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# Effect of artificial aging on Mode I delamination properties of composites with an [0/90] interface

Master's thesis in Produktutvikling og produksjon

Supervisor: Andreas Echtermeyer

June 2023



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Norwegian University of Science and Technology  
Faculty of Engineering  
Department of Mechanical and Industrial Engineering







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## Abstract

This master's thesis is written in collaboration with Norges teknisk-naturvitenskapelige universitet (NTNU) in Trondheim. The work's objective is to get a better understanding of the effect of artificial aging on the Mode I delamination strength of polymer matrix composites. The aging effect was tested in static and fatigue tests, and the whole project was supervised by Andreas Echtermeyer. Several industries are interested in using composites in new and innovative designs, and therefore it is crucial to have a good understanding of the subject studied in the work done for this thesis.

The master's project is a continuation of a specialization project performed in the autumn semester of 2022. In the specialization project, the focus was to learn how to produce test specimens and determine which test methods to use and how to perform them. Some figures are therefore the same as those used in the specialization project, as well as some sections being based on the previous work.

During the work with the master's project, polymer matrix composite specimens were produced using the vacuum-assisted resin transfer method. The specimens were produced with a  $[0/90]_3$  ( $[0/90/0/90/0/90]$ ) fiber orientation, and made with epoxy and reinforcing glass fibers. The chosen layup promotes a Mode I delamination in the interface between a  $0^\circ$  layer and a  $90^\circ$  layer. Delamination in the  $[0/90]$  interface is of interest, due to Mode I failure results most often are acquired by tests performed on specimens with an unidirectional layup.

The tests performed during the project are the Double Cantilever Beam (DCB) test and a Mode I cyclic loading test. The tests gave results for the static strength of the specimens with the  $[0/90]$  interface and the fatigue behavior of the material and layup combination. Both unaged specimens and artificially aged specimens were tested and compared to get an understanding of how aging affects the chosen material and layup.

Aging of the specimens was done by submerging them in a hot water bath filled with distilled water kept at  $60^\circ\text{C}$ . The specimens were taken up when their weight had stabilized and the specimens were fully saturated. The aging resulted in a large loss in flexural strength in the specimens, a minor decrease in fracture energy release rate, and a weakened fatigue life.

The Double Cantilever Beam (DCB) test and a Mode I cyclic loading test were also planned performed on thermoplastic specimens as well, but some problems arose during testing. The thermoplastic specimens were cut out of polypropylene plates and were not reinforced with any fibers. Due to the lack of fibers, the specimens experienced excessive bending instead of the desired delamination. Due to the bending in the specimens, the focus of the work with thermoplastic shifted from performing the planned tests to how to make the specimens behave as expected.

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## Sammendrag

Masteroppgaven er skrevet i samarbeid med Norges teknisk-naturvitenskapelige universitet (NTNU) i Trondheim, med Andreas Echtermeyer som veileder. Målet med arbeidet og oppgaven er å få en bedre forståelse av hva slags effekt kunstig aldring har på Mode I delaminering av polymerkompositter. Hvordan aldring påvirker materialet ble testet gjennom både dynamisk og statisk testing. Interessen av å bruke kompositter i nye og innovative design er økende, og det er derfor viktig å ha en god forståelse av hvordan kompositter blir påvirket av miljøet det skal brukes i.

Masterprosjektet er en videreføring av et fordypningsprosjekt som ble gjennomført på høstsemesteret 2022. I fordypningsprosjektet var fokuset å lære hvordan å produsere komposittpøver og bestemme hvilke testmetoder som gir best mulig resultater og hvordan disse utføres. Siden dette er en videreføring av et tidligere prosjekt er noen deler av oppgaven basert på det forrige arbeidet, og noen figurer er derfor også de samme som i forrige prosjekt.

Komposittpøvene som ble testet er laget ved å bruke Vacuum Assisted Resin Transfer (VART) metoden, med en fiberorientering på  $[0/90]_3$  ( $[0/90/0/90/0/90]$ ). Materialene brukt under produksjon av prøvene var glassfiber og epoxy. Fiberorienteringen til prøvene resulterer i en Mode I-delaminering i grensesnittet mellom et  $0^\circ$ -lag og et  $90^\circ$ -lag. Delamineringsresultater i  $[0/90]$ -grensesnittet er av interesse, fordi delamineringsresultater vanligvis oppnås ved å teste kompositter der alle fibrene er i samme retning.

Prøvene ble testet ved å gjennomføre en Double Cantilever Beam (DCB) test både statisk og med varierende last. Den statiske styrken til materialet og hvordan det oppfører seg utsatt for varierende laster ble funnet både før og etter kunstig aldring av materialet, og ga gode resultater og forståelse av hvordan materialet oppfører seg med denne fiberorienteringen.

Den kunstige aldringen av prøvene ble gjennomført ved å legge dem i et varmtvannsbad fylt med destillert vann holdt på  $60^\circ\text{C}$  til vannopptaket og vekten til prøvene hadde stabilisert seg. Etter aldringsprosessen viste det seg at materialets motstanden mot delaminering og bøyespenningsmodulusen var kraftig redusert. Evnen kompositten hadde til å motstå sprekkvekst under utmatting ble også redusert etter aldring.

Det var planlagt å gjennomføre testene på en termoplast i tillegg til komposittpøvene, men ettersom det oppstod en del problemer under testingen av disse ble fokuset endret. Målet med termoplast prøvene ble etterhvert å finne en måte å få gjennomført en test istedenfor å oppnå gode resultater.

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## Acronyms

**ASTM** American Society for Testing and Materials. 17, 21, 22

**DCB** Double Cantilever Beam. i, ii, vii, viii, 11, 16, 22–24, 26, 28, 35, 36, 39, 48–51, 55

**MBT** Modified Beam Theory. 20

**PMC** Polymer Matrix Composite. 1, 5–7

**VART** Vacuum Assisted Resin Transfer. ii, vii, 13, 14, 16

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# 1 Introduction

With today's focus on minimizing the carbon footprint and saving the environment, new technologies and materials are utilized on a continuously increasing scale. By utilizing composite materials it is possible to produce ships with improved speed, range, payload, fuel consumption, and overall fuel efficiency, cars that are lighter and more fuel efficient while being as safe or safer as the equivalent steel chassis cars, lighter and more efficient airplanes and helicopters, as well as large wind turbines that produce pure and clean energy. Composite materials are seen in both large and small-scale projects within multiple disciplines, and their use rapidly increasing.

Within the shipping industry, there is a desire to use more composite materials to increase efficiency and reduce emissions and costs of operation. One way to reach this goal is to build tomorrow's ships with light thin and slender composite structures. This has been tested and utilized to produce large military warships that are light and nimble, and still strong and sturdy enough to withstand harsh environments. In the deep-sea shipping industry, there is limited use of polymer matrix composites even though there is a desire to decrease weight, costs, and carbon footprint. The lack of composites in large ships is due to little research on fire safety, which is a result of composites used as a building material for large vessels being relatively new. But research on the fire resistance of composites is evolving and in the future deep-sea shipping industry will build large composite vessels. [1]

Another area that is important to continue the research of composites is their fatigue life and how they are affected by environmental factors such as moisture, abrasion, and radiation. By knowing the effect of continuous loads and environment on the material it is possible to predict how a part or structure will be affected and behave in the years to come. The focus of this thesis is how the Mode I strength and fatigue life of composites are affected by moisture.

Polymer matrix composites (PMC) are heterogeneous, and this ability is the reason for their high strength-to-mass ratio, which has made them such a popular material choice. Since composites are heterogeneous the fibers and matrix which build up the material do not dissolve into one homogenous mixture but rather exploit the ability of the two components. A PMC is made out of reinforcing fibers and a polymer matrix that cures around the fibers, and the result is a polymer with exceptional strength along the reinforcing fibers. The fiber layup in composite parts can be tailored to each specific part created, by being reinforced with fibers where strength is needed and excluded to save weight where fewer loads are carried through the part.

Other advantages of polymer composites are their exceptional resistance against corrosion, and the manufacturing process is cheap, fast, and simple compared to steel and aluminum.

The results presented in this thesis are acquired from testing specimens made out of glass-fiber-reinforced epoxy, and some thermoplastic specimens cut out of polypropylene plates were also tested. Some of the composite specimens were artificially aged and were compared to similar unaged specimens. The chosen tests focused on Mode I delamination and gave results on bond strength between fibers and matrix, and the interlaminar shear strength of the matrix between the fiber mats. The Mode I delamination characteristics of the specimens were tested with static loading and cyclic fatigue loading.

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## 2 Polymers

The specimens tested in this work are made out of polymers. One set of specimens utilizes the polymer as a matrix material in a composite, whereas the other set of specimens is pure, unreinforced, polymer specimens. The composite specimens have an epoxy (thermoset) as matrix material while the unreinforced polymer specimens are made of polypropylene (thermoplastic).

Polymers are built up by repeated units of long organic molecules. Most commonly the polymer molecules consist of carbon, C, and hydrogen, H, elements, and are linked together by chemical bonds to form long chains of polymer molecules. The type of chemical bond binding the molecules together determines the behavior of the polymer. Based on the abilities and behavior of a polymer it falls into one of three subgroups, thermoplastic, thermoset, or elastomer. [2]

Thermoplastics have weak secondary bonds binding the long molecules together to create long polymer chains. The weak bonds between the molecules are easy to break up, resulting in a plastic material with the ability to be remelted, reshaped, and recycled. [2]

Elastomers have very elastic properties at room temperature and are therefore more commonly known as rubber. The polymer molecules in elastomers are bound together mostly by weak secondary bonds and by some strong covalent bonds. The composition of weak bindings with some strong bonds working as "anchors" holding the molecules together results in a highly elastic material that does not melt. These lightly crosslinked materials have a non-linear elasticity and can be exposed to very large strains. [2]

Thermosets are generally stronger and more heat-resistant than thermoplastics and elastomers, and their strength is a result of being highly crosslinked with covalent bonds. The large amount of strong covalent bonds binding the molecules together requires a lot of energy to be broken. Thermosets are therefore commonly used in polymer composites, but there is a drawback with their high strength and stiffness, and that is their inability to be melted or re-formed. When thermosets are exposed to heat they barely soften before they start to burn and degrade, which makes it hard to recycle them compared to thermoplastics. [2]

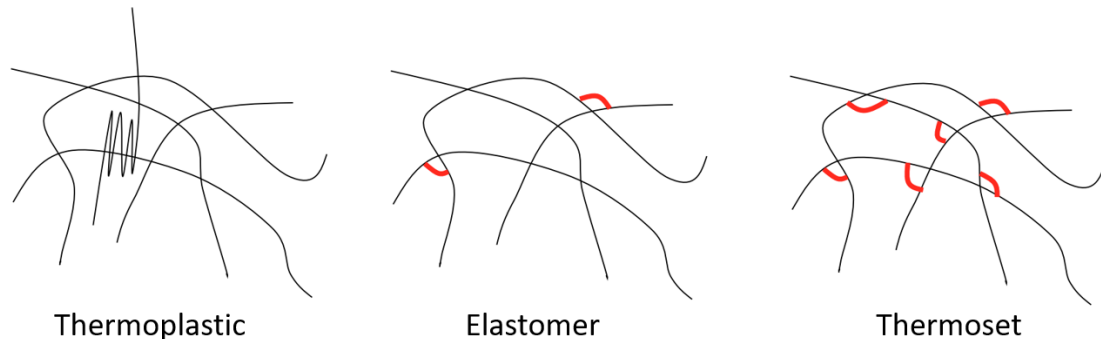


Figure 1: The difference of bonds between polymer chains of thermoplastics, thermosets, and elastomers. [2]

### 2.1 Effect of temperature

Parts produced by polymers are usually lighter and cheaper to manufacture compared to metals, work well as insulators, and have dampening abilities. If thermoplastics are used it is possible to remelt and recycle the part, due to the weak bonds holding the polymer chains together. The downside of polymer parts, where metal parts are superior, is operating at elevated temperatures.

Thermoplastics can either be fully amorphous or have a semi-crystalline structure. The strength and hardness of the amorphous regions in a thermoplastic are dependent on the material's glass transition temperature,  $T_g$ . While the temperature is below  $T_g$  these regions are hard and brittle which provides strength, but at temperatures over  $T_g$ , they become soft and ductile. As shown in Figure 2 the strength of fully amorphous thermoplastics drops rapidly after  $T_g$  compared to semi-crystalline thermoplastics, where the crystalline regions still ensure some strength in the material. For both amorphous and semi-crystalline thermoplastics all strength is lost and the material melts when the temperature reaches  $T_m$  (melting temperature). [3]

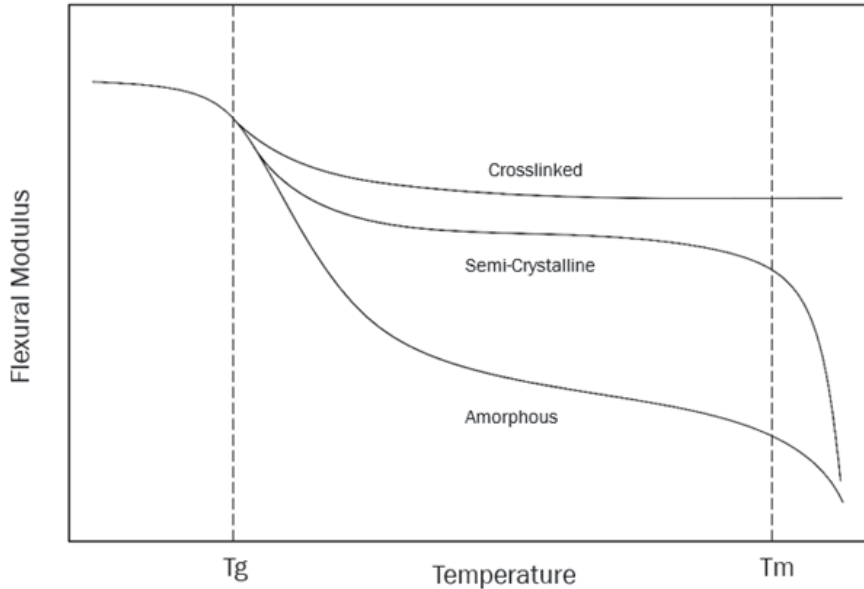


Figure 2: How temperature affects the strength and flexural modulus of crosslinked, semi-crystalline, and amorphous polymers. [4]

The crosslinked polymers, thermosets and elastomers, do not melt due to the strong covalent bonds, Figure 2. Their ability to not melt makes them more suited for use in higher temperature operations, but when the temperature reaches the limit of what the crosslinked polymers can handle they deteriorate and burn. Therefore metals are still superior and commonly a better choice for parts designed to operate at very high temperatures.

## 2.2 Viscoelastic behavior

Polymers have the ability to behave both like a fluid and solid material, and this type of behavior is described as a viscoelastic behavior. This phenomenon occurs because the long molecules building up the polymer are able to move and re-orientate in the direction of applied loads. The movements are caused by forces exceeding the strength of the weak secondary bonds between the chains of molecules. The re-orientation of molecules is slow, so therefore the viscoelastic properties of polymers only occur when loads are applied over time. Polymer's viscoelastic behavior affects them in two ways, relaxation and creep.

When a polymer is stretched out and held at a constant strain, the forces working on the polymer will decrease over time, see Figure 3. This reduction in forces working on the polymer is caused by the re-orientation of the molecule chains and is known as relaxation. Due to the re-orientation process being slow the polymer will react as a solid when first stretched out, and as the molecules align along the direction of the working forces the material "relaxes" and experience less stress at the same strain. [5]

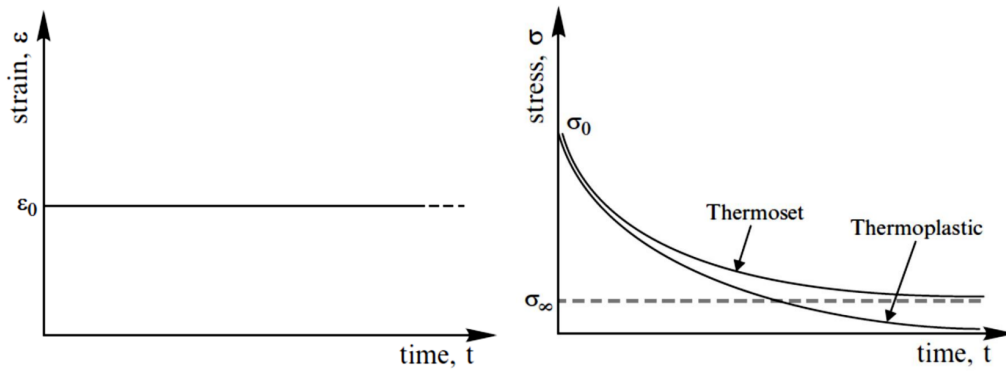


Figure 3: **Relaxation:** Visualizes how stresses reduce over time when strains are kept constant. [5]

Creep, like relaxation, is caused by the movement of polymer chains when stresses are experienced by the polymer. The difference between the two is that creep is a phenomenon where a part elongates during a constant load. In practice, this means that a load-bearing part made with a polymer will act like a solid and perform as expected at first. But over time the polymer chains will flow and the part will stretch out, and the stress will stay constant. See Figure 4 for a visual representation. [5]

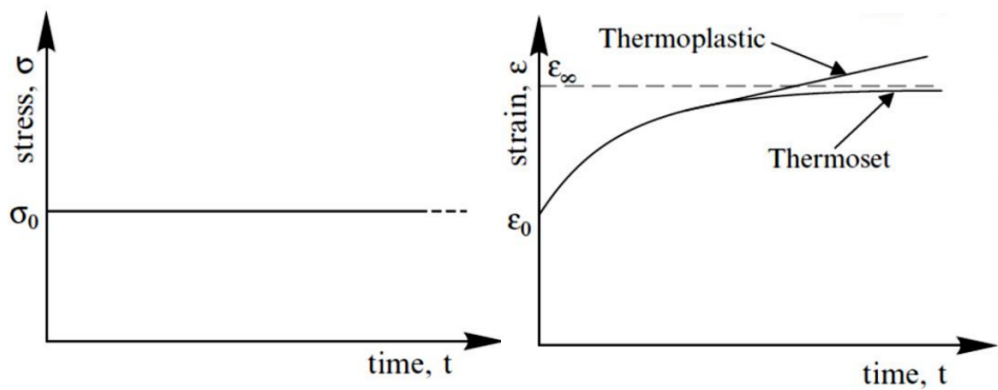


Figure 4: **Creep:** Visualizes the extension in strains over time at constant stresses. [5]

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### 3 Aging

The components that build up a polymer matrix composite are the reinforcing fibers, the matrix which binds the fibers together, and a protective coating around the fibers called the sizing. The sizing is applied on the surface of the fibers to protect them during handling, and it also provides a strong physical and chemical bond between the matrix and fibers. When the chemicals in the protective coating react with the polymer resin to form a strong bond between fibers and matrix, a sizing-rich phase is produced in the matrix.

One of the strengths of polymer matrix composites is their phenomenal corrosion resistance, and this is why composites are a popular material choice for parts that operate in corrosive environments. Even though PMC's does not corrode like metals in such environments, they also are affected and may be altered by reactions with the environment. Typically a composite part or structure will react and be altered by fluids, moisture, temperature, and UV radiation, and result in defects developing at an increased rate. The increase in speed at which the defects occur and grow might lead to failure taking place much earlier than expected. [6]

#### 3.1 Aging effect - Matrix

A common choice for matrix material in PMC's is epoxy polymers. There are many different epoxies on the market, which is a result of the large number of epoxy producers who all have a product of a unique composition of both chemical and physical properties. When mixing an epoxy compound with a curing agent a chemical reaction will take place and the epoxy will cure and harden, resulting in a material with good mechanical and chemical properties. The large number of different epoxies and their good properties are what make them a popular choice as matrix material in composites. [6]

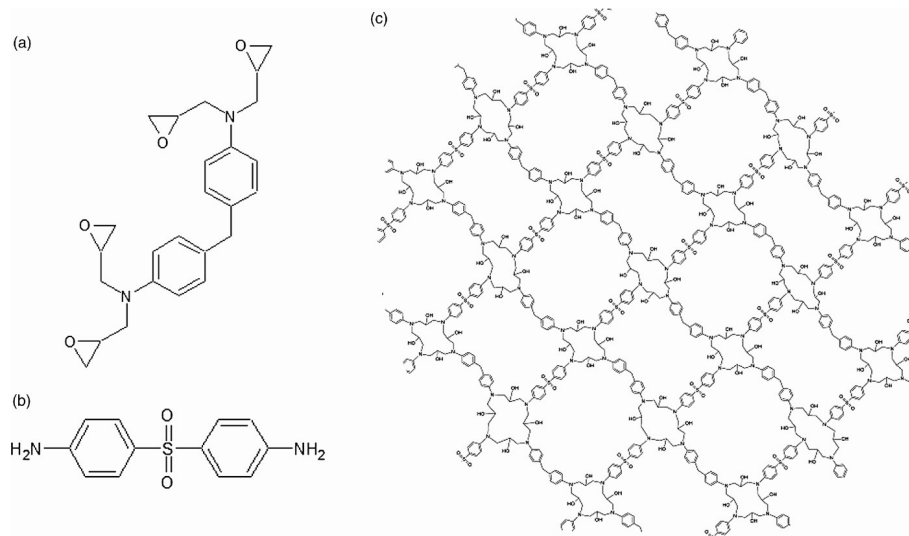


Figure 5: Chemical structures: (a) Epoxy compound. (b) Curing agent. (c) Mixed Epoxy. [7]

When in contact with water, all types of epoxy will react. The reaction between the epoxy and water might change the epoxy's properties. During the reaction, there is a migration of water molecules into the epoxy. When water molecules are absorbed and travel into the epoxy structure, its properties tend to become weakened.

Some epoxies can have hydrophilic abilities, which makes it possible for them to create hydrogen bonds between the polymer chains and the absorbed water molecules. For an epoxy to have hydrophilic abilities it must be amine-cured or be highly crosslinked. The mechanical properties of an epoxy where hydrogen bonds have formed between water molecules and the polymer chains will be significantly weakened.



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As a result of water uptake in PMC's plasticization and swelling stresses often occur. These phenomena are well-known and are known to reduce both the performance and durability of composite materials.

The absorbed water will damage the epoxy, but in some cases the damages caused are reversible. The damage caused by water can therefore be divided into two categories, these are irreversible damage and reversible damage. If an epoxy part that has absorbed water molecules is taken out of the moist environment and dries up, the water will depart the epoxy. When there is no water left in the material the part may have reacquired its properties from before the initial water uptake. If this is the case the damage caused was reversible. But, if the properties of the re-dried material differ from the original material's properties irreversible damage has been caused by the water molecules. The altered properties are often caused by hydrolysis, chain-scission, residual curing, leaching, or oxidation. [6]

### 3.2 Aging effect - Fiber

In addition to having a lot of different polymers to choose from when making polymer matrix composite parts, there is a large variety of reinforcing fibers to choose from as well. The most known fibers used are probably carbon-fiber and glass-fiber, where glass-fiber is the most commonly used reinforcement. The popularity of the glass-fibers is a result of their high strength, hardness, and stiffness while at the same time being cheap to manufacture. There is an almost unlimited supply of the raw materials used in the manufacturing process of glass-fiber, which is why they are so cheap and the availability is as high as it is.

There is still one big drawback with using glass-fiber as reinforcement in composites, which is their ability to react with water. When glass-fiber is in contact with water hydrogen bonds may form between water molecules and the fiber. The hydrogen bonds form due to the hydrophilic abilities of glass-fiber, and might cause surface flaws in the form of surface cracks, Figure 6, or even corrosion-induced defects. The defects created on the reinforcing fibers lead to a large reduction their in mechanical strength. If already degraded fibers are mechanically loaded the degradation process will speed up even more. Composite parts where the glass-fiber reinforcement has reacted with water will have significantly reduced strength and durability.

The use of carbon-fiber as reinforcement may be a better option in many cases, at least if it is impossible to work around the major problem that is caused by the reaction between glass-fiber and water. Reinforcing fibers made out of carbon is a better choice because they are known to not react with water, and will therefore not degrade. The price of carbon-fiber is on the other hand a negative factor, they are very expensive. Due to the high cost of carbon fiber, and the fact that they do not react when in contact with water, this study will focus on how glass-fiber-reinforced polymers are affected by water. [6]

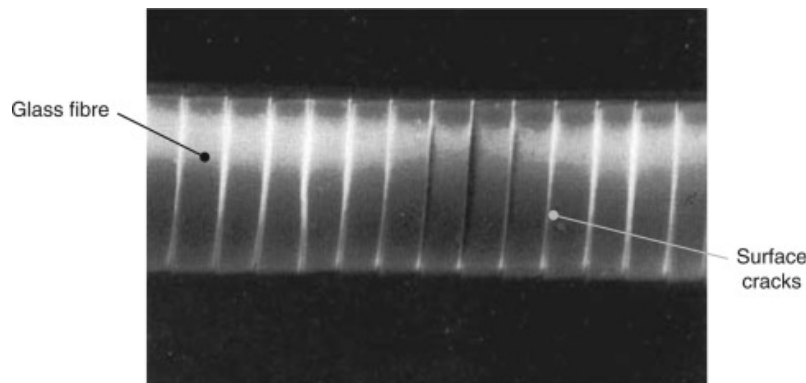


Figure 6: Cracks on the surface of a glass-fiber. [8]

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### 3.3 Aging effect - Sizing-rich composite

During the production of reinforcing fibers which are used when manufacturing PMC parts and structures, there is applied a protective coating on the fibers. The coating is made up of different chemicals, which protect the fibers during handling as well as ensure a strong and good adhesive bond between the matrix and the fibers used as reinforcement. This coating is referred to as a sizing. The chemicals in the sizing affect the matrix-fiber interphase, which is a vital part of the composite because it transfers forces throughout the material. Flaws in the sizing-rich matrix-fiber interphase may result in water being trapped when the material experiences moist environments. Water trapped in the sizing-rich phase, Figure 7, might react with both the fibers and matrix and result in a large loss in material strength and stiffness.

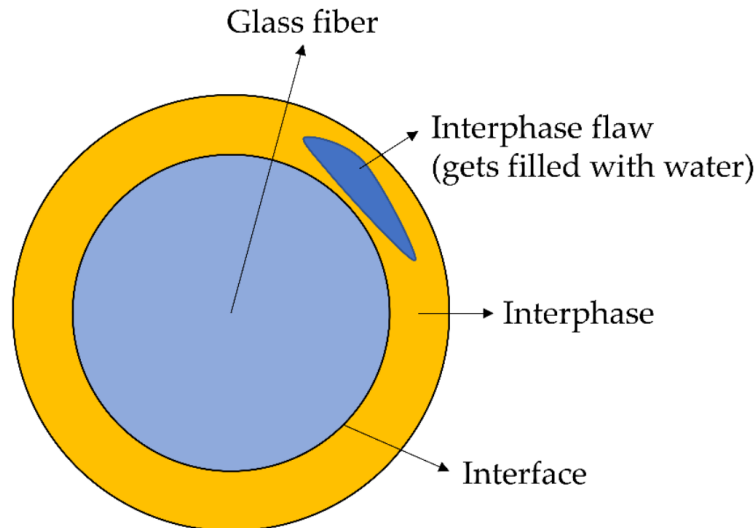


Figure 7: Schematic of the sizing-rich interphase, and a visualization of how water can be caught in it. [6]

How the sizing-rich matrix-fiber interphase is affected by moist and aquatic environments is an important subject within the research on the long-term properties of composite materials. This interphase is especially important because of how forces are transferred through the composite via the matrix-fiber interphase, and damages to this sizing-rich part of the matrix will lead to a loss in strength, stiffness, and a part's integrity. Research in this area has been minimal, and so far no method has been found to calculate the actual degradation and loss in the sizing-rich interphase due to environmental aging. For further research, this is therefore an important study area. [6]

### 3.4 Accelerated aging

Accelerated aging is a process that speeds up the natural aging of a material, and makes it possible to simulate the effect many years in service have got on the material in a short time period. The sped-up aging process works by exposing material specimens either to heat, humidity, oxygen, chemicals, UV-radiation, and vibration over time. A specimen exposed to one or multiple aging factors will age and develop defects at an increased rate. [9] This technique is used in large-scale projects, especially in industries where their products are used in harsh environments.

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### 3.4.1 The aging process

The accelerated aging process used to age the composite specimens tested in this study exposed the specimens to a combination of both moisture and heat. This was done by submerging the specimens in a hot water bath filled with distilled water kept at a constant temperature of 60°C. The specimens were kept in the hot water bath until they had reached a constant weight. The weight before and after the aging process is shown in Table 1. When the weight of the specimen stabilized an average weight increase of 0.65% was registered.

Table 1: Weight difference of specimens before and after aging.  $M_1$  is the original weight, and  $M_2$  is the specimen weight after aging.

Specimen weight before and after aging		
Specimen	$M_1$ (g)	$M_2$ (g)
5	34.6	34.73
6	34.6	35.00
7	34.7	34.93
8	34.6	34.87
9	34.8	35.00
10	34.7	34.87
11	34.6	35.00
12	34.6	34.46
13	33.9	34.27

The testing of the aged specimens should ideally be performed while the specimens were submerged in water, but they were taken out of the water before being tested in "air". Testing while the specimens are submerged in water is complicated, and requires machines that are designed to work in such conditions. To make this kind of testing possible with the test machines available at the lab, a watertight chamber would have been needed, and the machines would most likely start to rust because they are designed to operate in "air".

When an aged specimen is taken out of the water, the redrying process of the epoxy will start. For the specimens to completely dry up after being taken out of the water bath takes some time. The results acquired from testing the aged samples in "air" instead of water are therefore very similar as well as easier to perform. An exception where the results may vary more is for tests that take a long time to perform, or if the specimens are exposed to air over a longer time period the larger the potential errors become.

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## 4 Fatigue

In addition to age the samples in a hot water bath to simulate the effect of being degraded by the environment, cyclic loading will be applied to a portion of the test specimens. The cyclic loading applied to the specimens simulates the variable loading a part will be exposed to during its life. During the load cycles, a crack will form and grow within the specimen, even though the applied loads are relatively low.

The fatigue failure process of polymer composites differs from metals. Crack growth in composites starts and grows within the material, where a crack occurs on the surface and grows inwards in metals. Delamination between fibers and polymers is the most common failure mechanism caused by cyclic loading, which again can lead to catastrophic failure.

The interlaminar cracks caused by cyclic loading initiate from microcracks and other defects in the matrix-rich zones between the reinforcing layers. Crack initiation and growth occur in the matrix due to its low toughness and cyclic strength compared to the reinforcing fibers. Fatigue characteristics of composites can be explained by the volume fraction between the matrix and fibers. By increasing the amount of fibers compared to the matrix the fatigue resistance of a composite will improve, due to less material for cracks to develop and grow. But a sufficient amount of matrix is required, and if this line is crossed there will not be enough matrix to hold the fibers in place. [10]

### 4.1 Variables that affect the fatigue life of PMC's

Mode I fatigue behavior of polymer composites relies heavily on fiber bridging, temperature, and the load/stress ratio the part or specimen is exposed to. [10]

#### 4.1.1 Fiber bridging

Fiber bridging occurs when a growing crack interferes with the fibers in the layers surrounding the matrix where it grows and leaves unbroken fibers. These unbroken fibers are then connected to both sides of the crack hindering its growth, seen in Figure 8. [11] This phenomenon increases the fatigue resistance of composite parts exposed to cyclic loading, due to the bridging fiber's ability to restrict the crack growth and store and release large amounts of strain energy. The longer the crack becomes, the more restrictive the effect of the bridging fibers becomes. [10]



Figure 8: Left: Delamination without bridging. Right: Delamination with fiber bridging. [11]

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### 4.1.2 Temperature

Since the crack grows in the material where it is easiest to progress, it stays in the matrix. As a result, how temperatures affect the matrix determines the fatigue life of the composite. Temperatures exceeding room temperature result in a more soft and ductile matrix, while low temperatures make the matrix harder and more brittle. The hard and brittle matrix at low temperatures slows down the delamination growth. [10]

### 4.1.3 Load/Stress Ratio

The load and stress ratio in fatigue testing is defined as the ratio between the minimum and maximum stress or load to which the specimen is exposed to during the test. A high or low stress or load ratio will affect the fatigue life of a composite, where high ratios tend to promote more fiber bridging than low load/stress ratios. [10]

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## 5 Experimental methods

Polymer matrix composites are heterogeneous materials, and their strength does therefore not only depend on the mechanical properties of the matrix and reinforcing fibers. Since the fibers and matrix does not dissolve into one substance the bond between them, and the lamination order and ply orientation of the reinforcing fibers heavily influence the strength of the composite. Forces going along the direction of the fibers are absorbed by the high tensile strength of the reinforcing fiber. For a part to maintain its integrity and survive loads applied normal to the fiber direction, the strength of the matrix is put to the test.

If loads applied to a composite part exceed what it is capable of supporting it has a complex fracture process. Normally the fracture process consists of fiber breakage, debonding between matrix and fibers, and formation of matrix micro-cracks. The development of these kinds of defects can also be a result of usage over time.

Debonding between fibers and matrix can cause a crack to grow throughout the composite material and cause a catastrophic loss in the strength and stiffness of a component. This type of failure is also referred to as delamination and has a large influence on the performance of a part. Delamination is therefore an important failure mode to study and understand. [12]

The focus area in this study is how delamination, the strength of the bond between matrix and fibers, and the shear strength of the matrix itself are affected by artificial aging and fatigue loading. Therefore the Double Cantilever Beam (DCB) was the test chosen to determine how the Mode I fracture energy is affected, Figure 9. This test method was used in both static and fatigue loading, and with two different materials. The specimens used are cut out from glass-fiber/epoxy laminates and plates of polypropylene.

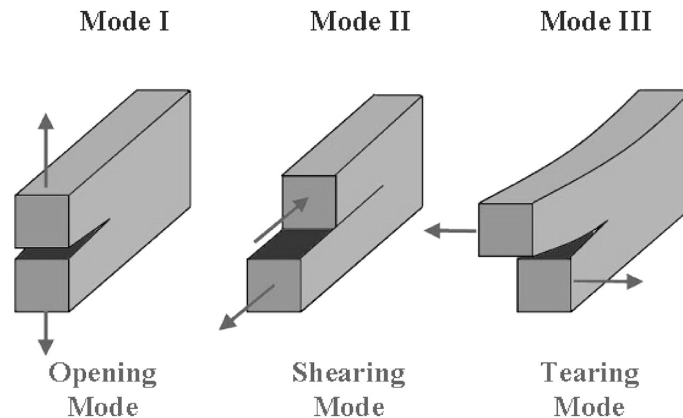


Figure 9: Different delamination modes. [13]

### 5.1 Static Mode I - Double Cantilever Beam

The double cantilever beam test is used to determine the required energy for delamination growth to occur via Mode I loading. The specimens used in these tests have a crack manufactured into them, this way the location of the crack is controlled. During the DCB test, specimens are loaded normal to the manufactured crack, Figure 10. [14] While the specimen is under load, the delamination growth, applied load, and displacement of the load head are constantly recorded. The recorded data makes it possible to determine The Mode I fracture energy,  $G_{Ic}$ , of the material. [15]

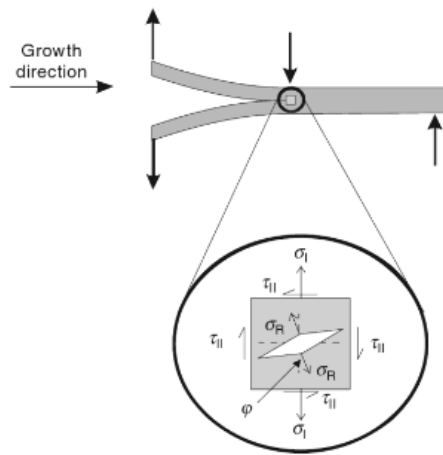


Figure 10: Schematic of how forces behave in the delamination front during Mode I delamination. [8]

## 5.2 Fatigue Mode I - Double Cantilever Beam

By performing the double cantilever beam test with variable loads, the crack propagation at energy levels lower than the static Mode I fracture energy can be determined. Even though the applied forces are small, a fatigue crack will grow for each cycle until a critical limit where there is no more material left to support even small loads. [16]

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## 6 Production method

The specimens made from thermoplastic are cut out of premade plates made by Röchling. Since the thermoplastic plates are bought, the focus of this section will be how composite laminates are produced.

### 6.1 Production of composites using the Vacuum-Assisted Resin Transfer method

To produce the glass-fiber/epoxy laminates which the composite specimens tested in this study are cut out from, the vacuum-assisted resin transfer (VART) method was used. This method utilizes a vacuum to draw the resin, in this case, the epoxy, into the mold where the reinforcing fibers are placed in the desired orientations and layers.

Production of high-quality composite parts using this technique requires some consumables and the right method of procedure. The composite itself consists of a resin compound, a curing agent, and the reinforcing fibers, and in addition to these materials a release agent, peel-ply, vacuum bag, bag tape, flow mesh, some tubes, and a vacuum pump is needed. To avoid the excess resin to be drawn into the vacuum pump a catch-can is useful.

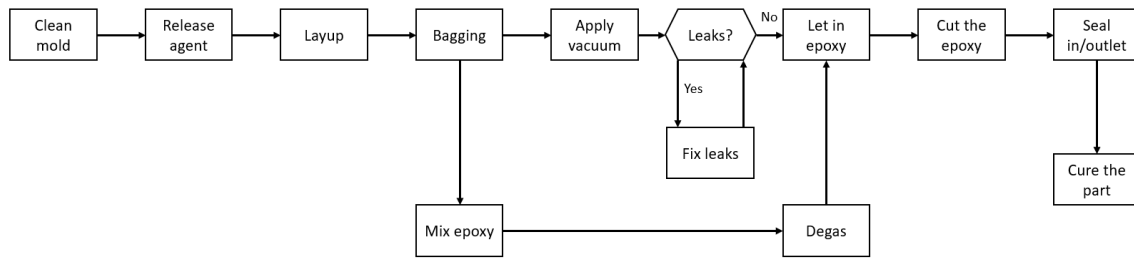


Figure 11: Step-by-step of the VART process.

The process of making a composite part using the VART method is visualized in Figure 11, and each step is vital for a high-quality result. The first step is to clean the mold, this is to avoid dirt or other unwanted particles in the composite. When the surface of the mold is cleaned a release agent must be applied. The release agent ensures that there is no adhesion between the mold and the part.

The next step in the process is to apply the bag tape around the mold, and then continue with the rest of the layup. From the bottom and up the fibers will be laid down, before applying the peel-ply and flow mesh, and finally the vacuum bag. A schematic of the layup is shown in Figure 12.

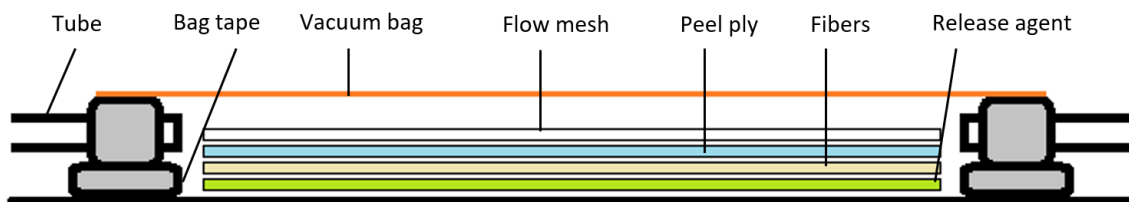


Figure 12: Model of a VART layup with materials and consumables commonly used.



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A good seal between the vacuum bag, mold, and the inlet and outlet tubes is vital. If there is a vacuum leak while the resin infusion or the curing process takes place, the part will not be cured under pressure which will lead to a lower quality part than expected. In the worst case, the infusion process will draw in air and resin simultaneously. Air in the laminate is not desirable at all and will lead to voids in the cured matrix. It is therefore important to check the setup for leaks before starting the infusion.

When the setup is vacuum-tight the infusion can start. By submerging the inlet tube in resin and applying a vacuum that is connected to the outlet tube, the resin will flow into the mold. In the mold, the resin will mix with the fibers while all air will be drawn out of the mold. The part will then cure under pressure applied by the vacuum bag, and result in a high-quality part. [17]

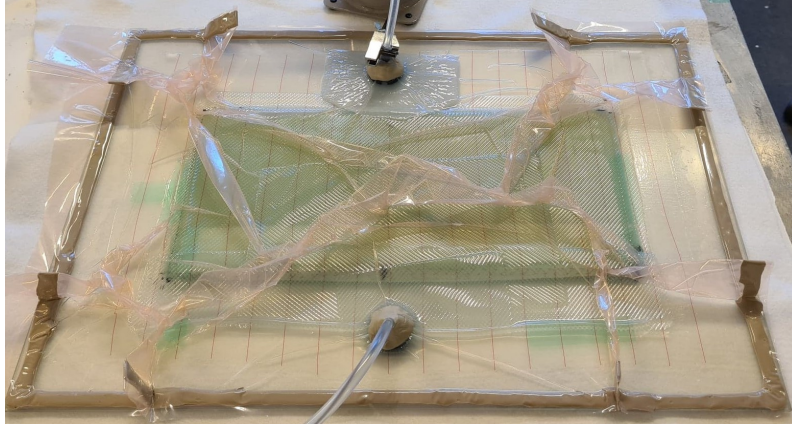


Figure 13: Production of the laminate using VART.

### 6.1.1 Preparing the resin

The resin consists of two parts, an epoxy compound, and a curing agent. When mixing the two substances together it is important to follow the mixing ratios stated in the technical data sheets. The epoxy used to produce the glass-fiber/epoxy composites tested in this study had a mixing ratio of 100:30. [18] When the epoxy components were mixed together the epoxy was placed in a degassing chamber. The degassing process pulls air trapped inside the epoxy out and results in a composite part with fewer voids due to air bubbles.

### 6.1.2 Curing of the resin

When the VART process was completed, and the epoxy was successfully drawn into the mold, the part cured in the mold at room temperature for 48 hours. After 48 hours the composite laminates were taken out of the mold and placed in an oven, where they sat for 15 hours at 60°C.

---

## 7 Welding of Thermoplastic

Unlike thermosets, which are often used in composites, thermoplastics can be melted and reshaped, see section 2.1. This ability can be utilized to weld thermoplastic parts together. The welding process is done by heating up the surface of the thermoplastic until it melts, then the parts can be placed together, and when the surface solidifies again a weld is made.

There are different techniques for making thermoplastic welds, and these are divided into three main groups based on the method used to introduce heat to the weld. The heat can be introduced by mechanical movement, an external heat source, or from electromagnetism. [19]

### 7.1 Hot-Plate welding

To weld the thermoplastic specimens used in this work, an external heat source was used in the form of a hot plate. The hot-plate technique involves heating the parts to be welded against a heated plate. When the parts to be joined together are molten, the hot plate is removed before the parts are pressed together. After the joining of the parts, the weld must be cooled down for strength to develop. [19]

#### 7.1.1 Weld Setup

The plate used to melt the thermoplastic specimens is cut out of a large steel plate. It is approximately 20 cm long and 7 cm wide and has a thickness of about 1 cm. The thickness of the plate ensures that the plate maintains a high temperature during the welding process. To minimize the amount of material left on the plate and ensure a better weld, the surface is smoothed out and polished.

To heat up the welding plate, a curing oven placed in the lab was used. The plate was heated to a temperature of  $177^{\circ}\text{C}$ , which is  $10^{\circ}\text{C}$  over the melting point of the polypropylene used to make the specimens. [20] The high temperature is to guarantee that the plate is hot enough to melt the material when it is taken out of the oven.

When the plate reached its target temperature it was taken out of the oven with a pair of pliers. The two parts which were to be welded were then placed on the plate, see Figure 14. After the specimen parts visibly had melted, they were pressed together to ensure a good weld.

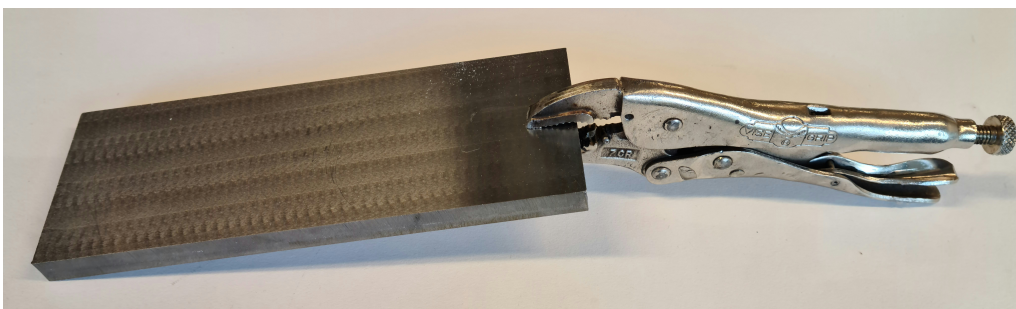


Figure 14: The hot plate weld setup. The specimen parts to be welded are pressed against the plate before being merged together.

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## 8 Materials and Specimens

During this project, the double cantilever beam setup has been used in both static and fatigue loading of specimens from two different materials. The specimens were cut out of polypropylene plates and glass-fiber/epoxy laminates.

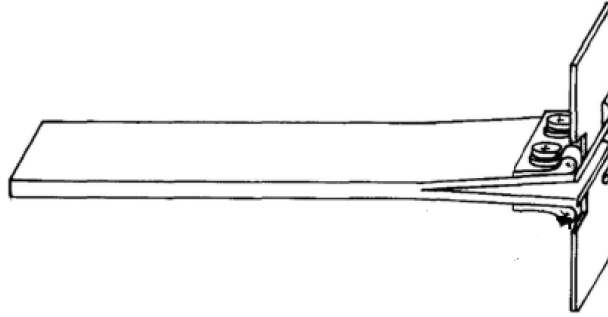


Figure 15: Schematic of the DCB specimen.

### 8.1 Composite specimens - glass-fiber/epoxy

Production of the composite specimens was done by utilizing the VART method to produce high-quality glass-fiber/epoxy laminates, section 8.1.1. The layup of the laminates was  $[0/90]_3$ , and was achieved by laying down unidirectional glass-fiber mats in alternating directions, Figure 16. The layup promotes the delamination front to grow between a  $0^\circ$  and a  $90^\circ$  layer, in the middle of the specimen. To ensure delamination happening between the intended layers, an initial crack was manufactured in the specimens. While laying up the fibers in the mold, a strip of teflon tape was laid down between the middle  $0^\circ$  and  $90^\circ$  layer. Teflon tape does not adhere to epoxy and was therefore used to manufacture the initial crack. A specimen schematic is shown in Figure 15.

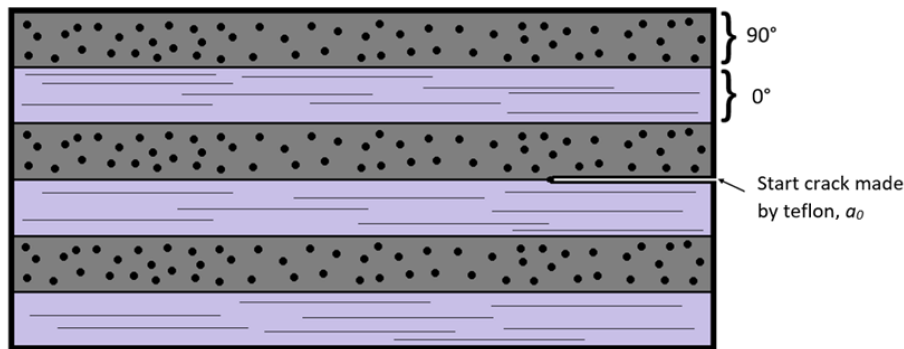


Figure 16: Schematic of the specimen layup, and crack location.

#### 8.1.1 Materials

The composites tested in this work are made out of reinforcing fibers of glass and an epoxy as matrix material. The epoxy components are produced by HEXION™ and when mixing them together the epoxy is created. EPIKOTE™ Resin MGS™ RIMR 135 and EPIKURE™ Curing Agent MGS™ RIMH 137 were the two compounds making up the epoxy, and a mixing ratio of 100:30 was used. The final volume fraction of fibers and resin was approximately 0.5.

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### 8.1.2 Cutting and preparing the specimen

A high-pressure water jet was utilized to cut the specimens out of the composite laminates, Figure 17. At this point, the specimens were marked, before some of them were placed in a hot water bath for aging.

To be able to secure the specimens in the test machine, piano hinges were glued on with araldite. To ensure a good bond between the hinges and specimens they were scrubbed with sandpaper before being cleaned with acetone. The hinges are applied to keep the load perpendicular to the face of the specimen, this way any loading moments are avoided.

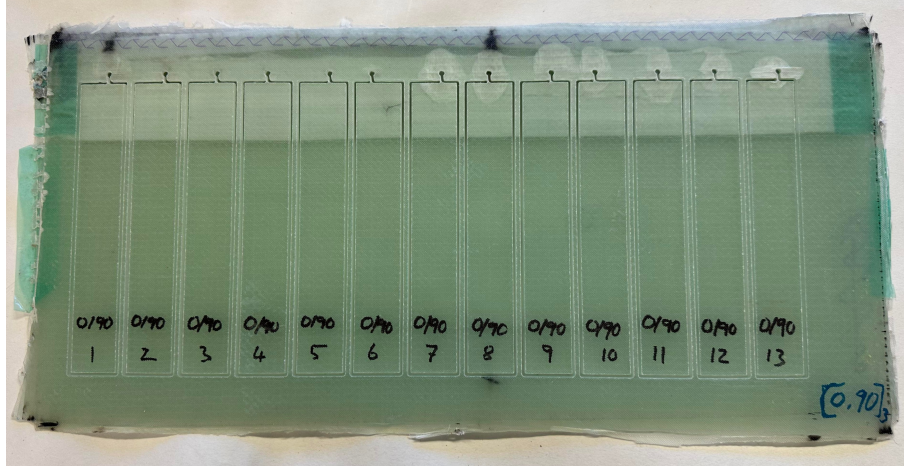


Figure 17: One set of specimens still in the laminate after being cut out with a high-pressure water jet.

### 8.1.3 Specimen measurements

Some measurements for specimens to be used for finding Mode I fracture energy release rate by using the double cantilever beam test have been set by the American Society for Testing and Materials (ASTM). A length of at least 125 mm, a width between 20 to 25 mm, and a thickness between 3-5 mm is recommended. The length of the manufactured start crack shall be around 50 mm while staying within the maximum allowed length requirement set by equation (1). This is to ensure valid results and minimize large deflections in the specimen arms which may lead to unrealistic results. [21]

$$a_0 \leq 0.042 \sqrt{\frac{(h)^3 \cdot E_{11}}{G_{Ic}}} \quad (1)$$

Where  $a_0$  is the initial crack length,  $h$  is the specimen thickness,  $G_{Ic}$  is the fracture energy, and  $E_{11}$  is the modulus of elasticity along the length of the specimen.

Some of the unaged specimens and all of the aged specimens tested in this work were cut out of the same composite laminate (specimens 1-13) and had an average total thickness,  $h$ , of 4.9 mm, initial crack length,  $a_0$  of 36.2 mm, width,  $b$ , of 24.1 mm, while the rest of the unaged specimen (specimens 28-48) had an average thickness of 5.66 mm, initial crack length of 55.67 mm, width of 24.01 mm and came from another laminate. By keeping the initial crack length shorter than what is allowed by equation (1), the likelihood of acquiring valid results increases. For exact measurements of both the aged composite specimens and the unaged specimens, see Tables 2 and 3.

Table 2: Measurements of unaged specimens before testing.

Measurements of unaged specimens			
Specimen number	$b$ (mm)	$h$ (mm)	$a_0$ (mm)
1	24.10	4.88	32.57
2	24.10	4.95	37.87
3	24.14	4.92	37.14
4	24.09	4.95	37.15
28	24.00	5.70	54.45
29	23.97	5.83	52.90
30	23.97	5.60	56.10
31	24.05	5.68	55.80
41	24.01	5.83	57.47
42	24.00	5.77	57.96
43	24.00	5.75	57.47
47	24.01	5.71	55.00
48	24.08	5.09	53.85

Table 3: Measurements of aged specimens before testing.

Measurements of aged specimens			
Specimen number	$b$ (mm)	$h$ (mm)	$a_0$ (mm)
5	24.10	5.18	44.10
6	24.10	5.18	43.40
7	24.10	5.15	45.50
8	23.82	5.20	42.60
9	24.08	5.22	43.90
10	24.09	5.13	36.75
11	24.11	5.09	34.70
12	24.10	5.07	37.71
13	24.10	5.07	32.33



Figure 18: Specimens with piano hinges attached.

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## 8.2 Thermoplastic specimens

From the thermoplastic, two different specimens were produced. The specimens differed in that one type was made by welding two thin plates together, while the other set of specimens was cut out of a thick plate. By performing the same test on the different types of specimens, base values for  $G_{Ic}$  for the material itself and for the weld were found. Two different specimens were made from polypropylene, which is a thermoplastic. The polypropylene specimens were cut out of Polystone<sup>®</sup> P Homopolymer plates made by Röchling.

The thermoplastic specimens are cut out of polypropylene plates with a high-pressure water jet. The solid and unwelded specimens are cut out of a 10 mm thick plate, and a 5 mm thick plate was used to cut out the two parts for the welded specimens. The average dimensions of width and length of the cut-out specimens are 24 mm wide and 150 mm long. To be able to mount the specimens in the test machines piano hinges were also glued to these specimens. To ensure adhesion on polypropylene which is classified as a low surface energy plastic a special glue was used, Loctite Superglue All Plastics.

### 8.2.1 Unwelded specimen

The dimensions of the unwelded specimens are shown in Table 4. The dimensions shown in the table are not the final specimen dimensions, which is due to some problems encountered during testing. Further work on the specimens is shown in section 11.5.1.

Table 4: Measurements of the unwelded thermoplastic specimens before testing. Where the specimen width is  $b$ , the thickness is  $h$ , and the manufactured starter crack is  $a_0$ .

Measurements of unwelded specimens			
Specimen number	$b_{specimen}$ (mm)	$h$ (mm)	$a_0$ (mm)
100	24.10	10.0	21.6
101	24.10	10.0	44.1
102	24.09	10.0	43.4
103	24.09	10.0	45.5
104	24.10	10.1	43.5
110	24.11	10.0	44.1
111	24.10	10.1	43.9

### 8.2.2 Welded specimen

Two and two of the cutouts of the 5 mm polypropylene plates were welded together using the hot plate method described in section 7.1. Dimensions of each specimen are shown in Table 4.

Table 5: Measurements of the welded thermoplastic specimens before testing. Where the specimen width is  $b$ , the thickness is  $h$ , and the manufactured starter crack is  $a_0$ .

Measurements of welded specimens			
Specimen number	$b_{specimen}$ (mm)	$h$ (mm)	$a_0$ (mm)
200	24.10	9.8	44.1
201	24.09	9.7	43.4



---

## 9 Static Mode I fracture energy - Double Cantilever Beam

### 9.1 Theory

The method used to calculate the Mode I fracture energy release rate,  $G_{Ic}$ , of the different material specimens, was the Modified Beam Theory (MBT). This is one of three techniques for finding a materials Mode I fracture energy which has been approved by the American Society for Testing and Materials. The modified beam theory was chosen because it is the method that delivers the most conservative results. [21]

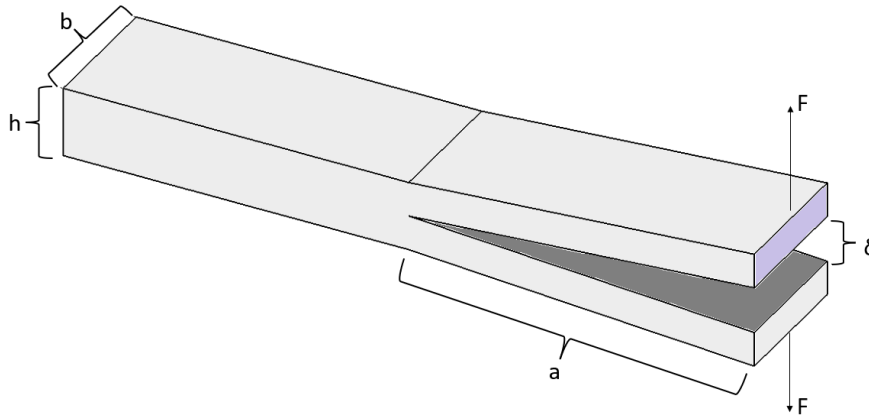


Figure 19: Schematic of a specimen, with measurements and where loads are applied.

#### 9.1.1 Calculations

By using the modified beam theory it is possible to calculate the flexural modulus,  $E_f$ , of the material with the same parameters used for finding the materials  $G_{Ic}$ . The variables needed to find both  $G_{Ic}$  and  $E_f$  are measures taken from the specimen geometry, the delamination length, and the applied load and displacement. The equations return the best and most valid results at relatively low displacements. Therefore it is important to ensure that the initial start crack is within the limitations set by equation (1). Large deflections in the specimen arms result in forces being "absorbed" in the bending of the specimen arms instead of being concentrated in the delamination front. Listed below are all the parameters used in equations (2) and (3):

- Load,  $F$
- Displacement at the load point,  $\delta$
- Width of the specimen,  $b$
- Thickness of the specimen,  $h$

$$G_{Ic} = \frac{3F\delta}{2ba} \quad (2)$$

$$E_{1f} = \frac{64 \cdot a^3 \cdot F}{\delta b \cdot h^3} \quad (3)$$

---

### 9.1.2 Correction of the delamination length

The energy release rate of the materials tested will be overestimated if the delamination lengths measured on the specimens are used without correcting them. The correction value is found by recording load, displacement, and delamination length at several points during the tests. From the registered data the compliance,  $C$ , of the material specimens can be found by calculating the ratio of displacement to load,  $\delta/F$ , at each recorded delamination length. The correction value for the delamination length,  $\Delta$ , can then be found by generating a least squares plot where the cube root of the compliance,  $C^{1/3}$ , is shown as a function of the recorded delamination lengths, as shown in Figure 20. [21]

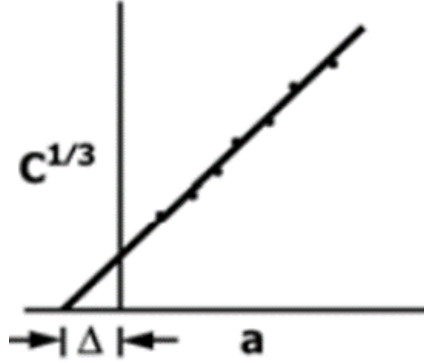


Figure 20: How the correction value,  $\Delta$ , is found by plotting the experimental data. [21]

The delamination length,  $a$ , used to find both  $G_{Ic}$  and  $E_f$  in equations (2) and (3) must be replaced by  $(a + |\Delta|)$ . This results in more reliable results, and the formulas after correction are then:

$$G_{Ic} = \frac{3F\delta}{2b(a + |\Delta|)} \quad (4)$$

$$E_{1f} = \frac{64 \cdot (a + |\Delta|)^3 \cdot F}{\delta b \cdot h^3} \quad (5)$$

### 9.1.3 Load and Displacement values

When performing calculations of  $G_{Ic}$  and  $E_f$  the values for the load and displacement are found by studying the R-curves plotted from the data. R-curves are made by plotting the loads acquired from the performed tests as a function of the displacements recorded by the test machine, Figure 21. The ASTM standard suggests three different methods for acquiring the correct data from the plotted R-curves.



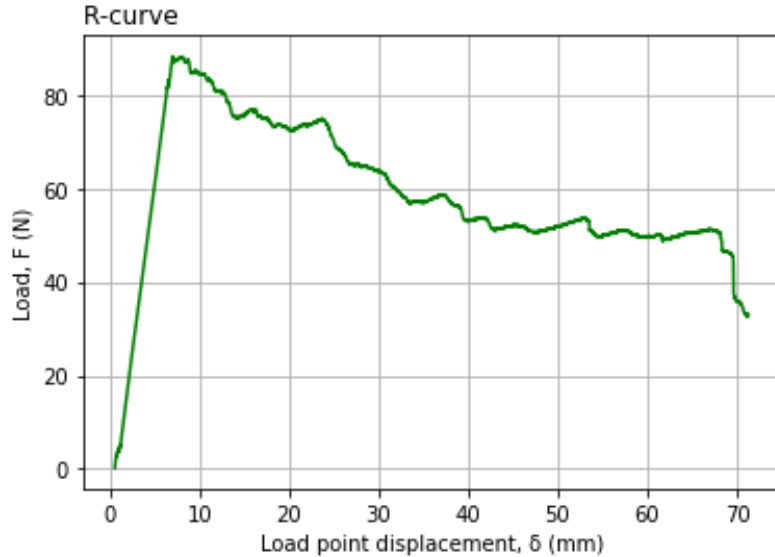


Figure 21: Example of an R-curve. Acquired from one of the performed tests. [B.1]

The method used to acquire the correct load and displacement parameters for further calculations was ASTM's 5% method. Finding the load and displacement by the 5% method is done by offsetting the linear part of an R-cure by 5%. The values of  $F$  and  $\delta$  at the point where the offset line and R-curve intersect are used in equations (4) and (5). It may happen that the specimen's maximum load is registered between the linearity of the R-curve and the offset line, and if this is the case the maximum load and corresponding displacement values are to be used in the calculations. [21]

## 9.2 Experimental work

An estimation of the required force necessary for the delamination front to grow was performed before the tests were carried out. The estimated value of the force required was used to choose the machine that would give the best possible result. The equation used for the estimation was equation (6). An approximately anticipated value of  $G_{Ic}$  was used in the calculation. The expected  $G_{Ic}$  value was based on values found by V. Alfred Franklin. [12] in a similar test setup.

$$F_{max} = \frac{b}{a} \sqrt{\frac{G_{Ic}(h)^3 E}{96}} \quad (6)$$

### 9.2.1 Test setup

Before mounting the specimens in the test machine, they were coated with a thin layer of type-writer correction fluid. The white coating made the delamination growth easier to spot. Each specimen was also marked with vertical lines. For the first 5 mm from the tip of the manufactured delamination front, every 1 mm was marked. The next 45 mm was marked with 5 mm between each mark, Figure 22.

An MTS Criterion Model 42 test machine was chosen for the DCB tests. The specimens were exposed to a constant displacement rate of 5 mm/min during loading and a constant unloading rate of 25 mm/min.



Figure 22: Glass-fiber/Epoxy specimens ready to be tested with mounted hinges, and coated and marked on the side.

### 9.2.2 Test procedure

To ensure a delamination growth as natural as possible, the specimens were loaded until the delamination had grown to about 3 mm. At that point, the specimens were unloaded. By performing this load cycle on each specimen before the actual tests were carried out, all the specimens had a natural delamination front that resulted in more reliable data.

During the actual DCB test of the specimens, the load  $F$  and displacement  $\delta$  at each of the vertical lines marked on the specimens were registered. The data acquired at each point where the delamination front reached one of the marks on the specimens were used to find the correction value for the delamination length.

After the tests, the data recorded by the test machine was plotted as R-curves. The correct values of load and displacement to use in the calculations of  $G_{Ic}$  and  $E_{1f}$  were then found by the intersection between the offset line and the curve from the data.

---

## 10 Fatigue Mode I fracture energy

### 10.1 Theory

Exposing a composite laminate to cyclic loading makes it possible to calculate and visualize the material's delamination growth rate, which represents the material's fatigue life and crack growth. The results are visualized in a graph, Figure 23, where delamination growth per loading cycle is a function of the energy release rate over material resistance.

The growth is divided into three sections, which are limited by the point where the applied force is too small for the crack to develop,  $G_{Ith}/G_{IR}$ , and where the force is equal to that necessary for the specimen to crack on the first cycle,  $G_{I_{max}}/G_{IR}$  equal to 1. Within the limitations the growth regions are the initiation stage where the growth is subcritical, the main growth region where the crack growth is stable, and the unstable region where the growth increases exponentially.

The parameters needed to calculate the delamination growth rate are found by both static Mode I testing, section 9, and data acquired during the cyclic loading. [22]

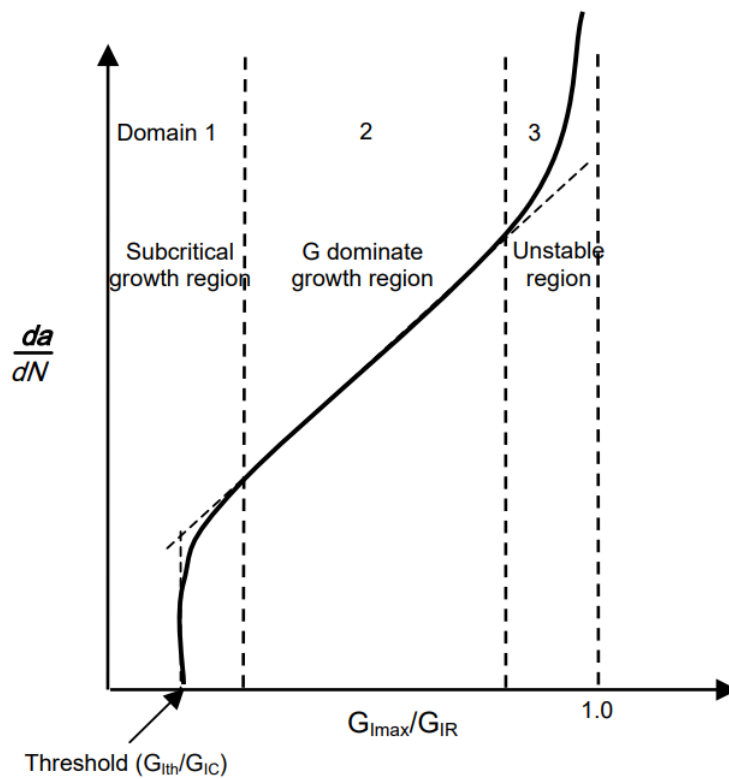


Figure 23: Hypothetical delamination growth rate plot. [22]

#### 10.1.1 Paris law equation

The Paris law equation represents the fatigue life of the material, shown in Figure 23. To express the Paris law equation, an equation for the material resistance as a function of delamination length,  $G_{IR}$ , applied fracture energy as a function of load cycles,  $G_{I_{max}}$ , and the material constants  $A$  and  $m$  are needed.

The material resistance,  $G_{IR}$ , can be found with the experimental results from the static DCB testing. Material resistance is a function of Mode 1 fracture energy release rate and the delamination length, and found by curve-fitting the visualized DCB results, Figure 24. With larger delaminations the resistance increases, this is due to an increase in fiber bridging. [22]

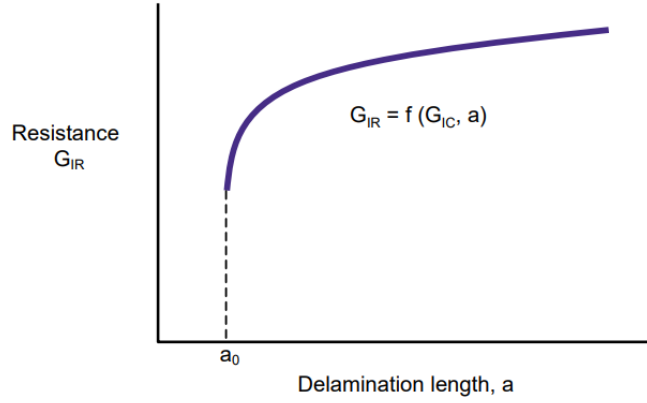


Figure 24: Hypothetical plot of Material resistance. [22]

The equation for applied fracture energy,  $G_{I_{max}}$ , at different fatigue load cycles, is found by curve fitting of the raw data of applied load, displacement, delamination, and cycle count recorded during the fatigue tests. An example of the graph acquired from the raw data is shown in Figure 25.

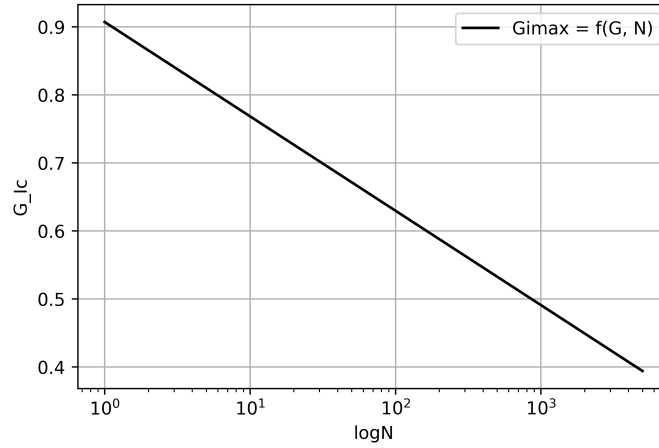


Figure 25: Hypothetical plot of experienced Fracture energy.

From the equations for  $G_{I_{max}}$  and  $G_{IR}$  it is possible to calculate  $\Delta G$ , equation (7), as a function of both delamination length and cycle count.

$$\Delta G = \frac{G_{I_{max}}}{G_{IR}} \quad (7)$$

When  $\Delta G$  is known it is possible to express the results by the Paris law, equation (8).  $A$  and  $m$  are material constants used in the calculations and are found by fitting the curve to the stable growth section found by testing, Figure 23.

$$\frac{da}{dN} = A \cdot \Delta G^m \quad (8)$$

### 10.1.2 Test procedure

To determine the displacement to expose the specimens to during the fatigue testing equation (9) was used. The equation returns an approximate displacement when given what percentage of  $G_{Ic}$  each specimen is to be exposed to. [22]

$$\delta_{I_{max}} = \sqrt{\frac{G_{I_{max}}}{G_{I_c}} \left( \frac{a_0 + \Delta}{a_{I_c} + \Delta} \right)^2} \delta_{I_c} \quad (9)$$

The specimens used in the Mode I fatigue test were equal to the ones used in the Double Cantilever Beam (DCB) test, Figure 22, but had markings for delamination lengths every 2 mm, Figure 26. For every delamination marking reached during testing the cycle count, delamination length, and the applied load and displacement were noted. The acquired parameters at each delamination length were then used to calculate the values of  $da/dN$  (delamination length per load cycle) and  $G_{I_{max}}/G_{IR}$  (applied energy compared to the material resistance), which are used to produce a fatigue life curve like the one in Figure 23.

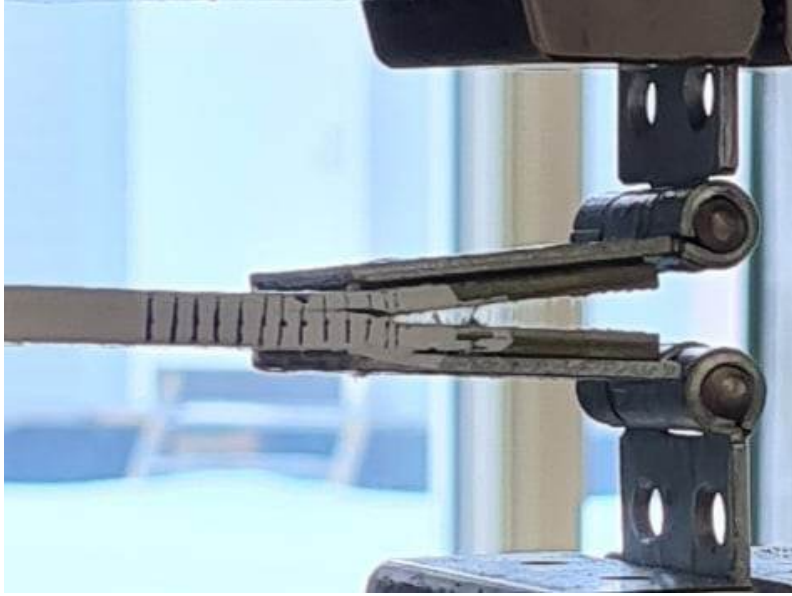


Figure 26: A fatigue specimen mounted in the test machine.

$G_{I_{max}}$  values are found by the same equation that was used for calculations of the static  $G_{I_c}$  values, equation (4), with the load and displacement values acquired at each marked delamination length at the specimen, and the average  $\Delta$  value found by the static DCB test as variables.

From the curve fit used to create the graph in Figure 24 an equation for  $G_{IR}$  with delamination growth as a variable is obtained. The results from the  $G_{IR}$  equation at the different delamination lengths marked along the specimens are used in the calculations of  $G_{I_{max}}/G_{IR}$  at each delamination length. The results of  $da/dN$  as a function of  $G_{I_{max}}/G_{IR}$  are then plotted to visualize the fatigue life of the material.

## 10.2 Experimental work

### 10.2.1 Test machine setup

The machine used in the fatigue testing was an MTS Landmark 50 kN load frame, with a ramp-up speed of 2 mm/min to the maximum amplitude, before a cyclic loading at  $R = 0.1$ .  $R$  is the ratio between the maximum and minimum amplitude, and when  $R = 0.1$  it means that the minimum amplitude equals 10% of the maximum amplitude.

The maximum displacement applied to each specimen differed and was dependent on both the initial crack length,  $a_0$ , of the specimen itself and the desired value of  $G_{I_{max}}/G_{I_c}$  to apply. Knowing both  $a_0$  and  $G_{I_{max}}/G_{I_c}$  the maximum displacement to apply to the individual specimen was

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calculated by equation (9). The minimum displacement was then found by equation (10), where  $A_{max}$  is the maximum displacement.

$$A_{min} = A_{max} \cdot 0.1 \quad (10)$$

After acquiring the maximum and minimum displacement to expose each individual specimen to the displacement values were plotted into the MTS Landmark, a frequency of 2 Hz was also chosen. The low Hz was chosen to be able to monitor the growth of the crack on the specimen.

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## 11 Results

### 11.1 Static Mode I - Unaged Glass-fiber/Epoxy specimens

The raw data registered by the test machine during the DCB testing of the unaged specimens are shown in Figure 27. Specimens 1-4 and specimens 41-43 originate from different laminates, and the different behavior of the two sets of specimens is due to the difference in the initial delamination,  $a_0$ .

The load and displacement data registered at each point where the delamination front reached one of the pre-marked delamination lengths on specimens 1-4 are shown in Table 6 and the data from specimens 41-43 in Table 7. Further on in the calculations of the Mode I fracture energy release rate the data registered at these markings are used to calculate the correction value for the delamination lengths and ensure a better final result of the calculations, as explained in section 9.1.

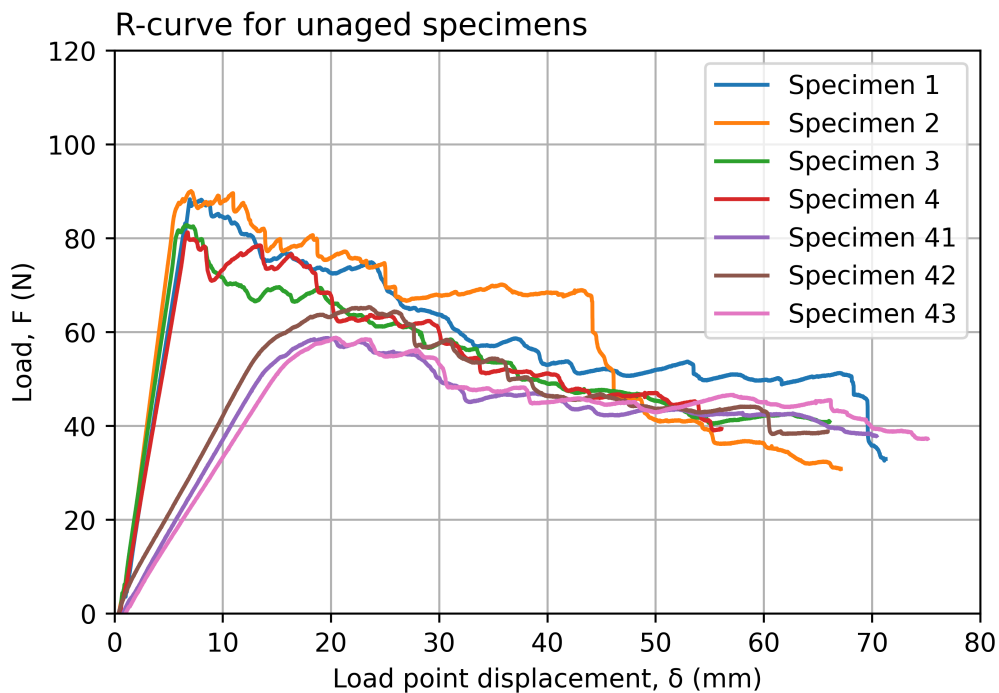


Figure 27: R-curves for the unaged specimens. Specimens 1-4 and specimens 41-43 are from different laminates with different  $a_0$ , which results in their different behavior. [B.1]

Table 6: Raw data acquired from specimens 1-4.

$a$ (mm)	Specimen 1		Specimen 2		Specimen 3		Specimen 4	
	$F$ (N)	$\delta$ (mm)	$F$ (N)	$\delta$ (mm)	$F$ (N)	$\delta$ (mm)	$F$ (N)	$\delta$ (mm)
1	-	-	88.87	6.94	40.46	3.16	42.95	3.83
2	-	-	88.84	9.51	56.97	4.25	79.67	6.95
3	59.75	4.90	87.72	9.92	70.98	5.17	78.08	8.22
4	78.75	6.21	88.07	10.26	82.73	6.64	71.53	8.82
5	86.49	6.84	86.35	11.00	72.27	9.60	70.99	8.94
10	84.53	9.98	74.93	23.09	68.80	12.19	74.35	10.34
15	83.14	10.88	69.37	36.30	68.68	19.26	68.35	19.45
20	72.48	20.19	57.45	44.62	61.20	24.17	62.50	22.75
25	65.21	26.89	42.68	49.03	56.72	28.88	62.12	28.69
30	60.54	31.49	41.07	51.55	53.45	36.55	54.50	32.46
35	53.22	39.66	36.21	56.26	48.40	40.20	51.47	37.74
40	52.03	44.95	33.38	62.83	46.72	48.57	46.00	44.31
45	50.41	53.65	30.99	66.77	40.86	65.87	44.82	51.33
50	33.29	70.82	-	-	-	-	39.16	55.45

Table 7: Raw data acquired from specimens 41-43.

$a$ (mm)	Specimen 41		Specimen 42		Specimen 43	
	$F$ (N)	$\delta$ (mm)	$F$ (N)	$\delta$ (mm)	$F$ (N)	$\delta$ (mm)
1	57.03	16.98	54.34	13.02	55.10	16.82
2	58.30	18.53	59.68	15.62	56.96	18.23
3	58.68	19.61	61.60	17.12	58.09	19.67
4	58.54	20.05	63.60	18.96	58.69	20.51
5	57.08	20.70	63.30	20.00	57.78	21.10
10	55.40	24.90	64.18	26.22	55.21	26.42
15	52.60	29.16	58.2	30.60	48.45	30.74
20	45.4	32.51	53.70	39.96	47.91	34.03
25	46.86	38.58	47.64	38.92	45.03	39.87
30	43.56	42.65	45.58	42.10	44.95	47.39
35	43.26	49.60	44.27	48.34	46.13	57.79
40	42.28	58.46	42.84	54.13	44.19	63.00
45	40.37	65.54	43.11	60.03	40.12	69.83
50	38.13	70.01	38.67	65.44	37.27	74.99



### 11.1.1 Finding the Load and Displacement

The equation for Mode I fracture energy release rate, equation (4), takes load and displacement as variables. The right load and displacement values are found by the 5% offset method, explained in section 9.1.3. Load and displacement are found by offsetting the linearity of the raw data recorded by the test machine by 5%. At the intersection between the plotted raw data and the offset line values for load and displacement to be used in the calculation of  $G_{Ic}$  are found. Figure 28 shows the process of offsetting the linearity and locating the values to be used in the calculations. The process is performed on every specimen tested and presented in appendix A.1, and all the results are shown in Table 8.

#### Specimen 1:

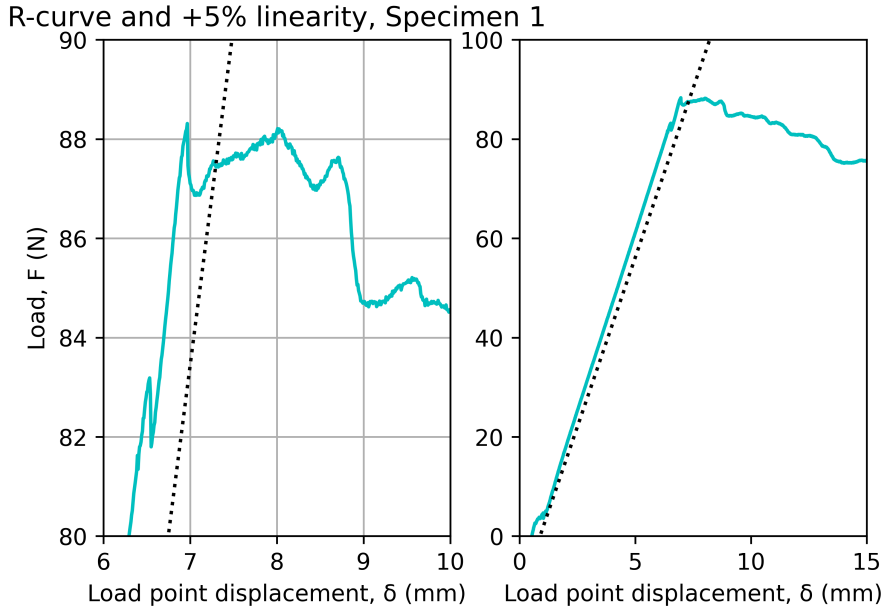


Figure 28: R-curve for specimen 1, with a 5% offset-line. [B.2]

Table 8: Load,  $F$ , and Displacement,  $\delta$ , values after 5% offset.

Load and Displacement		
Specimen	$F$ (N)	$\delta$ (mm)
1	88.31	6.968
2	87.30	6.049
3	81.98	6.298
4	81.25	6.759
41	53.30	14.65
42	57.80	14.38
43	53.80	16.10

### 11.1.2 Correcting the delamination length

A correction of the delamination value is performed to avoid overestimation of the  $G_{Ic}$  value. The process is explained in detail in section 9.1.1 and shown in Figure 29. As seen in the figure, the correction value,  $\Delta$ , is the x-axis value where  $C^{1/3}$  equals zero. The correction values for all the unaged specimens are shown in Table 9. For the rest of the plots used to find the  $\Delta$  values see appendix A.2.

**Specimen 1:**

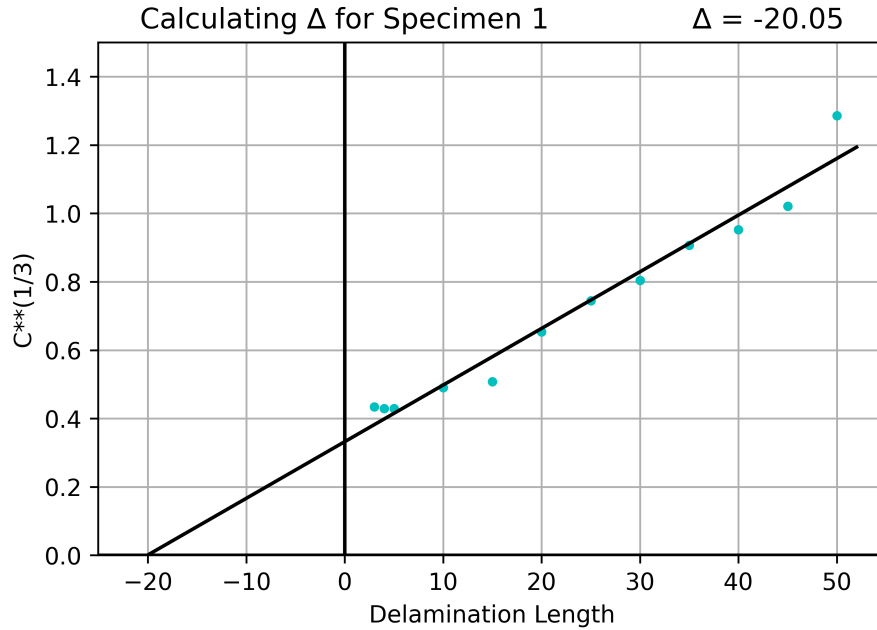


Figure 29: Finding the value of  $\Delta$  for specimen 1. [B.3]

Table 9: Correction values,  $\Delta$ .

Correction values, $\Delta$	
Specimen	$\Delta$
1	-20.05
2	-21.58
3	-24.06
4	-30.78
41	-57.67
42	-54.86
43	-55.33

### 11.1.3 Calculations

The loads, displacements, and correction values in Tables 8 and 9 together with the other specimen variables needed in the calculations of the fracture energy release rate are found in Table 10. Calculations of  $G_{Ic}$ , equation (4), are presented in Table 11, and  $E_{1f}$  results are shown in Table 12 which are calculated by equation (5).

Table 10: Data acquired from the experiments, and measurements of the specimens.

Data for calculations						
Specimen	$F$ (N)	$\delta$ (mm)	$ \Delta $ (mm)	$a$ (mm)	$b$ (mm)	$h$ (mm)
1	88.31	6.968	20.05	36.57	24.10	4.87
2	87.30	6.049	21.58	37.87	24.10	4.95
3	81.98	6.298	24.06	41.14	24.14	4.93
4	81.25	6.759	30.78	39.15	24.09	4.95
41	53.3	14.65	57.67	57.47	24.01	5.83
42	57.8	14.38	54.86	57.96	24.00	5.77
43	53.8	16.10	55.33	57.47	24.00	5.75

Table 11: Fracture energy results, calculated by using the experimental data.

$G_{Ic}$ results	
Specimen	$G_{Ic}$ ( $J/m^2$ )
1	676
2	553
3	492
4	489
41	424
42	460
43	480

Table 12: Flexural modulus results, calculated by using the experimental data.

$E_{1f}$ results	
Specimen	$E_{1f}$ (MPa)
1	52 892
2	66 395
3	79 827
4	90 045
41	74 705
42	80 125
43	67 274

## 11.2 Static Mode I - Aged Glass-fiber/Epoxy specimens

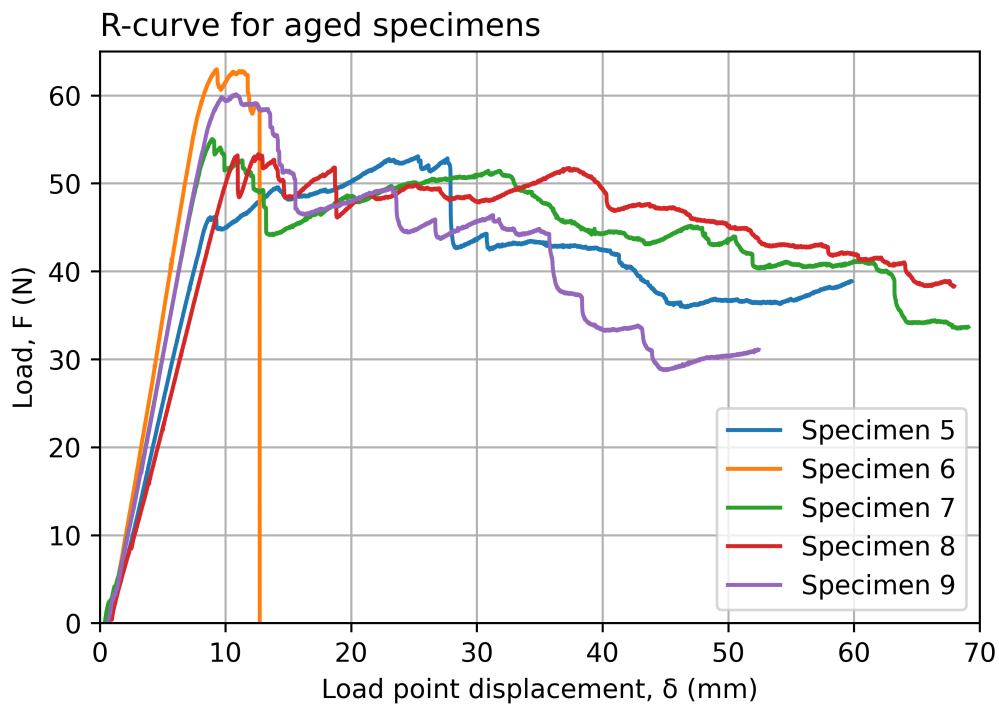


Figure 30: R-curves for the aged specimens. The immediate drop-off in load at specimen 6 is due to its hinges falling off. [B.1]

As seen in the results acquired from the double cantilever beam test of the aged specimens in Figure 30, the values for specimen 6 are an outlier. The reason for the sudden drop in load was that one of the hinges attached to the specimen was torn off. The torn-off hinge resulted in not enough data being recorded for specimen 6, and therefore this specimen will be excluded from the calculations.

Table 13: Raw data acquired by testing of aged DCB specimen.

$a$ (mm)	Specimen 5		Specimen 7		Specimen 8		Specimen 9	
	$F$ (N)	$\delta$ (mm)	$F$ (N)	$\delta$ (mm)	$F$ (N)	$\delta$ (mm)	$F$ (N)	$\delta$ (mm)
1	33.70	6.40	53.27	9.80	49.06	11.30	59.43	10.18
2	48.10	12.90	51.17	11.62	49.70	16.50	59.10	11.93
3	49.20	14.29	44.20	13.35	50.50	17.32	57.79	13.56
4	49.20	18.54	44.19	13.87	46.20	19.04	55.40	14.04
5	51.59	21.70	44.94	14.99	48.20	22.03	46.79	17.04
10	43.10	35.19	50.76	29.60	48.04	30.99	44.60	28.37
15	-	-	46.06	36.43	47.50	42.23	30.75	51.52
20	-	-	44.66	46.13	46.67	51.76	-	-
25	-	-	-	-	42.94	57.05	-	-

---

### 11.2.1 Calculations

The loads, displacements, and correction values for delamination lengths for the aged specimens shown in Table 14 are found by the same method as the unaged specimens described in sections 11.1.1 and 11.1.2. The plots used to find the specimen variables in Table 14 are found in the appendix A.1 and A.2. Calculations of fracture energy release rate and flexural modulus of the aged material are shown in Tables 15 and 16.

Table 14: Data acquired from the experiments, and measurements of the aged specimens.

Data for calculations						
Specimen	$F$ (N)	$\delta$ (mm)	$ \Delta $ (mm)	$a$ (mm)	$b$ (mm)	$h$ (mm)
5	46.17	9.10	-14.31	47.1	24.10	5.18
7	55.05	8.95	-25.58	45.5	24.10	5.15
8	48.65	11.03	-33.45	45.6	23.82	5.20
9	59.45	9.95	-11.05	43.9	24.08	5.22

Table 15: Fracture energy results, calculated by using the experimental data.

$G_{Ic}$ results	
Specimen	$G_{Ic}$ ( $J/m^2$ )
5	433
7	431
8	439
9	671

Table 16: Flexural modulus results, calculated by using the experimental data.

$E_{1f}$ results	
Specimen	$E_{1f}$ (MPa)
5	21 371
7	42 946
8	38 553
9	18 524

---

## 11.3 Fatigue Mode I - Unaged Glass-fiber/Epoxy specimens

### 11.3.1 Raw data

Figure 31 shows the experienced fracture energy during fatigue testing compared to the average fracture energy release rate found by static DCB testing in section 11.1 as a function of loading cycles. The equation for  $G_{I_{max}}$  at different load levels is:

$$G_{I_{max}} = 0.463 - 0.031 \cdot \log(N) \quad (11)$$

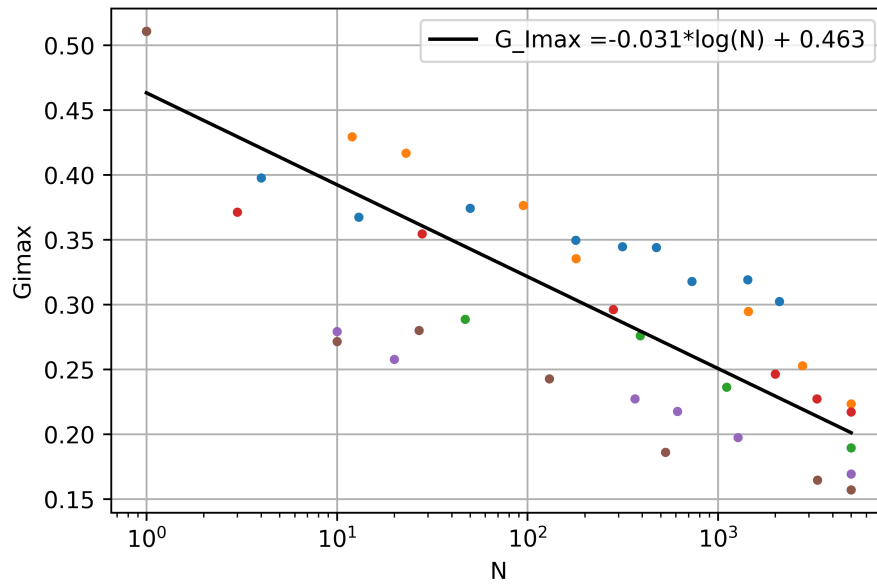


Figure 31: Applied fracture energy release rate compared to the fracture energy release rate found by static DCB tests previously performed. [B.6]

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### 11.3.2 Material resistance

Material resistance,  $G_{IR}$ , is a material variable needed in the calculation of fatigue life and delamination growth rate, as described in section 10.1. To find the material resistance of the unaged material the raw data from the static DCB tests found in Tables 6 and 7 are used in equation (4). The results are then plotted, Figure 32, and by curve-fitting equation (12) are acquired.

$$G_{IR} = 1.003 + 0.27 \cdot \log(a) \quad (12)$$

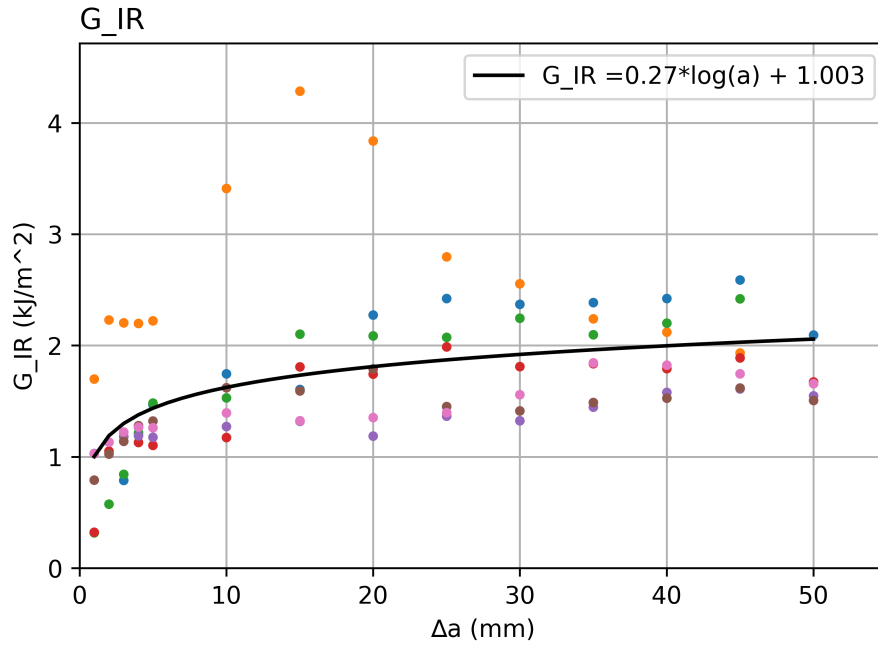


Figure 32: Material resistance,  $G_{IR}$ , of the unaged specimens. [B.5]

### 11.3.3 Calculations

Table 17 shows specimen measurements, the intended value of applied stresses in the form of energy required to encourage delamination in the material, the applied displacement, measured delamination and force registered, and the calculated energy which is applied and how this value is compared to the fracture energy release rate. In addition to the values shown in Table 17 the complete fatigue life results are shown in Figure 33. Every test was run until 5000 cycles were reached, due to the lack of visible growth after 3000 cycles.

Table 17: Parameters from the cyclic loading of unaged composite specimens.

#	$b(mm)$	$a_0(mm)$	Intended	Applied	Measured		Actual	
			$\frac{G_{I_{max}}}{G_{Ic}}$	$\delta_{I_{max}}(mm)$	$\Delta a(mm)$	$F_{I_{max}}(N)$	$G_{I_{max}}$	$\frac{G_{I_{max}}}{G_{Ic}}$
28	24.00	54.45	0.70	11.89	11	58.81	395.95	0.78
29	23.97	52.90	0.64	11.00	11	55.84	353.25	0.69
30	23.97	56.10	0.50	10.35	10	48.85	281.63	0.55
31	24.05	55.80	0.55	10.80	9	45.66	273.76	0.54
47	24.01	55.00	0.65	11.57	10	62.33	406.05	0.80
48	23.99	54.33	0.60	10.98	16	61.51	465.13	0.91

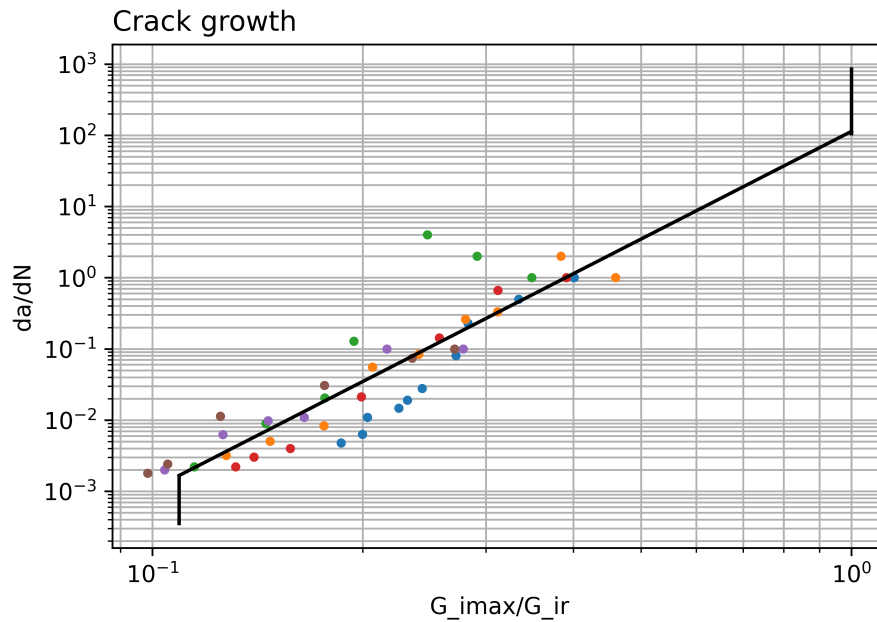


Figure 33: The crack growth results from the fatigue Mode I testing of the unaged specimens. [B.6]



### 11.3.4 Paris law equation

The material constants  $A$  and  $m$  for the unaged specimens used in the Paris law, equation (8), are determined by fitting the Paris law curve to the slope of the stable growth as seen in Figure 34. The dotted vertical lines in the plot represent the different regions of the fatigue crack growth, divided into subcritical growth, stable growth, and unstable growth.

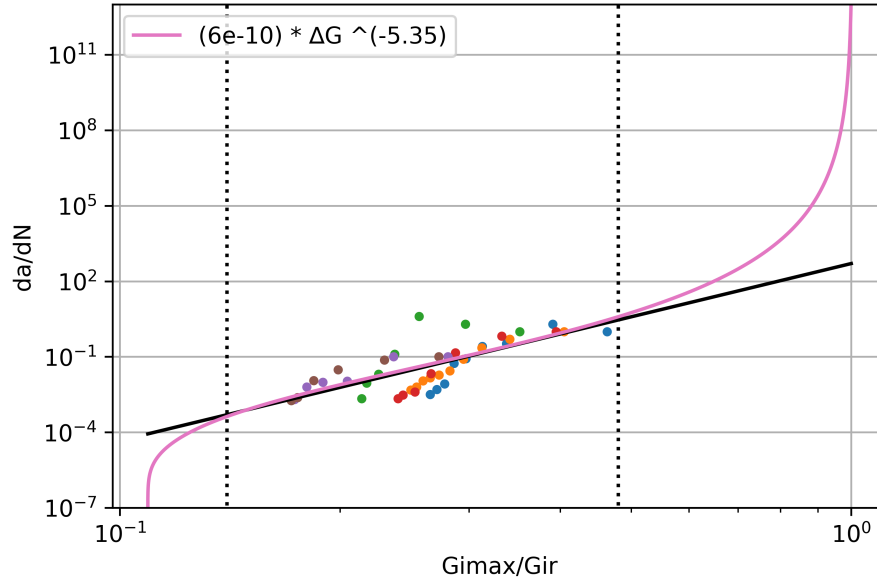


Figure 34: The Paris equation of the unaged specimens. [B.6]

Values for the constants  $A$  and  $m$  are  $(0.6 \cdot 10^{-9})$  and  $(-5.35)$ . The Paris equation for the unaged composite material is:

$$\frac{da}{dN} = 0.6 \cdot 10^{-9} \cdot \Delta G^{-5.35} \quad (13)$$

Where  $\Delta G = \frac{G_{imax}}{G_{ir}}$  and is determined by equations (11) and (12).

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## 11.4 Fatigue Mode I - Aged Glass-fiber/Epoxy specimens

### 11.4.1 Raw data

The raw data of experienced fracture energy are compared to the  $G_{Ic}$  of the aged material for each specimen tested are plotted at a function of load cycles, Figure 35, for each of the aged specimens tested, which resulted in the equation:

$$G_{I_{max}} = 0.455 - 0.035 \cdot \log(N) \quad (14)$$

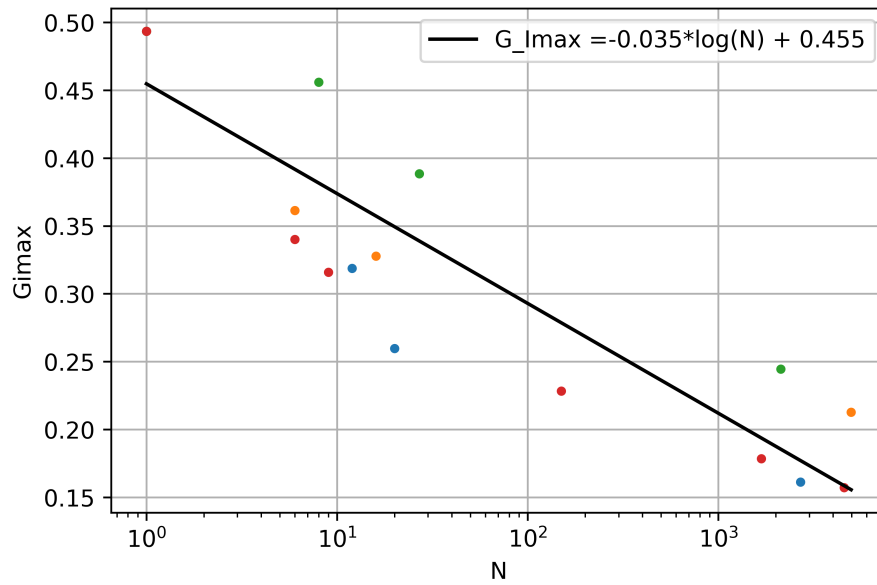


Figure 35: Applied fracture energy release rate compared to the fracture energy release rate found by static DCB tests previously performed. [B.6]

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### 11.4.2 Material resistance

Same as for the unaged specimens, the material resistance is found by using the results acquired from the static test. The material resistance of the aged specimens is shown in Figure 36, and from the plot equation (15) is found.

$$G_{IR} = 0.457 \cdot \log(a) + 1.705 \quad (15)$$

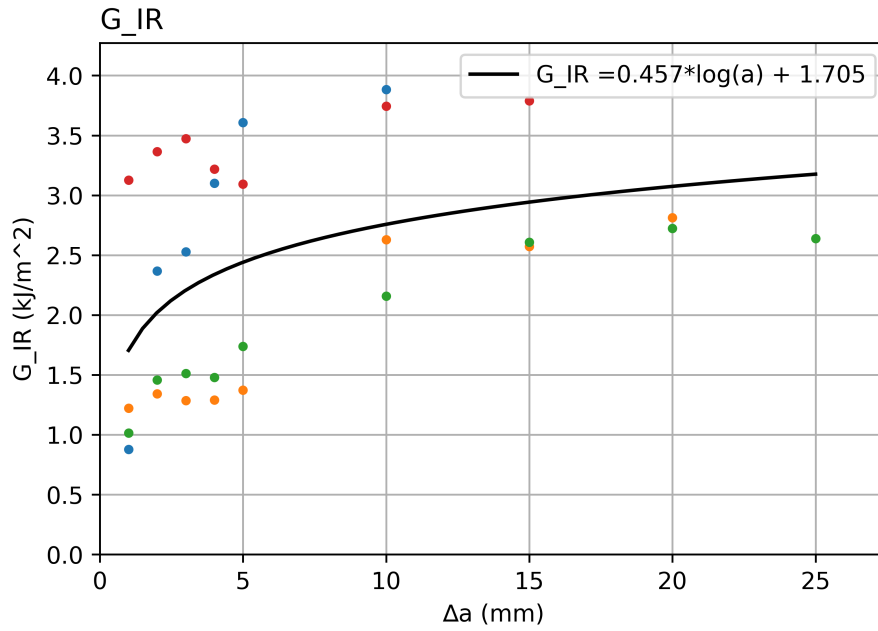


Figure 36: Material resistance,  $G_{IR}$ , of the aged specimens. [B.5]

### 11.4.3 Calculations

Registered data for every aged specimen tested are shown in Table 18, and Figure 37 shows the growth of delamination caused by the cyclic loading. Each specimen where exposed to 5000 cycles of displacement-controlled loading.

Table 18: Parameters from the cyclic loading of aged composite specimens.

#	$b(mm)$	$a_0(mm)$	Intended	Applied	Measured		Actual	
			$\frac{G_{I_{max}}}{G_{I_c}}$	$\delta_{I_{max}}(mm)$	$\Delta a(mm)$	$F_{I_{max}}(N)$	$G_{I_{max}}$	$\frac{G_{I_{max}}}{G_{I_c}}$
10	24.11	36.75	0.5	5.18	8	64.31	363	0.74
11	24.10	34.70	0.65	5.52	10	68.01	418	0.85
12	24.10	37.71	0.8	6.80	8	71.26	512	1.04
13	24.08	32.33	0.7	5.25	14	64.31	393	0.8

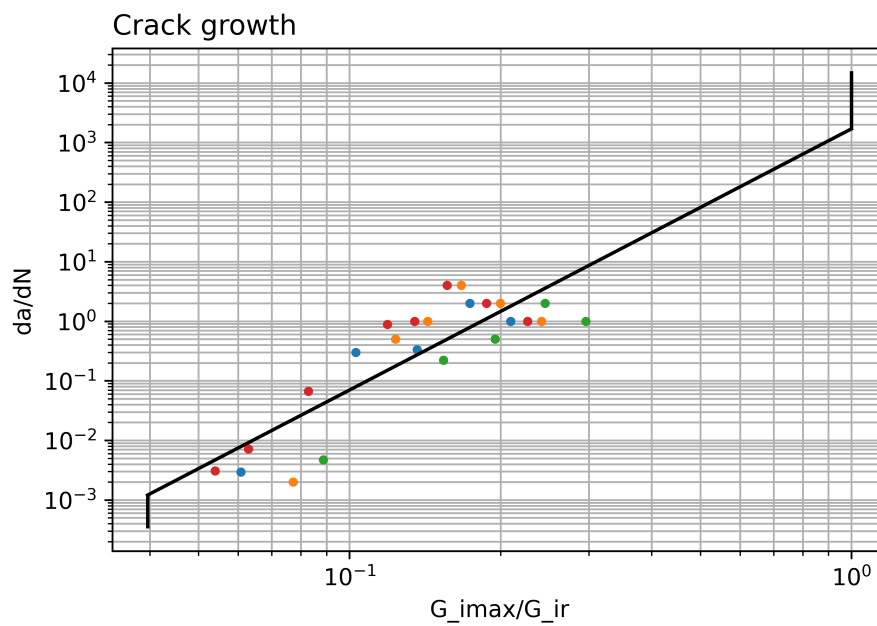


Figure 37: The crack growth results from the fatigue Mode I testing of the aged specimens. [B.6]

#### 11.4.4 Paris law equation

Figure 38 show the fatigue life results of the aged specimen expressed with the Paris law, equation (8), shown in the top left corner of the graph. The dashed vertical lines separate the different growth regions explained in section 10.1.

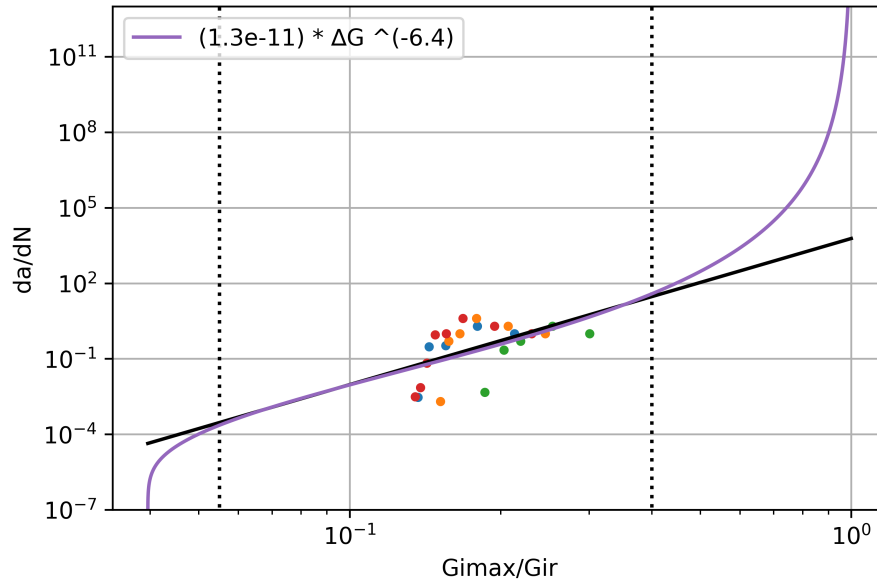


Figure 38: The Paris equation of the aged specimens. [B.6]

Values for the constants  $A$  and  $m$  are  $1.3 \cdot 10^{-11}$  and  $-6.4$ . The Paris equation for the aged composite material is:

$$\frac{da}{dN} = 1.3 \cdot 10^{-11} \cdot \Delta G^{-6.4} \quad (16)$$

Where  $\Delta G = \frac{G_{I_{max}}}{G_{I_R}}$  and is determined by equations (14) and (15).

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## 11.5 Static Mode I - Solid Polypropylene specimens

### 11.5.1 Specimen difficulties

#### Initial Specimens

The specimens are designed like the schematic in Figure 15, and the composite specimens which are described in section 8.1. To manufacture the initial crack on these specimens, a saw was used to cut into the side of the specimen. The saw produced a crack with a large radius, which is not desired. The radius of the crack was then made smaller by sharpening it with a razor blade.

When testing the initial specimens there was no delamination growth, due to a too-short initial delamination length (10 mm). During the loading, there was no displacement at the load point, and the hinges detached from the specimen due to large forces.

#### First Specimen improvement

To encourage delamination growth, the initial crack length was extended. The longer start crack was an improvement in the way that there was displacement at the load point. The displacement resulted in the opening of the "arms" between the delamination front and load point. But instead of delamination, the applied forces resulted in specimen failure between the initial crack and specimen surface, see Figure 39.



Figure 39: Failure of the initial polypropylene specimens.

#### Second Specimen improvement

Since the increased delamination length from the first improvement encourage displacement at the load point, an initial delamination of a similar length was used for the second improvement. To promote delamination a cut into the sides of the specimens was made, see Figure 40. The slits were made by cutting with a saw, before sanding the cut smooth. By making the slit into the specimens the applied forces will be concentrated in a smaller area, which increases the chance of delamination.

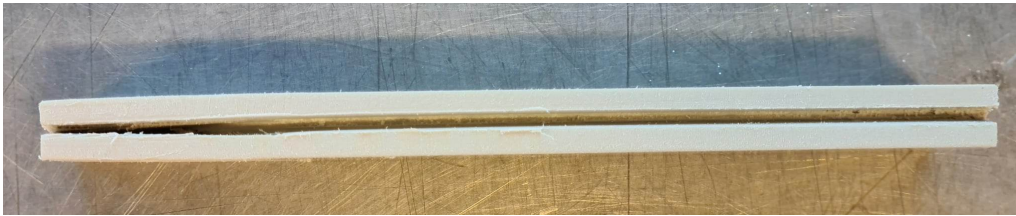


Figure 40: The slit on the improved polypropylene specimens.

The slit was an improvement, but the specimen broke in the same place as the un-slit specimen. The behavior of the slit specimen before failure was very different from that of the un-slit. Instead of just breaking off, the specimen arm between the delamination front and load point bent excessively before the lower arm broke off, Figure 41. As seen in the right side picture in Figure 41, a small delamination of about 1 mm was detected. Even though the delamination is minor, the slit worked as expected and did concentrate the applied forces in the desired area.



Figure 41: Behavior of the improved slit specimen, and the small delamination acquired.

### Third Specimen improvement

To increase the concentration even more and increase the chance of delamination the slit was made deeper and thinner. The deeper cut into the side of the specimens will result in a higher concentration of forces than the previously slit specimen. To reduce the bending of the specimen arms the slit is made thinner, which leaves more material to stiffen up the specimen. In addition to improving the specimen itself, the strain rate used during the test will be increased. By increasing the speed of the load cell the polypropylene's ability to behave viscoelastic and creep will be reduced, and therefore reduce the bending experienced by the specimen.

Even at increased strain speeds (10 mm/min), excessive bending took place in the specimens after the third improvement of the specimens as well, and no delamination growth was detected. The behavior of the specimens was similar to the behavior registered after the second improvement, as seen in Figure 41.

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Table 19: Measurements of the unwelded thermoplastic specimens before testing. Where the specimen width is  $b_{specimen}$ , the slit width is  $b_{slit}$ , the thickness is  $h$ , and the manufactured starter crack is  $a_0$ .

Measurements of unwelded specimens				
Specimen number	$b_{specimen}$ (mm)	$b_{slit}$ (mm)	$h$ (mm)	$a_0$ (mm)
100	24.10	-	5.18	44.1
101	24.10	-	5.18	43.4
102	24.10	-	5.15	45.5
103	24.10	19.1	5.18	43.5
110	24.10	15.8	5.18	44.1
111	24.10	13.4	5.15	43.9

As a result of time running out due to the deadline, there was no more time for the continuation of testing the thermoplastic specimens. The dimensions of the specimens tested, with and without slits are shown in Table 19.



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## 12 Discussion

### 12.1 Behavior of the [0/90] interface

The fracture energy and flexural modulus results are presented again in Table 20.

Table 20: Flexural modulus and Fracture energy results.

$E_{1f}$ & $G_{Ic}$ results		
Specimen	$E_{1f}$ (MPa)	$G_{Ic}$ (J/m <sup>2</sup> )
1	52 892	676
2	66 395	553
3	79 827	492
4	90 045	489

Table 20 shows the data acquired from the double cantilever beam test of the unaged specimens. The data collected during the test show a variation of results between the different specimens in both flexural modulus,  $E_{1f}$ , and the fracture energy release rate,  $G_{Ic}$ . Even though the results differ between the specimens there is a correlation between the values of  $E_{1f}$  and  $G_{Ic}$ . The specimens where less energy was absorbed during the delamination show a higher flexural modulus and vice versa.

During the loading of the specimens, the two sides of the crack behaved differently from each other. The different behavior registered from the two sides of the crack is due to the layup of the composite specimen. The layup resulted in one side being exposed to more bending than the other side, see Figure 42. Layers K:4-6, see Figure 43, has a [90/0/90] layup and experienced excessive bending compared to layers K:1-3 with a [0/90/0] layup.

The reinforcing fibers in the 0° direction go along the length of the specimen and stiffen up the specimen and increase its flexural strength. By looking at the layup of the sections on each side of the delamination the different behaviors can be explained. Layers K:1-3 with layup [0/90/0] have two layers of reinforcing fibers in the 0°, which results in a much higher flexural strength than layers K:4-6 has got with its [90/0/90] layup. Therefore layers K:4-6 with their lower flexural modulus tend to bend more than layers K:1-3.



Figure 42: The underside of the specimen bends much more than the top. This is due to the different layups on each side of the crack.

In some of the tests performed Mode II failure was recorded as well as the Mode I failure the test is designed to promote. Mode II failure occurs when the shear forces between the layers of glass-fiber mats exceed what the material is able to withstand, see Figure 9. This type of failure was only seen in layers K:4-6 with the [90/0/90] layup, which are the layers that experienced excessive bending, Figure 43.

For all the specimens where Mode II failure occurred, it started between layers 4 and 5 and grew parallel to the Mode I failure between layers 3 and 4. After the delaminations caused by Mode I and Mode II failure mechanisms had grown a bit the delamination between layers 3 and 4 tended to migrate through layer 4 and merge with the delamination between layers 4 and 5. At that point, further delamination was caused by Mode I delamination. This combination of failure mechanisms was recorded in some of the unaged and aged specimens.

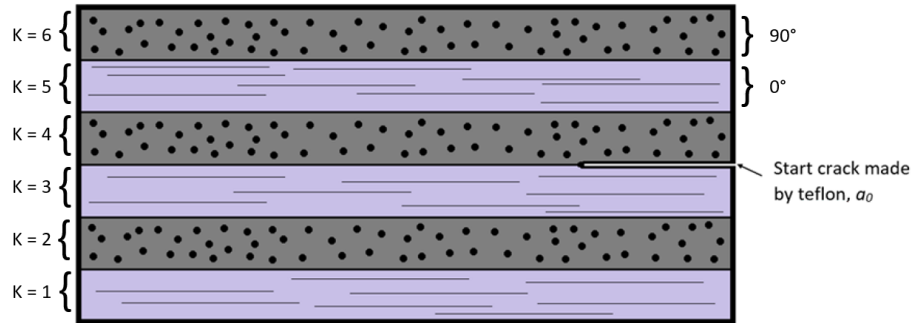


Figure 43: The layup of the specimen, with numbered layers. Where K indicates the layer number.

The energy consumed during the tests where the Mode II delamination occurred as well as the desired Mode I delamination was notably higher. The high energy consumption is caused by the simultaneous growth of the two parallel delamination fronts, and delamination is known to require a lot of energy. From the data in Table 20 both specimens 1 and 2 experienced a combination of Mode I and Mode II delamination.

For specimens 3 and 4 the registered energy consumed is notably less than for specimens 1 and 2, Table 20, because these specimens were only exposed to Mode I delamination and consumed therefore less energy during delamination development. The calculated flexural modulus for the specimens where only one delamination front was observed is much higher compared to the specimens which experienced Mode I and Mode II delamination. Their high flexural modulus is a result of the specimen's ability to withstand the flexural loads and not lose their integrity, caused by the Mode II failure. Figure 44 shows some of the delamination processes.

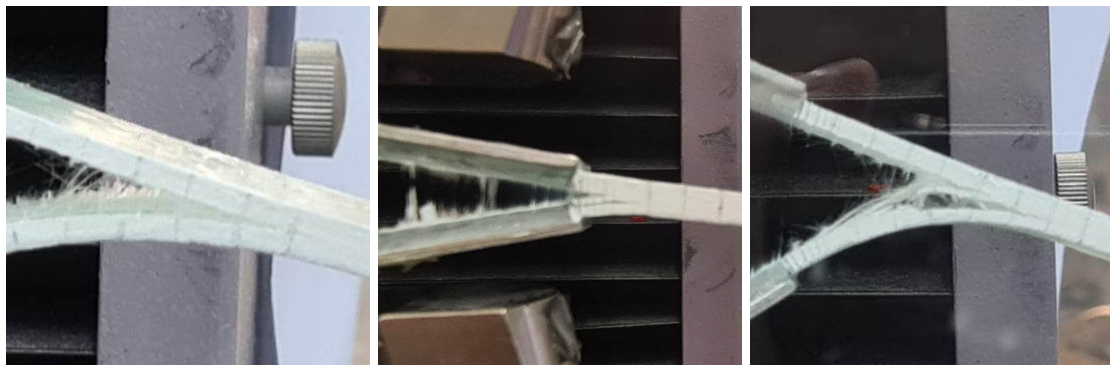


Figure 44: The different delamination processes. From the left: Specimen 4 - Mode I failure only, Specimen 1 - Mode I and Mode II, Specimen 2 - Mode I and Mode II.

During the fatigue testing of the specimens, only Mode I delamination took place, but crack

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migration was observed for every performed test. During this migration, the crack traveled through layer K:4 and stopped when it hit layer K:5, Figure 45. Since layer K:4 have reinforcing fibers 90° to the crack growth the delamination front can easily travel through the epoxy and around the fibers in this layer. When the delamination front reached the fibers going along the specimen in layer K:5 it was hindered and traveled along the interface of layers K:4-5.

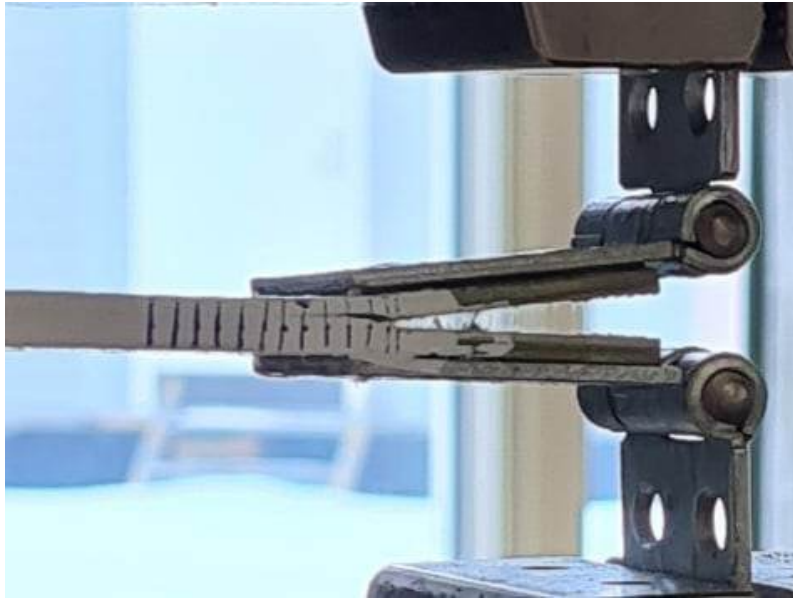


Figure 45: How the crack traveled from the middle-layer through the 90-layer until it hit the next 0-layer.

Unlike the crack migration in the specimens used in the double cantilever beam test, the crack migration experienced during the cyclic load tests started immediately after the loading of the specimens. This is due to the different failure mechanisms caused by the two tests. During the DCB tests, the applied forces are large enough to ensure that delamination took place between the reinforcing layers, while the loads applied during the fatigue testing were too low for this to happen. Therefore, since the matrix is the weakest part of the laminate the crack grew through the epoxy during the initial stage of the cyclic loading, until it hit the next layer with fibers going along the specimen.

## 12.2 Comparing the results of aged and unaged static DCB tests

The results of fracture energy and flexural modulus of the aged and unaged specimens cut out from the same laminate are shown in Table 21, and an average of the results in Table 22.

Table 21: Flexural modulus and Fracture energy results.

$E_{1f}$ & $G_{Ic}$ results		
Specimen	$E_{1f}$ (MPa)	$G_{Ic}$ (J/m <sup>2</sup> )
1 (unaged)	52 892	676
2 (unaged)	66 395	553
3 (unaged)	79 827	492
4 (unaged)	90 045	489
5 (aged)	21 371	433
7 (aged)	42 946	431
8 (aged)	38 553	439
9 (aged)	18 524	671

Table 22: Average Flexural modulus and Fracture energy of the aged and unaged specimens.

Average $E_{1f}$ & $G_{Ic}$ results		
Specimen	$E_{1f}$ (MPa)	$G_{Ic}$ (J/m <sup>2</sup> )
Unaged	72 290	553
Aged	30 348	493
Reduction	-58%	-11%

After the aging process, the flexural modulus of the material has been reduced by approximately 58%, and the fracture energy has been reduced by 11%.



Figure 46: The difference in bending, where the top side of the unaged specimen is bent and the bottom of the aged specimen is bent. From the left: Unaged specimen, Aged specimen.

The examples in Figure 46 show an unaged and an aged specimen during DCB testing. For the unaged specimen layers K:4-6, see Figure 43, are on the underside of the delamination, and over the delamination for the aged specimen. The different orientations of the specimens explain why the aged bend upwards while the unaged bend down. Section 12.1 describes why layers K:4-6 bend and K:1-3 stay straight.

During the testing of aged specimens, they visibly bent more than the unaged specimens. The

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excessive bending can be explained by the large reduction in the flexural modulus compared to the relatively small reduction in force absorbed to continue the delamination.

The delamination front works as an "anchor" during the delamination process. When forces are applied to the attached hinges, a moment will develop within the specimen arms between the delamination front and the hinges. During the test, this moment will be supported by the flexural strength of the material.

As a result of the low flexural strength compared to the forces needed to continue delamination in the aged specimens, the moment developed in the specimen is high compared to its flexural modulus. Because of this, the aged specimens bend much more than the unaged specimens during DCB testing.

At a point during the testing of the aged specimens, the delamination growth stopped and the bending of the top layer continued. The result of this was buckling on the top layer of the laminate, see Figure 47. The buckling further weakened the flexural strength, and at this point, the tests were stopped.

The reason for the stop in crack growth is that the moment developed between the delamination front and the applied force exceeded the moment the material was able to withstand. This was not seen during the testing of the unaged samples.

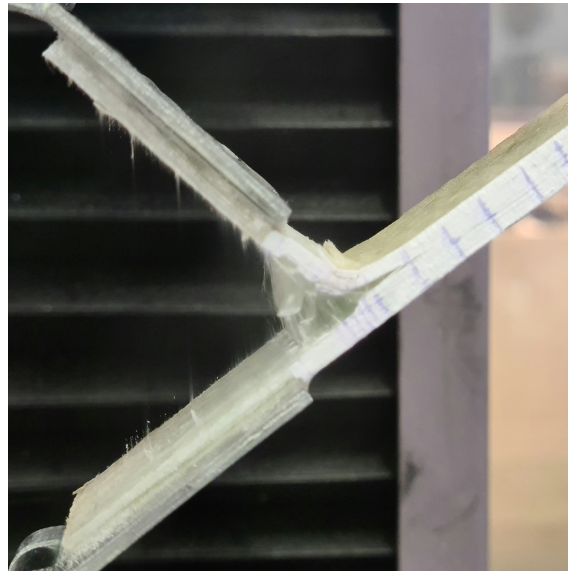


Figure 47: Buckling on the top layer, caused by bending.

The loss in both the flexural modulus and the amount of energy needed for the delamination to continue in the artificially aged specimens is caused by water uptake in the glass-fiber/epoxy composite.

The strength of the matrix seems to be significantly weakened, which can be seen in the significant bending in layers K:4-6. In these layers, there is only one layer of fibers contributing to flexural strength and therefore more of the strength is dependent on the strength of the matrix. This clearly shows the degradation of the matrix.

The sizing-rich phase of the matrix has also been weakened. The result of this is excessive fiber bridging, which is caused by bad adhesion between the matrix and fibers and can be seen in Figure 46. The weakened sizing-rich matrix as well as the damaged matrix reduces the flexural modulus of the material, due to less force being transferred from the matrix to the fibers.

By examining the aged and unaged specimens the minor loss in  $G_{Ic}$  compared to  $E_f$ , even though the material is weakened, can be explained by the large amount of fiber bridging. Even though the fiber bridging is a sign of less adhesion between the matrix and fibers, the phenomenon is known



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to "arrest" cracks. This results in the delamination front having a harder time growing.

### 12.3 Comparing the results of aged and unaged Mode I fatigue tests

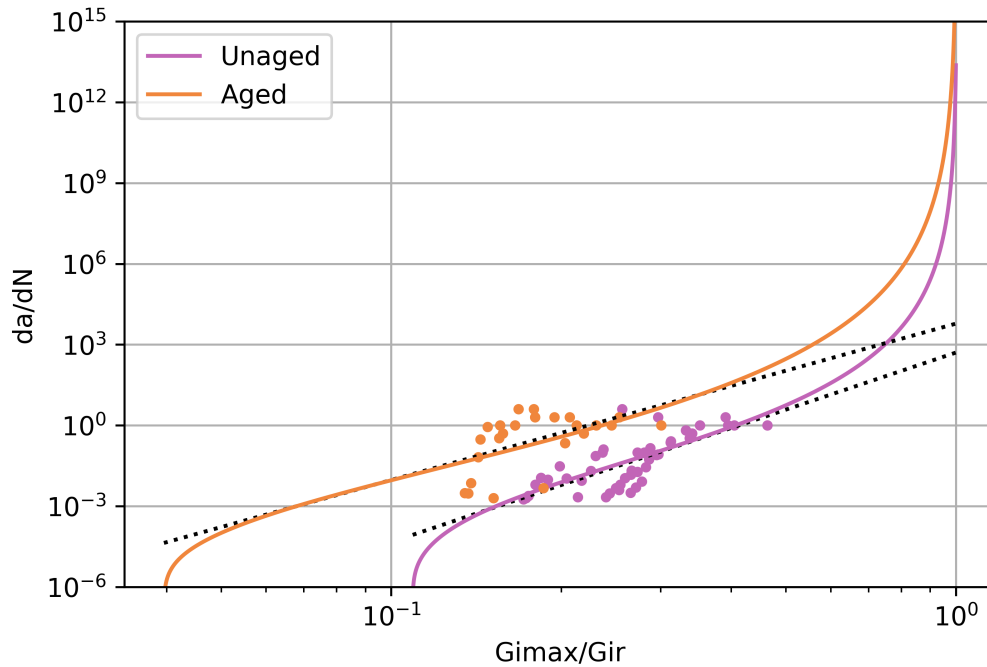


Figure 48: Comparison of the fatigue life of both the aged and unaged composite material. [B.8]

As Figure 48 shows, there is a large scatter of results for both the aged and unaged specimens. The large scatter may suggest that there is some uncertainty and variation in the fatigue life results. This uncertainty may be caused by using the average correction value,  $\Delta$ , from the DCB tests and not the specific  $\Delta$  value for each specimen during the calculations. The  $\Delta$  delta from the DCB tests showed some variation, especially for the aged specimens. Even though there is a large scatter in the results, there is a clear difference in the values for the two types of specimens.

For the aged specimens, the crack growth starts at a lower applied fracture energy than the material can resist compared to the unaged specimens. This is due to the reduction of the material strength of the epoxy and reinforcing fibers, and the interface between them caused by the hot water bath. At similar load levels, the aged material shows a larger growth at the delamination front per load cycle,  $da/dN$ , than the unaged specimens.

But the slopes of the curves suggest that the crack growth in the unaged specimens is slightly faster after it is initiated, due to the steeper slope. The slower growth of the aged specimens suggests that the epoxy has weakened. The weakened epoxy resulted in excessive bending in the specimen arm between the loading point and crack front. Due to the bending in the specimen arm, the loads were not supported and transferred to the delamination front.

In addition to forces not being transferred to the delamination front in the aged specimens due to the weakened epoxy, the crack growth was hindered by a large amount of fiber bridging. Fiber bridging is known to arrest cracks and increase fatigue life.

Even though the crack growth of the unaged specimens is faster than for the aged specimens the growth rate is more similar than expected. Commonly aged specimens tend to increase the fatigue life of the material due to an increased amount of fiber bridging caused by a change in the characteristics of the sizing which bonds the matrix and fibers. The increase in fibers connecting the two sides of the delamination in the aged specimens was expected to increase the fatigue life of

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the specimens significantly more than it did, Figure 48. Instead, the aged composite showed crack initiation at lower loads, a larger growth per cycle, and a slightly less steep slope compared to the unaged specimens.

One factor which can have had an effect on the fatigue results may be the fact that the aged and unaged specimens originate from different composite laminates, see section 8.1.3. Even though the material properties needed to find the fatigue life of the specimens are calculated for both of the different specimen sets, the different initial crack lengths might have an effect on the final results.

## 12.4 Improvement of the composite specimens

Since there was a large amount of bending, which caused Mode II failures in the double cantilever beam tests and migration through one of the reinforcing layers during the fatigue testing. The results acquired for the  $G_{Ic}$  and fatigue life of the [0/90] interface might have been affected.

The effect of bending might be limited by using another layup while producing the specimens. Since tests are designed for unidirectional specimens there is no guidance for a specimen with a [0/90] interface. This resulted in the production of a specimen that in total was balanced, but each side of the delamination was different. An improved layup might be [0/0/90/crack/0/0/90]. This will result in a specimen that is balanced on each side of the delamination front during testing. Since there are two 0° layers on each side of the crack, the specimen will be strong enough to not bend as much even if the crack migrates through the 90° layer in the delamination interface.

## 12.5 Improvement of the thermoplastic specimens

One way to increase the chances of achieving reliable results of  $G_{Ic}$  for the polypropylene specimens is to glue stiff beams to the specimens. This will concentrate the forces in the desired place while eliminating the bending problem experienced during this work and was not done due to the lack of time.

Another way to ensure delamination in the desired place is to use reinforced thermoplastic specimens. The reinforcement will ensure similar behavior to the composite specimens tested in this work, and result in good results of  $G_{Ic}$  for a composite with polypropylene as a matrix material.

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## 12.6 Sources of error

### 12.6.1 Camera detection

Since the delamination was detected manually by just watching the specimens during the tests, both static loading and cyclic loading. This way of detecting delamination opens the possibility of inaccurate results. To increase the accuracy of the results cameras can be used to monitor the delamination.

### 12.6.2 Aging process

The aging process used in this work was to submerge the specimens in distilled water at an elevated temperature until the weight of the specimens was stabilized. Before filling up the hot water bath with distilled water, the machine had to be drained of the oily fluid that it already was filled with. After the machine was drained and washed thoroughly it was filled with distilled water. When it was time for the first weighing of the specimens there was some oily contamination in the hot water bath. The oily substance came from the blue tubes seen in Figure 14, which are connected to a temperature regulator. The temperature regulator and tubes were not cleaned, because it was not informed that this also had to be cleaned in the user manual. The water was changed and the machine was cleaned again after the contamination, but the specimens had been affected by this initial contamination.



Figure 49: The machine used to age the specimens.

### 12.6.3 Testing of the aged composite specimens

The fatigue testing of the aged specimens took some time, approximately 40 minutes per test. The composite specimens would therefore dry up during the test and result in not as correct results as when first started. Since the testing times are relatively short, compared to many other fatigue life tests the errors caused by specimens drying up during testing are relatively small.

Another, and more significant source of error is that all the aged specimens were taken out of the hot water bath simultaneously. The results acquired from testing of the aged composite specimens may therefore not represent fully saturated specimens. The testing of the specimens was then carried out the following week, resulting in a larger potential error during the week.



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If the specimens had time to fully dry up during the week the results still showed an altered behavior from the aged specimens. There was a large reduction in flexural strength and an increase in fiber bridging, which might be caused by permanent damage in the epoxy and the sizing-rich epoxy binding the fibers and epoxy together.

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## 13 Conclusion

The goal and focus of the work this thesis is based on were to get an understanding and map the behavior of how a composite with [0/90]-interface reacts to Mode I failure situations. In this work, both aged and unaged specimens were tested in static and cyclic loading scenarios, and by doing this vital data have been acquired. The data is important for having a good understanding of the behavior of "virgin" parts and structures, as well as for those that have been in use for a long time. In addition to the composites, a thermoplastic material has been tested. Thermoplastics are also an interesting area to research, due to their ability to be recycled.

Data of Mode I fracture energy of the glass-fiber/epoxy composite specimens with an [0/90] interface was acquired by performing the Double Cantilever Beam (DCB) test. By testing both aged and unaged specimens a good understanding of how the integrity of the epoxy and the adhesion between the epoxy and reinforcing fibers were affected by exposure to moist environments. When comparing the results there was a reduction in the energy required for delamination to grow and a significant drop in the flexural modulus of the material.

Due to the layup used in the production of the composite specimens one side of the delamination tended to bend visibly more than the other side. For some of the unaged specimens tested in the DCB test the bending resulted in Mode II failure in the bent specimen arm. Excessive bending in the aged specimens tested by DCB was a result of weakened epoxy and poor adhesion between fibers and matrix, which again resulted in the specimen arm not being able to support the loads to the delamination front. The same problem was experienced in the cyclic loading of the aged and unaged specimens, where the delamination growth stopped due to the bending arm consumed instead of transferring the loads to the delamination front.

The visualized results from the cyclic loading of the specimens show that aged specimens with the [0/90]<sub>3</sub> layup experienced growth at lower applied loads compared to the unaged specimens. For both types of specimens, the slopes of the stable growth regions are quite similar. Even though the slopes are as similar as they are there is a slight difference, the aged material show a slightly steeper curve at an increased growth per load cycle. The growth at low applied loads and a large growth per load cycle clearly show a degradation of the composite material as a result of aging.

The goal of testing thermoplastic was to acquire a Mode I fracture energy release rate of the polypropylene and see if welding the material would have an effect on the energy consumed for delamination to take place. After some problems occurred during testing the focus shifted from getting results and over to how to be able to get the results. The shift in focus resulted in testing different methods to concentrate the applied loads in the desired area and achieve delamination growth. This was harder than expected and in the end, there was no more time for experimenting with how to achieve delamination. If this experiment is to be redone in the future the best results would possibly be achieved by gluing the specimen to some metal beams to stiffen it up and eliminate the bending which were the problem encountered in this work.

---

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---

# Appendix

## A Plots

### A.1 Load and Displacement

#### Unaged Specimens

R-curve and +5% linearity, Specimen 2

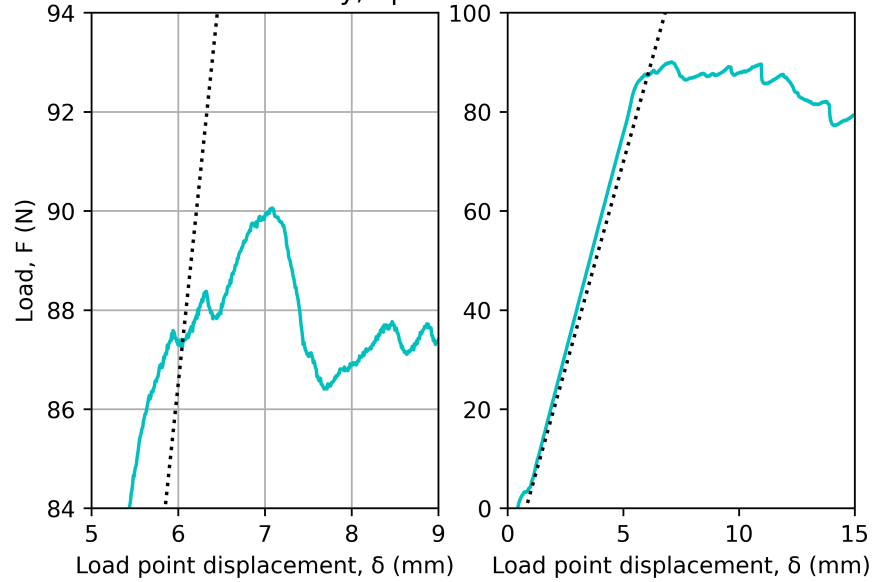


Figure 50: Specimen 2 R-curve. [B.2]

R-curve and +5% linearity, Specimen 3

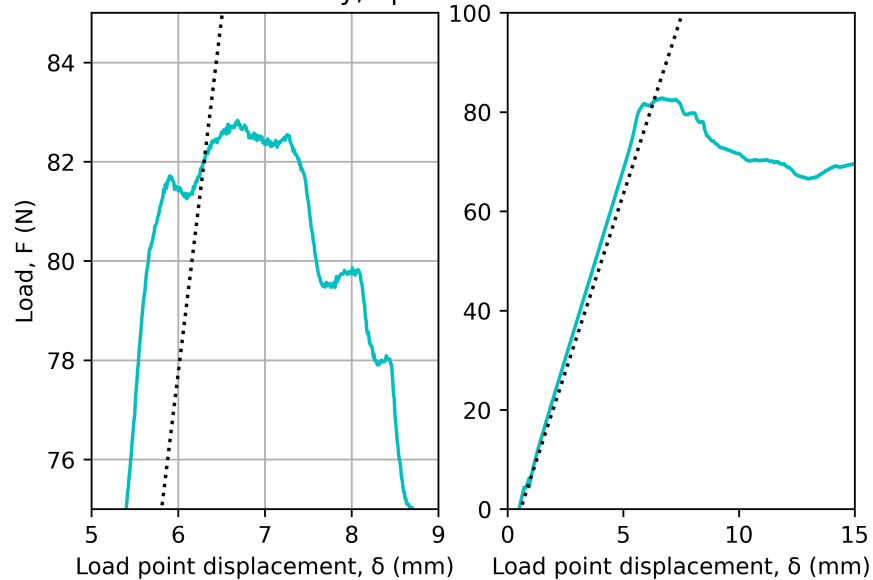


Figure 51: Specimen 3 R-curve. [B.2]

R-curve and +5% linearity, Specimen 4

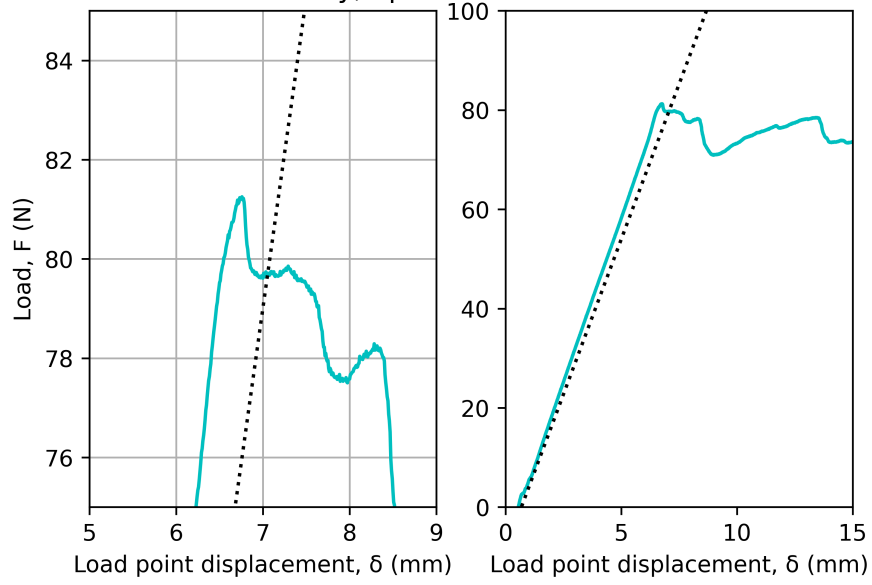


Figure 52: Specimen 4 R-curve. [B.2]

R-curve and +5% linearity, Specimen 41

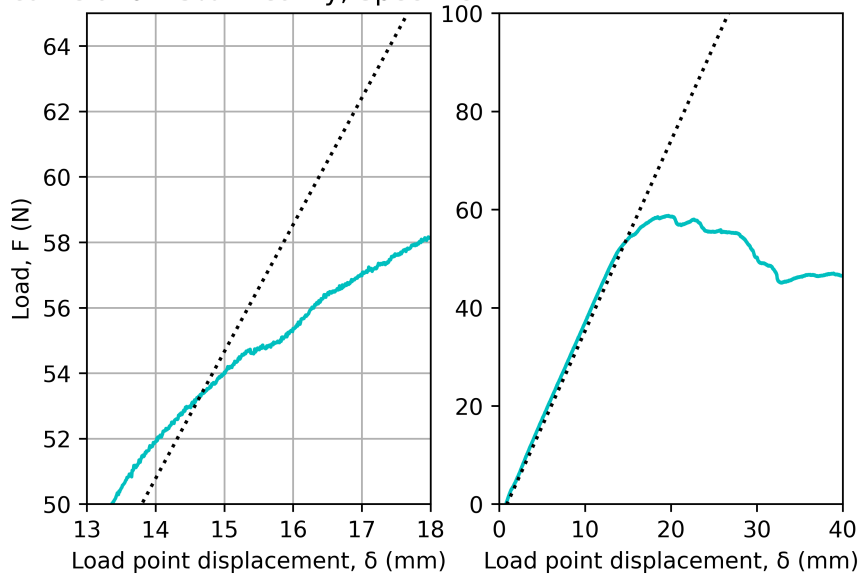


Figure 53: Specimen 41 R-curve. [B.2]

R-curve and +5% linearity, Specimen 42

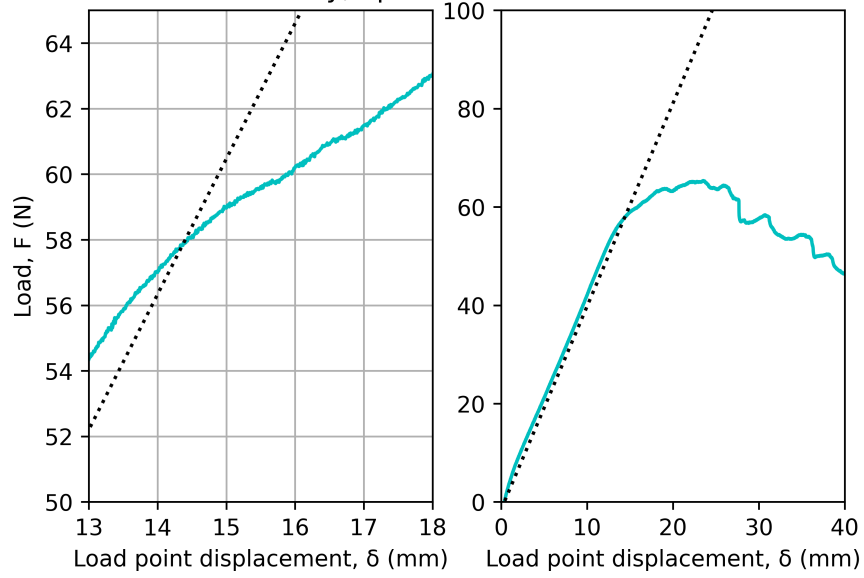


Figure 54: Specimen 42 R-curve. [B.2]

R-curve and +5% linearity, Specimen 43

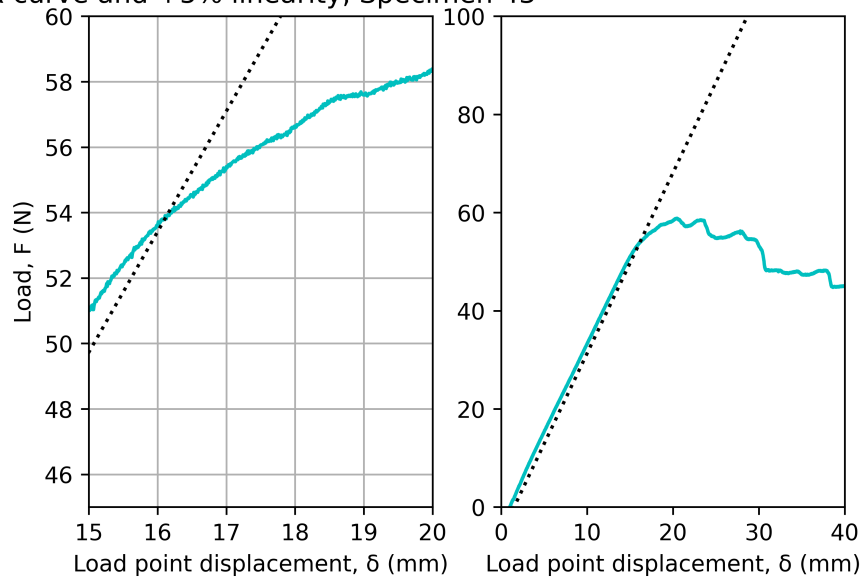


Figure 55: Specimen 43 R-curve. [B.2]

---

Aged Specimens

R-curve and +5% linearity, Specimen 5

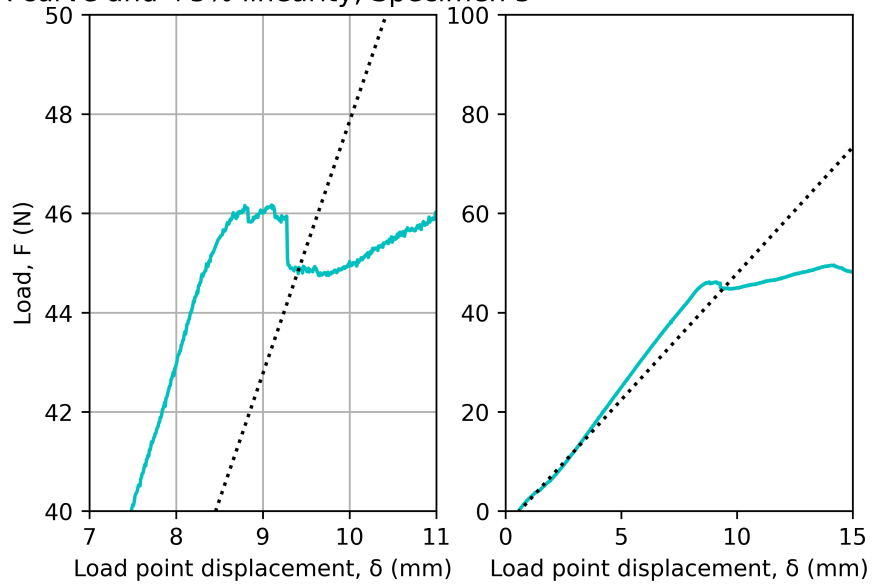


Figure 56: Specimen 5 R-curve. [B.2]

R-curve and +5% linearity, Specimen 6

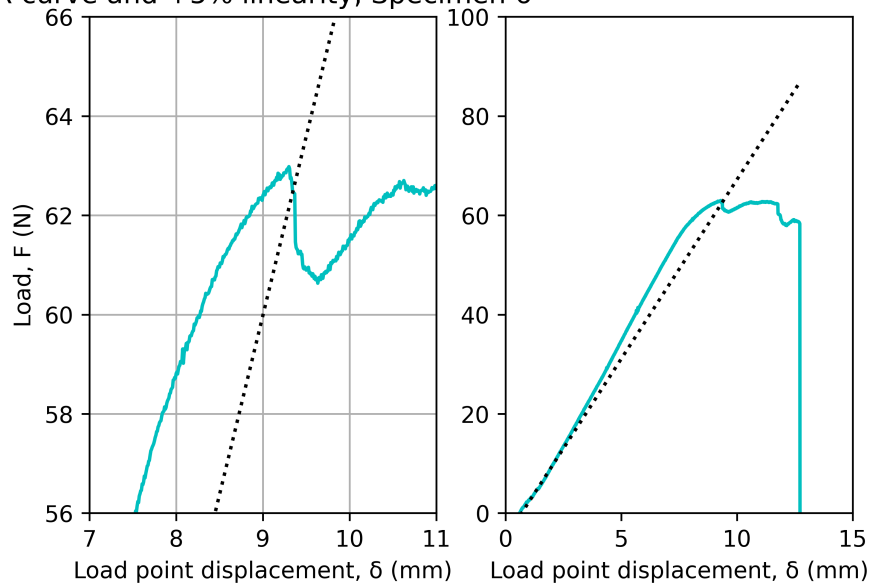


Figure 57: Specimen 6 R-curve. [B.2]

R-curve and +5% linearity, Specimen 7

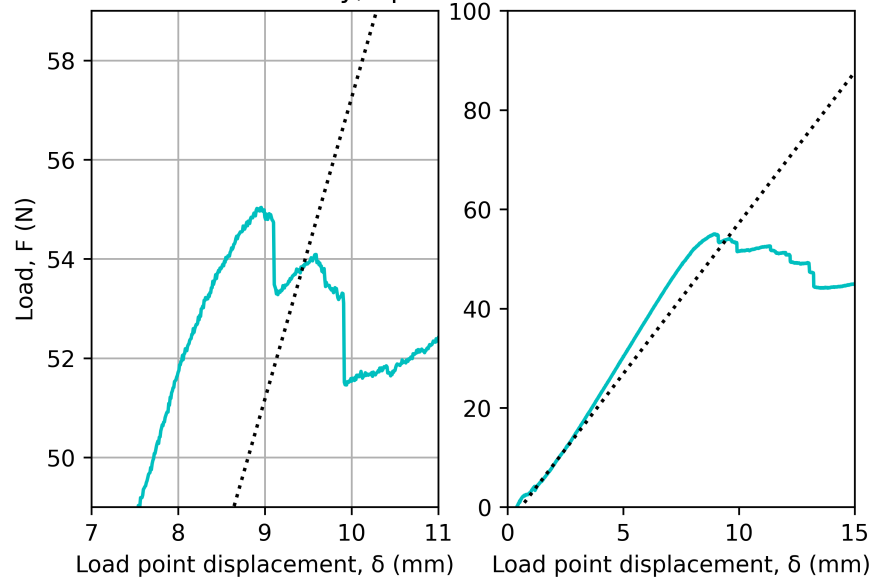


Figure 58: Specimen 7 R-curve. [B.2]

R-curve and +5% linearity, Specimen 8

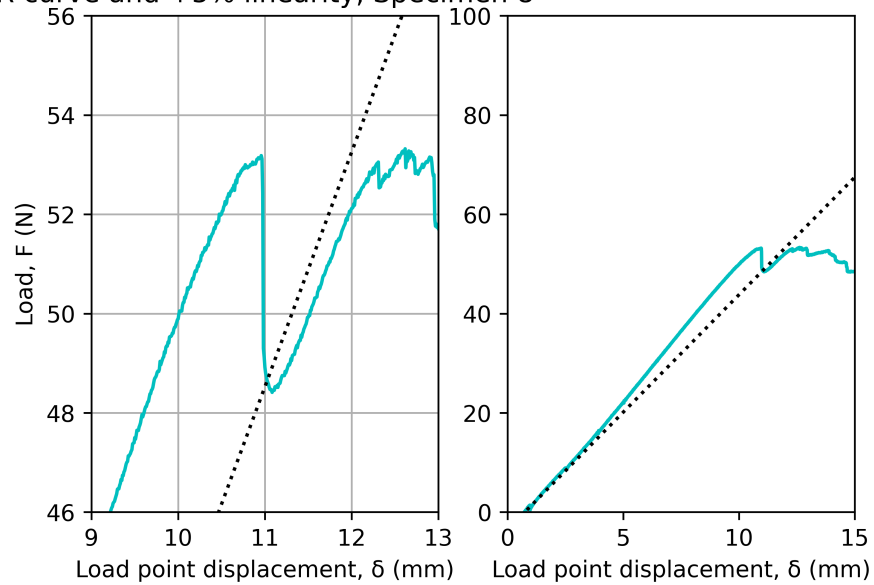


Figure 59: Specimen 8 R-curve. [B.2]



R-curve and +5% linearity, Specimen 9

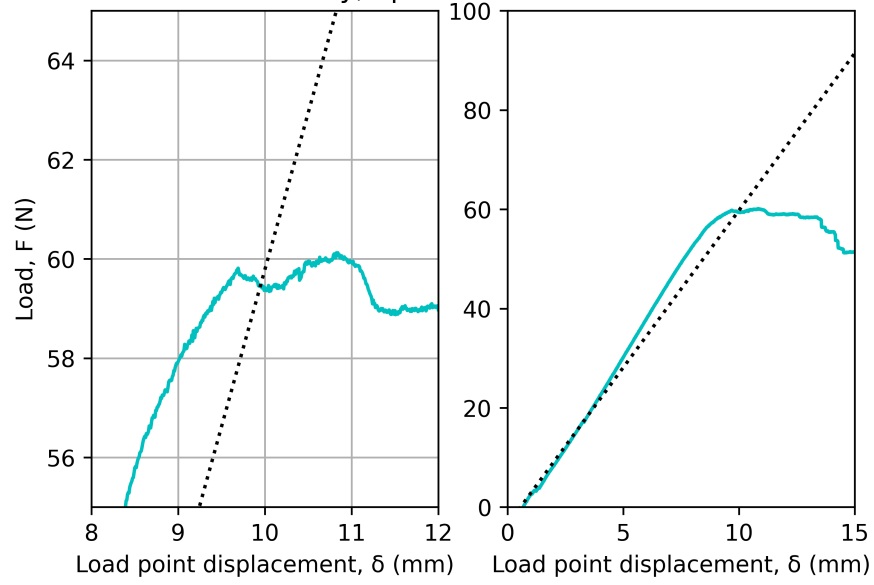


Figure 60: Specimen 9 R-curve. [B.2]

---

## A.2 Correction value

### Unaged Specimens

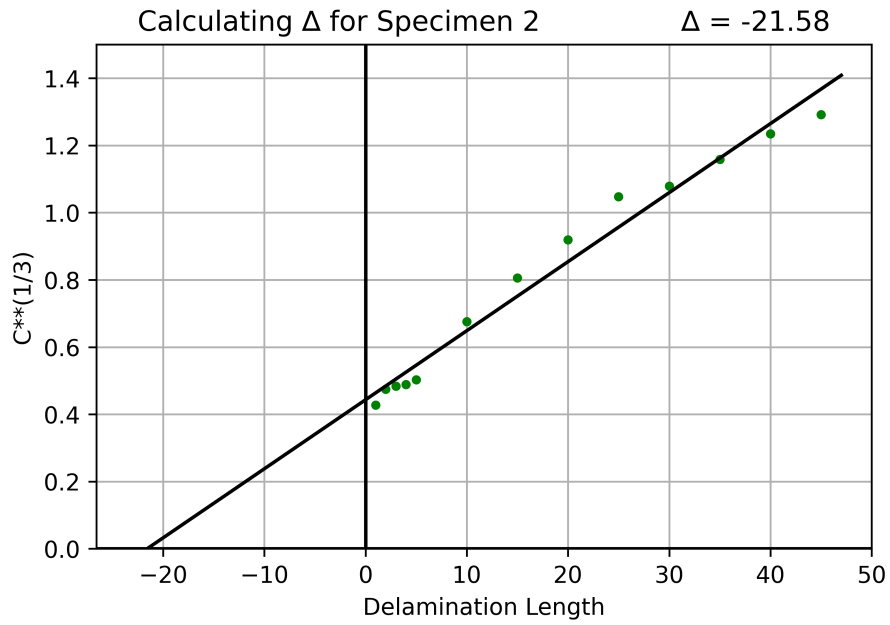


Figure 61: Correction value,  $\Delta$ , for specimen 2. [B.3]

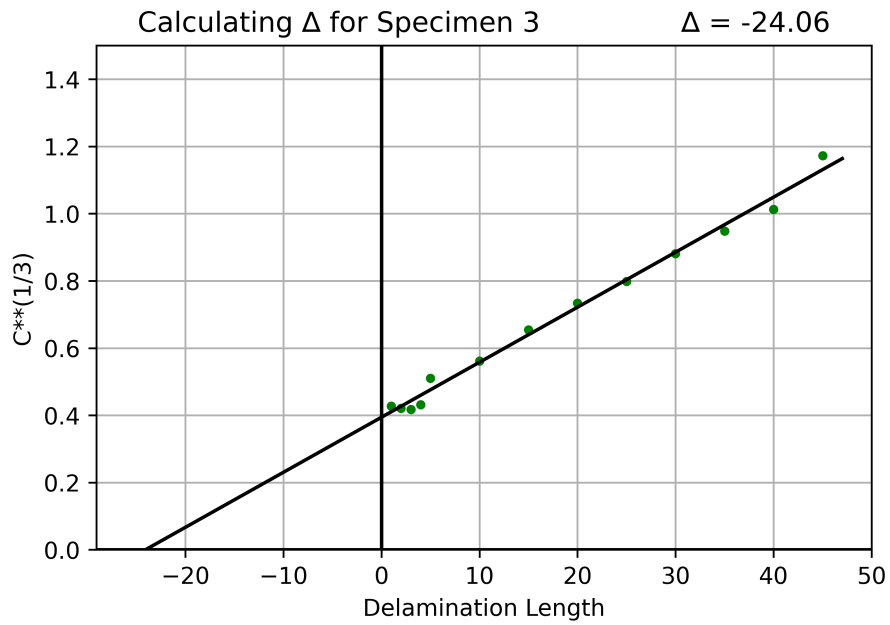


Figure 62: Correction value,  $\Delta$ , for specimen 3. [B.3]

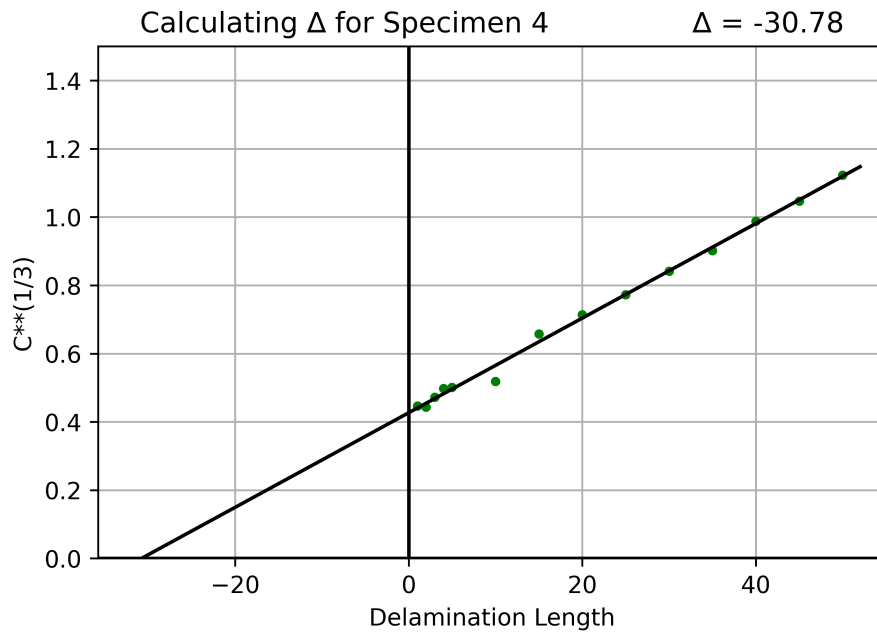


Figure 63: Correction value,  $\Delta$ , for specimen 4. [B.3]

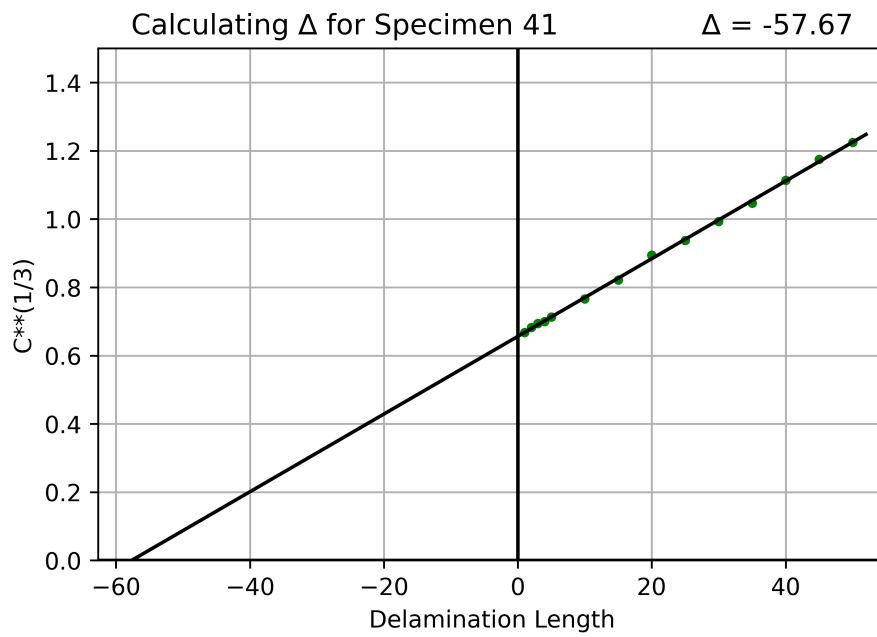


Figure 64: Correction value,  $\Delta$ , for specimen 41. [B.3]

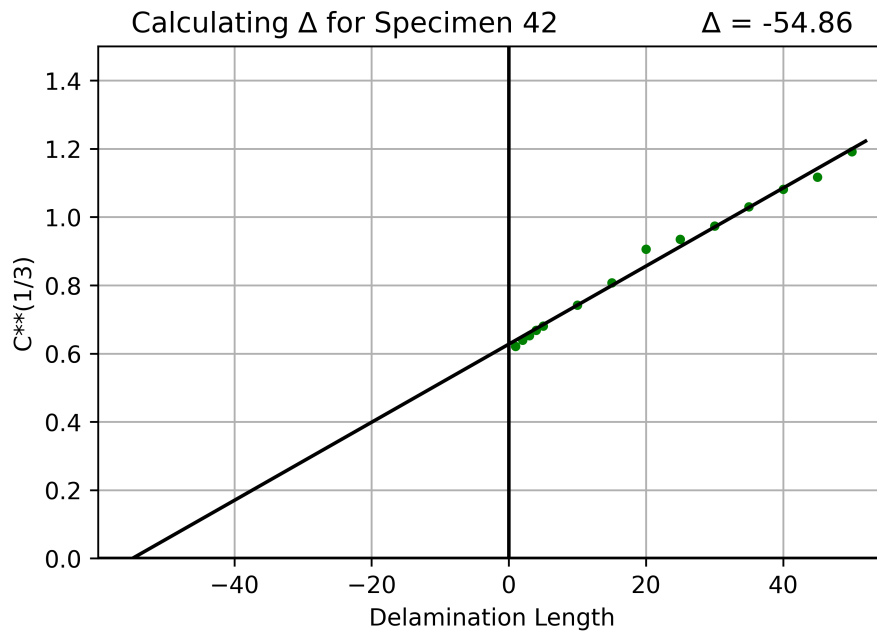


Figure 65: Correction value,  $\Delta$ , for specimen 42. [B.3]

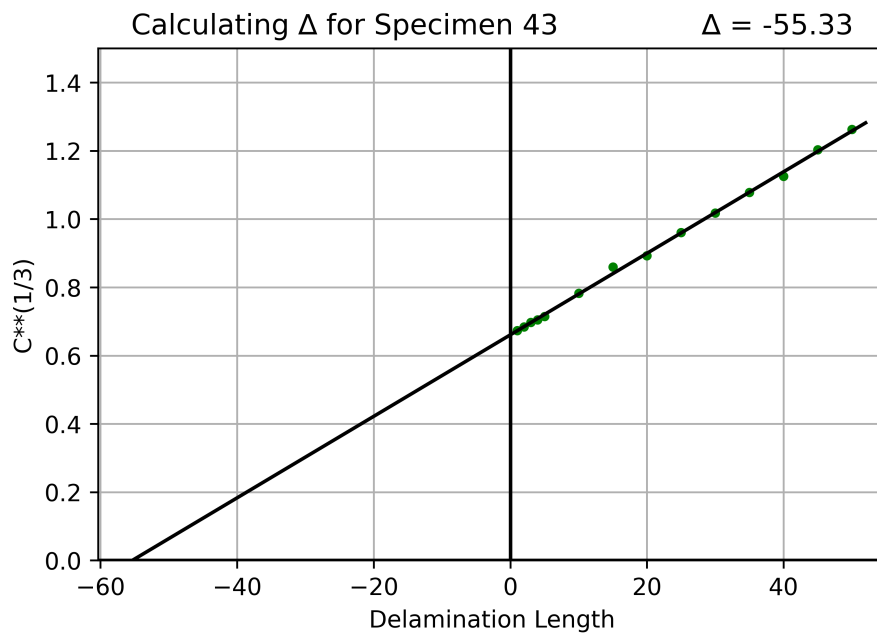


Figure 66: Correction value,  $\Delta$ , for specimen 43. [B.3]

---

Aged Specimens

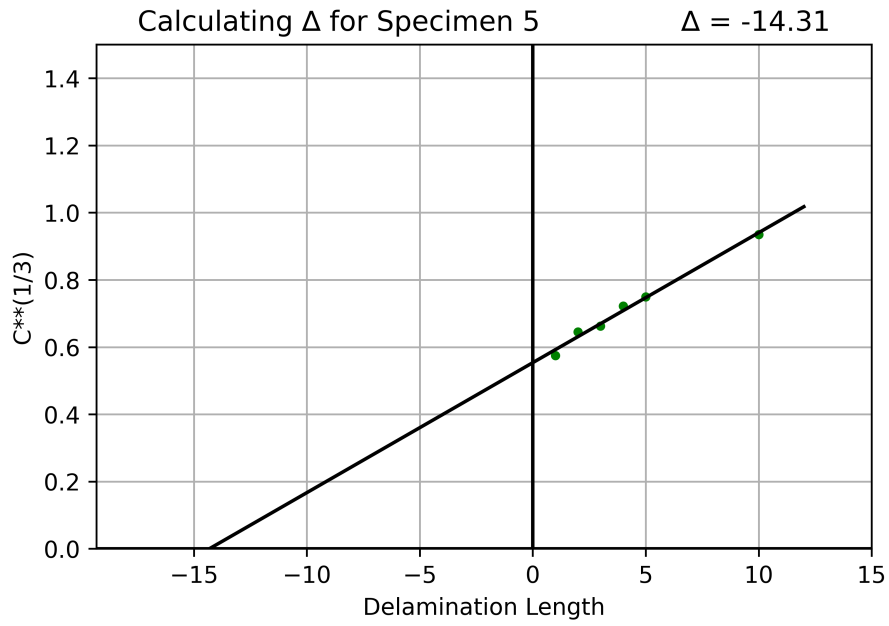


Figure 67: Correction value,  $\Delta$ , for specimen 5. [B.3]

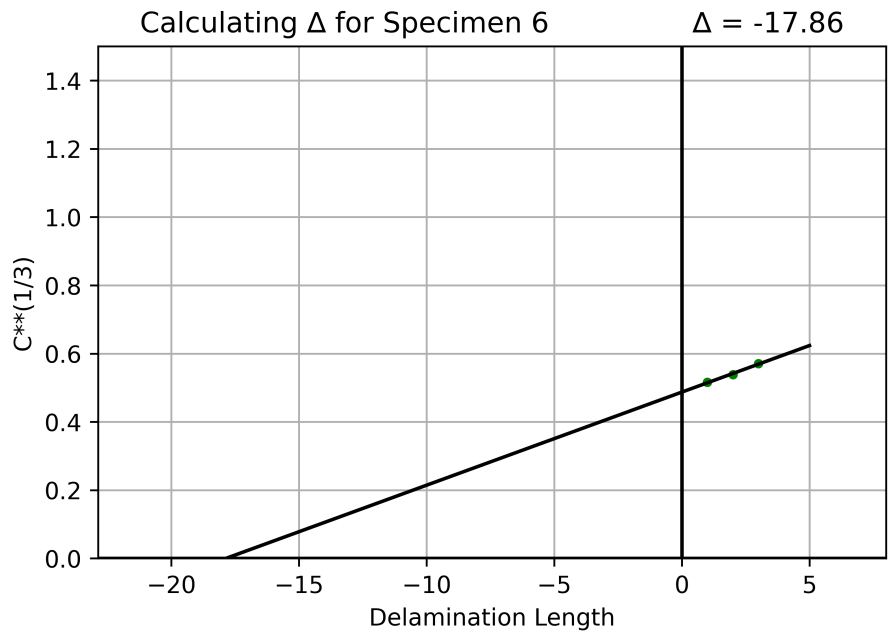


Figure 68: Correction value,  $\Delta$ , for specimen 6. [B.3]

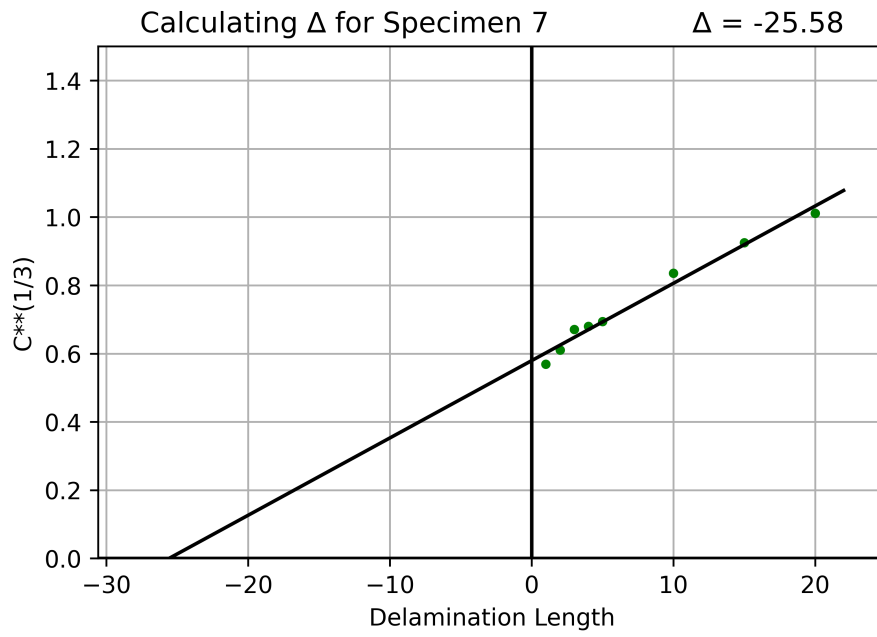


Figure 69: Correction value,  $\Delta$ , for specimen 7. [B.3]

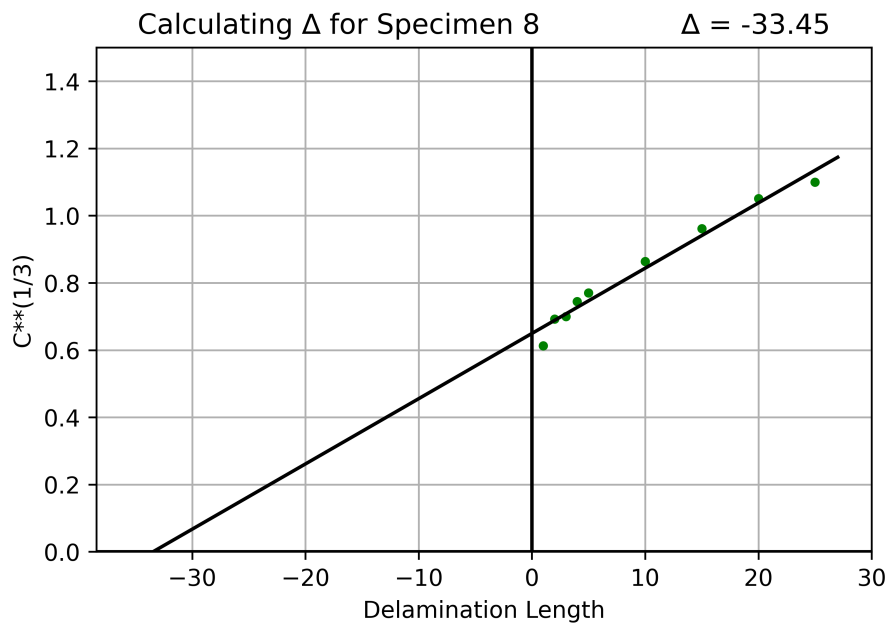


Figure 70: Correction value,  $\Delta$ , for specimen 8. [B.3]

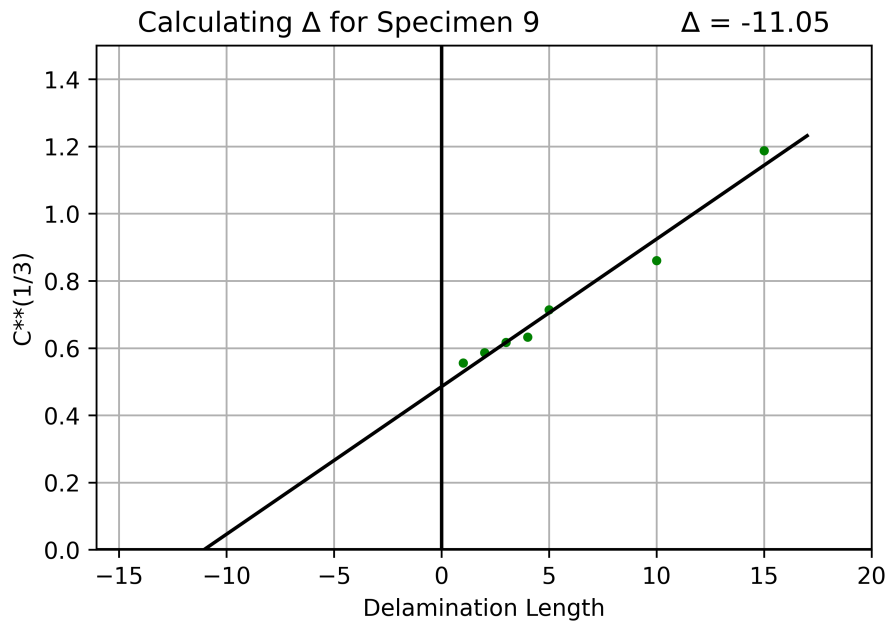


Figure 71: Correction value,  $\Delta$ , for specimen 9. [B.3]

---

## B Python code

### B.1 Plotting R-curve with multiple specimens

```
1
2 import pandas as pd
3 import matplotlib.pyplot as plt
4 import math
5
6
7 data1 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-1/
8 data1_w_crack.xlsx')
9 data2 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-2/
10 data2_w_crack.xlsx')
11 data3 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-3/
12 data3_w_crack.xlsx')
13 data4 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-4/
14 data4_w_crack.xlsx')
15 data5 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
16 \90-5\90_aged_5.xlsx')
17 data6 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
18 \90-6\90_aged_6.xlsx')
19 data7 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
20 \90-7\90_aged_7.xlsx')
21 data8 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
22 \90-8\90_aged_8.xlsx')
23 data9 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
24 \90-9\90_aged_9.xlsx')
25 data41 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-41/
26 data_41.xlsx')
27 data42 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-42/
28 data_42.xlsx')
29 data43 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-43/
30 data_43.xlsx')
31
32
33 datasett1 = [data1, data2, data3, data4]
34 datasett_aged = [data5, data6, data7, data8, data9]
35 datasett3 = [data41, data42, data43]
36 Datasett_all_unaged = [data1, data2, data3, data4, data41, data42, data43]
37
38 def R_plot_all_aged(datasett):
39     def length(A):
40         aa = []
41         for j in range(len(A)):
42             if A[j] > 0:
43                 aa.append(A[j])
44             else:
45                 break
46         return aa
47
48     for i in range(len(datasett)):
49         D = datasett[i]['Disp'].tolist()
50         F = datasett[i]['Load'].tolist()
51
52         plt.plot(D, F, label = 'Specimen '+str(i+1))
53
54         plt.ylabel("Load, F (N)")
55         plt.title('R-curve for aged specimens', loc = 'left')
56         plt.ylim([0,65])
57         plt.xlim([0,70])
58         plt.grid()
59         plt.legend()
60         plt.rcParams['figure.dpi'] = 600
61         plt.show()
62
63 def R_plot_all_unaged(datasett):
64     def length(A):
65         aa = []
66         for j in range(len(A)):
67             if A[j] > 0:
```



```

57         aa.append(A[j])
58     else:
59         break
60     return aa
61
62     for i in range(len(datasett)-3):
63         D = datasett[i]['Disp'].tolist()
64         F = datasett[i]['Load'].tolist()
65
66         plt.plot(D, F, label = 'Specimen '+str(i+1))
67
68     for j in range(len(datasett)-3, len(datasett)):
69         D = datasett[j]['Disp'].tolist()
70         F = datasett[j]['Load'].tolist()
71
72         plt.plot(D, F, label = 'Specimen '+str(j+37))
73         #plt.plot(Da, Fa, 'k|')
74
75     plt.ylabel("Load, F (N)")
76     plt.title('R-curve for unaged specimens', loc = 'left')
77     plt.ylim([0,120])
78     plt.xlim([0,80])
79     plt.grid()
80     plt.legend()
81     plt.rcParams['figure.dpi'] = 600
82     plt.show()
83
84
85 R_plot_all_aged(datasett_aged)
86 R_plot_all_unaged(Datasett_all_unaged)

```

## B.2 Plotting R-curve with the 5% linearity

```

1
2 import pandas as pd
3 import matplotlib.pyplot as plt
4 import math
5
6
7 data1 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-1/
8     data1_w_crack.xlsx')
9 data2 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-2/
10    data2_w_crack.xlsx')
11 data3 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-3/
12    data3_w_crack.xlsx')
13 data4 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-4/
14    data4_w_crack.xlsx')
15 data5 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
16    \90-5\90_aged_5.xlsx')
17 data6 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
18    \90-6\90_aged_6.xlsx')
19 data7 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
20    \90-7\90_aged_7.xlsx')
21 data8 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
22    \90-8\90_aged_8.xlsx')
23 data9 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
24    \90-9\90_aged_9.xlsx')
25 data41 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-41/
26    data_41.xlsx')
27 data42 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-42/
28    data_42.xlsx')
29 data43 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-43/
30    data_43.xlsx')
31
32 def fem_prosent(data, fors):
33     F = data['Load'].tolist()
34     d = data['Disp'].tolist()
35     d_lin = d[500]
36     d_fem = d_lin*1.05
37     load_fem = [F[100],F[500]]
38     disp_fem = [d[100],d_fem]

```

```

27
28 a = (load_fem[0]-load_fem[1])/(disp_fem[0]-disp_fem[1])
29 x = []
30
31 for i in range(len(d)):
32     X = a*d[i]- fors
33     x.append(X)
34
35 plt.subplot(1,2,1)
36 plt.plot(d, F, 'c')
37 plt.plot(d,x, 'k:')
38 plt.xlim([6.965, 6.97])
39 plt.ylim([88.3, 88.35])
40 plt.ylabel("Load, F (N)")
41 plt.title('R-curve and +5% linearity, Specimen 1')
42 plt.grid()
43
44 plt.subplot(1,2,2)
45 plt.plot(d, F, 'c')
46 plt.plot(d,x, 'k:')
47 plt.xlim([0, 15])
48 plt.ylim([0, 100])
49 plt.rcParams['figure.dpi'] = 600
50 plt.show()
51
52 fem_prosent(data1, 12)
53 fem_prosent(data2, 13.2)
54 fem_prosent(data3, 8)
55 fem_prosent(data4, 8.5)
56 fem_prosent(data5, 3)
57 fem_prosent(data6, 5)
58 fem_prosent(data7, 3.5)
59 fem_prosent(data8, 3.5)
60 fem_prosent(data9, 3.5)
61 fem_prosent(data41, 3.5)
62 fem_prosent(data42, 1.5)
63 fem_prosent(data43, 5.5)

```

### B.3 Generating least squares plots, and determining the correction value for delamination length

```

1
2
3 import pandas as pd
4 import matplotlib.pyplot as plt
5 import pylab as py
6 import numpy as np
7
8 data1 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-1/
9 data1_w_crack.xlsx')
10 data2 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-2/
11 data2_w_crack.xlsx')
12 data3 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-3/
13 data3_w_crack.xlsx')
14 data4 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-4/
15 data4_w_crack.xlsx')
16
17 data5 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
18 \90-5\90_aged_5.xlsx')
19 data6 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
20 \90-6\90_aged_6.xlsx')
21 data7 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
22 \90-7\90_aged_7.xlsx')
23 data8 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
24 \90-8\90_aged_8.xlsx')
25 data9 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
26 \90-9\90_aged_9.xlsx')

```

```

21 data41 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-41/
    data_41.xlsx')
22 data42 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-42/
    data_42.xlsx')
23 data43 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-43/
    data_43.xlsx')
24
25
26 def delta(data, a0, name, farge):
27     d = data['Da'].tolist()
28     l = data['La'].tolist()
29     A = data['a'].tolist()
30
31     def length_a(A):
32         aa = []
33         for j in range(len(A)):
34             if A[j] > 0:
35                 aa.append(A[j])
36             else:
37                 break
38         return aa
39
40     a = length_a(A)
41     C_13 = []
42     delam_length = []
43
44     for i in range(len(a)):
45         c = d[i]/l[i]
46         c_13 = c**(1/3)
47         C_13.append(c_13)
48         delam_length.append(a0 + a[i])
49
50     reg = py.polyfit(a,C_13, 1)
51     delta = round(-(reg[1]/reg[0]),2)
52
53     x = np.linspace(delta-5, a[-1]+2, 1000)
54     y = reg[0]*x + reg[1]
55
56
57     delta_str = str(delta)
58
59     plt.plot(a,C_13, farge)
60     plt.plot(x, y, 'k')
61     plt.ylabel("C**(1/3)")
62     plt.xlabel("Delamination Length")
63     plt.ylim([0, 1.5])
64     plt.xlim([delta-5, a[-1]+5])
65     plt.axvline(x = 0, color = 'k')
66     plt.axhline(y = 0, color = 'k')
67     plt.grid()
68     plt.rcParams['figure.dpi'] = 600
69     plt.show()
70
71
72
73
74 delta(data1, 32.57, "Specimen 1", 'c.')
75 delta(data2, 37.87, "Specimen 2", 'm.')
76 delta(data3, 37.14, "Specimen 3", 'r.')
77 delta(data4, 37.15, "Specimen 4", 'g.')
78 delta(data5, 44.1, "Specimen 5", 'g.')
79 delta(data6, 43.4, "Specimen 6", 'g.')
80 delta(data7, 45.5, "Specimen 7", 'g.')
81 delta(data8, 42.6, "Specimen 8", 'g.')
82 delta(data9, 43.9, "Specimen 9", 'g.')
83 delta(data41, 57.47, "Specimen 41", 'g.')
84 delta(data42, 57.96, "Specimen 42", 'r.')
85 delta(data43, 57.47, "Specimen 43", 'b.')

```

## B.4 Calculating Fracture energy and Flexural modulus

```

1 #S = [F , disp , b , delta , a0 , a , h ]
2 S1 = [88.31, 6.968, 24.10, 20.05, 32.57, 4, 4.87]
3 S2 = [87.30, 6.049, 24.10, 21.58, 37.87, 0, 4.95]
4 S3 = [81.98, 6.298, 24.14, 24.06, 37.14, 4, 4.93]
5 S4 = [81.25, 6.759, 24.09, 30.78, 37.15, 2, 4.95]
6
7 S5 = [46.17, 9.1, 24.1, 14.31, 44.1, 2, 5.18]
8 S6 = [63.0, 9.3, 24.1, 17.86, 43.4, 2, 5.19]
9 S7 = [55.05, 8.95, 24.1, 25.58, 45.5, 0, 5.15]
10 S8 = [48.65, 11.03, 23.82, 33.45, 42.6, 1, 5.2]
11 S9 = [59.45, 9.95, 24.08, 11.05, 43.9, 0, 5.22]
12
13 S41 = [53.3, 14.65, 24.01, 57.67, 57.47, 0, 5.83]
14 S42 = [57.8, 14.38, 24.00, 54.86, 57.96, 0, 5.77]
15 S43 = [53.8, 16.10, 24.00, 55.33, 57.47, 0, 5.75]
16
17 datasett1 = [S1, S2, S3, S4]
18 datasett2 = [S5, S7, S8, S9]
19
20 def G(S):
21     delam_length = S[3]+S[4]+S[5]
22     return round(((3*S[0]*S[1])/(2*S[2]*delam_length))*1000,2)
23
24 def E(S):
25     delam_length = S[3]+S[4]+S[5]
26     E = (64*(delam_length**3)*S[0])/(S[1]*S[2]*(S[6]**3))
27     return round(E,2)
28
29 def average(datasett):
30     Gic = []
31     Ef = []
32     g = 0
33     e = 0
34     for i in range(len(datasett)):
35         data = datasett[i]
36         Gic.append(G(data))
37         Ef.append(E(data))
38     for u in range(len(Gic)):
39         g += Gic[u]
40         e += Ef[u]
41     GG = g/len(Gic)
42     EE = e/len(Ef)
43     return round(GG,2), round(EE,2)
44
45 print("Un-aged specimens average results:")
46 print("Gic: ", average(datasett1)[0], " J/m^2")
47 print("Ef:", average(datasett1)[1], " MPa")
48 print()
49 print("Aged specimens average results:")
50 print("Gic: ", average(datasett2)[0], " J/m^2")
51 print("Ef:", average(datasett2)[1], " MPa")
52 print()
53
54 print("Specimen 1:")
55 print("G = ", G(S1), " J/m^2")
56 print("E =", E(S1), " MPa")
57 print()
58 print("Specimen 2:")
59 print("G = ", G(S2), " J/m^2")
60 print("E =", E(S2), " MPa")
61 print()
62 print("Specimen 3:")
63 print("G = ", G(S3), " J/m^2")
64 print("E =", E(S3), " MPa")
65 print()
66 print("Specimen 4:")
67 print("G = ", G(S4), " J/m^2")
68 print("E =", E(S4), " MPa")
69 print()
70 #Aged specimens
71 print("Specimen 5:")
72 print("G = ", G(S5), " J/m^2")
73 print("E =", E(S5), " MPa")

```

```

74 print()
75 """
76 print("Specimen 6:")
77 print("G = ", G(S6), " J/m^2")
78 print("E =", E(S6), " MPa")
79 print()
80 """
81 print("Specimen 7:")
82 print("G = ", G(S7), " J/m^2")
83 print("E =", E(S7), " MPa")
84 print()
85 print("Specimen 8:")
86 print("G = ", G(S8), " J/m^2")
87 print("E =", E(S8), " MPa")
88 print()
89
90 print("Specimen 9:")
91 print("G = ", G(S9), " J/m^2")
92 print("E =", E(S9), " MPa")
93 print()
94
95 print("Specimen 41:")
96 print("G = ", G(S41), " J/m^2")
97 print("E =", E(S41), " MPa")
98 print()
99 print("Specimen 42:")
100 print("G = ", G(S42), " J/m^2")
101 print("E =", E(S42), " MPa")
102 print()
103 print("Specimen 43:")
104 print("G = ", G(S43), " J/m^2")
105 print("E =", E(S43), " MPa")
106 print()

```

## B.5 Plot material resistance

```

1
2 data1 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-1/
  data1_w_crack.xlsx')
3 data2 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-2/
  data2_w_crack.xlsx')
4 data3 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-3/
  data3_w_crack.xlsx')
5 data4 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_1/90-4/
  data4_w_crack.xlsx')
6 data5 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
  \90-5\90_aged_5.xlsx')
7 data6 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
  \90-6\90_aged_6.xlsx')
8 data7 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
  \90-7\90_aged_7.xlsx')
9 data8 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
  \90-8\90_aged_8.xlsx')
10 data9 = pd.read_excel(r'C:\Users\trymg\Skrivebord\Master_DATA\DCB\DCB_2_aged
  \90-9\90_aged_9.xlsx')
11 data41 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-41/
  data_41.xlsx')
12 data42 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-42/
  data_42.xlsx')
13 data43 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/DCB/DCB_4/90-43/
  data_43.xlsx')
14
15 database = [data1, data2, data3, data4]
16 database2 = [data5, data7, data8, data9]
17 database3 = [data41, data42, data43]
18 database_unaged = [data1, data2, data3, data4, data41, data42, data43]
19
20 #TRENGER IKKE ENDRE NOE NEDENFOR
21
22 def G(F,disp,b,a,Delta):
23     return (3*F*disp)/(2*b*(a+abs(Delta)))

```

```

24
25 def length(A):
26     aa = []
27     for j in range(len(A)):
28         if A[j] > 0:
29             aa.append(A[j])
30         else:
31             break
32     return aa
33
34 def delta(a, a0, disp, F):
35     C_13 = []
36     delam_length = []
37     for i in range(len(a)):
38         c = disp[i]/F[i]
39         c_13 = c**(1/3)
40         C_13.append(c_13)
41         delam_length.append(a0 + a[i])
42     reg = py.polyfit(a,C_13, 1)
43     delta = round(-(reg[1]/reg[0]),2)
44     return delta
45
46 def variabler(data):
47     bb = data['b'].tolist()
48     FF = data['La'].tolist()
49     DD = data['Da'].tolist()
50     A = data['a'].tolist()
51     a0 = data['a0'].tolist()
52
53
54     #Variabler
55     b = bb[0]
56     a = length(A)
57     F = length(FF)
58     disp = length(DD)
59     Delta = delta(a, a0[0], disp, F)
60
61     return a, b, F, disp, Delta
62
63
64 def G_Ir(database):
65     #Regner ut G, og putter G og a verdier i lister
66     A = []
67     G_IR = []
68     for g in range(len(database)):
69         a, b, F, disp, Delta = variabler(database[g])
70
71         Gir = []
72         for i in range(len(a)):
73             Gir.append(G(F[i], disp[i], b, a[i], Delta))
74
75         A.append(a)
76         G_IR.append(Gir)
77
78     #Curve fit
79     x = []
80     y = []
81     for j in range(len(A)):
82         x += A[j]
83         y +=G_IR[j]
84
85     reg = py.polyfit(np.log(x),y, 1)
86     x_fit = np.linspace(min(x), max(x))
87     y_fit = reg[0]*np.log(x_fit) + reg[1]
88
89     #Plotter data, i forskjellige farger for hver specimen
90     for i in range(len(A)):
91         a_i = A[i]
92         G_i = G_IR[i]
93         plt.plot(a_i,G_i, '.')
94
95     #Plotting
96     plt.plot(x_fit,y_fit, 'k', label='G_IR = ' +str(round(reg[0],3))+ '*log(a) + ' +

```

```

106     str(round(reg[1],3))
107     plt.ylim([0,max(y)+(max(y)*0.1)])
108     plt.xlim([0,max(x)+(max(x)*0.1)])
109     plt.ylabel("G_IR (kJ/m^2)")
110     plt.title("G_IR", loc = 'left')
111     plt.legend()
112     plt.grid()
113     plt.rcParams['figure.dpi'] = 600
114     plt.show()
115
116     return round(reg[0],3), round(reg[1],3)
117
118 #G_Ir(database)
119 print("DCB-1 specimens:")
120 print("G_IR =",G_Ir(database)[0],"*log(a) +",G_Ir(database)[1])
121 print()
122 #G_Ir(database2)
123 print("Aged specimens:")
124 print("G_IR =",G_Ir(database2)[0],"*log(a) +",G_Ir(database2)[1])
125 print()
126 #G_Ir(database3)
127 print("DCB-4 specimens:")
128 print("G_IR =",G_Ir(database3)[0],"*log(a) +",G_Ir(database3)[1])
129 print()
130 #G_Ir(database_unaged)
131 print("All unaged specimens:")
132 print("G_IR =",G_Ir(database_unaged)[0],"*log(a) +",G_Ir(database_unaged)[1])
133 print()

```

## B.6 Plot raw fatigue data and fatigue crack growth

```

1
2 import pandas as pd
3 import matplotlib.pyplot as plt
4 import pylab as py
5 import numpy as np
6 import math
7
8
9 data10 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F2
10 /S10a/data10.xlsx')
11 data11 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F2
12 /S11a/data11.xlsx')
13 data12 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F2
14 /S12a/data12.xlsx')
15 data13 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F2
16 /S13a/data13.xlsx')
17 data48 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F2
18 /S48/data48.xlsx')
19 data47 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F1
20 /S47/data.xlsx')
21 data29 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F3
22 /data29.xlsx')
23 data28 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F4
24 /S28/data28.xlsx')
25 data30 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F4
26 /S30/data30.xlsx')
27 data31 = pd.read_excel(r'C:/Users/trymg/Skrivebord/Master_DATA/fatigue/composite/F4
28 /S31/data31.xlsx')
29
30 data_aged = [data10, data11, data12, data13]
31 data_unaged = [data47, data48, data29, data28, data30, data31]
32
33 #Functions
34
35 def length(A):
36     aa = []
37     for j in range(len(A)):

```

```

29     if A[j] > 0:
30         aa.append(A[j])
31     else:
32         break
33     return aa
34
35
36 def G(F, disp, b, a, delta):
37     return (3*F*disp)/(2*b*(a+delta))
38
39 def G_ir_aged(da):
40     return 0.457*math.log(da) + 1.705
41
42 def G_ir_unaged(da):
43     return 0.27*math.log(da) + 1.003
44
45 def da_dN(da, dN):
46     if dN == 0:
47         return (da/1)
48     else:
49         return (da/dN)
50
51 def GIth(x_data):
52     x = x_data
53     x.sort()
54     #print(x)
55     x_list = [x[0], x[1], x[2], x[3], x[4]]
56     var = 0
57     for i in range(len(x_list)):
58         var += x_list[i]
59     return var/len(x_list)
60
61
62 def specimen_data2(specimen, grapf_type, condition):
63     dN = length(specimen['dN'].tolist())
64     da = length(specimen['da'].tolist())
65     a0 = specimen['a0'].tolist()[0]
66     F = length(specimen['F'].tolist())
67     disp = length(specimen['disp'].tolist())
68     b = specimen['b'].tolist()[0]
69     delta = specimen['delta'].tolist()[0]
70
71     G_IR = []
72     if condition == 'aged':
73         G_IC = 493.36
74         for i in range(len(da)):
75             G_IR.append(G_ir_aged(da[i]))
76     elif condition == 'unaged':
77         G_IC = 510.57
78         for i in range(len(da)):
79             G_IR.append(G_ir_unaged(da[i]))
80
81     if grapf_type == 'raw':
82         #Experimental data
83         G_Imax = [G_IC/G_IC]
84         logN = [1]
85         for i in range(len(da)):
86             if dN[i] != 1:
87                 a = a0+da[i]
88                 G_Imax.append((G(F[i], disp[i], b, a, delta)*1000)/G_IC)
89                 logN.append((dN[i]))
90     return logN, G_Imax
91
92
93
94     elif grapf_type == 'growth':
95         G_Imax = G(F[0], disp[0], b, a0, delta)
96         dadN = []
97         Gimax_Gir = []
98         for i in range(len(da)):
99             a = a0 + da[i]
100             dadN.append((da_dN(da[i], dN[i])))
101             Gimax_Gir.append((G(F[i], disp[i], b, a, delta)/G_IR[i]))

```



```

102     return dadN, Gimax_Gir
103
104 def curvefit_raw(specimen_sett, condition):
105     #Experimental data
106     x_data = []
107     y_data = []
108     for g in range(len(specimen_sett)):
109         specimen = specimen_sett[g]
110         x_data += specimen_data2(specimen, 'raw', condition)[0]
111         y_data += specimen_data2(specimen, 'raw', condition)[1]
112
113     reg = py.polyfit(np.log(x_data),y_data, 1)
114     x_fit = np.linspace(min(x_data), max(x_data))
115     y_fit = reg[0]*np.log(x_fit) + reg[1]
116
117     return x_fit, y_fit
118
119 def plot_raw(specimen_sett, condition):
120     #Plots data for each specimen
121     #experimental data
122     for i in range(len(specimen_sett)):
123         specimen = specimen_sett[i]
124         x_data = specimen_data2(specimen, 'raw', condition)[0]
125         y_data = specimen_data2(specimen, 'raw', condition)[1]
126         plt.plot(x_data,y_data, '.', label = "Specimen"+str(i+10))
127
128     #curve fit data
129     x_model, y_model = curvefit_raw(specimen_sett, condition)
130     plt.plot(x_model,y_model, 'k')
131     plt.ylabel("G/G (Ic)")
132     plt.xlabel("logN")
133     plt.xscale('log')
134     plt.grid()
135     plt.show()
136
137 def plot_growth(specimen_sett, condition):
138     #Experimental data
139     x_data = []
140     y_data = []
141     for i in range(len(specimen_sett)):
142         specimen = specimen_sett[i]
143         x_spes = specimen_data2(specimen, 'growth', condition)[1]
144         y_spes = specimen_data2(specimen, 'growth', condition)[0]
145         x_data += (x_spes)
146         y_data += (y_spes)
147         x_log = np.log(x_data)
148         y_log = np.log(y_data)
149         plt.plot(x_spes,y_spes, '.')
150
151     #curve fit data
152     model1 = np.poly1d(np.polyfit((x_log),(y_log), 1))
153     polyline = np.linspace(math.log(GIth(x_data)), math.log(1), 50)
154     plt.plot(math.e**(polyline), math.e**(model1(polyline)), color='black')
155
156     #Plot lines for converging
157     if condition == 'unaged':
158         y1 = 0.0017
159         y2 = 100
160         y3 = y2+(y2*8)
161     elif condition == 'aged':
162         y1 = 0.013
163         y2 = 1750
164         y3 = y2+(y2*8)
165
166     plt.vlines(x=(GIth(x_data)), ymin=math.e**(-7), ymax=(y1), colors='black')
167     plt.vlines(x=(1), ymin=y2, ymax=y3, colors='black')
168
169     #Labels and limitations
170     plt.ylabel("da/dN")
171     plt.xlabel("G_imax/G_ir")
172     plt.title("Crack growth", loc = 'left')
173     plt.yscale('log')
174     plt.xscale('log')

```

```

175 plt.grid(True, which="both", ls="--")
176 plt.rcParams['figure.dpi'] = 600
177 plt.show()
178
179
180
181 def plot(condition, graph):
182     if condition == 'aged':
183         specimen = data_aged
184     elif condition == 'unaged':
185         specimen = data_unaged
186     else:
187         print('Wrong condition')
188
189     if graph == 'raw':
190         plot_raw(specimen, condition)
191     elif graph == 'growth':
192         plot_growth(specimen, condition)
193     else:
194         print('Wrong graph')
195
196
197 #Condition = aged & unaged
198 #Graph      = raw & growth
199 plot('aged', 'raw')

```

## B.7 Plot Paris law equation

```

1
2 import pandas as pd
3 import matplotlib.pyplot as plt
4 import numpy as np
5 import math
6
7
8 #Plotter eksperimentell data
9
10 data_U = [X_U, Y_U]
11 data_A = [X_A, Y_A]
12
13
14
15 #Funksjoner & variabler
16
17 Gith_unaged = 0.10951883749474212
18 Gith_aged   = 0.06751433124302118
19
20 def GIR_unaged(a):
21     return 0.27 * math.log(a) + 1.003
22
23 def GIR_aged(a):
24     return 0.457 * math.log(a) + 1.705
25
26 def GImax_unaged(N):
27     return -0.030481 * math.log(N) + 0.452399
28
29 def GImax_aged(N):
30     return -0.035144 * math.log(N) + 0.454714
31
32 def fatigue_life(dN, da, condition):
33     if condition == 'unaged':
34         Gir = GIR_unaged(da)
35         Gimax = GImax_unaged(dN)
36         A = 0.0000000006
37         m = 5.35
38
39
40     elif condition == 'aged':
41         Gir = GIR_aged(da)
42         Gimax = GImax_aged(dN)
43         A = 0.00000000013

```

```

44     m = 6.4
45     else:
46         print('Wrong condition')
47
48     dadN = (A*((Gimax/Gir)**-m))
49     return dadN
50
51 def plot_data(data, condition):
52     if condition == 'aged':
53         S1 = Gith_aged/GIR_aged(1)
54     elif condition == 'unaged':
55         S1 = Gith_unaged/GIR_unaged(1)
56
57     X = data[0]
58     Y = data[1]
59     x_data = []
60     y_data = []
61     for i in range(len(X)):
62         x_spes = X[i]
63         y_spes = Y[i]
64         plt.plot(x_spes, y_spes, '.')
65
66         x_data += (x_spes)
67         y_data += (y_spes)
68         x_log = np.log(x_data)
69         y_log = np.log(y_data)
70
71     #curve fit data
72     model1 = np.poly1d(np.polyfit((x_log),(y_log), 1))
73     polyline = np.linspace(math.log(S1), math.log(1), 50)
74     plt.plot(math.e**(polyline), math.e**(model1(polyline)), color='black')
75
76
77 def plot_likning(condition):
78     num = 50000
79     if condition == 'unaged':
80         data_sett = data_U
81         Gith = Gith_unaged
82         Gir = GIR_unaged(1)
83         N_value = np.linspace(1,2780000, num)
84         A = 0.0000000006
85         m = -5.35
86
87     elif condition == 'aged':
88         data_sett = data_A
89         Gith = Gith_aged
90         Gir = GIR_aged(1)
91         N_value = np.linspace(1,415000, num)
92         A = 0.00000000013
93         m = -6.4
94
95
96     Y_data = []
97     X_data = np.linspace((Gith/Gir),1, num)
98     a_value = np.linspace(1,50, num)
99
100
101     for i in range(num):
102         y = fatigue_life(N_value[i], a_value[i], condition)
103         Y_data.append(y)
104
105     plot_data(data_sett, condition)
106
107     plt.plot(X_data, Y_data)
108     plt.legend()
109     plt.ylabel("da/dN")
110     plt.xlabel("Gimax/Gir")
111     plt.yscale('log')
112     plt.xscale('log')
113     plt.grid()
114     plt.rcParams['figure.dpi'] = 600
115     plt.show()
116

```

```
117
118 plot_likning('unaged')
```

## B.8 Comparing fatigue life of aged and unaged specimens

```
1
2 data_U = [X_U, Y_U]
3 data_A = [X_A, Y_A]
4
5
6
7 #Funksjoner & variabler
8
9 Gith_unaged = 0.10951883749474212
10 Gith_aged = 0.06751433124302118
11
12 def GIR_unaged(a):
13     return 0.27 * math.log(a) + 1.003
14
15 def GIR_aged(a):
16     return 0.457 * math.log(a) + 1.705
17
18 def GImax_unaged(N):
19     return -0.030481 * math.log(N) + 0.452399
20
21 def GImax_aged(N):
22     return -0.035144 * math.log(N) + 0.454714
23
24 def fatigue_life(dN, da, condition):
25     if condition == 'unaged':
26         Gir = GIR_unaged(da)
27         Gimax = GImax_unaged(dN)
28         A = 0.0000000006
29         m = 5.35
30
31
32     elif condition == 'aged':
33         Gir = GIR_aged(da)
34         Gimax = GImax_aged(dN)
35         A = 0.00000000013
36         m = 6.4
37     else:
38         print('Wrong condition')
39
40     dadN = (A*((Gimax/Gir)**-m))
41     return dadN
42
43 def plot_data(data, condition):
44     if condition == 'aged':
45         S1 = Gith_aged/GIR_aged(1)
46     elif condition == 'unaged':
47         S1 = Gith_unaged/GIR_unaged(1)
48
49     X = data[0]
50     Y = data[1]
51     x_data = []
52     y_data = []
53     for i in range(len(X)):
54         x_spes = X[i]
55         y_spes = Y[i]
56         plt.plot(x_spes, y_spes, '.')
57
58         x_data += (x_spes)
59         y_data += (y_spes)
60         x_log = np.log(x_data)
61         y_log = np.log(y_data)
62
63     #curve fit data
64     #model1 = np.poly1d(np.polyfit((x_log),(y_log), 1))
65     #polyline = np.linspace(math.log(S1), math.log(1), 50)
66     #plt.plot(math.e**(polyline), math.e**(model1(polyline)), color='black')
```

```

67
68
69 def plot_likning(condition, data_sett):
70     num = 50000
71     if condition == 'unaged':
72         data_sett = data_U
73         Gith = Gith_unaged
74         Gir = GIR_unaged(1)
75         N_value = np.linspace(1,2780000, num)
76         A = 0.0000000006
77         m = -5.35
78
79     elif condition == 'aged':
80         data_sett = data_A
81         Gith = Gith_aged
82         Gir = GIR_aged(1)
83         N_value = np.linspace(1,415000, num)
84         A = 0.00000000013
85         m = -6.4
86
87
88     Y_data = []
89     X_data = np.linspace((Gith/Gir),1, num)
90     a_value = np.linspace(1,50, num)
91
92
93
94     for i in range(num):
95         y = fatigue_life(N_value[i], a_value[i], condition)
96         Y_data.append(y)
97
98     plot_data(data_sett, condition)
99
100     return X_data, Y_data
101
102
103
104
105 def plot_both():
106     for i in range(1,3):
107         if i == 1:
108             condition = 'unaged'
109             datasett = data_U
110         elif i == 2:
111             condition = 'aged'
112             datasett = data_A
113
114         X_data, Y_data = plot_likning(condition, datasett)
115         plt.plot(X_data, Y_data, label = condition)
116
117     plt.legend()
118     plt.ylabel("da/dN")
119     plt.xlabel("Gimax/Gir")
120     plt.yscale('log')
121     plt.xscale('log')
122     plt.grid()
123     plt.rcParams['figure.dpi'] = 600
124     plt.show()
125
126
127 plot_both()

```



<b>5.2 Korrigerende Tiltak – Corrective Actions</b>					
Nr.	Korrigerende tiltak – Corrective action	Sannsynlighet – Probability	Konsekvens – Consequence	Risiko – Risk	Utført dato – Date of action
1	Do not lift fabric/bag rolls alone, and ensure good space around the lifting area	2	A	A1	Always
3	Make sure to wear gloves while cutting fiber, and to place finger away so they do not get chopped off	2	B	B2	Always
4	Wear gloves	2	A	A2	Always
6	Wear gloves approved for the chemical, wear goggles, wear cloths covering all of the body (except head) Work under the hood as far as possible.	2	C	C2	Always
7	Be focused on the task and think through the steps of the job before starting. If it happens mix resin and hardener. Have towels ready to clean	2	B	B2	Always
8	Follow the mixing ratio, mix small batches. Have bucket ready to carry resin out. Last resort fire extinguisher	2	D	D2	Always
9	Be present during initial part of curing. Otherwise see point 8. Especially important for thick laminates	2	D	D2	Always
10	Do not let the pump run open for long times, be present while the pump is running	1	D	D1	Always
12	Make sure all materials including packaging can tolerate the set temperature and curing time	1	D	D1	Always
13	Do not drink/eat in the lab, and make sure to wear gloves and throw them before touch your face.	1	D	D1	Always
14	Use gloves approved for the chemical, and wear clothes that cover the entire body.	1	B	B1	Always
15, 16, 19, 23	Do not throw chemicals in nature, but dispose in the correct way.	1	D	D1	Always
17	Use gloves approved for the chemical, and wear clothes that cover the entire body, and safety glasses.	1	C	C1	Always
18, 20	Avoid touching chemicals without gloves, and wear safety glasses and cover the body.	1	C	C1	Always
22	Use eye protection. If chemicals get in the eyes, rinse immediately.	1	B	B1	Always
<b>Updated 11.11.2022:</b>					
24	The amount of Araldite needed is low and the process is controlled under an extraction fan, while wearing gloves and glasses.	1	C	C1	Always
25	Take off gloves before touching the face or mouth	1	D	D1	Always
26, 27, 28, 29, 30, 31, 34, 35, 36	Use gloves, safety glasses and clothes that cover up the body	1	B	B1	Always
32, 33, 37	Do not throw chemicals in nature, but dispose in the correct way.	1	D	D1	Always

## C.2 Fatigue lab

### Detailed risk evaluation:

Risks
1. Starting the machines, the piston might start to move and crush itself.
2. Mounting/removing the specimen into the machine. Fingers might be pinched
3. Mounting/removing the specimen into the machine. If the machine suddenly <u>move</u> , the arm/hand might be crushed.
4. When running the test, splinters from the test specimen might accelerate and hit the body or eyes
5. During the test the machine might crush itself

### Risk matrix of the activity before any safety measures has been applied (Include corresponding color):

Risk	Probability (P) (1-5)	Consequence (C)				Risk value (P x C)
		Health (1-5)	Material values (1-5)	Environment (1-5)	Reputation (1-5)	
1	3	1	4	1	3	12
2	4	2	1	1	1	8
3	3	4	2	1	3	12
4	5	2	1	1	1	10
5	3	1	4	1	3	12

### Required safety equipment (mark with X the risk that applies for the activity):

Glasses	X	Safety shoes	
Helmet		Gloves	
Screen	X	Lifting equipment	
Ear protection		Hazard suit	
Harness ropes, other measures to prevent falling		Fume hood	
Lab coat			



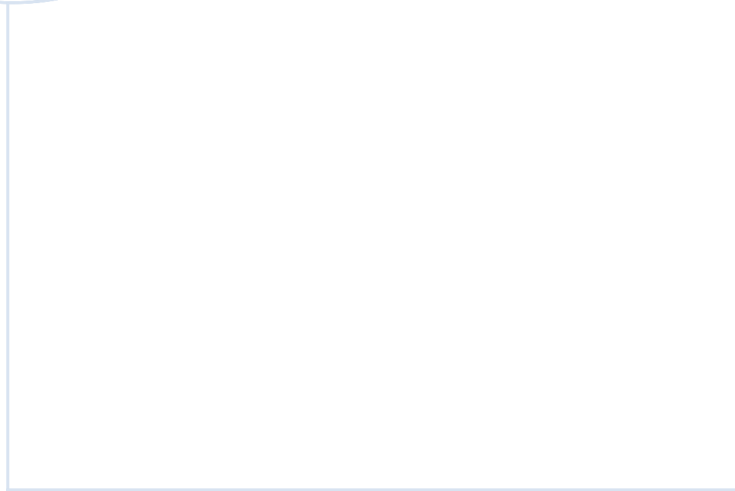
**Description of other safety measurements:** Eg. Safety cap on the instrument prevents the risk of... and/ or the probability of...

**Risk after preventative and corrective measures:**

Risks	Preventative and corrective measures
1. Starting the machines, the piston might start to move and crush itself.	Get help from an experienced user when setting up and starting the first experiment
2. Mounting/removing the specimen into the machine. Fingers might be pinched	Ensure that fingers are placed so they cannot get into the grips
3. Mounting/removing the specimen into the machine. If the machine suddenly <u>move</u> , the arm/hand might be crushed.	Set a displacement limit, and ensure that no one interfere with the machine during this part of the test
4. When running the test, splinters from the test specimen might accelerate and hit the body or eyes	Set up the protective screen, wear clothes that cover the body, and use protective glasses
5. During the test the machine might crush itself	Set a displacement limit, and make sure this limit is correct so that the machine cannot hit itself

**Risk matrix of the activity after safety measures has been applied:**

Risk	Probability (P) (1-5)	Consequence (C)				Risk value (P x C)
		Health (1-5)	Material values (1-5)	Environment (1-5)	Reputation (1-5)	
1	2	1	4	1	2	8
2	2	2	1	1	1	4
3	2	4	2	1	3	8
4	2	1	1	1	1	2
5	2	1	4	1	3	8



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