Fatigue of Injection Moulded Short Fibre Reinforced Polymers

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Fatigue of Injection Moulded Short Fibre Reinforced Polymers

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A thesis submitted in fulfilment of the requirements for the degree of Master in engineering

the

Department of Solid Mechanics

June 3, 2019
Abstract

In order to keep up with the increasing demand of fuel-efficiency in the transportation industry, the interest of making the vehicles as lightweight as possible is steadily increasing. One of the ways of reducing the weight is to introduce an anisotropic material as Short Fibre Reinforced Polymers (SFRP) as a replacement for structural parts made out of metals. To meet the modern vehicle design process which strives towards a more simulation driven workflow, the need for accurate simulations of fibre reinforced composites is of importance.

This thesis aims to evaluate and find a working process for fatigue analysis of injection moulded SFRP components. To evaluate the fatigue analysis procedure an existing SFRP component has been studied. The component is the front bracket that mounts the roof air deflector to the roof on Scania trucks. To correlate the fatigue life estimation from the fatigue analysis, experiments were performed at ÅF Test Center in Borlänge.

The anisotropic behaviour is modelled using the commercial software Digimat together with an injection simulation provided by Scania, to estimate the fibre orientation and thereby the material behaviour of the SFRP component. The fatigue analysis was conducted by performing a coupled structural analysis between Digimat-Abaqus and then import the resulting stress- and strain-fields into the fatigue post-processor nCode DesignLife. The stress is then cyclic tested towards experimentally determined S-N curves determined in Digimat.

Due to restriction of available fatigue data for the plastic in the front bracket, a fatigue material model for a plastic containing the same fibres and matrix but with a different fibre amount was implemented. The fatigue data were scaled using the UTS method to get a good characterisation of the real-life material behaviour of the plastic of the front bracket component.

From the correlation between the fatigue analysis and performed experiments, it was shown that the simulated fatigue life was conservative compared to the fatigue life determined from the experiments. However, the correlation between the fatigue analysis and experiments is not fully captured but gives a better estimation of the fatigue life compared to performing the fatigue analysis using an isotropic material model.

Keywords: Short Fibre Reinforced Polymers, Composites, Fatigue, Finite Element, Digimat, nCode DesignLife, Injection Moulding, Anisotropy.
Sammanfattning

För att möta efterfrågan av minskning av bränsleförbrukning inom transportsektorn så har intresset att minska vikten på transportfordon ökat. För att minska vikten så har anisotropiska material som polymerer förstärkta med korta fibrer setts som en potential ersättare för vitala delar i strukturen. För att kunna möta den moderna design processen av fordon som strävar mot en mer simulering driven process så har behovet av att kunna utföra simuleringar med hög precision av fiberförstärkta kompositer ökat.

Detta examensarbete strävar mot att kunna utvärdera och bestämma en arbetsprocess för utmattningsanalys av injektions sprutade kompositer förstärkta med korta fibrer. För att utvärdera utmattningsanalysen så har en existerande fiber förstärkt komponent studerats. Komponenten är fästet som monterar taklufttriktaren på hytten utav Scania lastbilar. Jämförelsen har utförts genom att jämföra utmattningsanalysen med utförda experiment vid ÅF’s Test Center i Borlänge.

Det anisotropiska beteendet hos kompositen modelleras med hjälp av den kommersiella programvaran Digimat tillsammans med en utförd injektionssimulering som tillhandahållits av Scania för att uppskatta fiberriktningarna i komponenten och därigenom kunna modellera det anisotropiska material beteendet hos kompositen. Utmattningsanalysen utfördes genom att importera resultatet från en strukturanalys med Digimat kopplat till Abaqus, där de resulterande spännings- och töjningsresultaten importeras till utmattnings post-processorn nCode DesignLife där spänningsnär läggs på som en cyklisk last och jämförs mot experimentella S-N kurvor bestämda i Digimat.

På grund av den begränsade tillgängligheten av relevant utmattningsdata för plasten som takfästet består utav, så användes en materialmodell för en plast innehållande samma sorts fibrer och matris men med en större mängd fibrer. Utmattningsdatan skalades med hjälp utav UTS-metoden för att få en bra karakterisering utav det verkliga materialbeteendet hos plasten som takfästet är gjord utav.

Från jämförelsen mellan utmattningsanalysen och de utförda experimenten så kunde det konstateras att den simulerade livslängden är konservativ jämfört med livslängden bestämd från experimenten. Skillnaden mellan utmattningsanalysen och experimenten ger att det fulla utmattnings beteendet för den anisotropiska komponenten kunde inte bestämmas helt men ger en bättre uppskattning av livslängden än tidigare utförda analyser där en isotropisk materialmodell använts.
Acknowledgements

I would first and foremost like to thank my supervisor M.Sc. Max Ericsson for his unyielding support, helpful advice and uplifting spirit throughout the whole thesis.

I would also like to thank my contacts at Scania RCCC M.Sc. Hanna Wilander and M.Sc. Yoann Prigent for providing advice and support when needed. A special thanks to M.Sc. Hanna Wilander who have been a constant help with everything from booking meetings to providing interesting coffee talks.

I would also like to thank Bernard Alsteens and Hedi Skhiri at e-Xstream Engineering, MSC Company for providing explanation about the theory and usage of Digimat which has helped extremely in understanding the analysis procedure.

I would also like to thank all co-workers at ÅF. You have all been very welcoming and always provided new topics to talk about each coffee break.

Finally, I would like to thank Prof. Bo Alfredsson at KTH for always providing support about the structure of the thesis and giving his advise on how to proceed when problems arise.

Stockholm, June 2019

Axel Eriksson
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Acronyms

**ABS**  Acrylonitrile Butadiene Styrene

**CAE**  Computer-Aided Engineering

**CF**  Carbon Fibre

**CLD**  Constant Life Diagram

**FE**  Finite Element

**GF**  Glass Fibre

**HCF**  High Cycle Fatigue

**LCF**  Low Cycle Fatigue

**MFH**  Mean-Field Homogenization

**PA**  Polyamide

**PE**  Polyethylene

**PP**  Polypropylene

**PS**  Polystyrené

**RH**  Relative Humidity

**RVE**  Representative Volume Element

**S-N**  Stress - Number of cycles

**SFRP**  Short Fibre Reinforced Polymers

**UTS**  Ultimate Tensile Strength
# Nomenclature

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<td>stress range</td>
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<td>$\sigma_{\text{max}}$</td>
<td>maximum stress</td>
<td>[MPa]</td>
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<td>$\sigma_{\text{min}}$</td>
<td>minimum stress</td>
<td>[MPa]</td>
</tr>
<tr>
<td>$\sigma_{a}$</td>
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<td>$\sigma_{m}$</td>
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<td>$\Delta T$</td>
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<tr>
<td>$f$</td>
<td>test frequency</td>
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<tr>
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<tr>
<td>$l_i$</td>
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Chapter 1

Introduction

Fatigue failure in load bearing structures is a common problem to take into consideration when designing components. The fatigue phenomena have caused many structures to collapse without any noticeable warning signs. The initiation of fatigue can be caused by a local imperfection such as a crack or cavitation in the material which can be hard or even impossible to detect. From this, a local crack can be initiated and start to propagate which can ultimately lead to structural failure.

At the group for Dynamic and Strength analysis, in Scania CV AB, RCCC, crash simulations and fatigue evaluations are performed on the cabin of the trucks. For fatigue evaluations, the Finite Element Method is mainly used in conjunction with stress- or strain-based fatigue criteria. A simplification of commonly used schematic workflow for fatigue analysis is demonstrated in Figure 1.1.

The workflow contains the setup of the FE-model with boundaries and load-case adequate to the desired investigation. The FE-model also needs to contain a sufficiently refined structural mesh to avoid a dependency which could lead to results of poor quality. For standard fatigue analysis, the material behaviour is usually
Chapter 1. Introduction

modelled with the assumption of a homogenised isotropic behaviour which is an adequate assumption for many used materials. From a structural analysis, the local stress and strain are determined. The fatigue analysis is performed by taking the result from the structural analysis and performing a repetitive loading (often simulated as a cyclic repetition). The analysis is compared to a test determined fatigue criteria specific to the material used for the simulations. The fatigue criteria is often illustrated by a S-N curve which is described as amplitude stress as function of fatigue life. Commercial fatigue software then predicts the fatigue lifetime by taking the multi-axial stress/strain to determine the accumulated damage corresponding to the material specific fatigue criterion.

To be able to adapt to the increasing demand for fuel efficiency in trucks/transportation, lightweight structures are vital for further advancement in the transportation sector. A large portion of the load carrying components are investigated in order to optimise the mass of the trucks further. Reinforced polymers are implemented to a greater extent as a replacement for the material of load carrying components in order to gain a more light-weight component with equivalent mechanical properties.

From this desire to replace the material of important components with materials that have better load-carrying to weight relation, the demands of precision in fatigue life prediction of these materials increases. Since the modern vehicle design process moves towards more simulation driven workflows, the capability to make precise fatigue simulations are of the essence. There are commercial CAE-software that claim to offer the capability to perform fatigue analysis of fibre reinforced polymers. To assess these software the correlation between fatigue life acquired from simulation and experimental tests needs to be evaluated.

1.1 Objective

The aim of this thesis is to evaluate and find a working process for fatigue analysis of injection moulded Short Fibre Reinforced Polymers (SFRP) composites. To evaluate the fatigue analysis procedure an existing SFRP component is studied. This component has been noticed to experience fatigue failure during shake rig tests before fulfilling the required fatigue life. In order to correlate the fatigue analysis made by simulations, experiments are performed at ÅF Test Center in Borlänge. The simulation is performed by simulating the test setup using Finite Element-modelling with usage of the pre-processor ANSA 18.1.4 for analysis in Abaqus 2017.

To reproduce the anisotropic material behaviour of the SFRP an injection moulding analysis is provided by Scania using the commercial software Moldflow. The injection analysis together with the material properties of the constituents is mapped to the Finite Element model using the software Digimat. From this coupled static analysis a fatigue analysis is carried out using the external post-processor software nCode DesignLife V18.0.0 to correlate the simulations to the experiments. The resulting fatigue analysis is compared to the integrated fatigue post-processor added to Digimat 2019.0 to assess its capabilities.

From this work, a practical workflow is to be presented in order to facilitate further fatigue analysis of SFRP components. The goal is also to compare the accuracy and reliability of the methods used in order to recommend future work.
1.2 Delimiter

The experiments is limited by the number of test specimens provided by Scania. From this the scattering material behaviour of the front bracket component could not be determined. The focus of the experiments is to get a good estimation of the fatigue life for different loads to be able to correlate to the fatigue analysis.

The material behaviour of the plastic used for the front bracket component is limited by the lack of material data available and needs to be estimated from the available material data from equivalent plastics.

The complex fibre distribution occurring from the injection moulding of the front bracket is not capable to be fully captured by the injection moulding simulation. However, using the injection moulding simulation together with the coupling to Digimat 2019.0 the material behaviour of the SFRP component is well captured compared to using a isotropic material model.

The fatigue analysis of SFRP is limited to linear elastic material models. This limitation is due to the restriction from Digimat 2019.0 for the usage of nonlinear material models in fatigue analysis.

The CPU usage is limited to be performed locally on the computer due to the restriction to transfer the coupling between Digimat 2019.0 and Abaqus 2017 to a external solver. From this restriction, to get a efficient analysis procedure, the fatigue analysis is performed for a linear simplified structural analysis.
Chapter 2

Theory

2.1 Background

With an increasing demand for reducing carbon dioxide emissions the interest of finding new more fuel-efficient solutions for the transportation industry is steadily growing. In order to reduce the emissions from transport vehicles, the consumption of fossil fuels in the engine has been studied to a large extent. From this research, the engine has been developed to be very fuel efficient and to further minimize the consumption research has shifted focus towards minimising the mass of the vehicle. Besides making the structure of the vehicles as lightweight as possible with the already used materials, new more lightweight materials are being investigated as a replacement. One of the more common materials used for this sort of replacement is fibre reinforced polymers, also referred to as composites, and further research of its capabilities is currently of key interest.

By replacing the material of a component from a heavier material to a composite with the corresponding mechanical properties the weight reduction and manufacturing possibilities improve. However, to directly replace the material of a component from a metallic alloy to a composite is not straight forward. Since the mechanical properties of a composite change depending on the alignment of the fibres to the applied load it has a intrinsic anisotropic behaviour, compared to the isotropic behaviour of a metallic alloy. The anisotropic behaviour of the composite, therefore, has to be taken into consideration when designing a fatigue loaded component. Depending on how the composite is manufactured and which properties that are desired the arrangement of the reinforcing fibres can vary, two different arrangements of fibre reinforced composites are illustrated in Figure 2.1 [1].

A composite consists of two or more constituents with significantly different properties, which when combined creates a material with characteristics from the individual components. The result is that the composite increases in strength and
2.2 Fatigue Theory

Hertzberg [3] interpreted fatigue as the loss of strength or other important property as a result of stressing over a period of time. This phenomena generally occurs in most materials. From the immense amount of research that has been made on the fatigue phenomena of materials, engineers and designers are well aware of the insidious effects of structural damage occurring from repetitive loading.

The fatigue phenomena are divided into two different stages, the initiation of a small crack and the propagation of this crack until fatigue failure occurs. Depending on the material, geometry and load level the majority of the fatigue life can be consumed by one of these stages. The line between these two stages is generally not well defined. For example, depending on the assumption if the test specimen might have an initial defect from manufacturing makes a huge impact on which stage the fatigue life will be consumed. For an unnotched specimen Hertzberg [3] claims that the larger part of the fatigue life will be spent in the crack initiation regime but for a test specimen where design, manufacturing or self-induced defects may be present then the life estimation should be dominated by the crack propagation.

The fatigue life is also generally classified into the two regions Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF). The difference between the different regions is characterised by the deformations that occur. For LCF plastic deformation occurs corresponding to the high-stress level that is applied, this region usually is defined to somewhere around $10^2 - 10^3$ number of cycles. HCF is characterised by the elastic deformation that occurs, this leads to a higher number of cycles until fatigue failure. The transition between LCF and HCF has no fixed transition line but is determined by the stress level where the deformation goes from elastic to plastic and depends on the ductility of the material [4]. For certain materials, a lower stress limit (also referred to as endurance limit) can be seen. Stresses below this limit are said to have an “infinite” lifetime since fatigue failure will not occur in a realistic time frame.

To be able to predict the total fatigue life of a component certain experimental tests have to be performed in a controlled manner. Depending on the loading occurring...
on the component the choice of test procedure can vary significantly. Two of the most
used fatigue testing methods is stress- and strain-controlled. In the stress-controlled
or corresponding load-controlled test, a cyclic sinusoidal load is applied to the com-
ponent where the alternating stress or stress range is the delimiter for the test pro-
dure. As for the strain-controlled, often also referred as displacement-controlled, the
component is subjected to a predetermined alternating strain or strain range where
the delimiter is the measured strain or equivalent displacement that the component
is subjected to.

The result from experimental tests is often presented in a S-N curve, also denoted
as a Wöhler-curve. In a S-N curve, the stress amplitude for the number of cycles,
which is attained from experiments performed until fatigue failure, in Figure 2.2 an
eexample S-N curve for true stress is displayed.

Some of the quantities that contribute during a stress-controlled test are the \( \sigma_{\text{max}} \) and \( \sigma_{\text{min}} \) which are the maximum and minimum stresses, the stress range \( \Delta \sigma \) derived as

\[
\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}},
\]

(2.1)

the amplitude stress \( \sigma_a \) derived as

\[
\sigma_a = \frac{1}{2} (\sigma_{\text{max}} - \sigma_{\text{min}}),
\]

(2.2)

the mean stress \( \sigma_m \) derived as

\[
\sigma_m = \frac{1}{2} (\sigma_{\text{max}} + \sigma_{\text{min}}),
\]

(2.3)

and the stress ratio, also denoted as load ratio, \( R \) derived as

\[
R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}},
\]

(2.4)

The load ratio \( R \) is a very important parameter for fatigue testing which is explained
by Van Paepegem [5]. Since the maximum \( \sigma_{\text{max}} \) and minimum \( \sigma_{\text{min}} \) stress levels are
investigated with their algebraic sign, a negative value of the load ratio \( R \) \(( -\infty < R < 0 )\) refers to a tension-compression loading, \(( 0 < R < 1 )\) refers to the tension-
tension loading and \(( 1 < R < +\infty )\) refers to compression-compression loading. For
most composite materials the worst loading is the fully reversed axial fatigue, or tension-compression loading \((R = -1)\)[5].

From a structural point of view, the mechanical properties of a composite are proportionate to that of metallic materials when designed in a suitable manner. However, the fatigue phenomena for metals occur without any general plastic deformation but a localised plastic deformation around already existing imperfections. This behaviour does not correspond to the fatigue phenomena of a non-metallic material, as discussed by Pineau and Bathias [6].

For amorphous or semi-crystalline polymers, which are illustrated in Figure 2.3, the fatigue phenomena is not related to plasticity since there is no dislocation happening within polymers. The damage mechanisms are instead related to the forming of cavities or cavitations. The damage is accumulated in a general fashion rather than focused on a local imperfection [1].

Figure 2.3: Crystalline and amorphous regions in plastics. Figure taken from [1]

Pineau and Bathias further describes at a micro level that the plasticity of metals is governed by the shear components of the stress tensor which give rise to dislocation movement along slip bands [6]. Fatigue initiation for metals at a micro level is induced by the dislocation movement and microscopic plasticity. For polymer materials, the forming of cavities and cavitations do not just depend on the shearing part, but also on the hydrostatic part of the stress tensor as well as the main principal strains. This means that elastomers may crack during compressive fatigue loading which is not normally the case for metals.

For fatigue estimation using simulation tools, the procedures and theory behind it for determining fatigue in metallic crystalline materials is a well-studied topic. Since the adoption of composites into structural components is increasing a larger focus has been made the last decade in fatigue analysis of composites. To be able to correlate fatigue results using simulation the need for experiments of composites has been significant and thereby the need for knowledge of the theory behind it.
In general, the application of fibre reinforcement improves the fatigue strength for all polymers. For injection moulded composites the fibres are in general very short, unlike chopped strands, the fibres are not bundled together but individually dispersed. The orientation of the short fibres are significantly influenced by the melt flow direction as can be seen in Figure 2.4. Depending on the specific flow pattern the short fibres tend to orient themselves differently. According to Rosato [7] short fibres have a tendency to align themselves parallel closer to the walls of the mould and distribute more randomly away from the walls which creates a sandwich structure, this theory is supported by Mandell [8].

For injection moulded SFRP the damage accumulated during cyclic loading conditions shows a broader range of fatigue behaviour. Mandell [8] shows that several modes for tensile failure exists for plastics reinforced by short fibres. Some of the main failure modes are described as fibre breakage, matrix yield or rupture, debonding between the fibres and matrix and craze in the matrix. Craze is a phenomenon that can occur in polymers in regions of high tensile stress which can lead to microvoids that can elongate and break which can cause the microvoids to grow and form a crack.

For actual fatigue failure of SFRP, a combination of the different modes usually appear. Depending on the failure mode the reinforcing effect of the fibres can be either positive or negative to the fatigue life. For debonding, the effects of fibre reinforcement are gradually eliminated and the fatigue performance approaches that of the matrix containing cavities, which is inferior to the strength of a pure matrix constituent [3]. For fatigue crack growth the performance of composite is usually greater than that of the pure matrix.

2.3 Experimental Theory

The choice of method for experiments to get relevant results is not a straightforward procedure. Many different aspects have to be taken into account to be able to perform adequate tests which yield acceptable test data. This usually comes from both theoretical and knowledge and practical experience. To define or list different factors that may have an influence on a structural system is easy to do and quickly becomes long. To be able to know which of these factors that are relevant for a test procedure is considerably more complicated.
For fatigue testing of a SFRP composite, in order to avoid unwanted failure modes and testing artefacts many factors can have an impact on the test which has to be considered to be able to contain adequate fatigue results. Some of the limitations and possible factors to take into consideration are described in Section 2.3.1 and 2.3.2 below.

### 2.3.1 Limitations


#### Test Equipment

To be able to measure the experiments with adequate validity the test equipment must be chosen appropriately to not influence the result. To avoid excessive deflections which can corrupt the measured quantities, the testing machine needs to have sufficient mechanical stiffness in comparison to the load level applied to the specimen. Any resonance frequencies of the test machine need to be significantly higher than the applied test frequency [5].

The complex loading that acts on a composite component is often hard to reproduce in laboratory tests. Usually, the test machines are not equipped to apply a loading condition with that degree of complexity and the real-life loading condition is usually hard to distinguish and therefore hard to reproduce.

#### Hysteric Heating

For fatigue testing of materials to minimize the time and cost the loading frequency is set as high as possible to reduce the test duration. In theory, the fatigue damage is independent of the frequency and only dependent on the number of cycles [5].

For fibre reinforced polymers increasing the test frequency can cause a self-heating phenomenon that can reduce the material properties and fatigue performance. The frequency effect was investigated by Chebbi, Mars, Wali, et al. [10] on the material PA66-GF. It was found that the self-heating is resulting from the viscoelastic nature of the matrix and the frictional heating in the composite.

The accumulated heat generation from hysteric heating can lead to a temperature rise of the test specimen which can be so great as to cause the specimen to melt, which will cause premature failure since the specimen will not be able to withstand the load. Hertzberg [3] mentions that these sort of failures does not require the specimen to have a visible fracture.

Hertzberg also shows that the temperature increase $\Delta T$ of the specimen during constant loading conditions can be described as

$$\Delta T \propto \sigma_s^2 f d^2 D / E_d A_h$$  

(2.5)
where $f$ is the test frequency, $d$ the specimen diameter, $D$ the damping capacity of material, $E_d$ the dynamic modulus and $A_h$ the heat transfer parameter. From this relation, the parameters that are not inherent to the test specimen are the test frequency $f$ and amplitude stress $\sigma_a$.

From this for a predetermined specimen with a given material the two parameters that need to be considered to avoid the hysteric heating phenomena is the load level and test frequency during fatigue testing.

**Environmental effects**

For injection moulded composites Mandell [8] describes three of the prime aspects for environmental interaction with the test specimen as thermal effects, moisture plasticization in the matrix and environmental stress cracking in acidic solutions. Beside acidic solution which is for specific cases, the effect of the thermal environment, which is primarily generated from the hysteric heating as discussed above, can have a large impact on the test results and need to be considered and controlled to not let it contaminate the desired test results.

For the moisture effects, the Relative Humidity (RH) has a large impact on the matrix resin since the absorption of moisture has a discerning effect on the mechanical behaviour of the matrix and therefore the composite. To avoid this artefact the Relative Humidity of the surroundings and moisture absorption of the test specimen before the test procedure needs to be controlled or at least considered to not influence the results [11].

**2.3.2 Test Considerations**

Sims [9] concludes that there are many factors to take into consideration when performing fatigue testing. Some of the issues during the fatigue testing procedure is; the stress state to be applied (e.g. multi-axial, uni-axial), the failure criteria to be investigated (e.g. fracture, stiffness loss), the control mode of the equipment (e.g. load, displacement).

Other factors although important in their own right is secondary to these initial choices. Typically for polymer matrix composites Sims [9] describes some important considerations to take into account during fatigue testing as

- avoid hysteric heating (use reduced test frequencies),
- monitor the property changes of the specimen, such as stiffness or specimen temperature,
- avoid buckling situations for compression loads,
- be aware of the influence of the RH on the test environment,
- limit tensile grip pressures to avoid grip failures,
- specimen alignment to avoid unwanted bending stresses.
2.4 Previous Work

There are already numerous studies on the fatigue behaviour of SFRP. On this subject, many discuss the test procedure for investigating the fatigue life of composite. For example, the study made by Wilson and Heyes [12] of the fatigue behaviour of an engine mount includes the comparison between fatigue life determined through physical testing and fatigue life determined using simulation software. The material used in the study is a Polyamide (PA) reinforced with 50% weight Glass Fibre (referred to as PA66GF50). The fatigue properties of the material were tested using fatigue test coupons with geometry according to the ISO 527B standard. Three different specimens were used with different orientations to the injection flow direction, illustrated in Figure 2.5, where the 0° corresponds to the injection direction, while 90° is perpendicular to the injection direction. The 45° specimen is cut in a 45-degree angle to the injection direction.

![Figure 2.5: Specimen orientations. Figure taken from [12]](image)

Then from a tomography of the moulding process and an injection moulding simulation using Moldflow the fibre alignment for the engine mount is simulated. Combining this together with the material properties of the fibre and matrix and using the retrieved fatigue data from the test specimen in the form of S-N curves the material behaviour is implemented using Digimat.

To correlate the fatigue simulation of the engine mount a specific test rig was set up to perform fatigue experiments until part failure (severe decrease in part stiffness). The test was performed for a non-realistic load case to determine the fatigue result using two approaches, the physical testing and the simulation.

For the experiments, some precautions were made to ensure the test repeatability. To avoid environmental factors the experiments were performed in a climatic chamber at 25°C and at a RH of 50%. The tests were all conducted using load control where the test frequency was set to 3 Hz. The temperature of the engine mount was monitored during the whole test, if the temperature rise were higher than 5°C then the test frequency was set to 1 Hz. To avoid the risk of buckling in compression, the load ratio R was set to 0.1.

Simulations were made of the test specimens and the engine mount with Digimat coupled with Abaqus. To describe the local microstructure of each layer of the material Mori-Tanaka homogenization models was utilised. All simulations and components were meshed using 2D shell elements. The results from the simulations and
Chapter 2. Theory

physical tests are then compared using the elastic strain energy density approach. The elastic strain density $\Delta W_e$ is defined as

$$\Delta W_e = \frac{1}{2} \sigma : \epsilon$$

(2.6)

where $\sigma$ is the stress tensor and $\epsilon$ is the elastic strain tensor. The fatigue life $N$ was then estimated by

$$N = A \times \Delta W_e^b$$

(2.7)

where $A$ and $b$ are material parameters. To evaluate the life the elastic strain density method was used since the result using equivalent stress did not yield adequate results.

Using nCode DesignLife V18.0.0 the elastic strain energy quantity was calculated using two criteria: the non-local mean value by averaging the strain density for an element over the thickness and also using the local maximum to determine the maximum value over the whole specimen.

The conclusion was that from the performed experiments and simulations both the local and non-local criteria show promising results but the local maximum criteria approach appears to be over-conservative. For further work, the suggestion was to focus on the detailed description of material mechanical behaviour. The tests performed during this study also showed that the material has a strong creep behaviour.

Another example is the Master Thesis composed by Lindhult and Ljungberg [13] where a fatigue analysis of injection moulded SFRP is performed taking the anisotropy into account that occurs due to the material composition and manufacturing process. The material used for the analysis was a SFRP of Polyamide PA6, reinforced with 30% mass fraction of glass fibres also denoted as PA6GF30.

The fatigue analysis is carried out by analysing an existing SFRP component both using CAE software and physical fatigue test. To model the anisotropic behaviour of the composite the software Digimat is used, combined with the fibre orientation collected from a Moldflow analysis. The material model is defined in Digimat using the reverse engineering tool to determine the constituent’s properties based on experimental data. Digimat then computes the material response for each integration points based on the microscopic properties of the composite. Digimat makes the transition from the microscopic properties of the composite by introducing a Representative Volume Element (RVE), the RVE should contain a sufficient number of fibres to give a representative macroscopic response. The material properties at a macro scale are then determined by homogenization of the microstructure in Digimat using a Mean-Field Homogenization (MFH) method.

The fatigue data is implemented in a corresponding way as the method used by Wilson and Heyes as illustrated in 2.5. However since there was only one S-N curve of the moulded specimens available, the three S-N curves for the milled specimens which are implemented into Digimat was estimated from the available curve.

The base assumption for the estimation method is that the fatigue stress is changed in the same way as the Ultimate Tensile Strength (UTS) is changed. The S-N curves
for the specimens, loaded longitudinally and transversely to the injection flow, was then estimated from the data of the moulded specimen. This approach for estimating the S-N curves was proposed by Jain, Verpoest, Hack, et al. [14] to be able to reduce the number of tests required to retrieve the relevant fatigue data.
Chapter 3

Method

To be able to evaluate and find a working process for fatigue analysis of a SFRP component an existing SFRP component is used for this study. The component is the front bracket that mounts the roof air deflector to the roof on Scania trucks. The material of the component is an SFRP with the resin Polyamide 66 reinforced with 30% wt Glass Fibre, also referred as PA66GF30. An illustrating picture of the front bracket is shown in Figure 3.1. The component will be used throughout the analysis to correlate the fatigue analysis to performed experiments.

The experiments were conducted at ÅF Test Center in Borlänge. The test setup was determined to avoid unwanted factors, shortly discussed in Section 2.3, influencing the experiments and make the simulations as efficient as possible due to the limitations of computational capacity.

The anisotropic behaviour of the SFRP is estimated using the commercial software Digimat 2019.0 together with the fibre orientations of the component, described in Section 4.3. The fibre orientations are obtained from a simulation of the injection moulding process carried out by a material engineer at Scania CV AB.

The fatigue analysis is performed using the fatigue post-processor nCode Design-Life V18.0.0 coupled with Digimat 2019.0 to model the fatigue properties of the SFRP composite. The capabilities of the newly developed fatigue post-processor integrated into Digimat 2019 was investigated. To perform the fatigue analysis the result from a static structural analysis is needed. The static analysis is carried out using Abaqus 2017 coupled with Digimat where ANSA 18.1.4 and META 18.1.4 is
used as pre- and post-processor. The procedure of the fatigue analysis for a SFRP composite is illustrated in Figure 3.2 where the main simulation steps is shown as a workflow.

**Figure 3.2:** Workflow of fatigue analysis of a SFRP composite. The fatigue analysis is performed using ANSA 18.1.4 as pre-processor to setup a static analysis where the simulations are performed using Abaqus 2017 coupled with Digimat 2019.0, which models the anisotropic material behaviour of the composite. The fatigue analysis is performed using the post-processor nCode DesignLife V18.0.0 coupled with Digimat 2019.0, which models the fatigue properties of the composite.
Chapter 4

Material Behaviour of SFRP

A SFRP composite consist of two phases: a continuous phase, the matrix resin, and one or more discontinuous phases, the added short fibres, which remain separated and distinct inside the composite. For continuous fibre composites usually, laminate theory is used to determine the anisotropic behaviour. However, as discussed by Mandell [8] for a SFRP composite the fibre orientation needs to be estimated since the orientation of fibres can vary greatly throughout the whole structure as shown in Figure 2.4, to be able to determine the anisotropic behaviour.

4.1 Constituents properties

For a composite exposed to an external load, the load is carried through the matrix and transferred to the fibres by the fibre/matrix interface [15]. The effect of the fibre reinforcement is the restraining of the deformation of the matrix. The matrix resin also serves as protection for the rigid and brittle fibres against abrasion and corrosion [16].

Depending on the fibre dimensions and the mechanical properties of the constituents the stiffness and strength of the composite can vary substantially. These will also have an impact on the failure mode of the composite, for instance, the occurrence of fibre fracture, fibre debonding, matrix rupture and others [3], [17]. The dimensions of the reinforcing fibres are usually described by the aspect ratio which is defined as the fraction between the fibre length and diameter. Fibres used to reinforce polymers like Polyamide (PA) generally have dimensions of diameter in the order 10 - 14 µm and a length in the order of 150 - 220 µm [16], [18]. Agarwal [19] shows that for an increasing aspect ratio the longitudinal stiffness and strength of a composite increases and the properties approach that of a continuous fibre composite. The properties in the transverse direction are often assumed not to be influenced by the aspect ratio.

The strength and stiffness of the composite are directly correlated to the amount of reinforcing fibres added to the matrix resin. The fibre content of the composite is often expressed in terms of volume fraction \( v_f \) or corresponding weight fraction \( w_f \). The volume fraction \( v_f \) is the ratio of the volume of the fibres, \( V_f \), to the volume of the composite, \( V_c \). The weight fraction \( w_f \) is then related to the volume fraction \( v_f \) as

\[
    w_f = \frac{\rho_f V_f}{\rho_c V_c} = \frac{\rho_f}{\rho_c} v_f
\]

(4.1)

where \( \rho \) is the density and the subscripts \( f \) and \( c \) refer to the fibre and composite respectively [15].
For a SFRP composite there are many different combinations of constituents available. For matrix resins there are materials such as Polystyrene (PS), Polyethylene (PE), Acrylonitrile Butadiene Styrene (ABS), Polyamides (PA6 and PA66), Polypropylene (PP), etc. For reinforcing fibres there are alternatives as Carbon Fibre (CF)s, Glass Fibre (GF)s, Boron Fibres, Silicon Carbide Fibres, etc.

For this study the composite of interest is a Polyamide 66 with a weight fraction, \( w_f \), glass fibre of 30%. The mechanical properties of the composite can differ depending on the Relative Humidity in the test specimens. Some examples for the mechanical properties of the constituents and properties in the strongest direction of composites with different weight fractions are given in Table 4.1 [8], [15], [16], [20].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density ( \rho ) [g/cm(^3)]</th>
<th>Young’s Modulus ( E ) [GPa]</th>
<th>Tensile Strength (UTS) ( \sigma_{UTS} ) [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyamide PA66</td>
<td>1.14</td>
<td>2.5 – 5.0</td>
<td>0.05 - 0.09</td>
</tr>
<tr>
<td>Glass Fibre</td>
<td>2.5 – 2.54</td>
<td>70 – 72.4</td>
<td>1.5 – 3.5</td>
</tr>
<tr>
<td>PA66GF10</td>
<td>1.21</td>
<td>4.2</td>
<td>0.09</td>
</tr>
<tr>
<td>PA66GF30</td>
<td>1.37</td>
<td>9.1</td>
<td>0.18</td>
</tr>
<tr>
<td>PA66GF40</td>
<td>1.46</td>
<td>11.2</td>
<td>0.21</td>
</tr>
<tr>
<td>PA66GF50</td>
<td>1.57</td>
<td>15.4</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 4.1: Examples of mechanical properties of Polyamide 66 (PA66), glass fibre (GF) and composites containing different weight fraction \( w_f \), where the number after GF indicates \( w_f \) in %

For a short fibre composite, the fibre distribution is far from perfect which implies that the degree of anisotropy is generally less than for a continuous fibre composite. The level of anisotropy for SFRP thus increases for an increasing fibre content [20].

### 4.2 Injection Moulding

For the manufacturing of plastic components such as SFRP the most widely used process is injection moulding. The strength of the process is its ability to manufacture complex geometries on an industrial manufacturing rate. The basic principle of injection moulding is to inject a molten polymer into a closed mould, with a temperature below the melted polymer, where it solidifies into the wanted product [21].

The manufacturing process is best suited for thin components since the fibre distribution can vary considerably through the thickness and since a large part of the processing time is the cooling time. The cooling time is approximately proportionate to the square of the thickness of the component as discussed by Rosato [7].

The addition of short fibres to the molten polymer as a strengthening additive gives the characteristics of the SFRP. The added fibres are combined with the polymer matrix that provides cohesion between the two substituents, the fibres then become the load-bearing component of the composite.
During the manufacturing process, caution needs to be taken to avoid adverse effects of the matrix to fibre stress transfer. Some of the process control parameters discussed by Morton-Jones [21] are the temperature of the melt, pressure of the injection and speed of the injection. These together with the part shape of the component and the rheological properties of the material will influence the fibre orientations and residual stresses in the structure.

Depending on the part shape, the location of the injection gate could lead to two flow fronts interacting with each other and weld together, forming a weld line. The forming of a weld line is mainly made when two flow fronts meet head on but parallel flow fronts could also lead to a less distinct weld line. Examples of the occurrence of weld lines are shown in Figure 4.1.

![Figure 4.1: Illustration of the occurrence of weld lines for meeting flow fronts (left figure) and parallel fronts (right figure). Figure taken from [7]](image)

The occurring residual stresses, fibre orientation and weld lines from the injection moulding process can be estimated using CAE software that simulates the injection process, for this thesis the commercial software Moldflow is used for this estimation.

### 4.3 Fibre Distribution

As discussed in Chapter 2.2 the fibre distribution inside a SFRP has a large influence on the mechanical and fatigue properties. The fibre distribution can vary widely in terms of orientation and length of the fibers for a injection moulded component.

To be able to model this complex anisotropic behaviour of the injection moulded SFRP, many CAE software describes the fibre orientation using the second-order orientation tensor $a_{ij}$. The orientation tensor is derived by the use of orientation probability distribution functions $\psi(p)$, which is governed by the unit vector $p(\theta, \phi)$ as shown by Jansson, Gustafsson, Salomonsson, et al. [22].
The unit vector is in turn determined in 3D with two angles \( \theta \) and \( \phi \), describing a spherical coordinate system as illustrated in Figure 4.2.

![Figure 4.2: Illustration of the unit vector \( \mathbf{p} \) in regards of the spherical coordinate system for a single fibre. Figure taken from [23]](image)

The unit vector \( \mathbf{p}(\theta, \phi) \) is thereby derived as

\[
\mathbf{p} = \begin{pmatrix}
\sin(\theta) \cos(\phi) \\
\sin(\theta) \sin(\phi) \\
\cos(\theta)
\end{pmatrix}.
\]  

(4.2)

Zheng [24] describes the function, \( \psi(\mathbf{p}) \), as the probability to find a fiber oriented in the range between \( \mathbf{p} \) and \( \mathbf{p} + d\mathbf{p} \). The second-order orientation tensor \( a_{ij} \) are further defined as the dyadic products of the unit vector \( \mathbf{p} \), derived as

\[
a_{ij} = \iint \mathbf{p}_i \mathbf{p}_j \psi(\mathbf{p}) d\mathbf{p} = \begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
0 & 0 & a_{33}
\end{bmatrix}.
\]  

SYM

(4.3)

An illustration of some different fibre orientation distributions with corresponding orientation tensor components is shown in Figure 4.3.

![Figure 4.3: Different fibre orientation distributions and corresponding second-order orientation tensor components: (a) completely aligned in the 1-direction, (b) random in the 1-2 plane, (c) completely random in 3D. Figure taken from [24]](image)
4.4 Representative Volume Element (RVE)

For a SFRP the material has a heterogeneous microstructure, which is generated by the combination of the two constituents: the fibres and polymer matrix.

The heterogeneous microstructure of the composite could theoretically be determined by computing the material behaviour at a microscopic scale. However, for most of the applications where the model is considerably large, this approach would be computationally demanding.

Another approach is to introduce a link between the microscopic scale of the material to a macroscopic scale where the material can be seen as locally homogeneous. This link is made by introducing a representative volume, which needs to be sufficiently large to represent the heterogeneous microstructure of the material and small with respect to the total size of the body in consideration. This volume is denoted as Representative Volume Element (RVE) [23]. An illustration of the transition from a microscopic behaviour of a heterogeneous medium to the constitutive macroscopic response of the RVE where the medium can be seen as locally homogeneous is illustrated in Figure 4.4.

![Figure 4.4: Transition of the material behaviour at microscopic scale (upper left) to equivalent behaviour at macroscopic scale (upper right) using RVE. Figure taken from [23]](image)

Gudmundson [25] describes the theoretical approach of the RVE by introducing volume averages of the stresses and strains. To describe the stresses and strains at both the micro- and macro-structural scale a new denotation is used to distinguish between them. For local stresses and strains at the micro-structural level, the standard notation $\sigma_{ij}$ and $\epsilon_{ij}$ in tensor form is used. These stresses and strains normally vary within a RVE. For the macroscopic level the stresses and strains are denoted in tensor notation as $\Sigma_{ij}$ and $E_{ij}$.
4.5 Micro to Macro transition

In the interconnection between macroscopic and micro-structural properties, volume averages are normally introduced. The volume averages of the micro-structural stresses and strains are denoted as $\langle \sigma_{ij} \rangle$ and $\langle \epsilon_{ij} \rangle$ which are derived as

$$
\langle \sigma_{ij} \rangle = \frac{1}{V} \int_V \sigma_{ij} dV,
$$

$$
\langle \epsilon_{ij} \rangle = \frac{1}{V} \int_V \epsilon_{ij} dV,
$$

where $V$ is the volume over which the average is taken.

By definition the macroscopic stress, $\Sigma_{ij}$, and strain, $E_{ij}$, are constant within the RVE, which means the volume average for the RVE is equal to the the macroscopic stress and strain and can be evaluated as

$$
\langle \sigma_{ij} \rangle = \Sigma_{ij},
$$

$$
\langle \epsilon_{ij} \rangle = E_{ij},
$$

for any micro-structural stress, $\sigma_{ij}$, and strain, $\epsilon_{ij}$, field that satisfies equilibrium and the boundary condition on the boundary of the RVE. The relations in Equation 4.5 is used for formulation of different homogenization methods.

To derive homogenization methods the Hill’s theorem is can be used. The theorem is based on the consideration of volume averages of energy expressions denoted as $\langle \sigma_{ij} \epsilon_{ij} \rangle$. The theorem states that for certain conditions, the average of a product of this type is the product of the representative averages. Thus for a arbitrary stress field, $\sigma_{ij}$, that satisfy boundary conditions corresponding to a constant macroscopic stress field, $\Sigma_{ij}$, or if a arbitrary strain, $\epsilon'_{ij}$, satisfy the boundary conditions corresponding to a constant macroscopic strain field, $E_{ij}$, the energy expression can be described as [25]

$$
\langle \sigma_{ij} \epsilon'_{ij} \rangle = \langle \sigma_{ij} \rangle \langle \epsilon'_{ij} \rangle.
$$

This is known as the Hill-Mandell condition, and is a useful condition for the derivation of homogenization methods from different formulations [23].

4.6 Digimat

To be able to compute the material behaviour of a heterogeneous composite with two or more constituents, the anisotropic behaviour of the material needs to be derived. This is the fundamental problem of homogenization, to find an equivalent homogeneous material which has the same macroscopic behaviour as the heterogeneous composite, for the same boundary conditions. To address this problem Digimat has focused on developing two approaches, direct finite element analysis and Mean-Field Homogenization (MFH). The different methods have both advantages and disadvantages that needs to be taken into account when choosing a suitable one for a specific problem.

The direct finite element analysis is very general and accurate, and gives detailed micro stress and strain fields. However, the drawbacks of using this method for
realistic micro-structures are substantial in terms of computational time. The other method, MFH, is based on semi-analytical models and its main advantages is the simplification to use, low computational time and reduced memory usage. The main disadvantage is that it only gives approximations of the volume average of stresses and strains [23]. For this analysis the method of interest is the usage of the MFH to address its capabilities to model the heterogeneous microstructure of composites.

A concise description of the different steps that Digimat makes to be able to model the complex behaviour of the composite and how the fatigue life is determined is discussed in the sections below.

4.6.1 Homogenization

To determine the transition between the microscopic and macroscopic scale of a composite, Digimat uses the RVE described in Section 4.4. At the macroscopic level each material point is the centre of an RVE, at the microscopic level the RVE needs to have a volume allowing it to contain a sufficiently number of short fibres to be able to give a adequate macroscopic response [23]. The transition is made by adopting homogenization methods that fulfils the Hill-Mandel condition described in Equation 4.6 in Section 4.5.

The constitutive properties of the composite at macroscopic scale is represented using a MFH of the RVE microstructure. The purpose of the MFH is to be able to compute a approximate but accurate homogeneous material with the a corresponding stiffness to the actual microstructure.

There are different MFH methods, all based on specific assumptions of the microscopic behaviour. For this analysis the MFH method utilised is the Mori-Tanaka model. The model is derived based on the assumption that the each inclusion behaves as if it was isolated in the matrix resin. In Figure 4.5 an illustration of the Mori-Tanaka model is shown.

\[ \text{E} \]

\[ \langle \varepsilon \rangle \hat{\omega}_0 \]

\[ \text{M-Tscheme} \]

\[ \text{Homogenization} \]

\[ \langle \varepsilon \rangle \omega_0 \]

**Figure 4.5:** Illustration of the Mori-Tanaka model. Figure from [23]
The RVE is then treated as a single inclusion problem subjected to the volume average strain in the matrix constituent. The assumptions makes the model very efficient at predicting the material behaviour of composites with a fibre volume fraction up to approximately 25%. However, it has been proven to give good predictions well beyond that limit.

For the MFH procedure of an SFRP, the homogenization is made by introducing the concept of pseudo-grain, where the fibre orientation distribution of the RVE is decomposed into grains with unidirectional fibre alignment, an illustration of the concept of pseudo-grains is shown in Figure 4.6.

Each pseudo-grain represents a unique segment of the space, equivalent to one angular increment. So every pseudo-grain expresses a different state of orientation. The number of angular increments allowed ranges from 6 to 16. Digimat suggests the usage of 12 increments to get a good compromise between accuracy and computation time. Unless the fibre are randomly distributed, in which case all pseudo-grains are of equal importance, the pseudo-grains with the corresponding orientations are more important than the others. For a injection moulded component where the fibre alignment is highly dependent on the flow of the injection the pseudo-grains with the corresponding alignment is of importance. To account for this each pseudo-grain is assigned different weighting factors, where the weighting is greater for pseudo-grains oriented in the direction corresponding to the fibre alignment, estimated from orientation tensor. From this all the pseudo-grains together reconstitute the RVE and gives a realistic representation of the orientation of fibres.

The homogenization of the unidirectional pseudo-grains is then made by first using the Mori-Tanaka model, where each pseudo-grain is homogenized separately. Then all the pseudo-grains are homogenized with each other using Voigt model which assumes that the macroscopic stiffness is equal to the volume average of the microscopic stiffness. The assumption made in Voigt model makes it inappropriate for a real composite, but for a decomposed RVE into aggregates of pseudo-grains it has been shown to give a good prediction of the material behaviour of a composite, especially for composites containing only one type of inclusions.
Chapter 4. Material Behaviour of SFRP

The principle of the two-step homogenization procedure is shown in Figure 4.7.

4.6.2 Pseudo-Grain Fatigue Criteria

For the pseudo-grain HCF model, the mechanical behaviour is modelled as an oscillating stress state between the imposed maximum and minimum stresses $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$. Simultaneously, the material strength deteriorates so that failure is reached after a critical number of cycles [23]. The approach is illustrated in Figure 4.8.
For the imposed macroscopic stress state from the cyclic loading, the indicator for fatigue failure determined by the following operations. The strain state corresponding to the cyclic load is computed by the homogenization procedure described in Section 4.6.1. The stresses in the pseudo grains are computed according to the Voigt model, which makes the assumption that the strain throughout the composite is uniform [26].

The failure of the composite is determined using the Tsai-Hill 3D transversely isotropic criterion. Alsteens [27] discuss the accuracy of the simulation of Multi-Phase materials together with the implementation of the modified Tsai-Hill failure criterion. The usage of the Tsai-Hill criteria implies the assumption of uniformly aligned fibres in the composite which is contradictory to the misalignment of fibres that characterises a SFRP. This problem is solved by applying the criteria at a pseudo-grain level. The criteria are also modified to be transversely isotropic, where the failure parameters are the axial strength, the transverse strength and the in-plane strength of the composite. These strength parameters can also be replaced by a strength dependency assignment, where the dependency parameter is the critical number of cycles $N_c$ and the dependency relationship is described by a piece-wise log-linear function (S-N curve) [23]. These functions are determined experiments on specimens taken out of injected plates with different orientations, typically $0^\circ$, $90^\circ$ and some intermediate angle around $30^\circ$ – $45^\circ$. The angle is in relation to the direction of the injection flow. The basic principle of the reverse engineering procedure used by Digimat to obtain the strength parameters for the fatigue failure criteria is shown in Figure 4.9.
Alsteen further describes the strength of the model to its ability to provide accurate failure prediction. The limitation of the model is the inability to show any difference between the different failure mechanisms [27]. The Tsai-Hill 3D transversely isotropic criteria is derived in Digimat [23] for the failure indicator $F$ as

$$F(N) = \frac{\sigma_L^2}{S_L^2(N)} - \frac{\sigma_T1 + \sigma_T2}{S_T^2(N)} + \frac{\sigma_L^2 + \sigma_T^2}{S_T^2(N)} + \left( \frac{1}{S_L^2(N)} - \frac{2}{S_T^2(N)} \right) \sigma_{T1} \sigma_{T2}$$

$$+ \frac{\sigma_{LT1}^2 + \sigma_{LT2}^2}{S_{LT}^2(N)} + \left( \frac{4}{S_T^2(N)} - \frac{1}{S_T^2(N)} \right) \sigma_{TT}^2,$$

(4.7)

where $\sigma_L$, $\sigma_{T1}$ and $\sigma_{T2}$ denotes the longitudinal and the two transverse stress amplitudes. $\sigma_{LT1}$ and $\sigma_{LT2}$ are the shear stress amplitudes, in between the longitudinal direction and the transverse directions, and $\sigma_{TT}$ is the shear stress amplitude in the plane normal to the longitudinal direction. $S_L$, $S_T$ and $S_{LT}$ is the longitudinal, transverse and shear stress amplitude at failure (in other words the fatigue strengths) corresponding to the S-N curves for the critical number of cycles, $N_c$, of unidirectional composites.

At the macroscopic level of the composite, the average failure indicator $F_{avg}$ is computed for the number of cycles estimate. The average is derived according to the pseudo-grain weights, $w$, corresponding to the decomposition of the pseudo-grain equivalent to the orientation tensor considered as

$$F_{avg}(N) = \sum_{i=1}^{n} w_i F_i(N).$$

(4.8)

The critical number of cycles $N_c$ is then determined by varying the number of cycles $N$ until $F_{avg}(N) = 1$ [23].

To account for the influence on the material strength of an composite due to the mean stress which may make it vary, due to creep or compressive effects, an mean stress sensitivity can be used in Digimat. The mean stress sensitivity is defined in a Constant Life Diagram (CLD) representative for the behaviour of a unidirectional composite, an example of a CLD for a glass fibre reinforced polyamide is shown in Figure 4.10. These diagrams contains the same information as several S-N curves at constant load ratios.
The mean stress sensitivity is accounted in the failure indicator $F$ described in Equation 4.7 by adding a dependency on the fatigue strength parameters, $S_{ij}$ from the load ratio $R$ at the pseudo-grain level. The dependency is added to the failure indicator by a stress amplitude multiplier, $\mu(R)$, uncoupled from the dependencies on the number of cycles, $N$, for a reference load ratio $R_{\text{ref}}$ as

$$S_{ij}(N, R) = \mu(R)S(N, R_{\text{ref}}). \quad (4.9)$$

The stress amplitude multiplier, $\mu(R)$, is determined from the chosen CLD type. Digimat offers the option to choose between different simplified CLD types, for this analysis the linear symmetric CLD is the one utilized. The linear symmetric CLD exhibits two regimes [23]:

- a linear decrease of the stress amplitude with the mean stress with a constant negative slope when $R$ increases from a given value (at maximum stress amplitude) towards 1
- and a symmetric evolution with the mean stress outside this $R$ interval.

To determine the linear decrease of the stress amplitude and the symmetric evolution for the mean stress sensitivity analysis, experiments needs to be conducted for different load ratios $R$ to be able to estimate the needed parameters. Digimat recommends at least 3 different experiments with varying load ratios $R$ to get a good approximation of the mean stress effect on the material behaviour and thereby determine the CLD [23].
Chapter 5

Experimental Setup

Experiments were performed to get a reference to the results obtained from the fatigue analysis. The different load cases used for the experiments was determined as a trade-off between being a good approximation of the real-life load case and the functionality of the test rig setup. The fatigue experiment procedure was determined empirically from performed static failure experiments, pure alternating and pulsating fatigue experiments together with the information gathered in Section 2.3. The number of experiments was limited by the number of test specimen provided by Scania, which was 14 specimens. To keep track on each specimen they received an individual numbering denoted as ÅF nr: 1-14.

The static failure experiments and pure alternating fatigue experiments brought to light the anisotropic behaviour of the composite since the component showed a non-linear behaviour for different load cases. To be able to perform simulations of this behaviour a non-linear analysis using contact would be needed. In order to keep the simulations practical towards the limitations of computational capacity and since the goal of the experiments is to test the fatigue of the material and not how the contact influences, a linear analysis is preferred. From this mindset of keeping the simulations efficient, the fatigue experiments were chosen to focus on the pulsating fatigue experiments for correlation to the simulations. The test rig, static failure and pulsating fatigue experiments are briefly described in Section 5.1-5.3.

The complete experimental procedure can be read in test report 6176059:01 [28], which is archived by both ÅF Test Center and RCCC at Scania CV.

5.1 Test Setup

The test rig was specially made for the plastic front bracket considered to be capable of rearranging the front bracket for the different load cases. In Figure 5.1 the front bracket is shown mounted to the test rig [28].
5.2 Static Failure Experiments

The rig was assembled by the components described below:

- A load frame made by bolt joined aluminium profiles.
- A servo-hydraulic cylinder with an externally mounted position sensor mounted to the load frame.
- A load cell mounted to the cylinder rod.
- A mount rig specially made by ÅF Test Center for the front bracket to allow different load cases for both directions of the hydraulic cylinder.
- A load transferring part which connects with the original bolt from the front bracket.

The complete assembly of the test rig with the front bracket mounted is shown in Figure A.1 attached in Appendix A.

5.2 Static Failure Experiments

The static failure experiments were conducted with displacement as the control mode. The imposed displacement was set to 0.05 mm/s for all static failure experiments and the reaction force was documented. The experiment environment was taken into consideration but not altered, the room temperature was assumed to be constant at 25 °C and the average relative humidity (RH) for the whole duration of the experiments was retrieved and calculated from the data measured from the local weather station to approximately 93.9% which were read postliminary.
Three different test specimens (ÅF nr: 01 - 03) were tested for four different load cases. For all load cases, the bolts connecting the test specimen to the load transferring part are not tightened except to avoid a gap in between to avoid any pretension as shown in Figure 5.2 [28].

![Figure 5.2: Illustration of connection between load transferring part and front bracket using the original bolt](image)

Test specimen 01 - 02 was tested for each ear individually. The load was applied in the outward axial and downward radial direction according to the hole in the ear for test specimen 01. For test specimen 02, the load was applied in the outward axial direction for one ear and the upward radial direction for the other. For test specimen 03 both ears were connected with a loosely fitted bolt. The load was then applied in the bolt in the downwards radial direction.

The load directions and corresponding mountings of test specimen 01 loaded in each ear individually and test specimen 03 loaded in the bolt connected to both ears is illustrated in Figure 5.3 - 5.5 [28].

![Figure 5.3: Outward axial load direction and corresponding mounting for static failure experiment of test specimen 01 loaded in one ear](image)
5.3 Pulsating Fatigue Experiments

For the pulsating fatigue experiments, a sinus-shaped pulsating load was applied. The experiments were conducted with load as the control mode. Eight different test specimens (ÅF nr: 07 - 14) were used for different loads. The force from the
hydraulic cylinder was loaded in both ears in the downward radial direction. The load direction and corresponding mounting of the test specimens for the pulsating fatigue experiments is illustrated in Figure 5.6.

The experiment was conducted by cyclically loading the test specimen until the predetermined load limit and measuring the increasing deformation compared to the initial one, which is equivalent to a decrease in stiffness of the test specimen. To avoid any unwanted gap between the load bearing part and connecting bolt the test specimen was set with a pretension of 10 N in the load direction illustrated in Figure 5.6. The load ratio for all pulsating fatigue experiments is lower than 0.1.

The criterion used by Scania’s fatigue experiments is visible crack initiation. However, since the ability to notice a visible during fatigue experiments is very limited a sub-criterion used is the stiffness decrease of the test specimen. From these criteria, the experiments were initially set to be terminated if a 10% decrease in stiffness of the test specimen was registered and an initial crack was visible. As the experiments progressed the number of cycles and temperature of the test specimen was registered. The frequency of the experiments was initially set at 1 Hz to avoid the hysteric heating phenomena described in Section 2.3.1. The test frequency was increased for lower load levels while inspecting the temperature change in the test specimen. The experiment environment was taken into consideration but not altered, the room temperature was assumed to be constant at 25 °C and the average relative humidity (RH) for the whole duration of the experiments was retrieved and calculated from the data measured from the local weather station to approximately 93.9% which were read postliminary. The influence of the relative humidity on the fatigue experiments although important in its own right, was not taken into account since the relative humidity surrounding the component in real life application is not controlled during its lifetime.

The procedure of the pulsating fatigue experiment was conducted accordingly:

1. If the position of the piston rod exceeded predetermined limits, individual for each experiment, the experiment stopped.
2. If the deformation increased by 10% from the initial deformation, the experiment stopped.
3. If a temperature rise in the test specimen reached 5 °C above the room temperature, the test frequency was lowered.
4. If the number of cycles exceeded $2 \cdot 10^5$ cycles, the experiment stopped.
5. If a 10% increase from the initial deformation was reached but without any crack initiation, the number of cycles was registered and the experiment continued with increased allowed deformation by a step of 5% until crack initiation is visible.
5.3. Pulsating Fatigue Experiments

**Figure 5.6**: Pulsating load direction and corresponding mounting for fatigue experiments of test specimen 07-14
Chapter 6

Finite Element Modelling

6.1 Simulation Setup

From the performed experiments the simulation analysis is set up to represent the pulsating fatigue experiments described in Section 5.3. The front bracket was modelled using ANSA 18.1.4 for the structural analysis in Abaqus 2017. Due to the complex geometry of the front bracket and to capture the local material properties from the injection moulding simulation, solid quadratic tetrahedral elements denoted as C3D10I is used for the analysis. The size of the elements was initially set as 1 mm according to a batch mesh provided by RCCC. The elements are locally refined at the locations of interest and set to be coarser away from them.

The boundary conditions for the simulations are modelled to replicate the mounting of the pulsating fatigue experiments illustrated by Figure 5.6 in Section 5.3. The bolts fastening the front bracket to the test rig is modelled as four separate distributed couplings. The coupling master nodes are fixed in translation for x-, y- and z-direction. For the plate in contact with the front bracket, another distributed coupling corresponding to the contact area between them both is set. The master node of this coupling is set to be fixed in the surface plane.

The load transferring bolt was modelled by beam elements of type B31 with material properties corresponding to generic steel. The beam elements were then connected to the holes of the front bracket by creating two master nodes from distributed couplings of the nodes carrying the load corresponding to the pulsating fatigue experiments (bottom half of the hole nodes). To avoid transferring any axial load from the bolt a sliding connection is set between one of the master nodes and the beam element node using a connector element of type CONN3D2. The other master node was set to not transfer any bending moments. Thus only load is transferred to the component, not any moments. The FE model is shown in Figure 6.1 and 6.2 with distributed couplings, connected beam elements and load direction corresponding to the pulsating fatigue experiments.
These boundary conditions are linear simplifications to avoid convergence problems during the coupled structural analysis and to be efficient due to the limitations of computational capacity.
6.2 Digimat Coupling

To perform the coupled static analysis between Digimat 2019 and Abaqus 2017, the required parameters needs to be defined. The implementation of the parameters is done in the Digimat-CAE module by first defining the static and fatigue material parameters for the composite using Digimat-MF. This procedure only needs to be done once for each specific material. The fibre orientation estimated from the injection moulding simulation is then mapped to the structural analysis using the Digimat-MAP module. The resulting orientation file from Digimat-MAP is then implemented together with the elastic material model defined in Digimat-MF into Digimat-CAE. The implementation of the material parameters and injection moulding simulation into the Digimat-MF and Digimat-MAP module is described in Section 6.2.1 - 6.2.2 and Section 6.2.3.

The Digimat-CAE then transfers the anisotropic material parameters to the structural analysis. The option of multi-scale solution type is defined in Digimat-CAE where Digimat has the capability to perform three types of solutions, the Micro-, Hybrid- and Macro solution. The Micro solution uses a strong multi-scale coupling while the Hybrid- and Macro solution uses a weak multi-scale coupling. The Hybrid solution was created to offer a significant CPU speedup and robustness for coupled analysis [23]. The Hybrid solution pre-computes macroscopic material properties corresponding to different fibre orientations which are then used in order to communicate with the structural analysis of the overall computation. The Hybrid solution is the recommended solution to use for analysis of SFRP components due to its optimisation of CPU time and results with the same accuracy as the Micro solution. However, for fatigue analysis with an elastic material model the Hybrid solution does not bring that much of advantages. The Micro solution, which computes the material properties and communicates with the structural analysis for each iteration of the overall computation, is therefore recommended for coupled fatigue analysis since it allows for microscopic outputs, such as orientation tensors, which are needed for the fatigue analysis.

From the Digimat-CAE module interface files are generated which are implemented into the Abaqus input file, making the coupling between the two software possible during the analysis. The defined material properties in Digimat is then assigned to each separate volume element. Abaqus then interacts with Digimat to determine the macroscopic stress for each integration point of all volume elements. For each iteration, Digimat assess the macroscopic response using the Mori-Tanaka MFH model described in Section 4.6.1. The results from the coupled FE analysis are then stored as an Abaqus Output Database file containing the macroscopic stress and strain response, together with the fibre orientations.

6.2.1 Material Data

To be able to conduct the coupled FE analysis the material data for the specific composite needs to be implemented into the Digimat-MF module. The matrix and fibre are first defined by their separate material properties in the form of density, Young’s modulus and Poisson’s ratio. The microstructure then needs to be fully defined by putting in the quantities that define the fibre dimensions, the mass fraction, aspect ratio together with the fibre orientations. The fibre orientations are usually defined.
from a CT-scan of the composite made by the material supplier providing the material data.

The material of the front bracket considered is Scanamid 66 A123F30, which is a SFRP with a matrix of polyamide PA66, reinforced by glass fibres with a mass fraction of 30%. However, due to the restriction of available material data from this specific plastic, the material used in the simulation is Zytel 70G30HSLR BK099 which has the same constituents and assumed equivalent material attributes. The material is determined from experiments performed by DuPont Performance Materials and has been tested under the condition of the experiment environment where the temperature was 23°C and the relative humidity RH kept at 50%.

Due to confidentiality restrictions, the material properties of the constituents are classified. However, the second-order orientation tensor \( a_{ij} \) described in Equation 4.3 is determined as

\[
a_{ij} = \begin{bmatrix}
0.85 & 0 & 0 \\
0.12 & 0 & \text{SYM} \\
\text{SYM} & 0.03 &
\end{bmatrix}.
\]

From the determined orientation tensor the majority of the fibres are aligned in the first principal direction corresponding to the orientation tensor component \( a_{11} \) while being oriented slightly random in the two other principal directions.

To optimise the material chosen for the FE analysis according to the results from the performed static failure experiment, for the load case described in Section 5.2 and illustrated in Figure 5.5, the aspect ratio was calibrated so the stiffness of the simulation resembled the stiffness collected from the experiment. The aspect ratio was then determined from the calibration to 11, the resulting material behaviour for different fibre orientations is illustrated in Figure 6.3 as a stress-strain diagram for the first principal direction 11 with the stress normalised.
6.2.2 Fatigue Data

To conduct a coupled HCF fatigue analysis using the Pseudo-Grain Fatigue Criteria, as described in Section 4.6.2, experimental data in the form of S-N curves for unidirectional composites with different loading angles needs to be defined as a fatigue failure indicator in Digimat-MF. For an injection moulded SFRP, unidirectional composites with perfect fibre alignment are unattainable due to the complexity that follows with the injection flow of short fibres. To estimate S-N curves for the SFRP composites Digimat uses a reverse engineering procedure from S-N curves obtained from fatigue experiments on dumbbells with fibres oriented in different angles according to the applied load as shown in Figure 4.9. Due to the limitation of experimental data for fatigue for the plastic PA66GF30 considered, the only available data was for a plastic PA66GF50 from Dupont Performance Materials named 70G50HSLA BK039B. This plastic shares the same constituents, as the material described in Section 6.2.1, apart from the weight fraction of glass fibres which for this plastic is 50%.

The fatigue data given as three different S-N curves is based on fatigue experiments performed with a load ratio $R = 0.1$. The exact procedure for the fatigue experiments is not explicitly explained but assumed to have been performed on tensile test specimen with geometry according to standard ISO 527-1A or ISO 8256-3 with a cyclic loading applied. The condition of the experiments are stated to have been conducted at a temperature of 23°C and relative humidity (RH) of 50%.

Since the difference in weight fraction of fibres has a large impact on both the mechanical and fatigue properties of a SFRP composite the acquired S-N curves from the plastic containing 50% weight fraction of fibres cannot be directly used to simulate the fatigue response of a plastic with 30% weight fraction of fibres.
To determine corresponding S-N curves for a plastic with limited fatigue experiments performed, one method that has been proposed and used is to estimate the S-N curves by scaling them from a Master S-N curve. Jain, Verpoest, Hack, et al. proposed the method of scaling a master S-N curve achieved from fatigue experiments on specimens with random fibre orientation[14]. The basic assumption made behind this method is that the fatigue strength changes corresponding to the UTS. The S-N curves for the different fibre orientations needed to conduct simulations using Digimat can then be estimated by taking the ratio between the UTS of the specimens used for the master S-N curves and the UTS from the specimen with fibres oriented in the longitudinal and transverse direction according to the load.

To estimate the fatigue curves corresponding to the material PA66GF30 the assumption is made that the difference between the UTS for a plastic with a weight fraction of 50% and a weight fraction of 30% is the same as the difference between the fatigue strengths between the two different weight fractions. However, since an increase of weight fraction of fibres leads to a substantial increase of anisotropy in the composite, to directly scale each S-N curve according to a composite with a larger anisotropic behaviour would lead to a bad characterisation of the real behaviour of the composite. To achieve a good characterisation the assumption was made that the S-N curves corresponding to fibres oriented 45 degrees and transverse according to the load direction is approximately unchanged for a difference in weight fraction of fibres, this implies that the only S-N curve that is scaled according to the UTS is for the one with fibres aligned to the loading. The estimated ratio of UTS used for the scaling of the S-N curve for aligned fibre orientation was determined from the theoretical properties given in Table 4.1 to 0.857.

The S-N curves for PA66GF50 together with the estimated S-N curve for PA66GF30 reduced by the ratio of UTS (blue dashed line) is shown in Figure 6.4 with normalised amplitude stress.

![Figure 6.4: Normalised S-N curves from experiments of PA66GF50 with a load ratio $R$ equal to 0.1 and estimated S-N curve for PA66GF30 using the ratio of UTS for the strongest direction of the composite.](image-url)
6.2.3 Injection Moulding Simulation

From the injection moulding simulation provided by the material experts at Scania, an estimation of the fibre orientations and position of weld lines is obtained. The estimated first principal orientation tensor $a_{11}$ from the moulding simulation is illustrated in Figure 6.5. In Appendix C the estimation of the other main principal orientation tensor $a_{ij}$ is displayed in Figure C.1 - C.2.

From the injection moulding simulation, the fibre orientations are then mapped onto the structural mesh using the Digimat-MAP module. The data required from the moulding simulation is mapped by taking the information from the integration point/Node of the injection simulation to the integration point of the structural mesh. This method is the default option in the mapping process for Digimat. From the mapping onto the structural mesh the resulting first principal orientation tensor $a_{11}$ and the eigenvectors of the first principal fibre direction is illustrated in Figure 6.6 and Figure 6.7.
6.2. Digimat Coupling

**Figure 6.6:** Estimated principal orientation tensor $a_{11}$ from the mapping performed in Digimat.

**Figure 6.7:** Eigenvectors of the first principal fibre direction obtained from the injection moulding simulation mapped onto the structural mesh. A higher value (red) indicates that the fibres are locally aligned, whereas for lower values (blue), the fibres are more locally random oriented.
From the moulding simulation, the position of weld lines during the injection moulding process is estimated and illustrated in Figure 6.8.

![Image of estimated weld lines](image_url)

**Figure 6.8: Estimated position of weld lines**

Weld lines are only shown for reference and not taken into account in the simulations. Furthermore, the estimated position of weld lines is far from the regions where fatigue cracks appear.

The mean stress sensitivity illustrated in Figure 4.10 and described in Section 4.6.2 can be implemented to the material in the Digimat-MF module by adding experimental data for three different load ratios to estimate the slope for the positive mean stresses. However, for this thesis the fatigue data is restricted to only material data tested for a load ratio $R$ of 0.1 and will be neglected from the analysis.

### 6.3 Fatigue Analysis

To perform the fatigue analysis in nCode DesignLife V18.0.0, the results from a static FE analysis is needed, such as the Abaqus Output Database retrieved from the coupled FE analysis. The results from the static analysis are then imported into nCode DesignLife V18.0.0 where cyclic loading with a constant amplitude is defined.

To estimate the fatigue life of a SFRP composite, where the fatigue strength varies across the component depending on the fibre orientation, a local S-N curve is retrieved from Digimat for each fatigue calculation. The local S-N curve is estimated in Digimat based on the local fibre orientation tensor and the stress direction or stress state.

From this procedure, each fatigue calculation is provided by Digimat with a potentially unique S-N curve based on the experimental data shown in Figure 6.4. The
experimental data is used as a set of data where point between are estimated using logarithmic interpolation.

The fatigue analysis then uses the stress tensor history from the FE analysis to retrieve an equivalent amplitude stress which is cycle counted and compare to the estimated local S-N curve to determine the fatigue life. To make this calculation the stress tensor needs to be reduced to a scalar value which can be set as the amplitude stress. This equivalent scalar is defined by the *Absolute Maximum Principal* method, thus defined as the principal stress with the largest magnitude.

A measure of the fibre orientation in the loading direction used in nCode DesignLife V18.0.0 is the *fibre share* $\lambda$ which is a measure of the fibre alignment in the loading direction, where a value of 1 indicates perfect alignment with the dominant stress direction [29]. The fibre share $\lambda$ is derived as

$$
\lambda = l_i a_{ij} l_i^T, \tag{6.1}
$$

where $l_i$ is a vector in the direction of the dominant principal stress direction and $a_{ij}$ the orientation tensor derived in Equation 4.3.

The load ratio is then defined in nCode DesignLife V18.0.0 as $R = 0$ to follow the experiments where the load control was set as $R<0.1$ for all experiments. Since the restriction of fatigue data makes the mean stress sensitivity unattainable the fatigue data attained from experiments performed at a load ratio of $R = 0.1$ is assumed to be adequate to the load ratio used for the experiments.
Chapter 7

Results

7.1 Result From Experiments

The results from the static failure experiments described in Section 5.2 for load applied in the axial and radial direction are shown in Figure 7.1, Figure 7.2 and summarised in Table B.1 attached in Appendix B. The dashed lines illustrates the stiffness from each experiment.

Figure 7.1: Force vs displacement for load in the axial direction
7.1. Result From Experiments

The pulsating fatigue experiments were then performed for the downward radial load applied to the bolt connecting both ears with the corresponding mounting, as described in Section 5.3. The corresponding force to displacement is illustrated in Figure 7.3 with the fatigue load range marked. The fatigue load range for the pulsating fatigue experiments was in the range of 600 - 1000 N.

The resulting fatigue life from the pulsating fatigue experiments are shown in Figure 7.4 and summarised in Table B.2 attached in Appendix B. In Figure B.1-B.3 attached in Appendix B the placement of noticed crack initiation is illustrated for test specimen 07, 12 and 14. For all test specimen (ÅF nr: 07-14) except test specimen 11,
and 14 the position of crack initiation was noticed at the predicted location, on one of the large fillets of the front bracket. For specimen 11 the test was a run-out and stopped after $< 10^6$ cycles, for specimen 14 the position of crack initiation deviated from the predicted location.

![Figure 7.4: Force vs number of cycles for crack initiation and stiffness loss](image)

The fitted curves in Figure 7.4 for 10% stiffness loss and crack initiation are fitted to the relevant experimental result, excluding the results for test specimen 11 and 14.

### 7.2 Simulation Results

From the coupled static analysis using Digimat the stiffness is determined for the load case corresponding to the experiment of test specimen 03 loaded in the bolt connected to both ears, as shown in Figure 5.5, to 378.4 N/mm compared to the measured one from the experiment of 380.9 N/mm as shown in the force vs displacement curve illustrated in Figure 7.5.
7.2. Simulation Results

**Figure 7.5:** Force vs displacement for load in the axial direction from experiments and simulations

An overview of the resulting stress field from the static analysis and positions with high values (denoted as A-D) is shown in Figure 7.6 as combined absolute maximum principal stress in each element for a load level of 500 N.

**Figure 7.6:** Combined absolute maximum principal stress for a load of 500 N with maximum value of each element. Positions of high values denoted as A-D

The positions of high combined principal stresses correspond to the estimated position for initial fatigue failure in the fillets (A and B) but also in the ribs connected to the bolt holes (C and D) determined from the experiments, as shown in...
Figure B.1 and Figure B.3 attached in Appendix B. Close-ups of the combined absolute maximum principal stress field at the fillets (A and B) and ribs (C and D) is shown in Figure 7.7 and Figure 7.8 with the maximum value displayed for the corresponding elements.

**Figure 7.7:** Combined absolute maximum principal stress field at the estimated positions for initial fatigue failure in the fillets, for a applied load of 500 N. The maximum value and its corresponding element is displayed. Left image: left fillet (A). Right image: right fillet (B)

**Figure 7.8:** Combined absolute maximum principal stress field at the ribs, for a applied load of 500 N. The maximum value and its corresponding element is displayed. Left image: left rib (C). Right image: right rib (D)
From the coupled static analysis the fibre share described in Equation 6.1 estimated from the dominant stress direction and orientation tensor is illustrated for the positions of interest in Figure 7.9 and Figure 7.10 with the value displayed for the corresponding elements to the maximum stress.

**Figure 7.9:** Derived fibre share at the estimated positions for initial fatigue failure in the fillets, displaying the alignment between the fibre orientation and dominant stress direction. The value of the fibre share is displayed for the elements corresponding to the maximum stress. Left image: left fillet (A). Right image: right fillet (B)

**Figure 7.10:** Derived fibre share at the ribs, displaying the alignment between the fibre orientation and dominant stress direction. The value of the fibre share is displayed for the elements corresponding to the maximum stress. Left image: left rib (C). Right image: right rib (D)
From the result of the structural analysis the fatigue life of the component is predicted from nCode DesignLife V18.0.0 for the positions of interest. The resulting fatigue life for a load of 500 N and a load ratio of $R = 0$ at the positions of interest (A-D) can be seen in Figure 7.11 and 7.12 with the shortest life displayed for the corresponding elements.

**Figure 7.11**: Predicted fatigue life given as number of cycles until failure, at the estimated positions for initial fatigue failure in the fillets. With the shortest fatigue life displayed for the corresponding elements. Left image: left fillet (A). Right image: right fillet (B)

**Figure 7.12**: Predicted fatigue life given as number of cycles until failure, at the estimated positions for initial fatigue failure in the fillets. With the shortest fatigue life displayed for the corresponding elements. Left image: left rib (C). Right image: right rib (D)
7.2. Simulation Results

In Table 7.1 the result from the element with the shortest life at the positions of interest (A-D) is shown for a load of 500 N with the corresponding absolute maximum principal stress and fibre share.

**Table 7.1: Result from elements with shortest life at the positions of interest in the fillets (A-B) and ribs (C-D) for a load of 500 N**

<table>
<thead>
<tr>
<th>Position</th>
<th>Maximum principal stress [MPa]</th>
<th>Fibre share [-]</th>
<th>Fatigue life [Cycles]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left fillet (A)</td>
<td>76.5</td>
<td>0.790</td>
<td>1.37E+06</td>
</tr>
<tr>
<td>Right fillet (B)</td>
<td>85.2</td>
<td>0.817</td>
<td>334 400</td>
</tr>
<tr>
<td>Left rib (C)</td>
<td>94.0</td>
<td>0.456</td>
<td>38.7</td>
</tr>
<tr>
<td>Right rib (D)</td>
<td>93.0</td>
<td>0.437</td>
<td>31.3</td>
</tr>
</tbody>
</table>

From the result displayed in Table 7.1 the observation can be made that the element with the shortest fatigue life does not necessarily correspond to the highest stress level. The influence of the fibre share on the fatigue life can also be observed since the large difference in fatigue life between the fillets and ribs does not correspond to the difference in maximum principal stress between them.

The results from the performed fatigue analysis carried out in the post-processor nCode DesignLife V18.0.0 is shown for the element with the shortest life at the right fillet (B) and right rib (D) in Figure 7.13 as load to number of cycles and the corresponding combined absolute maximum principal stress to the number of cycles. The load level is displayed on the left y-axis and the stress level on the right axis.

**Figure 7.13: Load and stress to number of cycles for the elements with shortest life at the right fillet (B) and right rib (D). The left axis (blue) displays the load level applied and the right axis (orange) displays the corresponding combined absolute maximum principal stress**
7.3 Correlation

To correlate the experimental result to the simulation result the position of shortest fatigue life in the fillets (right fillet \(B\)) is investigated since the experiments were performed until a visible crack was noticed in that position. The simulated fatigue life using nCode DesignLife V18.0.0 and measured fatigue life from the experiments at the fillets for corresponding load level is shown in Figure 7.14.

From the correlation illustrated in Figure 7.14 it can be seen that the result from the fatigue analysis show a conservative fatigue life in comparison to the performed experiments for low number of cycles. For a larger number of cycles the result will be non-conservative but since the number of cycles considered as infinite life is over \(2E+05\) the fatigue analysis yields conservative life estimations for the region below this limit.

7.4 Mesh Dependency Study

To address the influence of the chosen mesh on the simulation result a mesh dependency study was carried out. The mesh was changed from the reference mesh used for the simulations in three different ways. The model was meshed using two different batch mesh files with a preset element size of 1 mm and 2 mm. The model was also locally refined from the reference mesh by dividing the element size in half. The variables checked for the study was the combined maximum principal stress, fatigue life and fibre share for the element showing the shortest fatigue life in the right fillet \(B\) for a load of 500 N to show the fluctuation caused by a change of mesh size. The different variables of interest together with the computational time for the static and fatigue analysis is displayed in Table 7.2 for the different mesh variants.
TABLE 7.2: Mesh dependency study of element with shortest life at the right fillet (B) for a load of 500 N

<table>
<thead>
<tr>
<th>Variables of interest</th>
<th>Local refinement</th>
<th>Reference mesh</th>
<th>Batch mesh 1 mm</th>
<th>Batch mesh 2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>element size</td>
<td>element size</td>
<td>element size</td>
<td>element size</td>
</tr>
<tr>
<td></td>
<td>0.2788 mm</td>
<td>0.653 mm</td>
<td>1.102 mm</td>
<td>1.630 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combined max principal stress [MPa]</th>
<th>87.0</th>
<th>85.2</th>
<th>72.7</th>
<th>67.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue life [Cycles]</td>
<td>1.02E+05</td>
<td>3.34E+05</td>
<td>5.99E+05</td>
<td>6.93E+07</td>
</tr>
<tr>
<td>Fibre share [-]</td>
<td>0.813</td>
<td>0.817</td>
<td>0.767</td>
<td>0.783</td>
</tr>
<tr>
<td>CPU time static [min:sec]</td>
<td>19:34</td>
<td>07:05</td>
<td>02:30</td>
<td>0:11</td>
</tr>
<tr>
<td>CPU time fatigue [min:sec]</td>
<td>36:26</td>
<td>15:23</td>
<td>03:51</td>
<td>0:27</td>
</tr>
</tbody>
</table>

From the variables illustrated in Table 7.2 the result of the mesh dependency study shows that for a smaller element size the solution converges and the reference mesh is assumed to be an adequate size to have a balance between good accuracy of the results and manageable computational time.
Chapter 8

Discussion

8.1 Experiments

From the experimental result presented in Figure 7.4 the different fatigue criteria shows a significant variation in the capability to predict the fatigue life of the component. For example, for the 10% stiffness decrease, there is no significant change in the number of cycles for some loads. This might be caused by the hysteric heating happening in the component which reduces the stiffness of the component before experiencing fatigue. Also, the fatigue criteria of crack initiation are highly dependent on the experience of the person performing the experiments and the method used for the detection of the initiation of crack. For this, the experiments should not only rely on the detection of an initial crack but be continued to a common stiffness reduction to get more data to analyse.

From the experiments the fatigue damage mechanism was not able to be determined. By checking the composite using a more advanced method than regular eyesight the different damage mechanisms could lead to a better understanding of the failure criteria to be used for the structural analysis and thereby improve the correlation.

Due to the restriction of available test specimens, the variability of the experiments could not be taken into account. To be able to determine the spread of the fatigue life estimation of the experiments a recommendation of at least three experiments for each load level is usually preferred to determine the statistical variability that may occur from the fluctuation of mechanical performance for different test specimens.

Since the front bracket component has a complex geometry the experiments become hard to perform without being influenced by factors that may lead to a misinterpretation of the results and thereby damage the accuracy of the correlation. A better correlation could be achieved by performing the experiments and simulations on a less complex geometry to avoid any unwanted geometric factors influencing the correlation results.

Due to the restriction of experimental equipment the only monitoring of the behaviour of the component was made by the externally mounted position sensor which monitored the displacement of the hydraulic cylinder. A improved way of monitoring the specimen deformation could have been to place extensometers on the positions of interest to measure the local strain during the whole experimental procedure. The local strain could be a better measurement method for correlation to the simulations.
Since the experiments performed for the alternating fatigue load showed a significant difference in stiffness between being loaded in a upward and downward direction the load ratio was set for a pure pulsating load to $R = 0$ in order to avoid the stiffness difference and to avoid a tension-compression loading. However, due to the shape of the geometry the applied load causes compression of the composite at different places which could lead to a locally unstable state for the fibres where they might experience a micro buckling type of failure. This could cause damage in the component that the fatigue analysis is not able to capture and thereby cause a larger difference between the results.

To better control the material behaviour of the SFRP composite the environmental factors needs to be controlled. To get a more accurate correlation between the simulations and experiments, parameters such as the ambient temperature and relative humidity needs to be replicated to each other. This in order to minimise the factors that may affect the correlations accuracy in a negative way.

The test specimen could no be checked for any initial defects that may occur during fabrication causing a deterioration of the fatigue performance of the specific specimen. This could be caused by a weaker interaction between the heated matrix resin and fibres causing a weaker composite than for other specimens. It could also be caused by damaging of the fibres during the manufacturing process, which could lead to a varying dimensions of the fibres distributed in the manufactured component.

To get a more straight forward correlation between experiments and fatigue analysis the influence of the geometry of the specimen needs to either be completely represented by the FE analysis or avoided during the experiment procedure to not influence the accuracy between both solutions. A simpler geometry like a dumbbell shaped specimen could lead to less influence of the geometry and a more straight forward transition of modelling the experimental procedure using FE analysis. This could also avoid any unwanted contact interaction happening during the experiments which may be difficult to model.

8.2 Simulations

Due to the recent update of Digimat the fatigue data retrieved from the material providers has not been calibrated for the 2019 version with the new updated features. The result could lead to a overestimation of the simulations of the fatigue life.

Since the only material model available for the coupled fatigue analysis is a linear elastic one, this simplification could lead to a misinterpretation of the real material behaviour and thereby influence the accuracy of the fatigue analysis. A more advanced material model could give a better approximation of the real-life behaviour and in theory capture the stiffness decrease caused by the fatigue phenomena.

Since the material data provided for the plastic front bracket component was insufficient for performing FE analysis coupled with Digimat the material used was taken from an available material model in Digimat with the same constituents.
However, the manufacturing process and mechanical properties of the constituents could differ between different manufacturers which could lead to a material model not corresponding to the actual material used for the front bracket and thereby contaminate the accuracy of the FE analysis. To be more certain of the similarity of the actual plastic behaviour and the one used for the simulations further information about parameters like the fibre dimensions, aspect ratio and fibre length, would strengthen the choice for a similar material by choosing one with the corresponding dimensions.

The response of a SFRP material is generally very strain rate dependent, which has not been taken into account. The material data is retrieved for the linear elastic material from static tensile experiments. The estimation of the UTS scaling used for the S-N curves, as described in Section 6.2.2, has a different strain rate than the fatigue experiments which are performed at a set or varying frequency which might lead to a difference in material behaviour between the static material data and the fatigue material data. This difference caused by the strain rate has not been taken into account but could diminish the accuracy of the UTS scaling assumptions credibility and thereby influence the accuracy of the fatigue analysis.

The reliability of the coupled FE analysis is highly dependent on the fibre distribution obtained from the injection moulding simulation. Depending on the local fibre alignment, the result from the static and fatigue analysis can vary significantly, which can be derived from the results displayed in Table 7.1, and needs to be performed in an accurate way to get a good fibre distribution estimation corresponding to the fibre alignment in the real-life SFRP component. Since the injection moulding simulation was provided the accuracy of it could not be evaluated. The mesh size used for the injection moulding simulation was assumed to be sufficiently small to capture the macroscopic behaviour of the SFRP composite. To be able to map the material behaviour from the injection moulding simulation the mesh of the structural analysis needs to be chosen so that the accurate amount of material data can be transferred to give a representing macroscopic material behaviour to the structural analysis.

From the injection moulding simulation the capability to estimate any occurring residual stresses is available but have not been investigated for this thesis. The residual stresses could have a significant effect on the life until fatigue failure. This could lead to a less accurate correlation.

The large difference in fatigue life between the positions in the fillets and ribs shown in Figure 7.13 could be caused by the local fibre alignment and affect the calculated fibre share and thereby affect the fatigue life estimation. This could be resulting from the actual local fibre alignment in the component or alternatively be caused by the injection moulding simulation giving a poor estimation of the actual fibre alignment.

To get a better optimisation of the material behaviour from experiments performed on dumbbell specimens, Digimat suggest importing the fibre alignment through the thickness which should be retrieved from a CT scan and imported into Digimat-MF. From this CT scan together with the material properties of the fibre and matrix constituents the RVE can be optimised to become even more accurate to the real life macroscopic behaviour.
8.2. Simulations

Since the influence of the mean stress could only be implemented to the material behaviour with more experiments, the influence could not be taken into account. However, for a SFRP composite which is highly influenced by the mean stress, the simulations could be suffering by the neglecting of the mean stress.

The difference in load ratios between the experiments and the fatigue material data could lead to a more non-conservative fatigue life estimations and the optimal would be to have the same load ratio for the fatigue material data and the experiments which could not be achieved for this thesis. If the usage of mean stress sensitivity could be performed the difference between the load ratios could be taken into account in the analysis.

Since the fatigue data was taken for a composite with 50% glass fibre, which has more anisotropy than a plastic with the same constituents but lesser amount of glass fibre, the accuracy of the fatigue analysis might be influenced. A better approximation could have been to use the fatigue data from a plastic with a different matrix but the same amount of glass fibres since the material behaviour for the different fibre alignments could be a better approximation to use for the UTS scaling.

To avoid the influence of high stress concentrations contaminating the fatigue life estimation, the local stress gradient could be taken into account to locate a stress concentration. For the current version of nCode DesignLife V18.0.0 the result imported from the structural analysis cannot include the stress gradients and thereby be taken into account. The constant amplitude fatigue post-processor implemented into Digimat has the option to use the stress gradient to average the lifetime estimation over several elements. However, the method is recently developed and have not been tested and proved accurate by the customers. In future versions of nCode DesignLife V18.0.0 the correction using stress gradients may be implemented.

Since the fatigue indicator used for the experiments is when crack initiation is noticed, the correlation to the fatigue analysis using the fatigue life of one single element may lead to a too conservative correlation, especially in regions with high stress gradient and a fine mesh. A balance between the reading of the results from the fatigue analysis and the fatigue indicator used for the experiments needs to set to avoid a poor quality correlation.

The difference in the slopes of the S-N curve illustrated in Figure 7.14 could be a result from the difference in amount of glass fibres between the plastic material used in the experiments and the plastic used in the simulations. The slope is highly connected to the material behaviour and to further test the correlation possibility between experiments and simulations the need for further simulations using fatigue data from the correct plastic sort could lead to a closer estimation of the slope. Even simulations performed with another plastic matrix resin with the same amount of glass fibre could lead to a better estimation of the slope attained from the experiments.

The strength of performing a coupled analysis with Digimat to estimate the anisotropic behaviour from the fibre orientations is that the advantages of using a anisotropic material can be taken into account in comparison to performing an analysis with a isotropic material model which does not show the difference in strength that occurs from the alignment of the fibres.
For a constant amplitude fatigue analysis the integrated fatigue post-processor in
Digimat 2019.0 should in theory have the capacity to perform the fatigue analysis
without the need for an external post-processor. However, due to the restriction of
the integrated fatigue post-processor to only carry out fatigue analysis for a load
ratio of $R = -1$ if not the mean stress sensitivity is used, the resulting fatigue life
is too conservative to be relevant for the correlation. If the mean stress sensitivity
is available or if the load ratio is equal to -1 the post-processor have three different
correction methods available which could lead to a better correlation to the experi-
mental results. The three correction methods are lifetime averaging, stress averaging
and stress gradient averaging. These have been implemented into Digimat 2019.0
and have not been fully tested by customers but should give the option to correct
positions with a high stress gradient and thereby yield more reasonable estimation
of the fatigue life.

By implementing the coupling between Digimat and Abaqus for the structural anal-
ysis to be able to run on a external server the computational capacity could be sig-
ificantly increased. This could make it possible to model the behaviour of the com-
ponent during the experiments in a more realistic way and thereby lead to a more
correct correlation between them.
Chapter 9

Conclusions

- The experimental result shows that the anisotropic behaviour of a SFRP composite has a large influence depending on the fibre alignment according to the load direction. The stiffness of the component can vary significantly in different directions and influence the validity of the experimental results. To avoid any negative external influence on the experiments many factors have to be taken into consideration.

- The result of the fatigue experiments is highly dependent of the chosen fatigue indicator and the accuracy of the measurement from this indicator. Also to take into account the mean stress influence, experiments needs to be performed for different load ratios.

- Due to the limitation of available test specimens the statistical scattering caused by difference between mechanical behaviour of the test specimens could not be captured. This damages the total accuracy of the experimental result and thereby also the accuracy of the correlation.

- From the simulation analysis, the influence of the local fibre alignment is highly noticeable on the resulting fatigue life and needs to be accurately performed in order to keep the credibility of the simulation results.

- For the restriction of available fatigue material data the UTS scaling method makes it possible to perform fatigue analysis without the exact fatigue data. However, due to the large difference in anisotropy between SFRP composites with different fibre weight fraction gives an uncertainty in the resulting fatigue life estimation. If available, the material data of a SFRP composite with the same amount of fibres but different matrix resin is to prefer for performing the fatigue analysis compared to a material model with the same constituents but with a different amount of fibres.

- The correlation of the fatigue life from the experimental results and the fatigue analysis shows that the estimation of the fatigue life is conservative compared to the measured one from the performed experiments for fatigue life up to 2E+05. However, the correlation between the experiments and fatigue analysis is not fully captured as can be seen by the difference in slopes for fatigue life illustrated in Figure 7.14. This difference in correlation is believed to be caused by the limitations of material data which makes the correlation not able to fully capture the correct material behaviour. However, the fatigue life estimation shows signs of predicting better correlation to the experimental results compared to the correlation that would be achieved by using previous fatigue life estimation performed on an isotropic material model.
• Digimat could be used with the load ratio set to $R = -1$ knowing that the result is conservative to other load ratios. Combining the conservative result with the lifetime averaging methods and comparing to failure in usage, the location for crack initiation can possibly be found.
Chapter 10

Future Work

To obtain a better correlation between physical experiments and fatigue analysis using simulations software, more accurate material modelling and experimental setup is needed. A better correlation could be obtained by performing the fatigue analysis on injection moulded dumbbells. The influence of the geometry could be minimised and thereby get more reliable experimental results to correlate to. This would also make the possibility of a more accurate calibration of the material model used in Digimat. By performing fatigue experiments on the dumbbells the unidirectional S-N curves could be predicted and used for future fatigue analysis. With the fatigue data of SFRP composites with different constituents and/or fibre amount the UTS scaling method could be further evaluated.

Also for the measuring of the mechanical behaviour during the failure and fatigue experiments locally placed strain gauges should be placed to get a more relevant measurement to correlate to the simulations. The local strain could be a better measurement for a SFRP composite than the local stress. Specific strain gauges for plastic components are available and should at least be taken into consideration for future experiments performed on SFRP components.

Since the assumption of scaling the fatigue data between composites with different amount of fibres leads to the problem of a large change in anisotropy to take into account. A correlation using a material model with a different matrix resin but the same fibre amount could lead to a more accurate estimation of the fatigue behaviour.

The current material data available in Digimat 2019.0 is being updated constantly to correspond to the new features developed. The material data providers is working on updating their current material database. To get fatigue data available for a larger range of simulations, future experiments should be performed for different load ratios to enable the mean stress influence and make simulations of different load ratios more accurate even though the material data might not have been determined for the equivalent load ratio.

The correction using stress gradients is not available for nCode DesignLife V18.0.0 but could be under development for future versions. For the fatigue post-processor implemented into Digimat 2019.0 the stress gradients can be taken into consideration but is restricted to a load ratio of $R = -1$ if not the mean stress sensitivity is used. The correction methods have been released recently and the future development of these method is of great interest to be able to perform more accurate fatigue analysis.
Bibliography


Appendix A

Test Setup

Figure A.1: Assembled test rig with description of each component
Appendix B

Experiment Result

The results from the static failure test are presented in Table B.1 as failure load, corresponding displacement and measured stiffness of test specimen ÅF nr: 01-03.

**Table B.1:** Tabulated results from the static failure test

<table>
<thead>
<tr>
<th>ÅF nr</th>
<th>Failure load [N]:</th>
<th>Displacement [mm]:</th>
<th>Stiffness [N/mm]:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radial</td>
<td>Axial</td>
<td>Radial</td>
</tr>
<tr>
<td>01</td>
<td>685</td>
<td>1200</td>
<td>4.23</td>
</tr>
<tr>
<td>02</td>
<td>826</td>
<td>1278</td>
<td>15.0</td>
</tr>
<tr>
<td>03</td>
<td>1856</td>
<td>-</td>
<td>5.92</td>
</tr>
</tbody>
</table>

The results from the pulsating fatigue test are presented in Table B.2 as applied load level and the number of cycles measured for corresponding stiffness loss and detection of visible crack for test specimen ÅF nr: 07-14.

**Table B.2:** Tabulated results from the pulsating fatigue test, load ratio $R<0.1$. Highlighted number of cycles in bold font where a visible crack has been noticed and corresponding percentage of stiffness loss

<table>
<thead>
<tr>
<th>ÅF nr</th>
<th>Load [N]:</th>
<th>Number of cycles [-]:</th>
<th>Stiffness loss:</th>
<th>Visible crack:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10%</td>
<td>15%</td>
</tr>
<tr>
<td>07</td>
<td>10 - 1000</td>
<td>9 887</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>08</td>
<td>10 - 900</td>
<td>13 439</td>
<td>22 044</td>
<td>-</td>
</tr>
<tr>
<td>09</td>
<td>10 - 800</td>
<td>26 146</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>10 - 700</td>
<td>61 616</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>10 - 400</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>10 - 600</td>
<td>13 596</td>
<td>66129</td>
<td>139 594</td>
</tr>
<tr>
<td>13</td>
<td>10 - 750</td>
<td>13 279</td>
<td>24 439</td>
<td>39 847</td>
</tr>
<tr>
<td>14</td>
<td>10 - 650</td>
<td>71 281</td>
<td>175 983</td>
<td>-</td>
</tr>
</tbody>
</table>

At the detection of a visible crack on the test specimen, the experiments were stopped. The location of the visible crack is illustrated in Figure B.1-B.3 for test specimen 07, 12 and 14 with the measured number of cycles and corresponding stiffness loss at the detection of the crack.
Appendix B. Experiment Result

**Figure B.1:** Noticed crack initiation on specimen ÅF nr: 07, for a pulsating load of 10 - 1000 N. Crack first visible after 10% stiffness loss at 9 887 cycles at predicted location.

**Figure B.2:** Noticed crack initiation at on specimen ÅF nr: 12, for a pulsating load of 10 - 600 N. Crack first visible after 20% stiffness loss at 139 594 cycles at predicted location.

**Figure B.3:** Noticed crack initiation on specimen ÅF nr: 14, for a pulsating load of 10 - 650 N. Crack first visible after 15% stiffness loss at 175 983 cycles at deviating location.
Appendix C

Fibre Orientations

The estimated principal orientation tensor $a_{ij}$ from the injection moulding simulation is shown in Figure C.1 - C.2.

**Figure C.1**: Estimated principal orientation tensor $a_{22}$ from the injection moulding simulation

**Figure C.2**: Estimated principal orientation tensor $a_{33}$ from the injection moulding simulation