2024)

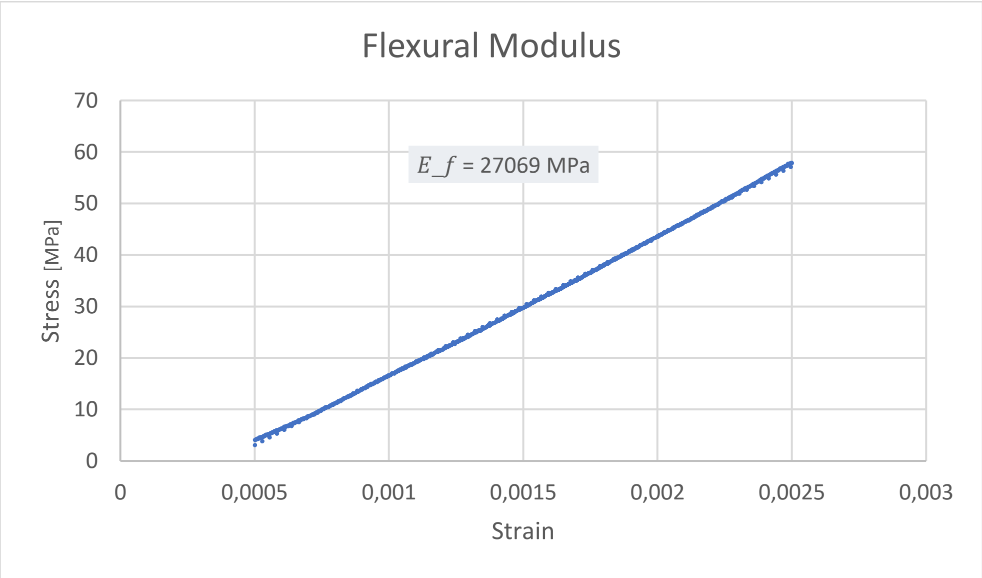

Figure 9 Wet lay-up sample 3 flexural modulus. Kuikka, M. (2024)

Table 3 Wet lay-up sample 3 results. Kuikka, M. (2024)

E_f (numerically)	26875 MPa
E_f (test result)	27069 MPa
$\sigma_{f\ max}$	552,58 MPa
F_{max}	663,10 N
δ_{max}	8,95
ε_{max}	0,0251853
m	8 g
ρ	0,001650165 g/mm^3

4.1.4 Wet lay-up sample 4

The sample has a Flexural Modulus of around 25 GPa, see Fig. 11. The sample breaks at a stress around 460 MPa, and the strain is around 2,2 %. This can be seen in Fig. 10.

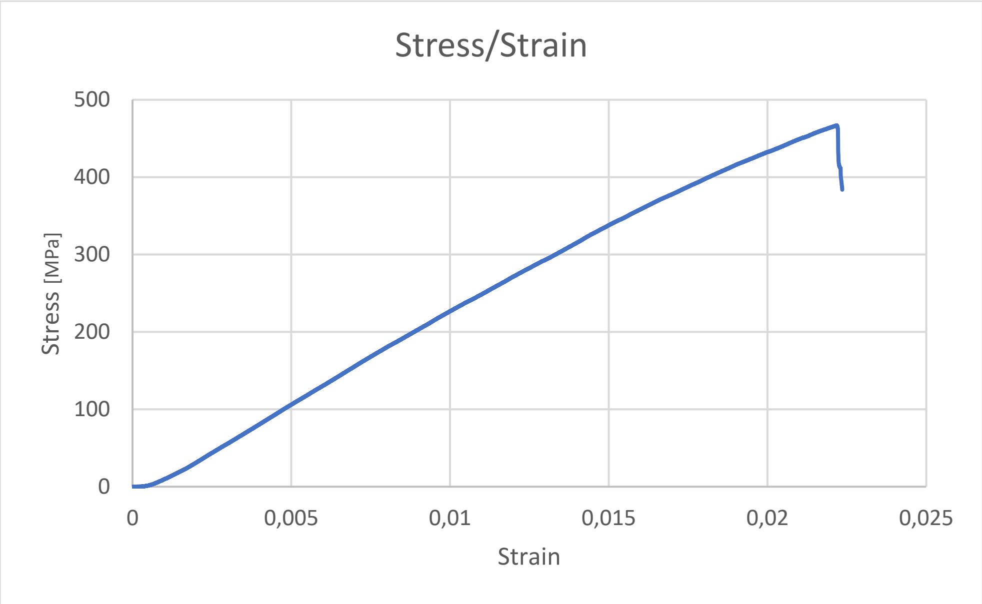

Figure 10 Wet lay-up sample 4 stress/strain curve. Kuikka, M. (2024)

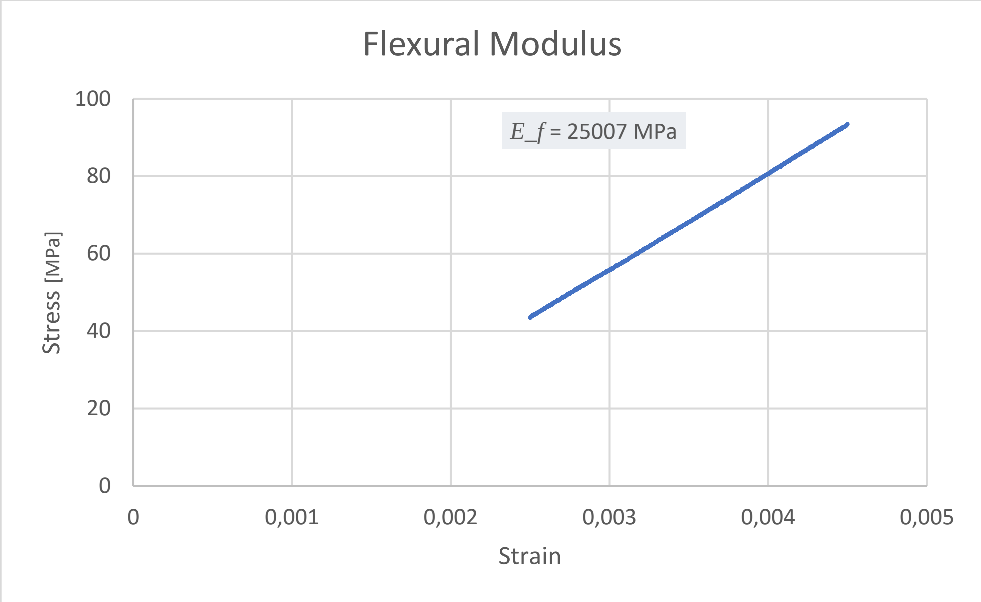

Figure 11 Wet lay-up sample 4 flexural modulus. Kuikka, M. (2024)

Table 4 Wet lay-up sample 4 results. Kuikka, M. (2024)

E_f (numerically)	24916,7 MPa
E_f (test result)	25007 MPa
$\sigma_{f\ max}$	466,833MPa
F_{max}	560,2 N
δ_{max}	7,9489
ε_{max}	0,02236
m	8 g
ρ	0,001666667 g/mm^3

4.1.5 Wet lay-up sample 5

The sample has a Flexural Modulus of around 29 GPa, see Fig. 13. The sample breaks at a stress around 620 MPa, and the strain is around 2,5 %. This can be seen in Fig. 12.

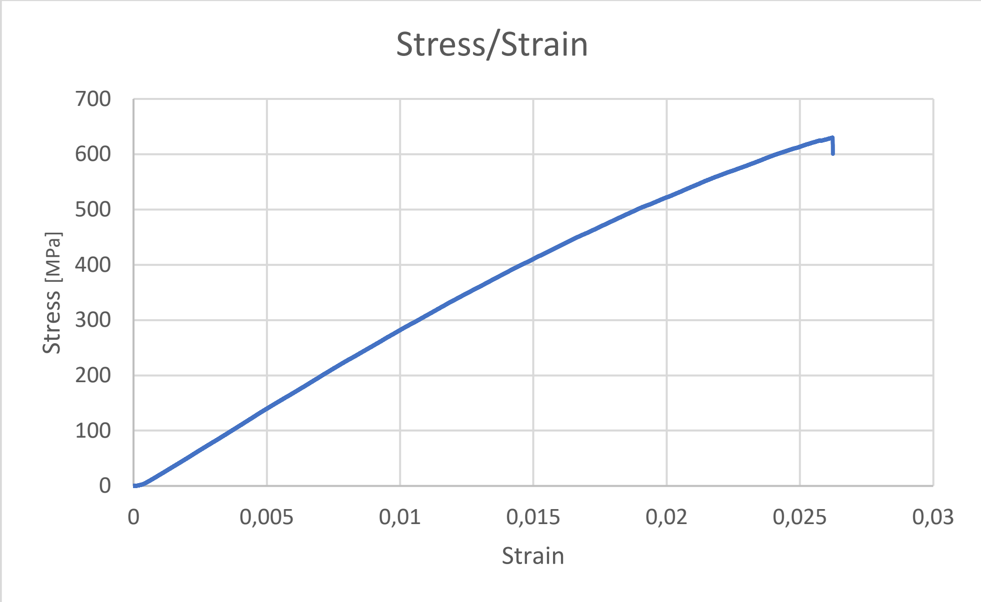

Figure 12 Wet lay-up sample 5 stress/strain curve. Kuikka, M. (2024)

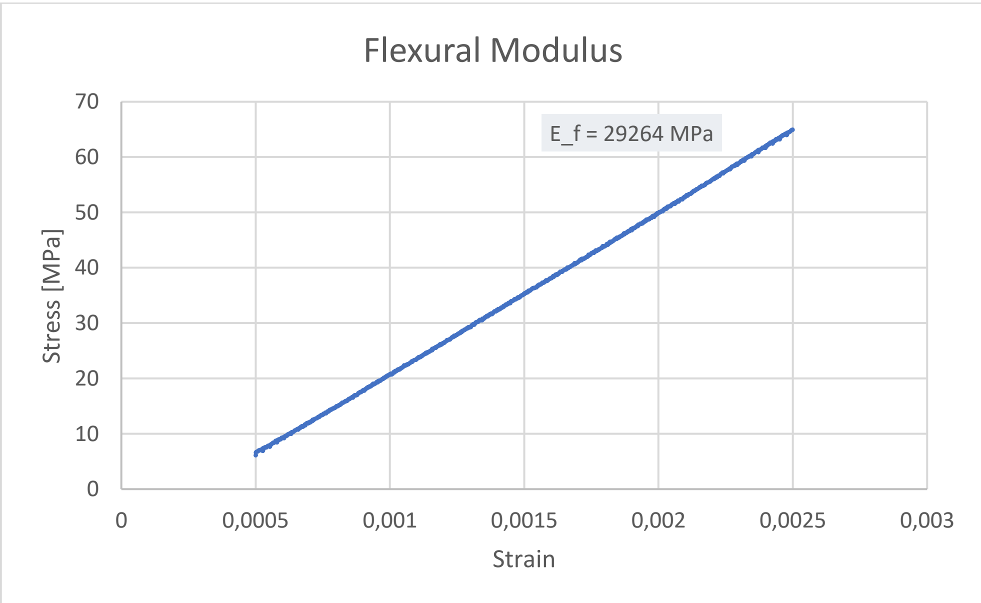

Figure 13 Wet lay-up sample 5 flexural modulus. Kuikka, M. (2024)

Table 5 Wet lay-up sample 5 results. Kuikka, M. (2024)

E_f (numerically)	29166,67 MPa
E_f (test result)	29264 MPa
$\sigma_{f\ max}$	630 MPa
F_{max}	756 N
δ_{max}	9,32899
ε_{max}	0,026238
m	8 g
ρ	0,001553096g/mm^3

4.1.6 Wet lay-up average results of all samples

In Fig. 14 we can see all the results from the three-point bending test. We can see there is variation between the samples. The samples broke between 460 and 630 MPa, making it a 160 MPa difference. There is also some variation in how long the samples were able to endure the stress.

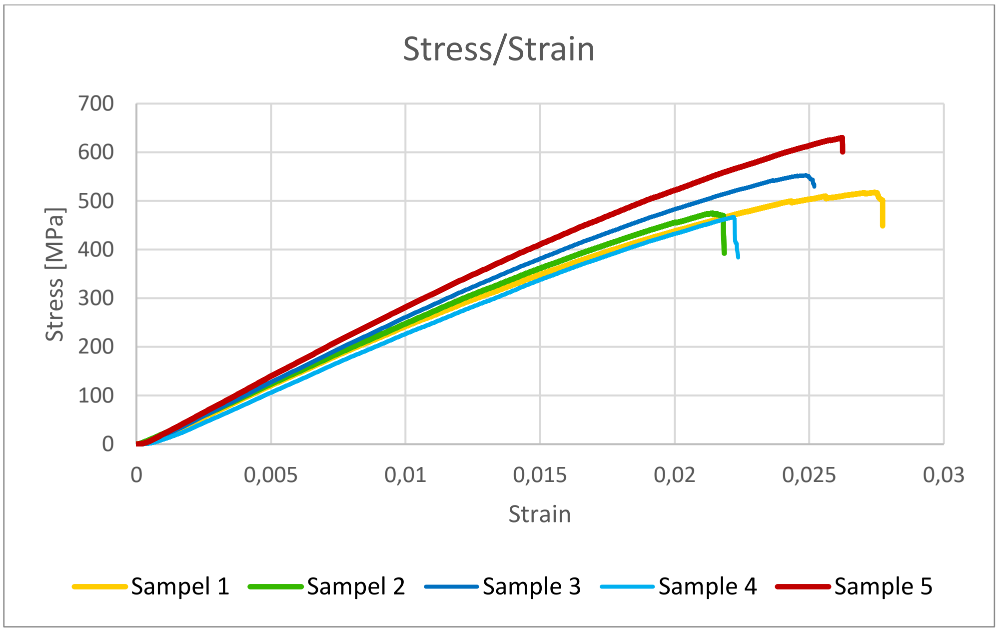

Figure 14 Wet lay-up sample 1- 5 stress/strain curve. Kuikka, M. (2024)

Table 6 Wet lay-up average results of sample 1-5. Kuikka, M. (2024)

E_f (numerically)	26775 MPa
E_f (test result)	26745,60 MPa
$\sigma_{f\ max}$	528,35 MPa
F_{max}	634,02 N
δ_{max}	7,39023
ε_{max}	0,0223419
m	8 g
ρ	0,006911603 g/mm^3

We can see in *Table 6* that the flexural modulus given by the test data and the one calculated has a difference of 30,4 MPa.

4.2 Vacuum infused lamination

4.2.1 Vacuum infused lamination sample 1

The sample has a Flexural Modulus of around 30 GPa, see Fig. 16. The sample breaks at a stress around 510 MPa, and the strain is around 2,1 %. This can be seen in Fig. 15.

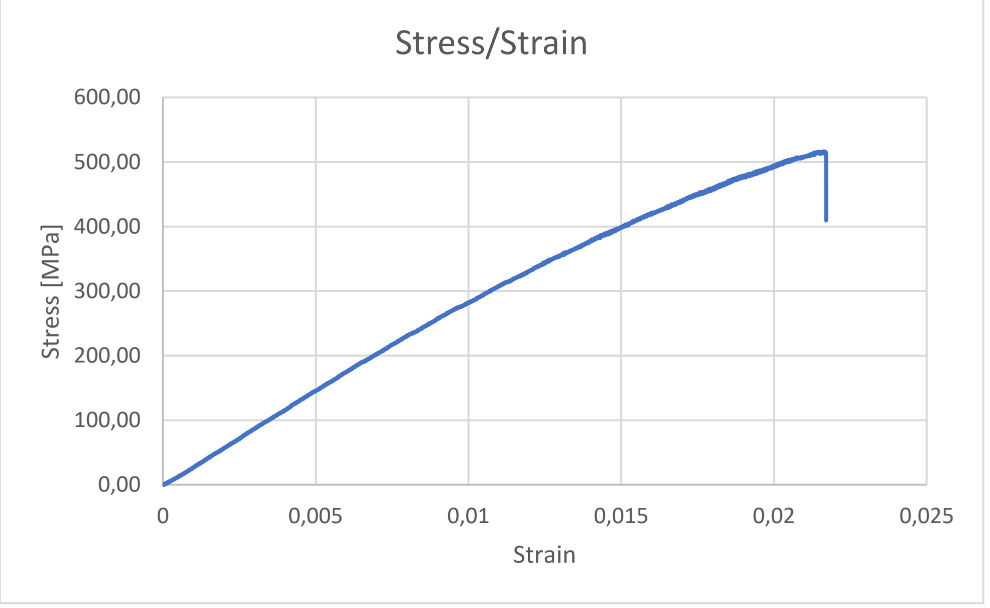

Figure 15 Vacuum infused lamination sample 1 stress/strain curve. Kuikka, M. (2024)

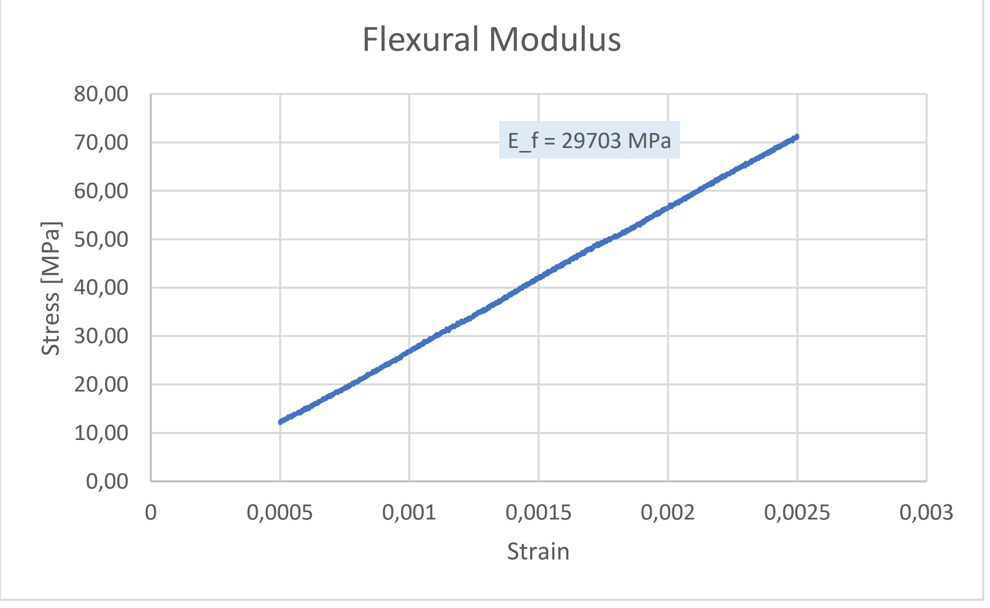

Figure 16 Vacuum infused lamination sample 1 flexural modulus. Kuikka, M. (2024)

Table 7 Vacuum infused lamination sample 1 results. Kuikka, M. (2024)

E_f (numerically)	29300 MPa
E_f (test result)	29703 MPa
$\sigma_{f\ max}$	516,40 MPa
F_{max}	258,20 N
δ_{max}	11,58
ε_{max}	0,026238
m	5 g
ρ	0,001650165g/mm^3

4.2.2 Vacuum infused lamination sample 2

The sample has a Flexural Modulus of around 30 GPa, see Fig. 18. The sample breaks completely at a stress around 560 MPa, and the strain is around 3,1 %. This can be seen in Fig. 17.

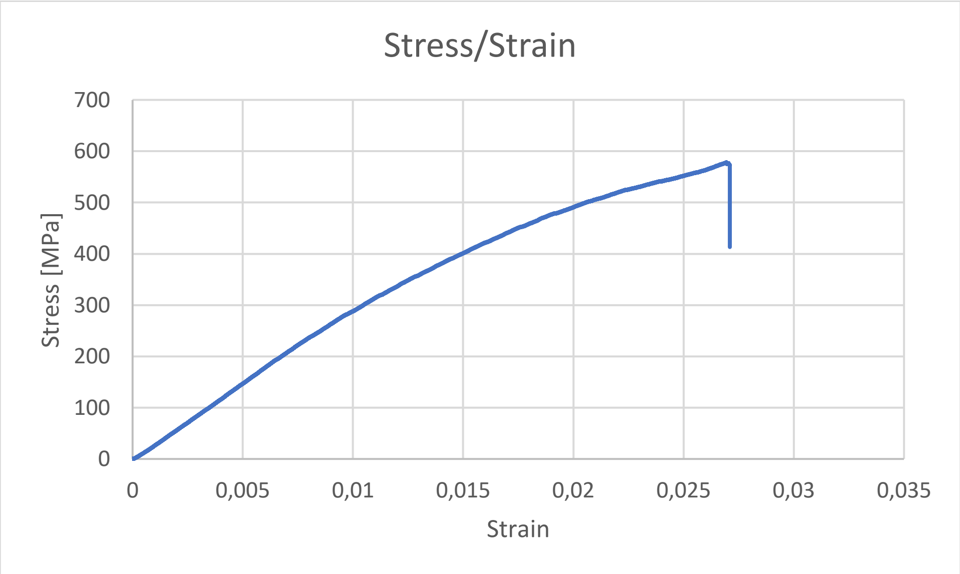

Figure 17 Vacuum infused lamination sample 2 stress/strain. Kuikka, M. (2024)

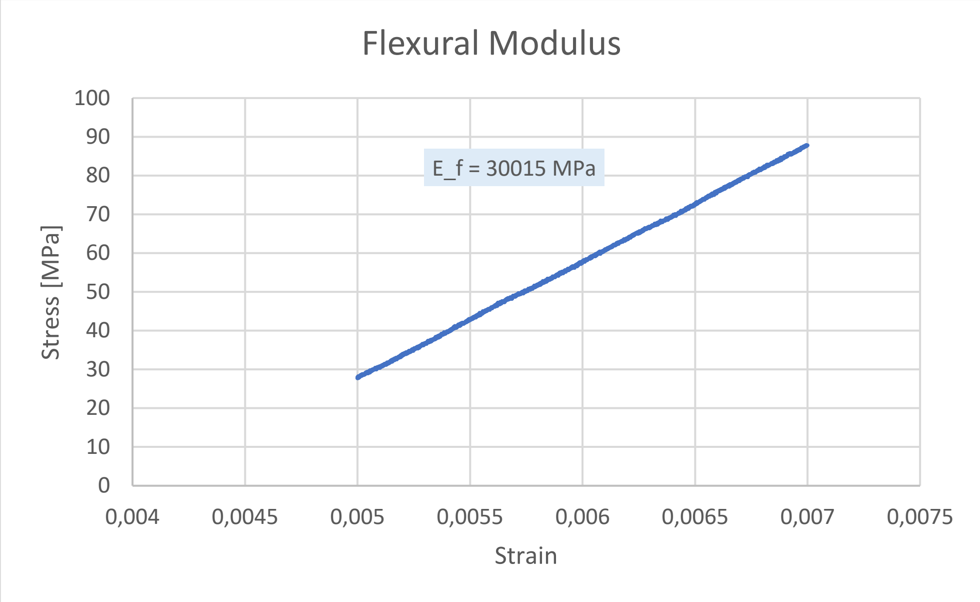

Figure 18 Vacuum infused lamination sample 2 flexural modulus. Kuikka, M. (2024)

Table 8 Vacuum infused lamination sample 2 results. Kuikka, M. (2024)

E_f (numerically)	29900 MPa
E_f (test result)	30015 MPa
$\sigma_{f\ max}$	566,8 MPa
F_{max}	283,40 N
δ_{max}	11,58
ε_{max}	0,03015
m	5 g
ρ	0,00154703 g/mm^3

The loading pin was not close enough to the sample, so the stress/strain curve started later than from strain 0, as seen in Fig. 19. Because of this $\varepsilon_f{}'$= 0,005 and $\varepsilon_f{}''$ = 0,007.

4.2.3 Vacuum infused lamination sample 3

The sample has a Flexural Modulus of around 32 GPa, see Fig. 20. The sample breaks completely at a stress around 510 MPa, and the strain is around 1,8 %. This can be seen in Fig. 19.

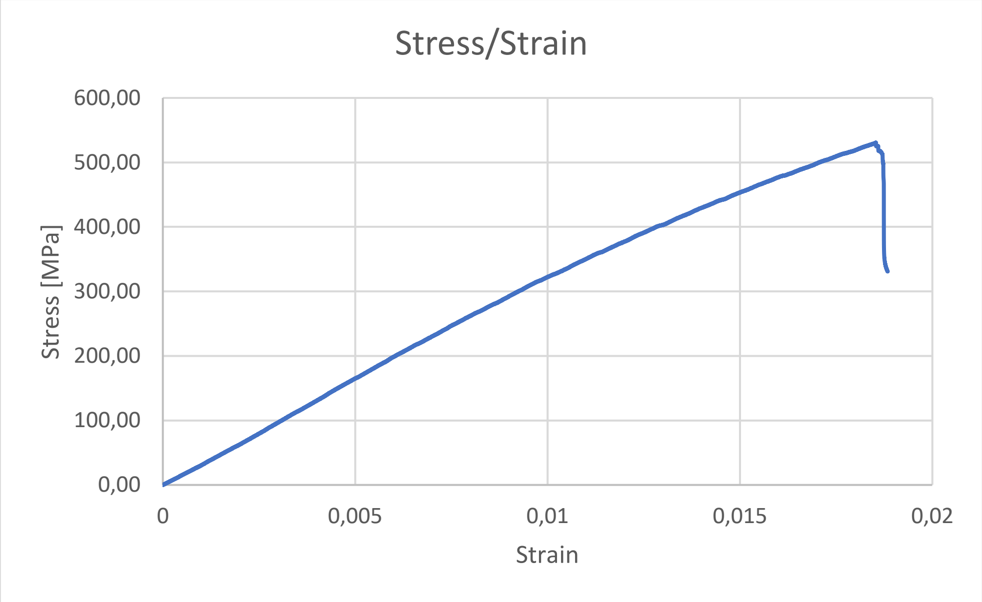

Figure 19 Vacuum infused lamination sample 3 stress/strain. Kuikka, M. (2024)

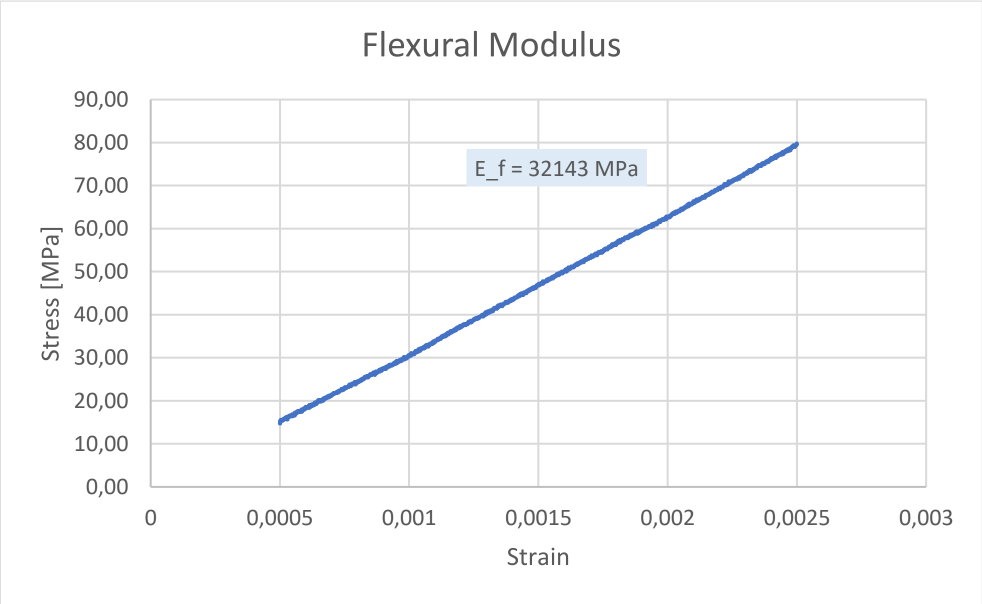

Figure 20 Vacuum infused lamination sample 3 flexural modulus. Kuikka, M. (2024)

Table 9 Vacuum infused lamination sample 3 results. Kuikka, M. (2024)

E_f (numerically)	32200 MPa
E_f (test result)	32143 MPa
$\sigma_{f\ max}$	530,80 MPa
F_{max}	265,40 N
δ_{max}	10,05
ε_{max}	0,018842
m	5 g
ρ	0,001470588 g/mm^3

4.2.4 Vacuum infused lamination sample 4

The sample has a Flexural Modulus of around 28 GPa, see Fig. 22. The sample breaks at a stress around 540 MPa, and the strain is around 2,4 %. This can be seen in Fig. 21.

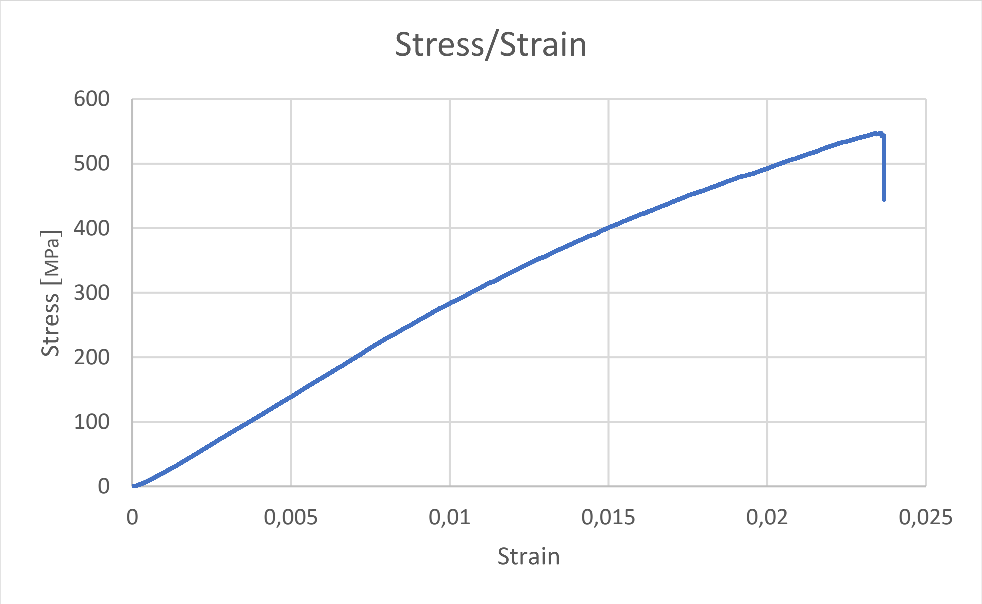

Figure 21 Vacuum infused lamination sample 4 stress/strain. Kuikka, M. (2024)

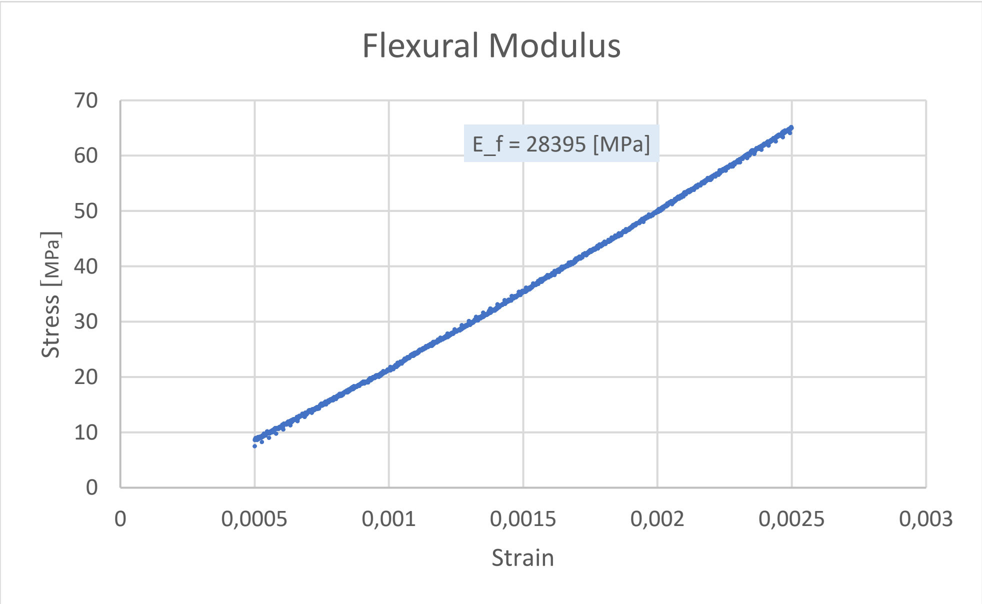

Figure 22 Vacuum infused lamination sample 4 flexural modulus. Kuikka, M. (2024)

Table 10 Vacuum infused lamination sample 4 results. Kuikka, M. (2024)

E_f (numerically)	28200 MPa
E_f (test result)	28395 MPa
$\sigma_{f\ max}$	273,60 MPa
F_{max}	547,20 N
δ_{max}	12,63
ε_{max}	0,02368
m	5 g
ρ	0,001666667 g/mm^3

4.2.5 Vacuum infused lamination sample 5

The sample has a Flexural Modulus of around 30 GPa, see Fig. 24. The specimen can be seen starting to fracture when the stress is around 420 MPa, and the strain is around 1,6%. The sample breaks completely at a stress around 430 MPa, and the strain is around 1,7 %. This can be seen in Fig. 23.

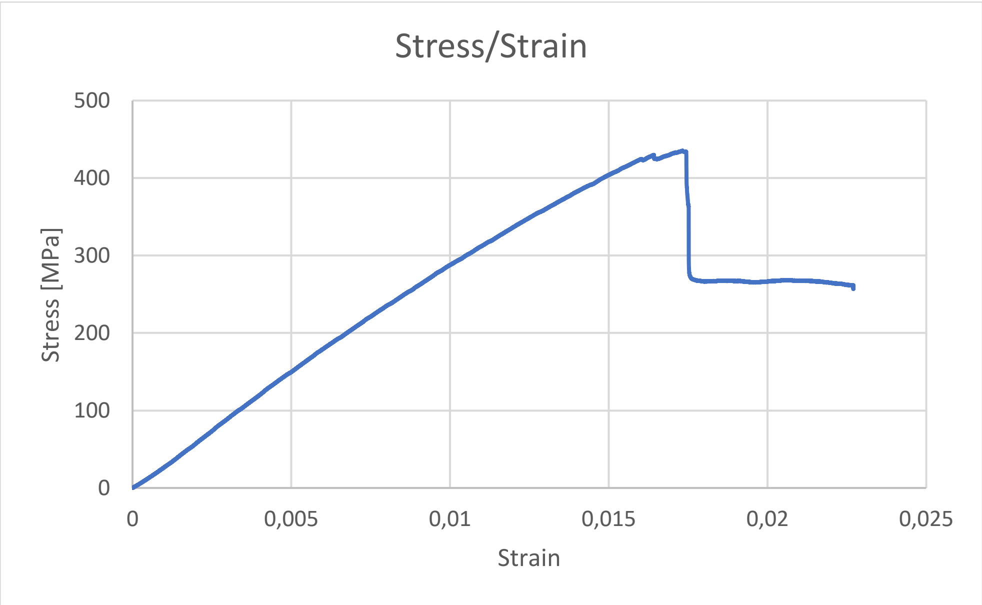

Figure 23 Vacuum infused lamination sample 5 stress/strain. Kuikka, M. (2024)

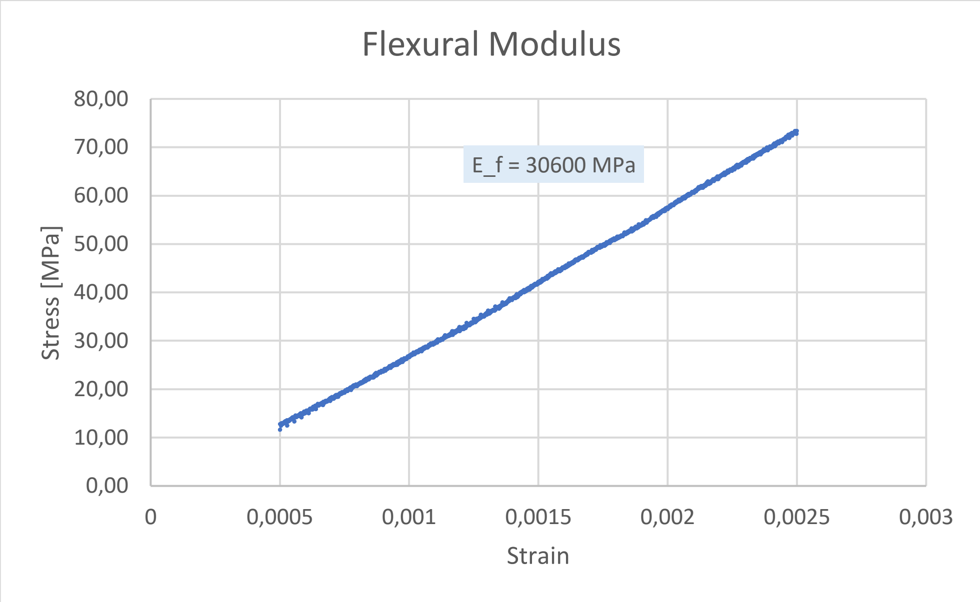

Figure 24 Vacuum infused lamination sample 5 flexural modulus. Kuikka, M. (2024)

Table 11 Vacuum infused lamination sample 5 results. Kuikka, M. (2024)

E_f (numerically)	30300 MPa
E_f (test result)	30600 MPa
$\sigma_{f\ max}$	435,40 MPa
F_{max}	217,70 N
δ_{max}	12,11
ε_{max}	0,02271
m	5 g
ρ	0,001470588 g/mm^3

4.2.6 Vacuum infused lamination average

We can see in Fig. 25 that the vacuum infused laminations samples broke between 415 and 575 MPa, making the difference 160 MPa. We can also see some variation in how long the samples could take the stress.

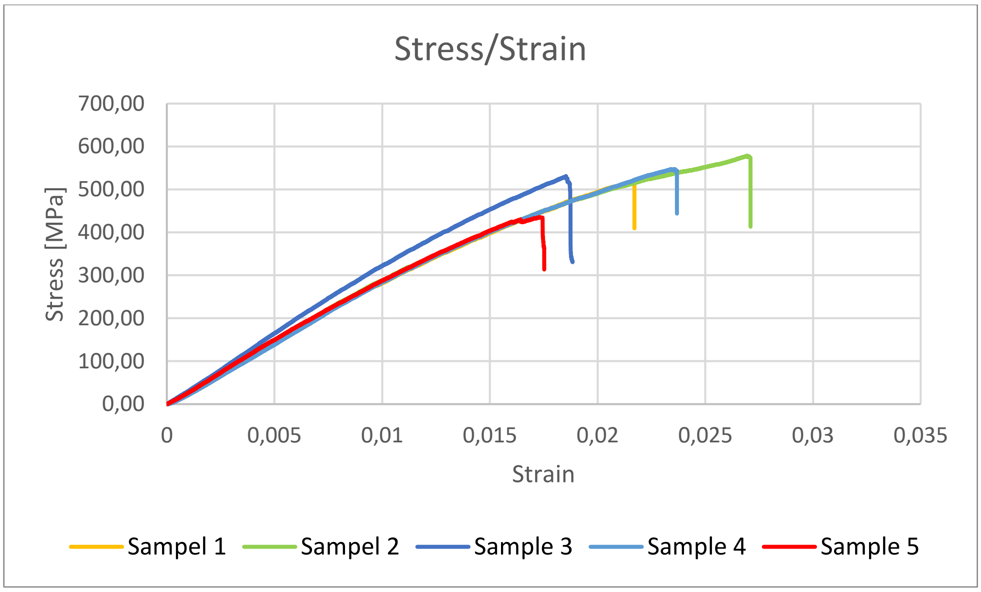

Figure 25 Vacuum infused lamination sample 1- 5 stress/strain curve. Kuikka, M. (2024)

Table 12 Vacuum infused lamination average results of sample 1-5. Kuikka, M. (2024)

E_f (numerically)	29980 MPa
E_f (test result)	30171,2 MPa
$\sigma_{f\ max}$	519,32 MPa
F_{max}	259,66 N
δ_{max}	12,29
ε_{max}	0,0223419
m	5 g
ρ	0,006628567 g/mm^3

We can see in *Table 12* that the flexural modulus given by the test data and the one calculated has a difference of 211 MPa.

4.3 Prepreg

4.3.1 Prepreg sample 1

The sample has a Flexural Modulus of around 29 GPa, see Fig. 27. The specimen can be seen starting to fracture when the stress is around 470 MPa, and the strain is around 1,7%. The sample breaks completely at a stress around 450 MPa, and the strain is around 1,8 %. This can be seen in Fig. 26.

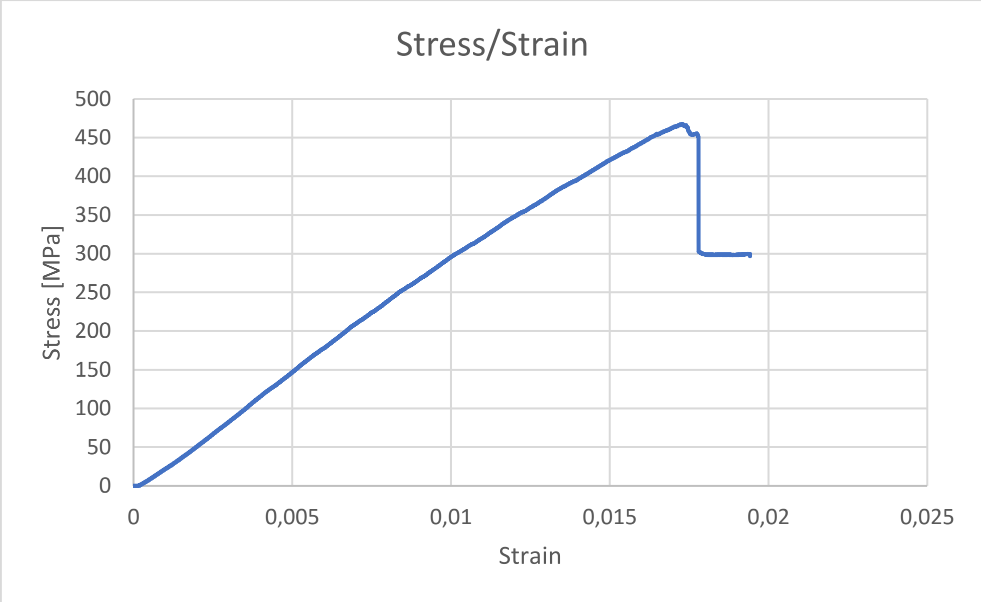

Figure 26 Prepreg sample 1 stress/strain. Kuikka, M. (2024)

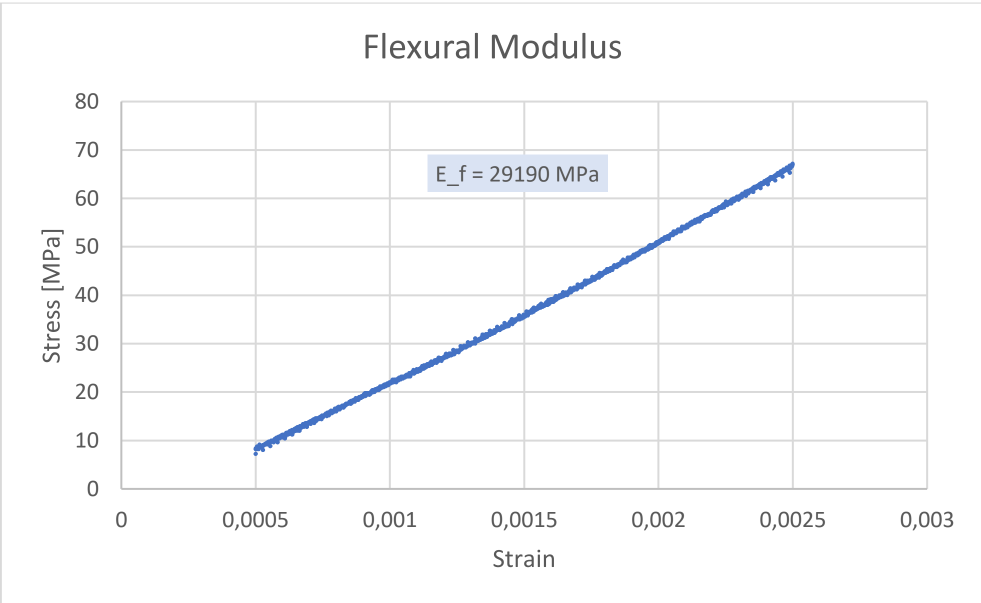

Figure 27 Prepreg sample 1 flexural modulus. Kuikka, M. (2024)

Table 13 Prepreg sample 1 results. Kuikka, M. (2024)

E_f (numerically)	29500 MPa
E_f (test result)	29190 MPa
$\sigma_{f\ max}$	467,60 MPa
F_{max}	233,80 N
δ_{max}	10,36
ε_{max}	0,01942
m	5 g
ρ	0,00154703 g/mm^3

4.3.2 Prepreg sample

The sample has a Flexural Modulus of around 31 GPa, see Fig. 29. The sample breaks completely at a stress around 490 MPa, and the strain is around 1,8 %. This can be seen in Fig. 28.

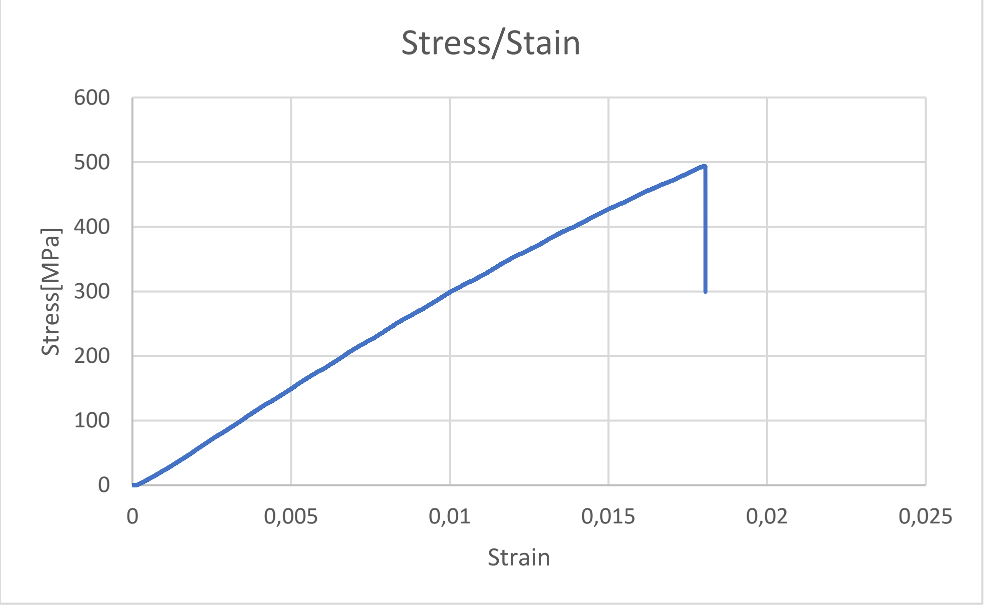

Figure 28 Prepreg sample 2 stress/strain. Kuikka, M. (2024)

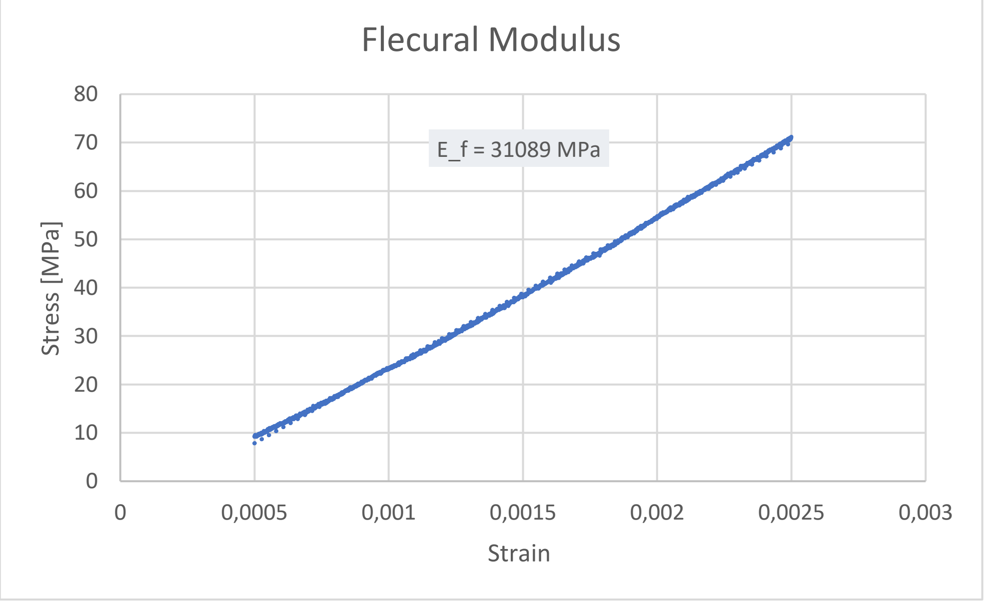

Figure 29 Prepreg sample 2 flexural modulus. Kuikka, M. (2024)

Table 14 Prepreg sample 2 results. Kuikka, M. (2024)

E_f (numerically)	31000 MPa
E_f (test result)	31089 MPa
$\sigma_{f\ max}$	494,20 MPa
F_{max}	247,10 N
δ_{max}	9,63
ε_{max}	0,018059
m	5 g
ρ	0,001470588 g/mm^3

4.3.3 Prepreg sample 3

The sample has a Flexural Modulus of around 33 GPa, see Fig. 31. The specimen can be seen starting to fracture when the stress is around 540 MPa, and the strain is around 1,8%. The sample breaks completely at a stress around 550 MPa, and the strain is around 1,9 %. This can be seen in Fig. 30.

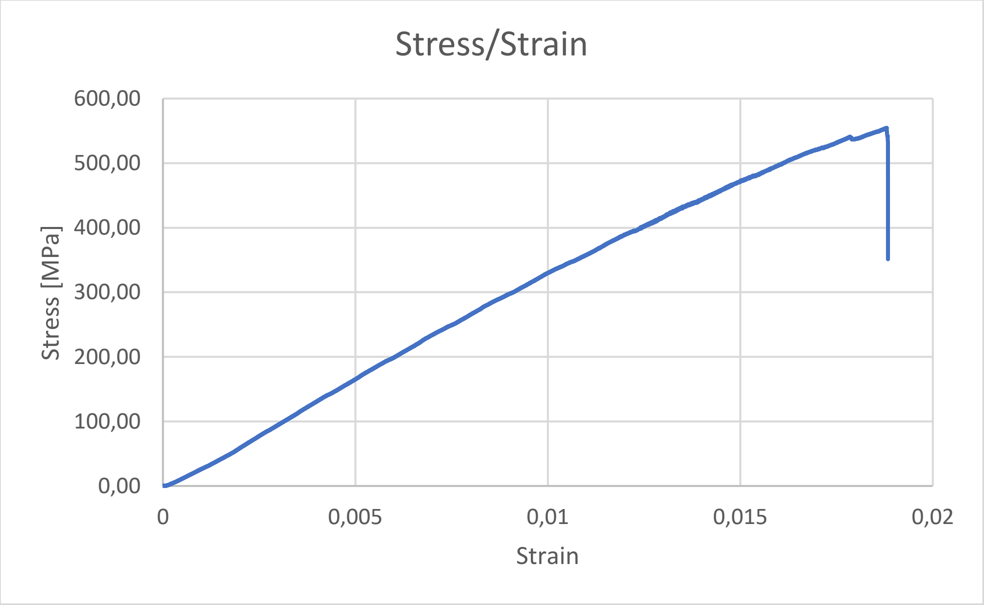

Figure 30 Prepreg sample 3 stress/strain. Kuikka, M. (2024)

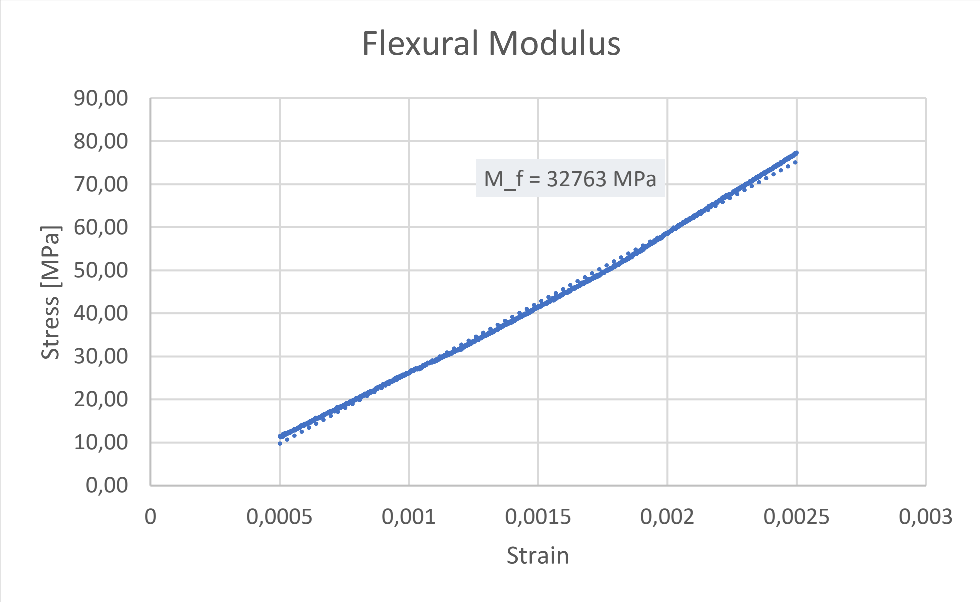

Figure 31 Prepreg sample 3 flexural modulus. Kuikka, M. (2024)

Table 15 Prepreg sample 3 results. Kuikka, M. (2024)

E_f (numerically)	33000 MPa
E_f (test result)	32763 MPa
$\sigma_{f\ max}$	554,80 MPa
F_{max}	277,40 N
δ_{max}	10,05
ε_{max}	0,018838
m	5 g
ρ	0,00154703 g/mm^3

4.3.4 Prepreg sample 4

The sample has a Flexural Modulus of around 32 GPa, see Fig. 33. The sample breaks completely at a stress around 570 MPa, and the strain is around 2,0 %. This can be seen in Fig. 32.

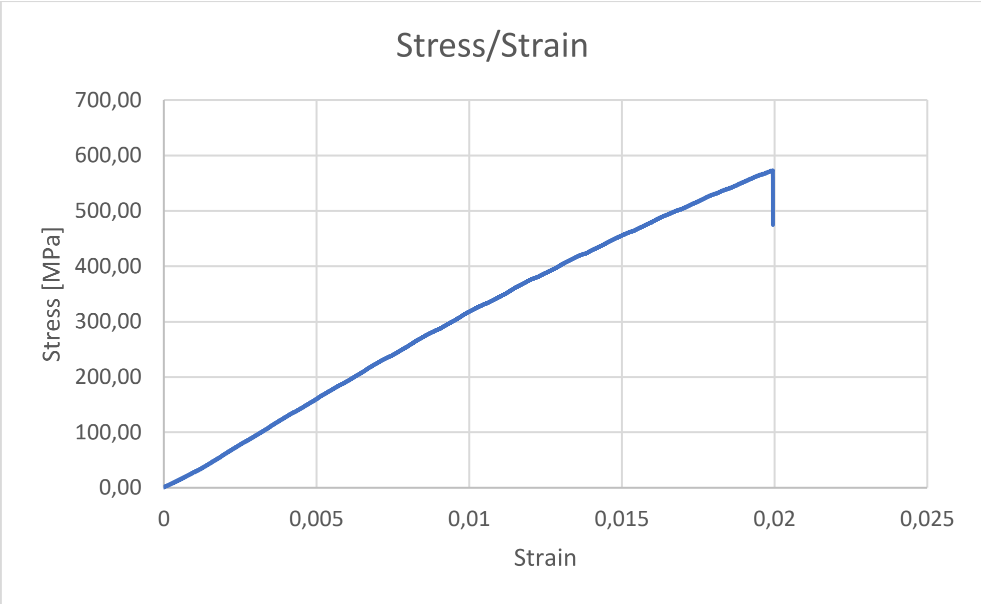

Figure 32 Prepreg sample 4 stress/strain. Kuikka, M. (2024)

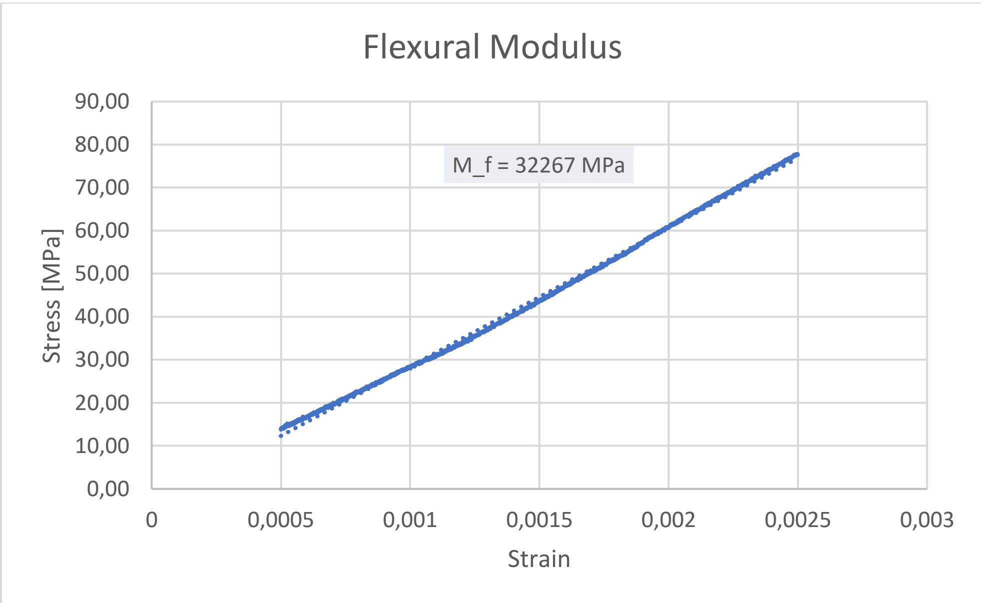

Figure 33 Prepreg sample 4 flexural modulus. Kuikka, M. (2024)

Table 16 Prepreg sample 4 results. Kuikka, M. (2024)

E_f (numerically)	31900 MPa
E_f (test result)	32267 MPa
$\sigma_{f\ max}$	572,80 MPa
F_{max}	286,40 N
δ_{max}	10,64
ε_{max}	0,019951
m	5 g
ρ	0,0015625 g/mm^3

4.3.5 Prepreg sample 5

The sample has a Flexural Modulus of around 27 GPa, see Fig. 35. The sample breaks completely at a stress around 520 MPa, and the strain is around 1,8 %. This can be seen in Fig. 34.

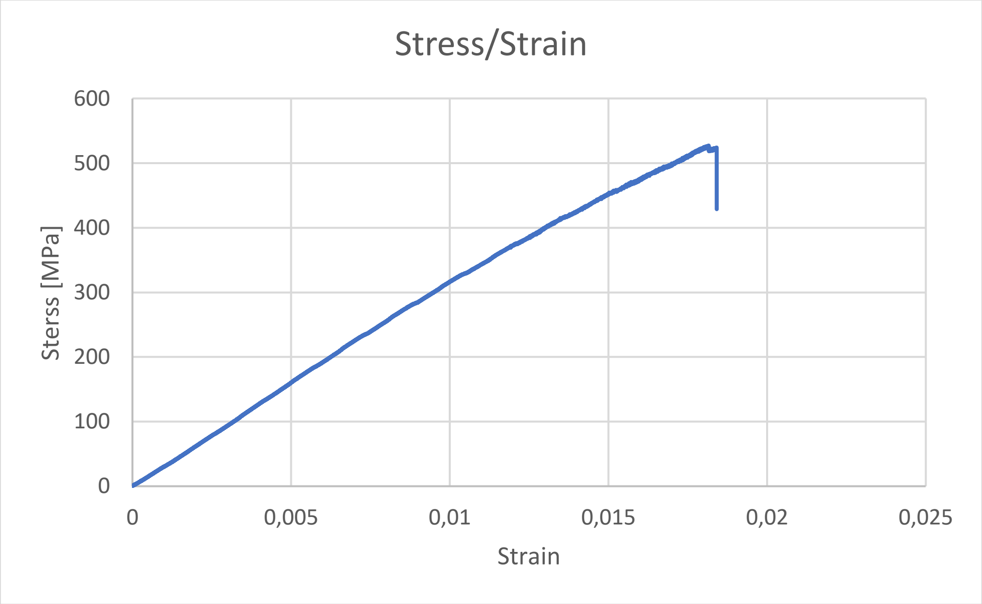

Figure 34 Prepreg sample 5 stress/strain. Kuikka, M. (2024)

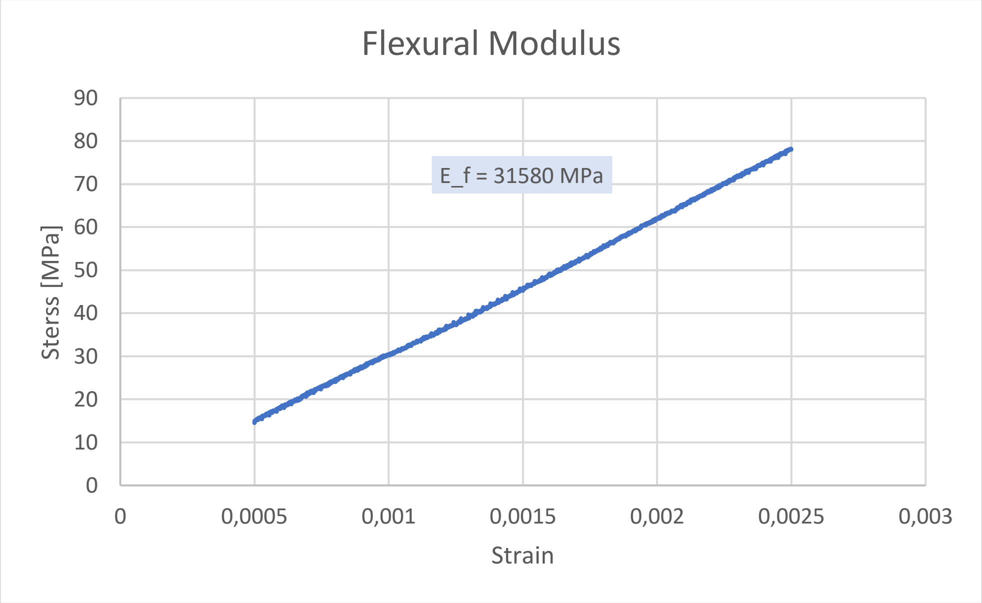

Figure 35 Prepreg sample 5 flexural modulus. Kuikka, M. (2024)

Table 17 Prepreg sample 5 results. Kuikka, M. (2024)

E_f (numerically)	31600 MPa
E_f (test result)	31580 MPa
$\sigma_{f\ max}$	527,20 MPa
F_{max}	263,60 N
δ_{max}	9,82
ε_{max}	0,01841
m	5 g
ρ	0,001470588 g/mm^3

4.3.6 Prepreg results

In Fig. 36 we can see all 5 prepreg samples. We can see that the samples break between 450 and 550 MPa. Making it the smallest difference between the sample groups. The prepreg samples have the most centered breaking point from the sample groups.

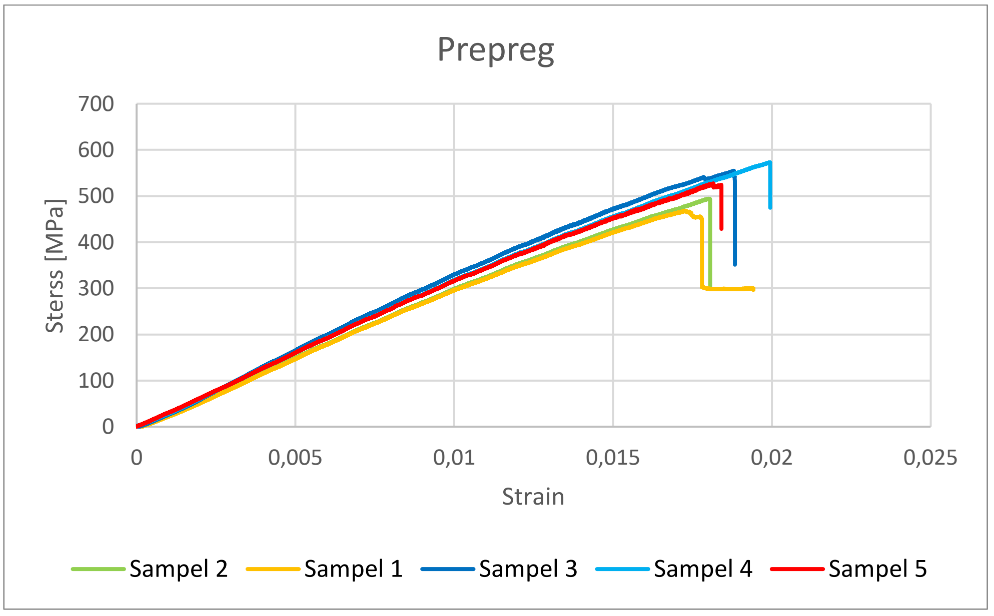

Figure 36 Prepreg sample 1- 5 stress/strain curve. Kuikka, M. (2024)

Table 18 Prepreg average results of sample 1-5. Kuikka, M. (2024)

E_f (numerically)	31377,8 MPa
E_f (test result)	31460 MPa
$\sigma_{f\ max}$	532,44 MPa
F_{max}	266,22 N
δ_{max}	10,2633
ε_{max}	0,01924
m	5 g
ρ	0,006421265 g/mm^3

We can see in Table 18 that the flexural modulus given by the test data and the one calculated has a difference of 171 MPa.

4.4 Sample dimensions

In Tab. 19 we can see the dimension for all the samples.

Table 19 Sample dimensions. Kuikka, M. (2024)

Sample	Length (mm)	Width (mm)	Height (mm)
Wet lay-up sample 1	101	15	3
Wet lay-up sample 2	102	16	3
Wet lay-up sample 3	101	15	3
Wet lay-up sample 4	100	16	3
Wet lay-up sample 5	101	17	3
Vacuum infused lamination sample 1	101	16	2
Vacuum infused lamination sample 2	101	15	2
Vacuum infused lamination sample 3	100	15	2
Vacuum infused lamination sample 4	100	16	2
Vacuum infused lamination sample 5	100	17	2
Prepreg sample 1	101	16	2
Prepreg sample 2	100	15	2
Prepreg sample 3	101	15	2
Prepreg sample 4	100	16	2
Prepreg sample 5	100	17	2

5 Discussion

The results showed that the prepreg and the vacuum infused lamination have a higher flexural modulus, fibre volume fraction and maximum flexural strength, while wet lay-up had the maximum force. This is due to the prepreg, and vacuum infused lamination samples were 1 mm thinner than the wet lay-up lamination although all three laminations have the same number of layers. A materials thickness has a significant impact on its flexural strength, since thicker materials have a higher moment of inertia which gives them a higher resistant to bending and flexural strength. A material with a higher moment of inertia can endure more force. This is why the vacuum infused lamination and the prepreg is more flexible than the wet lay-up, and why since there is a difference in thickness.

The prepreg and vacuum infused lamination samples have a flexural modulus of over 30 000 MPa, while wet lay-up has flexural modulus under 27 000 MPa, making it an over 3000 MPa difference. The force needed to break the laminates are logically the other way around. The maximum force for prepreg and vacuum infused lamination is around 260 N, and for wet lay-up it is over 630 N. These results show clearly how moment of inertia works.

When planning the experiment, it was discussed if the laminates should be made with the same number of layers or to make them the same thickness. It was decided that it should be made with the same number of layers since otherwise it would not give an accurate result how the technique itself affected the material. If we would have wanted to make the laminates the same thickness, we would have needed to add 2-3 layers to the prepreg and vacuum infused lamination. If this would have been decided, we would have one laminate that is 5 layers thick with 500 g of carbon fibre, and two laminates that are 8 layers thick with 800 g of carbon fibre. This would have made the three laminates inconsistent, since the mechanical properties would have been affected by the amount of carbon and epoxy in the laminate rather than the technique. In this experiment all three laminates have the same number of layers and carbon fibre in them, the only thing that differs is the technique that is used to laminate them. This way we can clearly see that the thickness is clearly affected by the technique used which in turn affects their mechanical properties.

Since the carbon fibre mat has the same weight in all three laminates, we can conclude that the weight difference comes from the resin. The vacuum has helped the prepreg and vacuum infused lamination to squeeze out the excess voids and resin, making them lighter, thinner, and giving them a higher fibre fraction volume.

Porosity is also something that affects the mechanical properties, making the material weaker and reducing its ability to endure stress. Since we didn’t get any result from our porosity test, we don’t know the porosity of our samples. A way to test how porosity affects the mechanical properties of a laminate is to laminate samples with the same thickness, one laminated with vacuum and one without, and then doing a three-point bending test to see the porosity affects their ability to endure stress.

6 Conclusion

Although the wet lay-up could endure approximately 370 N more force than the prepreg and vacuum infused lamination, the wet lay-up samples weighed 60 % more than the other two and is a third thicker. Since carbon fiber laminates are desired for their light weight and high strength this is not good, in a big scale laminate the weight and thickness would be too desirable if done with wet lay-up. If a less flexible and thicker prepreg or vacuum infused lamination is desired it needs more layers to get the same thickness as wet lay-up would need.

When choosing a technique for laminations there are several factors that will influence the choice, e.g. budget, purpose, size, and shape of lamination. If the purpose is only to make something small or to fix a small crack it might be easiest to use the wet lay-up method since investing in vacuum lamination materials can be expensive and not worth it for a small project. However, if someone is constantly making parts and the light weight and strong characteristics are important for the parts, it would be wise to invest in vacuum lamination materials. Since a simple addition of a vacuum can increase the modulus and fibre fraction while decreasing the weight of the laminate. When it comes to prepregs, the trickiest part is usually getting an available oven to work with. Since prepreg must cure in an oven, it is also its biggest limitations. Ovens for this purpose are quite expensive and the oven will restrict what size of parts you can make.

Prepreg is an excellent way of laminating and for companies that have the funds to invest into this technique would experience many benefits from it. Prepreg is easily the cleanest way of lamination, since the epoxy is pre-impregnated, and no mixing of resin is needed. This is ideal for manufacturers who produce high volume of carbon fibre parts that need to be light weight and have high mechanical properties. Since no mixing of epoxy is needed, a lot of work and human errors are avoided, ensuring constant quality throughout manufacturing.

7 Sammanfattning

Kolfiber har en snabbt växande marknad och det finns viktiga sektorer som är storkonsumenter av kolfiber. Exempelvis militären, flyg- och marinindustrin samt sportindustrin använder kolfiber i stora mängder. Kolfiber är populärt tack vare sin styrka fastän den är lätt. Detta har blivit en eftertraktad egenskap och något som det fortfarande forskas inom i förhoppningen om att kunna hitta förbättringar. Själva laminaten består av lager av kompositer i form av fibrer, vävar eller mattor som är bunden med harts. (Saarela et al., 2003, Chap.2.4.1) (IYRS, 2021)

I detta examensarbete analyseras ifall lamineringstekniken påverkar de mekaniska egenskaperna hos kolfiberkompositen. Ett experiment kommer att genomföras där tre laminat kommer att produceras med olika lamineringstekniker. Laminaten kommer att testas på sin böjhållfasthet och laminatens porositet kommer att testas. De lamineringstekniker som kommer att jämföras är våtlaminering, vakuuminfusionslaminering och prepreglaminering. Eftersom prepreg är utvecklat för att ha en optimal fibervolym fraktion för att optimera dess mekaniska egenskaper kan vi förvänta oss att prepreg testbitarna kommer klara av mest tryck före de går av. Medan våtlaminering brukar ha en dålig fibervolym fraktion eftersom epoxin läggs till för hand som kan leda till en överdriven mängd. Därför kan vi förvänta oss att våtlaminat testbitarna kommer vara skörast och gå av med minst mängd tryck jämfört med de andra.

Våtlaminering är den enklaste formen av laminering. En öppen form används och formen rengörs och förbereds med släppmedel. Därefter placeras fiberförstärkningen för hand och hartset appliceras med en rulle eller pensel. Ytterligare lager av fiberförstärkning kan appliceras för att få önskad tjocklek och/eller utseende. I Figure 1 (s. 12) visas hur en vanlig våtlaminering ser ut. Våtlaminering är en simpel och billig lamineringsmetod men den innebär en hög risk för tomrumsbildning. Detta beror på att luft kan fastna mellan skikten när skikten läggs ner för hand utan att ha en kraftig styrka att klämma ut luften. Våt-laminerings processen innebär också en risk för kvarvarande torra fibrer eftersom hartset appliceras för hand, vilket kan lämna den ojämn. Det är också därför som fibervolymfraktionen är svår att kontrollera. Våt-laminering kan utsättas för vakuum för att minimera risken för hålrum, ojämnt harts och torra fläckar. För detta experiment kommer våt-lamineringen inte att utsättas för vakuum. (Norco, 2019)

Vid vakuuminfusionslaminering används vakuumtryck för att pressa in hartset i fibrerna och för att få en jämn hartsfördelning. Formen förbereds på samma sätt som vid våtlaminering och fibrerna placeras sedan i den förberedda formen. Formen täcks sedan med ett plastmembran och kanterna tätas. En vakuumkanal är fäst i plastmembranet och en ingångskanal fastsätts för hartset. Eftersom fibern är så kompakt på grund av vakuumtrycket finns det inget överloppsharts. Figure 2 (s. 13) visar hur en vakuuminfusionslamineringsprocess ser ut. Det finns få tomrum i en vakuuminfusionslaminering och tack vare den jämna fördelningen av harts har laminatet en jämn hållfasthetsgrad. Verktygen för vakuumlaminering kan vara dyra och eftersom lamineringen måste vara innesluten kan storleken av kompositen bli begränsande. (Norco, 2019)

Namnet prepreg kommer från termen pre-impregnerad som syftar på materialets huvudsakliga egenskap. Medan våt-laminering och vakuuminfusionslaminering impregneras med harts under tillverkningen av en produkt eller komponent, medan prepregs fibrer impregneras med harts före tillverkningen av en produkt eller komponent. Detta innebär att prepreg är en halvfärdig produkt som kan rullas upp på rullar. Vid tillverkningen av produkten eller komponenten behöver tillverkaren bara skära en bit prepreg från rullen och lägga den i en form. Prepreg kan staplas i lager för att få önskad tjocklek, sedan täcks formen med ett plastmembran och sätts in i en ugn med vakuum för att härda. Vakuumet hjälper till att minimera tomrum och tvingar ut överloppsharts, vilket gör att fiberkoncentrationen blir hög och vidhäftningen mellan skikten bättre. Figure 3 (s. 14) visar hur en vanlig vakuumhärdad prepregsprocess ser ut. (Norco, 2019)

Prepreg tenderar att ha ett högre fibervolyminnehåll, vilket gör det mer vikteffektivt. Den har högre mekanisk hållfasthet och styvhetsegenskaper jämfört med andra lamineringstekniker. Med denna teknik styrs harts-/härdningsinnehållet och hartsnivåerna av materialtillverkaren. Tekniken möjliggör hög fiberhalt och låg tomrumshalt. Denna lamineringsteknik har dock extra kostnader och det kan vara besvärligt att lagra prepreg. Eftersom prepreg är färdigt impregnerad med harts så måste det förvaras och transporteras i kyla fram till dess användning. Om prepreg inte förvaras i kyla börjar hartset härda och prepreg blir oanvändbart. (Norco, 2019)

För detta experiment är målet att producera tre laminat som har mekaniska skillnader som endast orsakas av lamineringstekniken. För att eliminera så många andra variabler som möjligt används samma eller liknande material i alla laminat. Alla tre laminaten kommer att tillverkas av fem lager av 400g/m^2 biaxiell ±45° kolfiber väv/prepreg. Samma epoxi användes för våt- och vakuuminfusion lamineringen för att minimera skillnaderna mellan de två laminaten.

Laminaten skärs i 5 provbitar enligt ISO 14125-standarden och ett trepunktsböjningstest utförs enligt samma standard. Resultaten från testet kommer att plottas i Excel och kan ses på sidorna 21 – 41. Porositeten kommer att testas med vattenabsorptionsmetoden. Porositeten kan indikera hur mycket tomrum de olika laminaten har. Tomrum är luftfickor eller luckor i laminatet som är utan harts eller fibrer och därmed lämnar ett tomrum. Tomrum kan påverka materialets egenskaper negativt. Det är därför man försöker minimera risken för att de ska uppstå när man tillverkar ett laminat. Tomrum kan leda till sprickor och kan släppa in fukt i kompositen. En tomrumshalt på 1–3 % i laminaten kan redan leda till en minskning upp till 20 % av laminatets mekaniska egenskaper. Tomrum uppstår av olika anledningar på och mellan skikten under lamineringsprocessen. Bland annat ofullständig vätning av fibrerna, felaktig härdning, t.ex. fel temperatur eller tryck under härdningen, och luftinstängning under uppläggningen orsakar tomrum. Ett laminats porositet kan beräknas för att undersöka hålrumsinnehållet. Spänningskoncentration uppstår runt tomrummen när det finns en geometrisk oregelbundenhet i materialet. Det är detta fenomen som försvagar materialet. Tomrum hindrar en jämna fördelningen av spänningar i ett material eftersom spänningar tenderar att koncentrera sig runt tomrum. Eftersom tomrum kan leda till en betydande försämring av materialets mekaniska egenskaper används vakuumpackning för att minimera risken för tomrum att uppstå. (Ritchot, 2022)

När testerna genomfördes är det viktigaste att nämna från de insamlade resultaten hur prepreg- och vakuuminfusionslaminaten har en böjningsmodul på över 30 000 MPa, medan våt-laminering har en böjningsmodul på under 27 000 MPa, vilket innebär en skillnad över 3000 MPa. Å andra sidan är den kraft som behövs för att bryta laminaten tvärtom. Den maximala kraften för prepreg- och vakuuminfusionslaminering är cirka 260 N, medan den för våt-laminering är över 630 N. Detta beror på att när laminaten hade härdat var provbitarna av våt-lamineringen 3 g tyngre och 1 mm tjockare än provbitarna som tillverkats med prepreg och vakuuminfusionslaminering, trots att de har samma antal lager.

Vid planeringen av experimentet diskuterades det om laminaten skulle tillverkas med samma antal lager eller om de skulle ha samma tjocklek. Det beslutades att det skulle göras med samma antal lager eftersom det annars inte skulle ge ett korrekt resultat av hur tekniken i sig påverkade laminatet. Om vi skulle ha velat göra laminaten av samma tjocklek, skulle vi ha behövt lägga till 2–3 lager mera till prepreg- och vakuuminfusionslaminaten. Men då skulle vi ha ett laminat som är 5 lager tjockt med 500 g kolfiber och två laminat som är 8 lager tjocka med 800 g kolfiber, vilket betyder att dessa tre laminat inte skulle vara likadana. I det här experimentet har alla tre laminat samma antal lager och samma mängd kolfiber i sig, det enda som skiljer dem åt är lamineringstekniken som används. På så sätt kan vi tydligt se att tjocklekens skillnad påverkades endast av vilken teknik som användes.

Eftersom kolfibermattan har samma vikt i alla tre laminaten kan vi dra slutsatsen att viktskillnaden i provbitarna kommer från hartset. Vakuumet har hjälpt prepreg och vakuuminfusionslaminaten att pressa ut tomrum och överloppsharts. Detta gör dem lättare, tunnare och ger dem en högre fiberfraktionsvolym än om de skulle ha tillverkats utan vakuum. Det här experimentet borde göras på en vakuumförpackad våtlaminering för att se ifall det skulle ge liknande resultat som prepreg och vakuuminfusionslaminatet. Detta skulle ge oss en klarare bild gällande fördelarna gällande användning av vakuum under härdning.

Trots att våt-lamineringen hade i medeltal den högsta maximala kraften före provbitarna gick sönder hade prepreg i medeltal den högsta böjmodulen och böjspänningen. Detta kan också förklaras av tjockleksskillnaden. Vi kan därmed dra slutsatsen att den starkaste och lättaste laminatet kommer från prepreg.

Vid val av teknik för laminering finns det flera faktorer som påverkar valet, t.ex. budget, syfte, storlek och form på lamineringen. Om syftet är att bara tillverka något litet eller att fixa en liten spricka kan det vara bäst att använda våt-laminering eftersom det kan vara dyrt att investera i vakuumlamineringsmaterial. Men om du ständigt tillverkar delar och den lätta vikten och de starka egenskaperna är viktiga för delarna, skulle det vara klokt att investera i vakuumlamineringsmaterial. Eftersom en enkel tillsats av vakuum kan öka modul och fiberfraktionen, samtidigt som den minimerar laminatets vik. När det gäller prepregs är det svåraste oftast att få tag på en ugn. Eftersom prepreg måste härdas i en ugn innebär det begränsningar. Ugnar för detta ändamål är dyra och ugnen begränsar storleken på de delar som kan tillverkas. Prepreg är ett fantastiskt sätt att laminera och företag skulle erfara många fördelar med att investera i denna teknik. Prepreg är lätt det renaste sättet att laminera eftersom epoxin är färdigt impregnerat så ingen blandning av harts behövs göras på plats. Detta är idealiskt för tillverkare som producerar stora volymer av kolfiberdelar som måste vara lätta och ha höga mekaniska egenskaper. Eftersom ingen blandning av epoxi behövs undviks mycket arbete och mänskliga fel, vilket säkerställer konstant kvalitet under hela tillverkningen.

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Appendix A

CURED RESIN MECHANICAL AND THERMAL PROPERTIES

PROPERTIES	SYMBOL	UNITS	28 DAYS AT 21°C	16 HOURS AT 50°C**	5 HOURS AT 70°C**	TEST STANDARD
Glass Transition Temperature	Tg_2	°C	59	77	85	ISO 11357 (DSC)
Ultimate Glass Transition Temp.	UTg_2	°C	-	98	94	ISO 11357 (DSC)
Glass Transition Temperature	Tg_1	°C	-	74	88	ISO 6721 (DMA)
Cured Density	ρ_{CURED}	g/cm^3	-	1.164	-	ISO 1183-1A
Linear Shrinkage	-	%	-	1.85	-	ISO 1183-1A
28 Day Water Uptake (coupon size 60x60x1mm)	-	mg	-	32	-	ISO 62
Tensile Strength	σ_T	MPa	48.7	80.4	79.5	ISO 527-2
Tensile Modulus	E_T	GPa	3.59	3.49	3.26	ISO 527-2
Tensile Strain	ε_T	%	1.80	4.40	7.55	ISO 527-2
3-point flexural strength	σ_F	N/mm^2	84.4	131	124	ISO 178
3-point flexural modulus	E_F	GPa	3.47	3.42	3.22	ISO 178
3-point flexural Strain	ε_F	%	2.66	5.96	8.11	ISO 178

Appendix B

Composite

A composite is a fibre material that has been reinforced with filaments. A composite is identified as a material that acts as one completely merged material although it doesn't dissolve or merge completely into each other, thus making it a matrix.

Cure

To cure something is to irreversibly change the properties of a thermoset resin with the help of a chemical reaction. Pressure and heat can be used to help with the curing process, but they are not a must.

Cure cycle

A cure cycle is a cycle used to cure a prepreg or a thermoset resin. The cycle is made up by time/temperature/pressure.

Deformation

Deformation is when a material's shape is changed because of a force that is applied on to it.

Elasticity

Elasticity is the property materials have that allows them to return to their original shape after they have been put under a force that has caused the material to deform.

Fibre

A fibre is a single strand of a single homogeneous material.

Fibre content

Fibre content is the number of fibres that are in a cured composite. The value is commonly expressed as a percentage of the cured composite.

Hardener

The hardener is the component that when mixed with the resin creates a chemical reaction that forms a crosslinked (thermoset) plastic.

Lamina

A lamina is a laminate made from a single layer.

Laminate

A laminate is made from one or more materials that are bonded together. A laminate has two or more layers.

Matrix

The matrix is the component in a laminate or lamina that embeds itself in the fibres and keeps the laminate or lamina together.

Resin

Resin is a plastic/polymer. Resin is the polymer component of Fibre Reinforced Polymer (laminates). Resins are one of a two-part component, the other one being the hardener.

Strain

Strain is a non-dimensional unit, it can be unitless or presented in different units (e.g. percentage) Strain tells the changes that occur in a material body's shape or size do to force.

Stress

Stress tells the force's intensity at a certain point of the material body. Stress is expressed in force per unit area.

Tow (K)

Tow is the size of the thread that is used to make the fibre fabric. A tow size can be marked as 3K, 12K, 24K and so on. The number before the K tells us how many thousands od individual carbon filaments on tow is made from. 3K means the tow has 3000 individual filaments.