

KTH ROYAL INSTITUTE
OF TECHNOLOGY

Doctoral Thesis in Vehicle and Maritime Engineering

A Framework for Fatigue Analysis of Carbon Fiber Reinforced Polymer Structures

SARA ELIASSON

Stockholm, Sweden 2023

A Framework for Fatigue Analysis of Carbon Fiber Reinforced Polymer Structures

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Abstract

Our society depends on functional road communication, and Heavy Duty Vehicles (HDVs) offer convenient and limitless possibilities of transport and services. However, HDVs account for a quarter of the European Union's CO_2 road emissions. There is a substantial need to reduce the CO_2 emissions of HDVs to ensure a low negative environmental impact. To reduce the CO_2 emissions of HDVs, their energy usage must be reduced. One way to reduce energy usage is to improve the structural efficiency of the vehicle and use high-performance composite materials such as Carbon Fiber Reinforced Polymers (CFRP).

HDVs are continuously exposed to road-induced vibrations, and the fatigue loading often sets the design criteria for HDV components. Therefore, flexible simulation frameworks are needed to encourage and simplify the implementation of composite materials in engineering structural designs dimensioned for fatigue. This doctoral thesis proposes a probabilistic modeling framework for fatigue assessment of CFRP. The thesis aims to provide knowledge and insights into the fatigue modeling of composite materials and a better understanding of the proposed modeling framework.

A combination of experimental investigations and numerical modeling is conducted. To carry out fatigue testing, a fatigue testing procedure was established. Fatigue testing of anisotropic material involves accurately selecting process parameters to obtain specimens that fail in the gauge length. The fatigue damage progression of CFRP laminates was monitored throughout the fatigue tests by analyzing the stiffness change, finding that the initial stiffness loss can be related to the damage development of the specimens.

Composite materials are multi-scale, where constituents and damage are of a much lower order length scale than the laminate and structure. Therefore, the numerical modeling uses a two-scale modeling approach to capture the variability of a composite laminate. First, the micro-scale modeling uses Representative Volume Elements (RVE) to determine the effective macro-mechanical properties of a composite lamina. The RVE models are generated based on experimental data capturing micro-geometrical variations that could affect the composite laminate behavior. Second, macro-scale models, capturing the complexity and variability of composite materials, are used in a probabilistic modeling approach for fatigue assessment. A Weibull distribution in a weakest link formulation is used to consider the combined effect of material variability of a CFRP laminate.

The work proposes a probabilistic fatigue modeling framework for implementation in an industrial design process. The methodology is highly valuable in the progress of fatigue modeling of composites. It aims to encourage and simplify the implementation of composites in engineering structural designs and components dimensioned for fatigue. The insights and outcomes of this doctoral thesis play a crucial role in the advancement of future resource-efficient vehicles and an optimal selection of materials to design for the right material in the right place.

Sammanfattning

Vårt samhälle är byggt för en fungerande vägskommunikation och lastbilar erbjuder flexibla lösningar för transporter och tjänster. Lastbilstransporter står emellertid för en fjärdedel av Europeiska Unionens CO_2-utsläpp och i arbetet för ett mer hållbart transportsystem finns ett behov av att minska CO_2-utsläppen för tunga fordon för att säkerställa en minimal miljöpåverkan. För att minska CO_2-utsläppen för lastbilar måste deras energianvändning minskas. Ett sätt att minimera energianvändningen är att effektivisera lastbilens strukturella design och använda högpresterande material som kolfiberarmerade polymerer.

Tunga fordon utsätts kontinuerligt för väginducerade vibrationer och denna typ av utmattningslast sätter ofta designkriterierna för lastbilskomponenter. Därför behövs flexibla simuleringsmetoder för att främja och förenkla användandet av kompositmaterial i komponenter som dimensioneras för utmattning. Denna doktorsavhandling föreslår en probabilistisk modelleringsmetodik för att utvärdera utmattning av kolfiberkompositer. Avhandlingen bidrar till kunskap och insikt om utmattningsmodellering av kompositer samt en fördjupad förståelse av den föreslagna modelleringsmetodiken.

Arbetet består av experimentell provning och numerisk simulering. För att utföra utmattningsprovning etablerades en metodik som hjälper till att noggrant välja de parametrar som behövs för en lyckad provning av anisotropa material. För att bättre förstå skadeprogressionen hos kolfiberlaminat mäts och analyseras styvheten av provstaven under provets gång. Det kan konstateras att den initiala förlusten av styvhet kan relateras till skadeutvecklingen hos provstavarna.

Beståndsdelarna i kompositmaterial är av en mycket mindre längdskala än laminatet. Därför används en tvåstegsmodelleringsteknik, mikro- och makromodellering, för att fånga de naturliga variationerna i materialet. Mikromodelleringen använder sig av representativa volymselement för att bestämma de effektiva makromekaniska egenskaperna hos ett kompositlaminat. De representativa volymselementen genereras baserat på experimentell data för att ta hänsyn till mikrogeometriska variationer som kan påverka kompositlaminatets beteende. Med avseende på den komplexitet och variation som kompositer uppvisar valdes en probabilistisk modelleringsmetodik för utmattning. En Weibull-fördelning i en *Weakest link* formulering användes för att utvärdera den kombinerade effekten av materialvariationer hos ett kolfiberlaminat baserat på numeriska makromodeller.

Doktorsavhandlingen presenterar en probabilistisk utmattningmodelleringsmetodik som ska vara lämplig för en industriell designprocess. Den utvecklade metoden är av stort värde för framsteg inom utmattningsmodellering av kompositer och syftar till att möta behov samt främja användningen av kompositer i komponenter som är dimensionerade för utmattning. Resultaten av denna doktorsavhandling spelar en avgörande roll i utvecklingen av framtida resurseffektiva fordon och för innovativa konstruktioner som använder rätt material på rätt plats.

Acknowledgements

The research presented in this doctoral thesis has been performed at the Division of Lightweight Structures, Department of Engineering Mechanics, KTH Royal Institute of Technology. This project is funded by Scania CV AB and the Centre for ECO^2 Vehicle Design at KTH Royal Institute of Technology, funded by the Swedish Innovation Agency Vinnova (Grant Number 2016-05195). The financial support for this project is gratefully acknowledged.

There are a number of people who have contributed to this work and to whom I am very grateful. I want to thank my colleagues and friends at the Division of Lightweight Structures. Meeting you in the corridor and having fruitful discussions have contributed in many ways to the making of this doctoral thesis. A special thanks to Monica Norrby and Anders Beckman for supporting my work in the lab. Your work in the lab is invaluable. I also want to thank my colleagues and friends at the Department of Engineering Mechanics. Thank you for making my time here cheerful and something to remember. I am also grateful to my colleagues and friends from the Centre of ECO^2, and especially to Johan Nygren and Johan Larsson, thank you for being my office mates throughout these years.

I would like to express my deepest gratitude to my supervisors, Zuheir Barsoum and Per Wennhage. Thank you for always sharing your knowledge and expertise and always finding time for me when I needed it. Your unwavering support and guidance have meant everything, and you helped me through this. To Mathilda Karlsson Hagnell, you will forever have a special place in my heart as my supervisor. I also want to give a special thanks to Gustav Hultgren for always finding time and having insightful solutions. I value the collaborative and engaging discussions throughout our work together.

I want to express my sincere gratitude to my steering group from Scania: Niklas Melin, Lars Jerpdal, Taina Vouristo, and Ola Selin. Thank you for being a part of this project and always providing valuable guidance. I also have a special thanks to Joakim Ånestrand for believing I could do this and making it happen. And to all my colleagues at Scania, thank you for your support and always finding time when I had questions.

I am forever grateful for the unconditional love I get from my family. I also want to thank Fabian's family for their wholehearted support. And to Fabian, my other half, thank you for always being there, being my best friend, and supporting me through this process.

Lastly, to my grandmother Solveig, thank you for always believing in me!



Sara Eliasson,
Stockholm, November 2023

Dissertation

This doctoral thesis contains two parts. The first part is an introduction and overview of the area of research and the work performed. The second part consists of the appended papers (A-F) listed below.

Paper A

S. Eliasson, S. Wanner, Z. Barsoum, P. Wennhage. *Development of fatigue testing procedure for unidirectional carbon fiber composites.* Procedia Structural Integrity, 2019, Vol. 19, Pages 81-89. International Conference on Fatigue Design 2019, 8th Edition.

Paper B

S. Eliasson, L. J. Wenner Berg, P. Wennhage, Z. Barsoum. *Fatigue and damage assessment of CFRP material using digital image correlation.* Procedia Structural Integrity, 2022, Vol. 38, Pages 631-639. International Conference on Fatigue Design 2021, 9th Edition.

Paper C

S. Eliasson, M. Karlsson Hagnell, P. Wennhage, Z. Barsoum. *An experimentally based micromechanical framework exploring effects of void shape on macromechanical properties.* Materials, 2022, Vol. 15.

Paper D

S. Eliasson, M. Karlsson Hagnell, P. Wennhage, Z. Barsoum. *A statistical porosity characterization approach of carbon-fiber-reinforced polymer material using optical microscopy and neural network.* Materials, 2022, Vol. 15.

Paper E

S. Eliasson, G. Hultgren, Z. Barsoum, P. Wennhage (2023). *Probabilistic fatigue strength assessment of carbon fiber laminate: exploring effects of manufacturing defects through a two-scale modeling approach.* (Submitted to international research journal).

Paper F

S. Eliasson, G. Hultgren, P. Wennhage, Z. Barsoum (2023). *Numerical fatigue assessment of carbon fiber reinforced polymers using a probabilistic framework.* (Submitted to international research journal).

Publications not included in the thesis

The following work was also produced as part of this doctoral project, but is not included in this thesis:

- S. Eliasson, M. Karlsson Hagnell, R. Jonsson, P. Wennhage, Z. Barsoum. *A life cycle energy and weight comparison of a carbon fiber composite versus metallic component in a commercial vehicle.* Resource Efficient Vehicles Conference, June 2021.
- K. Shahrezaei, S. Eliasson, P. Wennhage, Z. Barsoum. *Enhancement of fatigue life modeling using a metamodel-based global sensitivity analysis framework.* International Conference on Fatigue Design 2023, 10th Edition.

Division of work among authors

Paper A

Eliasson, together with Wennhage and Barsoum, identified the need for a robust procedure to conduct fatigue testing in the Lightweight Structures laboratory. Eliasson supervised Wanner throughout her master thesis project. Eliasson and Wanner evaluated different solutions for the challenges of fatigue testing, leading to a final choice of specimen geometry and fatigue testing setup. Eliasson wrote the paper under the supervision of Wennhage and Barsoum.

Paper B

Eliasson, together with Wennhage and Barsoum, identified the challenges of capturing the fatigue behavior of composite materials during testing and decided to use a high-speed camera to continuously record the damage progression. Eliasson supervised Wenner Berg throughout his master thesis project. Wenner Berg was responsible for the test setup. Wenner Berg developed a methodology to set up high-speed cameras with a trigger connected to the fatigue rig. Eliasson conducted the digital image correlation analysis and evaluated the fatigue testing behavior. Eliasson wrote the paper under the supervision of Wennhage and Barsoum.

Paper C

Eliasson and Karlsson Hagnell conceptualized the idea and defined the methodology. Eliasson carried out the experimental investigation and Karlsson Hagnell supported the development of software code to analyze the experimental data. Eliasson built the framework, carried out all the modeling, from the creation of the RVEs to the analysis of the macro-mechanical properties, and conducted the formal analysis. Eliasson wrote the paper under the supervision of Karlsson Hagnell, Wennhage, and Barsoum.

Paper D

Eliasson and Karlsson Hagnell conceptualized the idea and defined the methodology. Eliasson carried out the experimental investigations and implemented the neural network for data analysis. Eliasson carried out the statistical analysis of the extracted void data. Eliasson wrote the paper under the supervision of Karlsson Hagnell, Wennhage, and Barsoum.

Paper E

Eliasson and Hultgren conceptualized the idea and defined the methodology. Eliasson performed the experimental tests and microscopic analyses. Eliasson carried out the modeling and implemented the probabilistic calculations. Hultgren supported the extraction of results and the validation of the simulations. Eliasson wrote the paper with the support of Hultgren and under the supervision of Wennhage and Barsoum.

Paper F

Eliasson and Hultgren conceptualized the idea and defined the methodology. Eliasson defined the modeling framework. Eliasson performed microscopic analyses and created a test plan for the fatigue testing. The fatigue test program was conducted by Monica Norrby and Anders Beckman in the Lightweight Structures laboratory. Eliasson carried out the modeling and implemented the probabilistic calculations. Hultgren supported the extraction of results and the validation of the simulations. Eliasson wrote the paper with the support of Hultgren and under the supervision of Wennhage and Barsoum.

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Chapter 1

Introduction

1.1 Background

More than 6 million Heavy Duty Vehicles (HDVs) circulate European roads today [1]. The necessity of HDVs can not only be connected to kilometers driven or goods transported, they also deliver functions and services. Our society is to a large extent built for functioning road communication and HDVs offer a convenient and limitless possibility of transport. Being one of the most accessible modes of transportation HDVs account for a quarter of the European Union's CO_2 road emissions [2]. To address the CO_2 emissions, regulations that demand emission reductions have been put into effect. From 2030 and onwards a 30 % reduction of the CO_2 emissions for HDV manufacturers is dictated [3], with the overall goal to be climate-neutral by 2050 [4]. Hence, the need has risen for commercial vehicle manufacturers to improve their HDV designs towards more climate neutral goals.

Scania is one of the world's leading HDV manufacturers, and they are driving the shift towards a sustainable transport system. For Scania, a sustainable transport system means moving goods and transporting people while at the same time contributing to economic growth and social development. This shall be achieved without endangering the environment. To lower the emissions from HDVs their energy usage needs to be reduced. The energy usage can be reduced by improving the drivelines' efficiency or minimizing structural mass. Lightweight design can significantly decrease the mass of the vehicle and, with such, the energy usage. Reducing the structural weight implies decreased fuel consumption for Internal Combustion Engine Vehicles (ICEVs), and for Battery Electric Vehicles (BEVs), with the added structural weight of the batteries, a lightweight design is vital not to compromise the driving range.

The increasing emphasis on sustainable development forces even well-established and experienced companies within metal design to adopt more advanced lightweight materials. Advanced lightweight materials are, e.g., composites, sandwich materials, aluminum, and high-strength steels. Utilizing these advanced materials in the design development process demands tools to have the possibility to design and evaluate them in-house. Allowing for design of *the right material in the right place*, with an array of materials to choose from, flexible simulation frameworks are needed to introduce these new materials in the design development process. HDVs are mainly dimensioned against fatigue and the design development process includes predicting the fatigue properties of components such that they can withstand the road-induced vibrations during the expected lifetime of the vehicle. Therefore, fatigue assessment methodologies are needed.

Composite materials exhibit a more complex failure behavior than metallic materials [5]. Metals are, in most cases, isotropic, and composite materials are anisotropic. The typical fatigue behavior and damage modes of composite materials are controlled by, e.g., material combination, fiber and matrix properties, layup, and manufacturing defects [6]. The fatigue failure of composite materials is often a result of damage accumulation, and the damage modes can change over the lifetime [7]. These facts make the prediction of fatigue behavior particularly complicated.

Fatigue in composite materials has been the focus of research for a long time and early fatigue investigations date back to the 1950's [8]. Over time, composite materials have matured and are an attractive alternative for metallic designs. However, there are still technical challenges related to the use of composite materials, e.g., recycling, joining, repair, and cycle times [9]. The wide structural variability and the individual response to different loading conditions complicate the prediction of fatigue behavior. Throughout the last decades fatigue modeling of composite materials has been the subject of intensive research investigations. Until today, there are still no commonly accepted solutions for the fatigue evaluation of composite materials. Because of the differences between metallic material and composite material behavior, modeling approaches developed for metallic materials are unsuited and not recommended for composite materials [10]. With the endless combination of materials and layups, finding a general approach to predict the fatigue behavior of composite materials will remain a challenge.

Considering the many design variables of composite materials, the material's variability is high, resulting in a high scatter for the material behavior. The significant variability strongly incentivizes the use of probabilistic modeling for fatigue simulations of composite materials. Chamis et al. [11] emphasize the many possible uncertainties of a composite structure and the possibilities of using probabilistic methods to determine structural reliability considering the uncertainties. The material variability present at differ-

ent length scales is important to consider in structural reliability analysis [12]. Using macro-scale models is, computationally, the most time-efficient; however, for composite materials, failure events at the micro-mechanical scale can advance and initiate failure events at higher scales (meso- and macro-scale). Capturing this material variability is preferably modeled using Multi-Scale Modeling (MSM) [13]. To understand which material characteristics need to be considered, experimental investigation is often the place to start. The challenge is to figure out which typical behavior is important for the specific material and problem formulation.

1.2 Aim and Research Questions

The main objective of the thesis is to provide insight into the fatigue life modeling of Carbon Fiber Reinforced Polymer (CFRP) structures and with a proposed and developed framework provide a tool for fatigue assessment for industrial applications, encouraging the use of composite materials in engineering structural designs and components exposed to fatigue loading.

The thesis attempts to answer the following research questions and research objectives:

(RQ1) - Is it possible to develop an engineering approach for designing CFRP components for commercial vehicle applications subjected to fatigue loading?

(RQ2) - How can probabilistic fatigue models be used for CFRP materials?

(RQ3) - Development of a methodology to characterize and analyze the mechanical properties of CFRP materials.

(RQ4) - Development of a systematic approach to characterize fatigue damage and degradation.

The produced research, which is published in the appended research papers A-F, attempt to answer the research questions and objectives. In Figure 1.1 the different research questions and objectives are connected to the appended research papers.

	Paper A	Paper B	Paper C	Paper D	Paper E	Paper F
RQ1					X	X
RQ2					X	X
RQ3			X	X		
RQ4	X	X				

Figure 1.1: *A table visualizing the connection of the appended papers and the research questions and objectives.*

1.3 Research Approach

The main part of the work consists of analyzing the characteristic material behavior using experimental investigations and numerical simulations. A summary and overview of different focus areas for each research paper are presented in Figure 1.2.

	Paper A	Paper B	Paper C	Paper D	Paper E	Paper F
Experimental investigations	Fatigue testing	Fatigue testing	Microscopy Static testing	Microscopy	Microscopy Fatigue testing	Microscopy Fatigue testing
Composite material	UD CFRP non-crimp fabric	UD CFRP non-crimp fabric	Cross-ply CFRP UD prepreg, snap cure v1	Cross-ply CFRP UD prepreg, snap cure v1	Cross-ply CFRP UD prepreg, snap cure v2	Cross-ply CFRP UD prepreg, snap cure v2
Material analysis	Fatigue behavior	Fatigue behavior	Macro-mechanical properties	Void characteristics	Fatigue strength	Fatigue assessment
Numerical simulations	N/A	N/A	Micro-mechanical	N/A	Micro-mechanical Macro-mechanical	Micro-mechanical Macro-mechanical
Research questions/ objectives	RQ4	RQ4	RQ3	RQ3	RQ1&2	RQ1&2

Figure 1.2: *A summary of focus areas for the appended papers.*

An outcome of the research process, attempting to answer the research questions and objectives, was the development of a probabilistic fatigue modeling framework. Considering composite materials' typical characteristics and existing modeling approaches, the developed framework uses a probabilistic modeling approach for fatigue life prediction and the modeling strategy is based on MSM to capture the variability of the material across different length scales. The defined framework can be considered modular, where steps and parts of the framework can be extended or exchanged to suit the different needs of a design process.

The research has been divided into two concurrent paths of investigation: numerical simulation and experimental work. Both paths are needed to capture the characteristics of composite materials in order to define a probabilistic fatigue modeling framework. In Figure 1.3 the framework is presented using different modules; micro-mechanical simulations, macro-mehcanical simulations, probabilistic fatigue modeling, 2D microscopy, and fatigue testing. The figure also visualizes how the different modules are related to research questions and objectives, and the appended research papers.

RQ1 is attended in **Paper F**, where a full probabilistic modeling approach for fatigue assessment using the weakest link theory is presented. **RQ2** is partly answered in **Paper F**, but also in **Paper E**. In **Paper E** the weakest link methodology is attempted for a CFRP material comparing the fatigue strength of three laminates by capturing their individual material variability. The modeling in **Paper E** and **Paper F** is based on the modeling presented in **Paper C**. **Paper C** provides answers to **RQ3**. In **Paper C** the foundation of the MSM approach is set; the micro-scale modeling. In **Paper C** the effective macro-mechanical properties of a CFRP material are investigated. The material's variability is captured by examining defects using microscopy investigations. Voids are found to be one of the main defect types in the manufactured material. A statistical void characteristic analysis is conducted in **Paper D**, providing more detailed input for **RQ3**. **RQ4** is attended in **Paper A** and **Paper B**. In **Paper A** and **Paper B** a fatigue test setup and experimental investigation give insight into characteristic behaviors of composite materials that affect the choice of the modeling approach.

The doctoral thesis shall give an overview of the conducted research and strive to give the reader enough insight to understand the choices made throughout the work. The doctoral thesis begins with an introduction to composite materials and the choice of composite material for the current research is highlighted. Then an overview of fatigue of composite materials is presented and the typical material behavior will be discussed. Fatigue modeling of composite materials will be introduced and the chosen modeling approach will be demonstrated. The thesis aims to put the research conducted into context and explore the underlying assumptions and possibilities of the developed framework. Theoretical formulations are more thoroughly discussed in the appended papers.

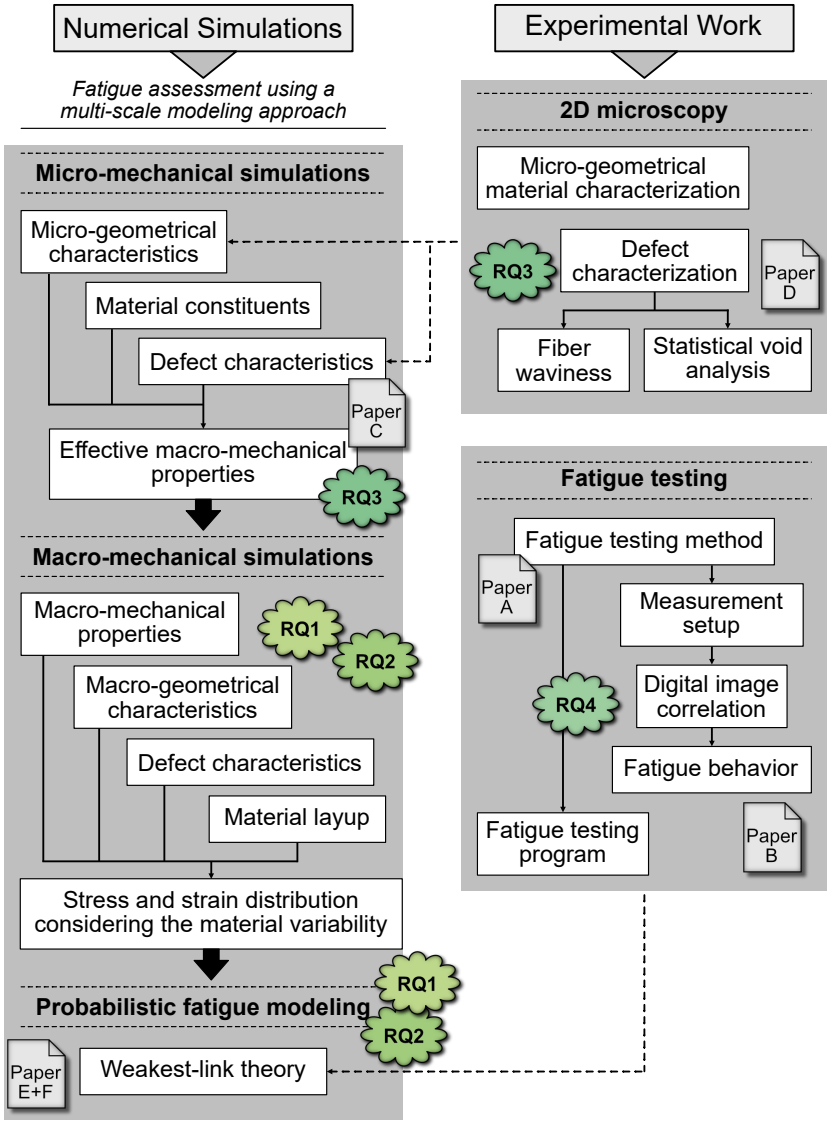


Figure 1.3: *A probabilistic fatigue modeling framework for CFRP materials.*

Chapter 2

Fatigue of Composite Materials

One of the major material property considerations for HDV components is fatigue strength. HDVs are exposed to a wide range of service loads and the road-induced vibrations often set the design criteria, and since advanced lightweight materials get more attention in lightweight design of structural components for commercial vehicles, reliable and efficient fatigue assessment methods have become of utmost importance. Metallic fatigue is a well-known topic, but still, there is a continuous need for research to solve new and critical problems. There is a continuous development of new advanced metallic structures using technologies such as Additive Manufacturing (AM) and high-strength steels. The commercial vehicle industry has worked with metal design for the last century and in a design development process where metal fatigue is familiar it might be tempting to apply the fatigue methodologies developed for metallic structures to composite structures. This is not recommended since the fatigue behavior of these materials is considerably different [10, 14]. The difference between damage evolution for metallic materials and composite materials is schematically illustrated in Figure 2.1. The main difference between the damage propagation is that metallic materials exhibit crack initiation and crack growth. For composite materials fatigue failure is often a result of damage accumulation, and the damage modes can change over time. It can be seen as crack initiation and multiplication rather than a pure growth [15] and there is not necessarily a dominating damage mode [7].

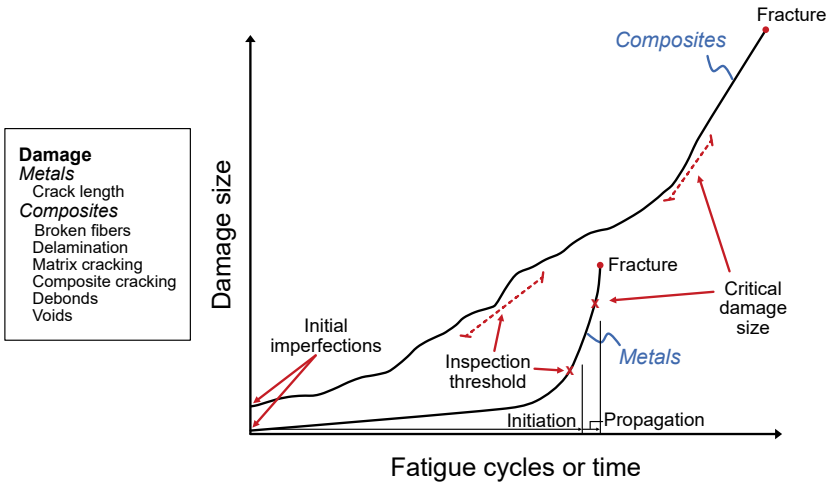


Figure 2.1: *Fatigue damage evolution for metallic materials and composite materials. Redrawn figure from [7].*

2.1 Carbon Fiber Reinforced Polymers

The expression *advanced lightweight materials* covers a wide range of materials: sandwich structures, polymer composites, ceramic composites, metal matrix composites, high-strength steels, aluminum etc. In the current thesis polymer matrix composites are investigated further. Polymer matrix composites are attractive for lightweight design because of their high strength-to-weight ratio (Figure 2.2).

Composites imply the composition of a minimum of two constituents: fiber and matrix. The fibers are the reinforcing material. Glass fibers, carbon fibers, natural fibers, and aramid fibers are some common options. The fibers can be prepared in varying ways, e.g., as weaves, pre-impregnated fibers or non-crimp fabrics. For all varieties of fibers it is possible to have different layups and angles. The polymer matrix is either a thermoplastic or a thermoset. The choice of material combination is based on the design requirements. If recyclability is a main focus, natural fibers and biobased thermoplastic matrix are a good choice [17]. If fatigue strength is an important design criterion, then a carbon fiber/epoxy is more suitable [6].

The research reported within this doctoral thesis focused on carbon fiber/epoxy laminates in two variants. The first laminate (referred to as Material 1) uses carbon fibers in a non-crimp fabric with an epoxy matrix and a Unidirectional (UD) layup, $[0^{\circ}_{8}]$. This composite is previously used in the automotive industry [18]. The laminate is manufactured using high

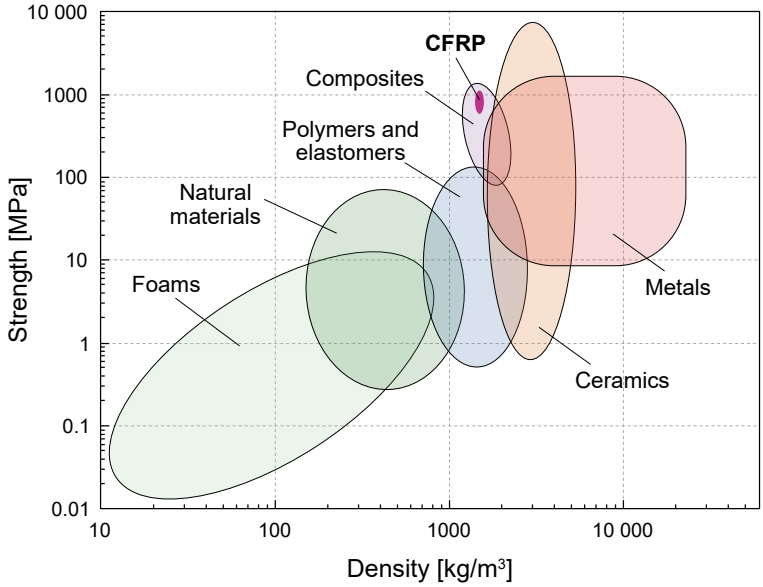


Figure 2.2: *A material selection chart comparing the strength and density performance of a variety of materials. Redrawn figure from [16].*

pressure Resin Transfer Molding (RTM). The second laminate (referred to as Material 2) is a UD carbon fiber/epoxy prepreg with a cross-ply layup, $[0_3^\circ/90_3^\circ]_S$. The laminate was manufactured with compression molding and was manufactured in-house at the university in the Lightweight Structures lab. This specific prepreg has a so-called "snap cure" matrix system with a cure time of minutes in an elevated temperature. The snap cure matrix systems have been developed to meet the demands of high-volume production [19]. The automotive industry needs the possibility to produce composite parts in minutes to meet up with the takt times for the assembly process. The materials are manufactured as flat plates to facilitate the production of relevant test specimens. The variety of possible choices and the final composite material used is illustrated in Figure 2.3.

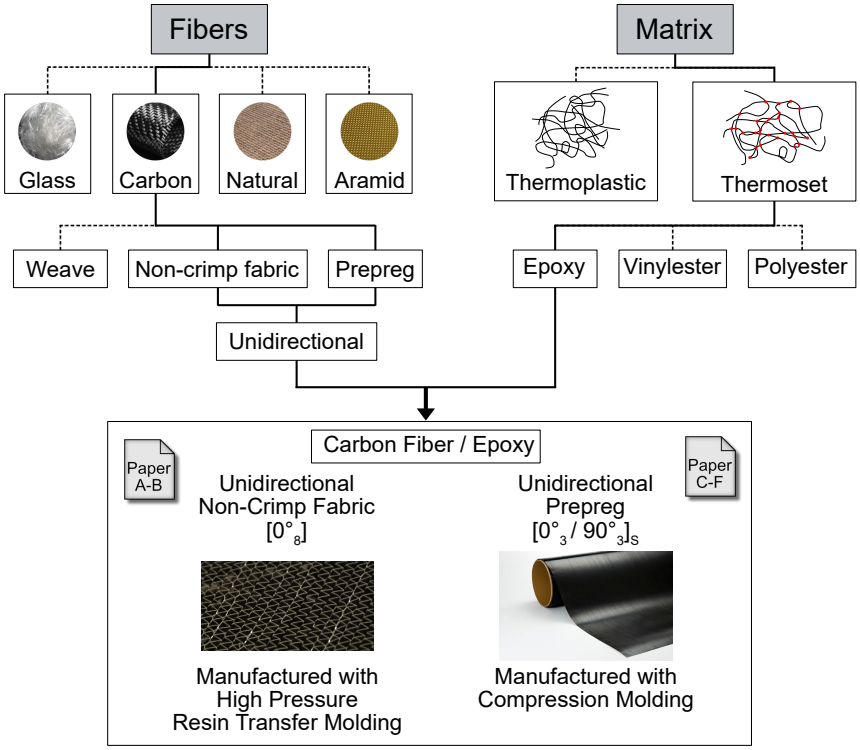


Figure 2.3: *A schematic illustration of selected options for polymer composite materials. The flow shows the variants of the two CFRP materials used in the current doctoral thesis.*

2.1.1 Manufacturing Defects

The quality of composite materials is profoundly influenced by the manufacturing method. The high variability in the material is controlled by the many commercial composite materials and the need for optimizing the manufacturing process for each material combination. Adjusting each manufacturing process and optimizing the quality comes at a certain cost. Different stages of automation of the manufacturing process can give rise to different manufacturing defects, and producing a defect-free composite is very expensive. Since defects can have detrimental effects on damage behavior, defect assessment is essential for industrial applications.

There are many different manufacturing defects, e.g., fiber waviness, voids, impurities, resin-rich areas, and more [20]. Investigations conducted confirm that defects highly influence the long-term properties of composite materials [21, 22]. The presented research found that for Material 2 voids were the main visible defect. Not tuning the process parameters correctly can lead to the air entrapped in the material not being evacuated before the matrix cures. In Figure 2.4 a micrograph of a section of the laminate from an early set of manufacturing is presented. For this set the processing parameters were badly tuned and the porosity of the laminate is very high.

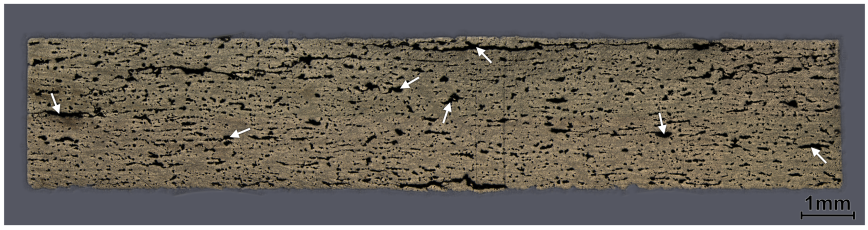


Figure 2.4: *Micrograph for Material 2 showing an early attempt of compression molding with badly tuned processing parameters causing high porosity in the material. White arrows indicate locations of selected defects.*

Another defect for Material 2 that appeared was in-plane fiber waviness (Figure 2.5). A microscopy investigation was carried out to define the reason behind this behavior and a theory was that the flow of the viscous matrix shifted the fibers near the edges. It could be concluded that the center of the manufactured plates was unaffected. The affected area was small and close to the edges. The flow of the matrix over the edges was captured in a micrograph presented in Figure 2.6.

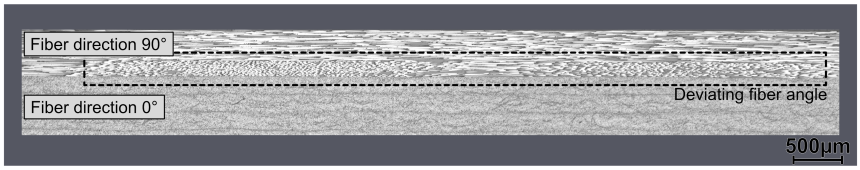


Figure 2.5: *Micrograph for Material 2 illustrating the fiber waviness that occurred as a manufacturing defect.*

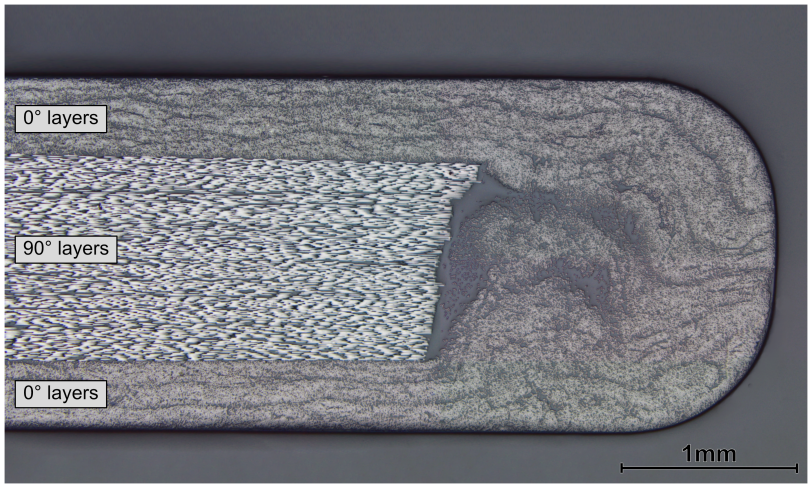


Figure 2.6: *Micrograph for Material 2 illustrating the matrix flow at the edges.*

2.2 Fatigue Behavior of Carbon Fiber Reinforced Polymers

Analyzing the S-N behavior has been a foundation of fatigue analysis since the 19th century. For composite materials, referring to strain rather than stress is often more suitable. This is because when loading the material the strain will be constant through the constituents and the stress varies. Talreja developed the concept of fatigue life curves [23] to assess the fatigue life mechanism of composite laminates and in contrast to the typical Wöhler curve, commonly used for metal fatigue, the fatigue life curves are adapted using strain. The fatigue life curve distinguishes between different governing mechanics in characteristic regions under specific loading conditions for composite materials. A characteristic fatigue life curve for a composite laminate is illustrated in Figure 2.7.

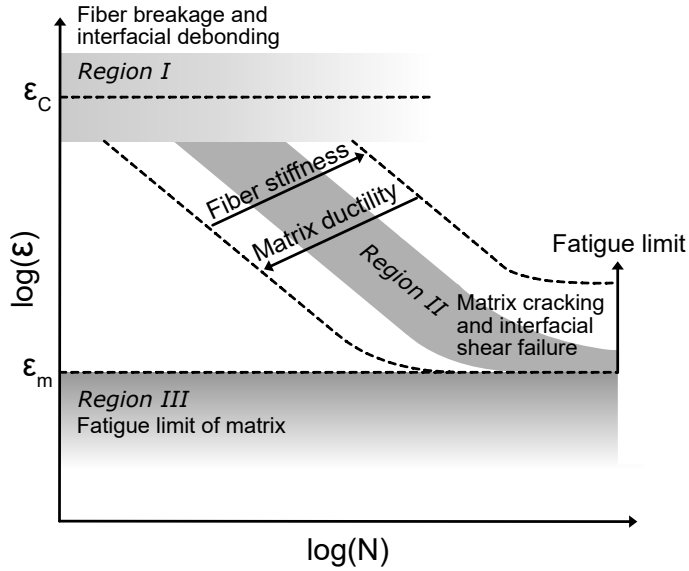


Figure 2.7: *A typical fatigue life curve for composite laminates. Redrawn figure from [24].*

The fatigue life curve is represented by three characteristic regions that represent the main damage mechanisms for certain ranges of strain. In the upper region, Region I, the failure is dominated by fiber breakage and interfacial debonding. The failure type is non-progressive and instead dependent on the fiber strength. Therefore, theoretically, failure could occur at any number of cycles. Region II represents the finite life regime, and the main damage is progressive represented by interfacial damage and fiber-bridged cracks [25]. The fatigue limit of the matrix defines Region III and in this region the load is low enough to stop any matrix crack propagation due to the inhomogeneous nature of the composite.

The basic concepts of fatigue analysis are the same for composite materials as for metals but the process is more complicated [26]. Composite materials are anisotropic, and the anisotropic nature of a laminate introduces different damage modes. The fatigue behavior and damage modes are influenced by, e.g., layup, material composition, geometry, and defects. The final fatigue failure is often a result of local stress concentrations resulting from the growth of several micro-defects in the material [6]. The damage modes can be connected to the laminate or its constituents. Different damage modes are outlined in Figure 2.8. A composite structure or component may exhibit one or several damage modes. Even though damage modes can be identified, it is difficult to quantify their effect on fatigue life.

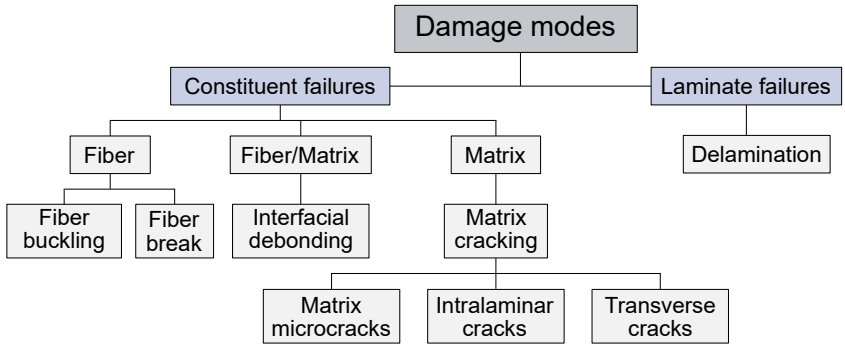


Figure 2.8: *Typical damage modes for composite laminates.*

Defining the typical behavior of composite materials has been done by many researchers. Reifsnider et al. [27] coined the concept of Characteristic Damage State (CDS) which refers to the unique crack patterns in off-axis plies that depend on the laminate properties. The authors outline the damage mechanics in different steps leading up to the final failure of a laminate. The initial steps are seen as subcritical, whereas the final steps are critical causing the final failure of the laminate [28]. The damage progression is visualized in Figure 2.9. There is an early stage of adjustment to the loading characterized by a more rapid damage development. At this stage mainly matrix cracking is involved. After the initial stage the damage development tends to have a flat trend. This region is mainly connected to the coupling and growth of matrix cracks where matrix cracks grow together and along interfaces. This would also trigger delamination that could arise and grow. The final part is a sharp incline of damage. This would arise as a sharp stiffness drop of the laminate. Thus, stiffness is a great indicator of fatigue damage [29].

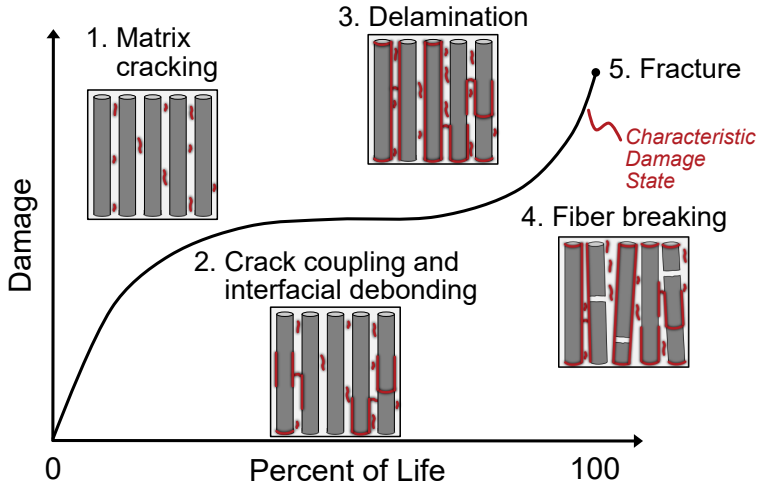


Figure 2.9: *Different damage states throughout the fatigue life of a composite laminate. Redrawn figure from [28].*

2.3 Experimental Characterization

To avoid redundancy and conservative structural design it is important to understand the fatigue behavior of the materials when conducting fatigue life calculations. An essential first step in comprehending and characterizing a material is through experimental testing. Characterizing anisotropic materials comes with challenges since weaker material property directions might affect the evaluation of stronger material property directions. There are recommendations from standards that can be followed, e.g., ASTM3479 [30] and ASTM3039 [31]. Still, every laboratory setup can be different and needs to be adjusted to fit the available equipment to extract the best results. Challenges involve load introduction [32], heating, specimen geometry [33], clamping pressure [34], and more.

In **Paper A** many of these difficulties were encountered when developing a fatigue testing procedure for the Lightweight Structures lab. **Paper A** presents a proposed procedure for setting up a functioning fatigue testing approach that can be followed step by step to overcome the main challenges of fatigue testing and achieving failure in the gauge length of composite laminate specimens. A systematic approach makes fatigue damage easier to measure and characterize. Many researchers have successfully conducted comprehensive fatigue testing programs, e.g., Kawai et al. [35, 36, 37]. Research is dependent on successful test programs contributing with valu-

able knowledge about material behavior that can be used for verification of numerical and analytical modeling approaches.

The fatigue test data results for the investigated composite laminates tend to have an increased scatter for higher loads. This scatter is a behavior that could be connected back to the fatigue life diagrams (Figure 2.7), where for Region I there is no fixed range of life for fatigue failure. A scatter could be connected to a variation in the strength of fibers, that the failure modes are different, or that the damage modes change over the lifetime creating discontinuities in the S-N data [38].

Figure 2.10 presents the S-N data of the two materials analyzed in this thesis. There are many models used for the characterization of materials using S-N curves [39]; however, Basquin (Eq. 2.1) [40] is commonly used to fit the S-N data in the finite life region.

$$S = \left(\frac{C}{N}\right)^{\frac{1}{m}} \tag{2.1}$$

Where S is the applied fatigue loading (σ), and N is the number of cycles to failure at the given load. C and m are material coefficients, where m is the slope coefficient. The Basquin fit for Material 1 is conducted for experimental data points tested at a load level 60-85 % of the Ultimate Tensile Strength (UTS). Runouts are excluded for the fitting for both data sets. Analyzing the data and comparing the two materials it becomes evident that the UD laminate, Material 1, has a much higher scatter and slope. The higher slope could be visualized as a smaller range of strain on the y-axis for region II in the fatigue life curves (Figure 2.7), supported by the results in [25].

Comparing the composite laminates' slopes there is a significant difference. The scatter for Material 1 is remarkable and the high variation is due to the fibers carrying most of the load. Comparing the experimental slope of the CFRP laminates to that of metals, it is considerably different. For metals, following the International Institute of Welding recommendations, the standardized slope for steels is 5, and for welded joints 3 [41].

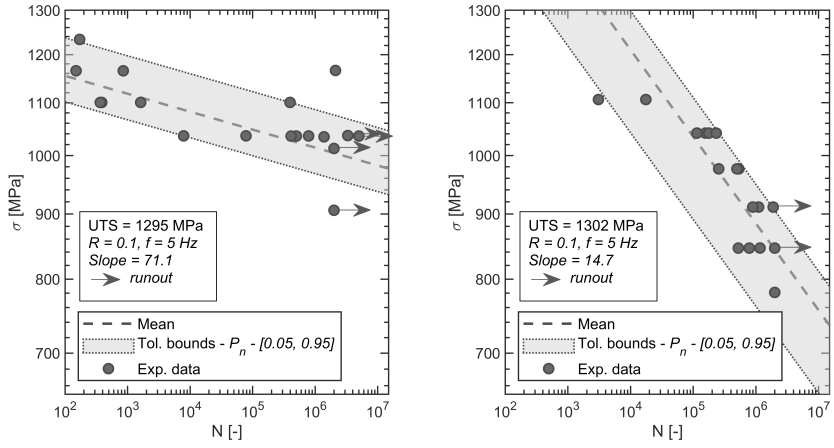


Figure 2.10: *(a) The S-N data and Basquin fit for Material 1 (**Paper B**), and (b) the S-N data and Basquin fit for Material 2 (**Paper F**).*

2.3.1 Damage Assessment

Since the damage accumulation of composite laminates causes the stiffness and strength of the material to degrade, utilizing stiffness as an indicator for fatigue damage and monitoring the stiffness reduction can be a convenient way to monitor the damage development during fatigue loading [15]. Stiffness is more commonly recorded than strength since the stiffness degradation can be measured continuously during fatigue testing using Non-Destructive Techniques (NDTs) [42]. Jamison et al. [43] defined a characteristic stiffness reduction trend for composite laminates. The stiffness reduction was plotted against the number of cycles and three distinct regions were identified for different laminates. A typical stiffness degradation curve for a composite laminate is schematically presented in Figure 2.11. The initial stage has a rapid stiffness reduction, followed by an intermediate region where the stiffness reduction is stable and can be seen as a linear function of the number of cycles. The final stage is rapid and abrupt, ending with a final failure. The three regions provide a framework for assessing damage development in composite laminates.

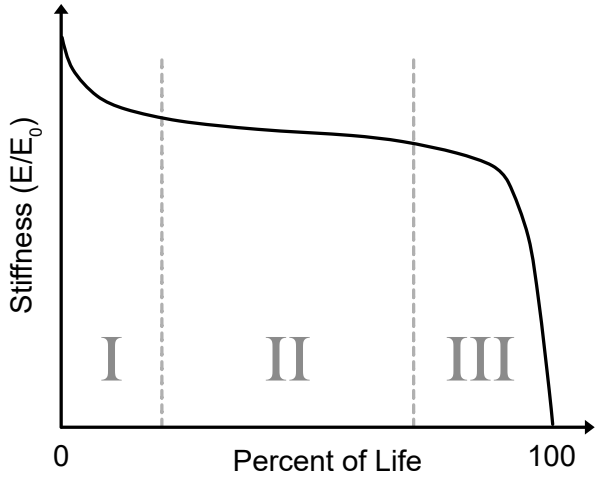


Figure 2.11: *Typical stages of stiffness degradation throughout the fatigue life of a composite laminate. Redrawn figure from [43].*

Different approaches are established to measure the stiffness degradation continuously. Peng et al. [44] conducts recordings of the global stiffness data using piezoelectric sensors. Sisoda et al. [45] used high-speed cameras to record surface displacements of fatigue specimens throughout the life cycle and used image processing to calculate strain and stiffness. To get an idea of the typical behavior the displacements of the testing rig can also be used; however, these data should just be used to determine a trend and not for exact measurements.

In **Paper B** a method to capture the stiffness loss is implemented. The fatigue test rig is connected to a high-speed camera triggered at predefined cycle counts. Utilizing Digital Image Correlation (DIC) the images that represent the peak load are used to calculate the strains and then compared to track the development of fatigue damage, i.e., the stiffness loss. The stiffness degradation for the investigated CFRP laminates tends to follow the trend outlined in Figure 2.11. In **Paper B** Material 1 is investigated and the first two regions are captured. The results are presented in Figure 2.12a. The UD laminate has a typical sudden death failure, making it hard to capture the final stage of stiffness loss and the final failure event. The predefined trigger signal can not be set to capture the final stage of damage because of the sudden death behavior and the large scatter. For Material 2 the material behavior is investigated using displacements from the fatigue test rig (**Paper F**). The methodology in **Paper B** is not utilized since DIC is impossible because fiber splintering on the surface of the specimens interrupts the image analysis. Utilizing the method of looking at

the displacement from the fatigue test rig is very blunt and probably can not capture the first stage. However, the trend of fatigue damage in the second and third stages can be identified (Figure 2.12b).

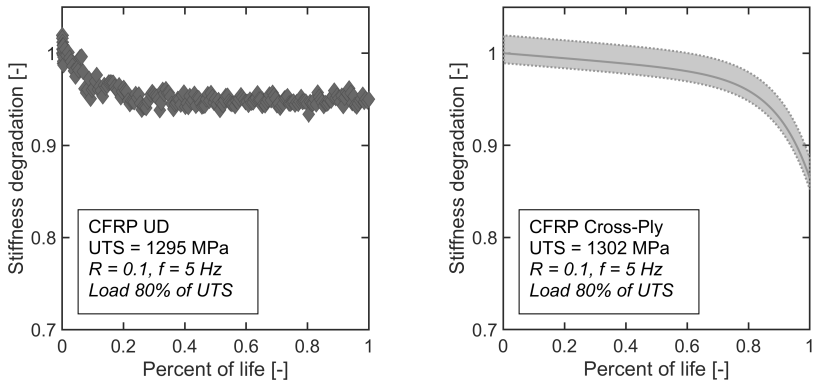


Figure 2.12: *(a) Stiffness degradation recorded with a high-speed camera and calculated using DIC for Material 1 (**Paper B**), and (b) stiffness degradation estimated from the displacement of the fatigue test rig for Material 2 (**Paper F**).*

Capturing the reason for stiffness reduction in composite laminates is more complicated and demands more advanced measuring systems. A common approach is utilizing advanced scanning techniques. An example is the study by Jespersen et al. [46] who used X-ray Computed Tomography (CT) ex-situ to record fatigue damage in non-crimp fabric laminates. The authors could continuously follow the crack accumulation and match it with the continuous stiffness loss. Advanced scanning techniques generate a lot of data; therefore, more simplistic techniques like microscopy are sometimes preferred to identify different types of damage, as was used in **Paper C** and **Paper D**. For damage assessment of composites it is important to capture what is happening during the fatigue life and to understand which damage modes are most important and mainly affect the material under consideration.

Stiffness is a good measure of what is happening in the material and how fatigue damage is evolving. Connecting back to Figure 2.11 and the results in Figure 2.12a there is the possibility of damage accumulating without affecting the global stiffness. Especially when the loading is only in one direction and in the fiber direction of a UD laminate. The composite laminate would probably behave differently or break if the loading direction changed.

Assessing the damage progression of composite laminates is important and the next step would be to define, based on damage progression, when the composite laminate is broken. One possible definition of failure is when the laminate no longer carries the applied load. Another interesting aspect would be knowing how the composite laminate with accumulated damage would withstand, e.g., an impact or an overload. This is out of the scope of this doctoral thesis but is an important topic to keep in mind when researching the fatigue of composites.

2.4 Fatigue Modeling

With the challenges of fatigue assessment for composite materials there are often large safety factors adopted in life prediction methodologies. This leads to unnecessarily conservative designs and extensive test programs to verify the fatigue life prediction. A challenge for composite materials is the reproducibility of experimental results. Because of all the uncertainties and variability in the material, it is impossible to produce identical specimens where the micro-geometrical features are well-characterized [47]. This might lead to the need for even more testing. Using numerical simulations design ideas can be evaluated and the cost for physical testing can be minimized [48]. To capture the correct behavior of composite laminates different damage mechanisms must be considered. These damage mechanisms occur at several length scales: at the micro-scale, the macro-scale, and up to structural levels. Ensuring the reliability of developed simulation models is important and increasing the complexity could decrease the control of the simulation results. Therefore, sometimes reducing the complexity of the simulations can be useful [49]. Efficient and reliable fatigue life modeling approaches can lead to better designs, using the right materials in the right place, keeping up with the short lead times, and taking new concepts to the market faster.

Fatigue life modeling approaches for composite materials are commonly divided into three categories: (1) Fatigue life models, (2) Phenomenological models, and (3) Progressive damage models. These categories are previously defined by Degrieck et al. [50] back in 2001. The three categories are outlined in Figure 2.13. Even though this categorization was set two decades ago, it is still relevant and most of the developed fatigue models today can be categorized accordingly.

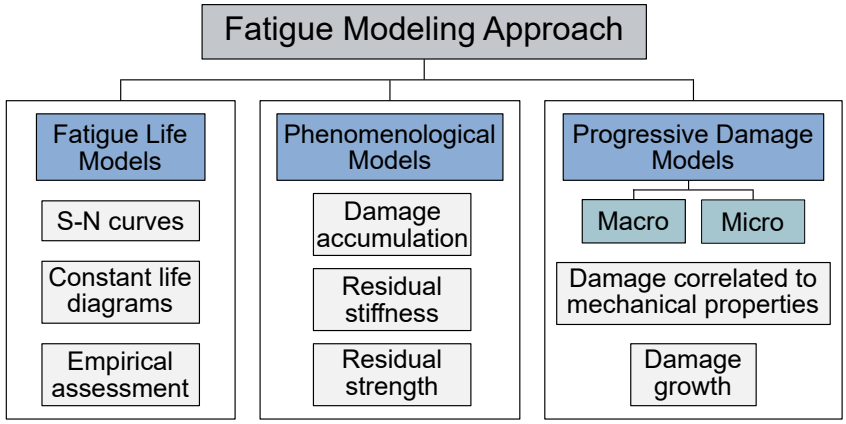


Figure 2.13: *The three categories for fatigue life modeling approaches.*

Fatigue life models are of an empirical nature and do not consider any degradation mechanisms. These models are mostly linear and require experimental testing programs to verify failure for different load cases and layups. Even though this methodology is limited it is popular in practice due to the fact that it is easy to use and implement. Fatigue life models often include methods based on S-N curves or Constant Life Diagrams (CLD) and the result often concludes the number of cycles to failure. Investigations comparing CLDs are conducted in [51], highlighting the importance of accurately selecting the CLD formulation to avoid very conservative designs. Methods developed to minimize experimental input [52] can sometimes compromise accuracy if adapted to other test data. A piecewise linear CLD formulation performs well; however, the more complicated approaches can be restricted to applications with limited load cases [53].

Phenomenological models take the fatigue life models one step further, not only defining the number of cycles to failure but also predicting changes in macroscopic properties and describing the gradual deterioration of the material. The models consider a damage accumulation and are often restricted to the macroscopically observed residual properties, i.e., stiffness and strength. Residual stiffness models often refer to stiffness loss as a damage parameter, D, a concept used in, e.g., [54]. Residual strength models [32, 55] continuously degrade the initial material strength during the fatigue life of the composite. The models can predict the lifetime and remaining life and are often based on statistical data [56, 57]. Developing residual strength models is limited since they do not allow for NDTs when calibrating them. There are also models that consider both stiffness and strength degradation [58].

Progressive damage models describe the deterioration of the material by connecting it to specific damage modes. These models are the most advanced and can be connected to pure damage growth or the damage of the mechanical properties, i.e., strength and stiffness. These models can be developed to be applicable to different layups thanks to the modeling considering different length scales. The generalized residual material property degradation technique, developed by Shokrieh and Lessard [59, 60], is well-known. This Progressive Fatigue Damage Model (PFDM) is one of the generalized models independent of the laminate layup. The PFDM is limited since extensive material characterization is required; however, reducing the material characterization will inevitably result in a less versatile model. The PFDM is continuously used [61, 62] and developed by researchers [63, 64, 65].

There is a wide range of developed modeling methods within the three categories of fatigue life modeling of composites. Many researchers believe the way to truly predict fatigue damage evolution with simulation methods is to use progressive damage models [50] and physically based models [66]. Focusing on an industrial approach, the progressive damage models are quite time-consuming, both with respect to simulations and experimental characterization. On the opposite end are the fatigue life models that are more simplistic, with the consequence of being less versatile. The fatigue life models are often calibrated for one kind of material and lay-up, not serving the general applicability that the industry demands.

2.4.1 Probabilistic Fatigue Assessment

A fatigue modeling approach can be deterministic or probabilistic. Deterministic models base their output on the input from experimental data. The models are based on and built from parameter values following a specific trend or initial values for, e.g., strength. The probabilistic model incorporates randomness and considers variation of properties and behavior. To capture the typical composite material behavior, uncertainties and material variability are important to consider to understand their effect on the structural reliability [11]. The significant variability of composite materials and their inconsistency in material behavior is a strong incentive to use probabilistic modeling for fatigue simulations of composite materials [67]. Probabilistic modeling is proposed by, e.g., Castro et al. [68] who utilized the variability in fatigue coupon tests for fatigue modeling, and Stefanou et al. [69] who linked the variability of the micro-mechanical properties to the variability of the macro-scale properties.

External loads and composite material's fatigue response are often main factors considered for probabilistic and uncertainty modeling [70]. The uncertainties or scatter produced in fatigue testing results are a consequence

of uncertainties in material properties, e.g., fiber and matrix properties. Another aspect is the defects in the material which also have a variability of their properties. Figure 2.14 illustrates examples of material variations and how they might affect the fatigue strength.

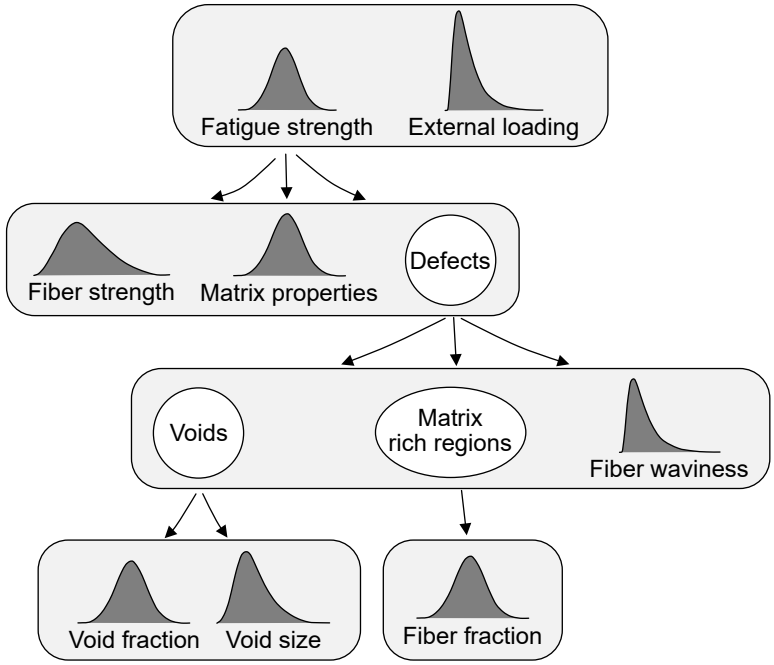


Figure 2.14: *Examples of how different variations in composite material properties influence the fatigue strength.*

Weibull's weakest link theory [71], commonly employed in probabilistic modeling for metals, can assess the combined effect on the material fatigue strength for randomly distributed defects. Information about actual defects in CFRP laminates is used to attempt to reduce the scatter of predicted fatigue life curves by scaling the nominal stresses to a characteristic fatigue strength, represented by an equivalent stress, σ_{equ}. Considering multiple defect regions their combined failure probability using the weakest link theory is expressed as

$$P_f = 1 - exp\left(\int_V \left(\frac{\sigma_{\text{eff}}(F)}{\sigma_0}\right)^{\beta} \frac{dV}{V_{ref}}\right). \tag{2.2}$$

Eq. 2.2 represents a two-parameter Weibull distribution and its parameters are defined in Table 2.1. Simplifying the expression in Eq. 2.2 by

substituting the weighted volume integral with an equivalent stress yields

$$P_f = 1 - exp\left[-\left(\frac{\sigma_{\text{equ}}}{\sigma_0}\right)^{\beta}\right]. \tag{2.3}$$

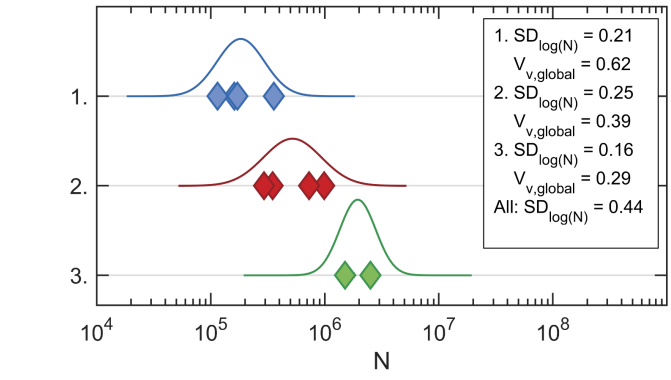
The Weibull modulus, β, weighs the element volume stresses by utilizing an equivalent stress, σ_{equ}. This equivalent stress is used as a reference stress for a characteristic fatigue strength that considers the combined effects of variations in the material. The equivalent stress is expressed as

$$\sigma_{\text{equ}} = \left[\int_V \sigma_{\text{eff}}^{\beta} \frac{dV}{V_{ref}}\right]^{\frac{1}{\beta}}. \tag{2.4}$$

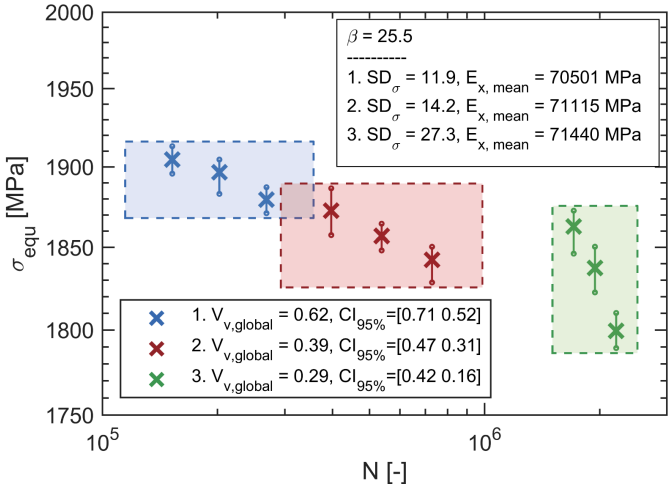
Table 2.1: *Description of parameters in the Weibull weakest link equation, Eq. 2.2.*

P_f	Probability of failure
V	Component volume
F	Fatigue load
β	Weibull modulus
σ_0	Characteristic fatigue strength
V_{ref}	Reference volume
σ_{eff}	Effective fatigue stress

Expressing the material's fatigue strength with an equivalent stress, it becomes evident that a significant variation in the material properties affects the fatigue performance for the numerical simulations. Utilizing the weakest link formulation the combined effects of the introduced defects can be captured and evaluated. Comparing just the characteristic fatigue strength of a material where the global void volume fraction varies, the variations in fatigue strength can be captured and connected to a variation in the fatigue testing results. In **Paper E** the weakest link formulation is used to compare the fatigue strength of three composite laminates with different global void volume fractions. The simulations are conducted for the extracted global void volume fractions and their respective 95 % Confidence Interval (CI) for the three composite laminates. The results are presented in Figure 2.15.



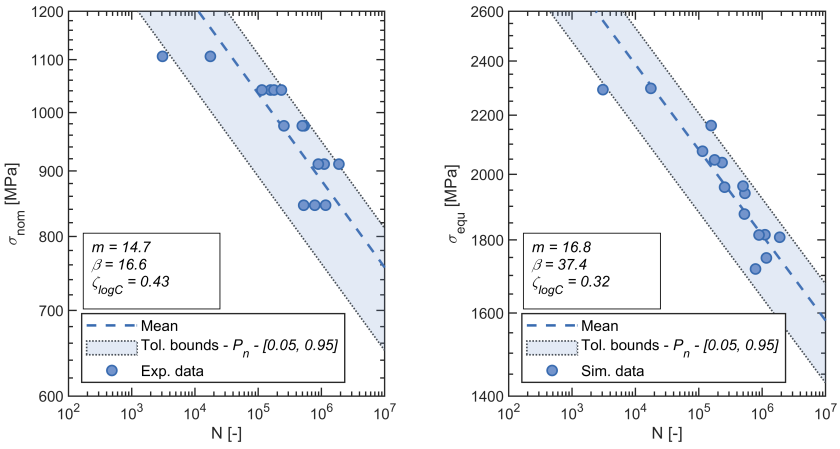
(a)



(b)

Figure 2.15: *Investigating the impact of global void volume fractions (**Paper E**) visualizing (a) the fatigue data at a load level of 70 % of UTS, and (b) the characteristic fatigue strength, σ_{equ}, using a two-parameter Weibull distribution.*

The two-parameter Weibull distribution is incorporated in the weakest link theory, attempting to reduce the scatter in the fatigue life curves by considering actual defects in the CFRP laminates. In **Paper F** experimental data points are matched with representative simulation models based on the probability of failure. A value for the characteristic fatigue strength is calculated using Eq. 2.4 for σ_{equ}. By considering the defects in the materials and calculating the characteristic fatigue strength the scatter decreases by up to 26 %. Utilizing this modeling technique and including the material variability, the scatter is decreased and the fatigue life prediction can be improved. The experimental data points and the numerical simulation results are presented in Figure 2.16.



(a) **(b)**

Figure 2.16: *Investigating the impact of material variability on fatigue life (**Paper F**), (a) the experimental fatigue data, excluding runouts, and (b) the characteristic fatigue strength, σ_{equ}, using a two-parameter Weibull distribution.*

2.5 Modeling and Analysis

For composite structures the constituents are of a much lower order scale than the material and structure; therefore, composite materials can be said to be of a multi-scale nature. Since the many different damage modes for composite materials do not just occur at one length scale, an MSM approach is beneficial for considering the complexity of different damage modes at various length scales. An MSM analysis could provide necessary information for specific criticalities at different length scales to determine under what conditions a structural part would fail [72].

2.5.1 Multi-Scale Modeling

Various MSM methods for composite materials exist and are reviewed in the study by Kanoute et al. [73]. Llorca et al. [74] developed a bottom-up multi-scale simulation strategy for the virtual testing of composites. The modeling has a clear separation of the length scales which is useful when information on homogenized properties at one length scale are to be carried to the simulation at the next length scale. The authors conclude the importance of a numerical design strategy for composites such that they can be tested and optimized before manufacturing. An MSM approach can also include processing parameters, as was done by Tan et al. [75]. The authors accounted for the processing parameters and their effect on matrix and fiber/matrix interface in a micro-scale modeling approach to predict the homogenized ply properties. MSM can also be successfully used for innovative composites such as chopped carbon fiber chip reinforced laminates where the distribution of the chips will affect the fatigue life [76].

A CFRP laminate can be defined by four length scales, excluding nano and atomic length scales. The different length scales are outlined in Figure 2.17. The four length scales are divided into micro-, meso-, macro-, and structural scales. The micro-scale considers the constituents of the composite material: fiber and matrix, and micro-geometrical defects. The constituents of the composite material together form a lamina, which is the building block of the laminate. The current interpretation considers the lamina and laminate at the meso-scale level. A lamina is approximately $0.1 - 0.3\,\text{mm}$ thick, and the laminate can be built up to several millimeters thick. The meso-scale is considered an intermediate scale. This scale is important for composite laminates built with, e.g., weaves, where the fibers' geometrical structure plays an important part in the laminate's stress distribution and damage development. The macro-scale considers the final laminate that sets the basis for components, or in this case; material specimens. The final level is the structural scale where full designs are considered.

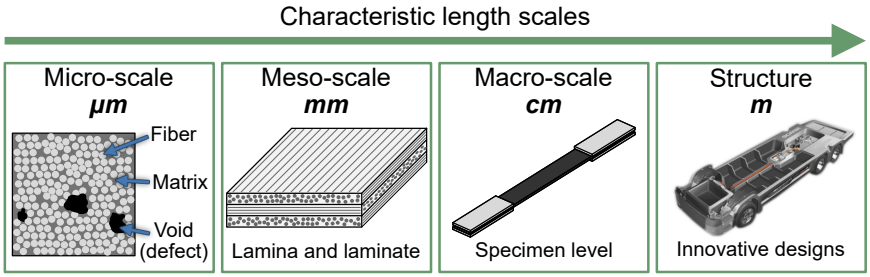


Figure 2.17: *Characteristic length scales for composite materials.*

2.5.2 Micro-Scale Modeling

With the development of computational power the possibility of modeling more complex materials evolves and more details at the micro-scale can be considered. Computational homogenization is a versatile technique to establish the relation of properties between micro- and macro-scales, where the collective behavior of a multi-phase structure is to be predicted [77]. The computational homogenization can be utilized to evaluate the scatter of the homogenized stress distribution defined by statistically characterizing the microstructure and finding the effects of the micro-scale variabilities [78].

It is common to use Representative Volume Elements (RVEs) as a representation of the micro-scale in an MSM approach [79]. The RVE can be seen as a unit cell, and the unit cell should mimic the continuous physical material by repeating itself along three dimensions. Utilizing RVE models allows to account for the complex microstructure of several constituents and extract the homogenized properties [77]. Utilizing this concept for composite materials it is assumed that the average mechanical properties of an RVE are equal to the average properties of the particular composite lamina. The effective macro-mechanical properties of the composite material, which can be transferred to the macro-scale simulations, are calculated using a first-order computational homogenization scheme [80]. The homogenization technique uses the stress field of the RVE that is determined numerically with Finite Element Analysis (FEA). The constitutive equation, in matrix notation, is [81]

$$\bar{\boldsymbol{\sigma}} = \boldsymbol{C}\bar{\boldsymbol{\epsilon}}. \tag{2.5}$$

Where $\boldsymbol{C}$ is the stiffness matrix, and $\bar{\boldsymbol{\sigma}}$ and $\bar{\boldsymbol{\epsilon}}$ are the average global stress and strain values, respectively. The average global values are computed as a volume average of the local stresses and strains from the RVE (Eq. 2.6).

$$\bar{\sigma}_{ij} = \frac{1}{V}\int_V \sigma_{ij} dV \qquad \bar{\epsilon}_{ij} = \frac{1}{V}\int_V \epsilon_{ij} dV \tag{2.6}$$

Where σ_{ij} and ϵ_{ij} are the local stress and strain values of the RVE and V is the volume of the RVE. For an orthotopic laminate there are nine unknown elastic constants to solve: Young's moduli E_x, E_y, E_z, shear moduli G_{xy}, G_{yz}, G_{xz}, and Poisson's ratios $\nu_{xy}, \nu_{yz}, \nu_{xz}$. These are solved through the compliance matrix, $\boldsymbol{S}$, which is the inverse of the stiffness matrix ($\boldsymbol{S} = \boldsymbol{C}^{-1}$).

To solve all nine elastic constants, six different load cases are applied through a set of global strains constituting a Boundary Value Problem (BVP) to be solved [82]. The RVE must be periodic such that displacements and stresses at the boundaries are continuous. This constraint is fulfilled by using Periodic Boundary Conditions (PBCs). PBCs are implemented by connecting two adjacent boundary nodes and ensuring constant displacement between them. With a periodic mesh for the Finite Element (FE) RVE model the equation for the displacements between two nodes on opposite surfaces of an RVE ($i+, i-$) is given by [83]

$$u_j^{i+} - u_j^{i-} = \epsilon_{ij}^0 l_i \quad (i, j = x, y, z). \tag{2.7}$$

Where u_j is the node displacement, ϵ_{ij}^0 is the macro strain tensor and l_i is the length of the RVE. Assuming periodicity, the global strain applied to the RVE can be implemented with the help of the PBCs. If the length of an RVE is constant, $\epsilon_{ij}^0 l_i$ can be exchanged to a displacement $\hat{u}_j^i$.

Analysis of heterogeneous materials commonly uses the concept of RVEs and there are many different techniques to generate an RVE, as outlined in the review by Bargmann et al. [84]. For composite materials, a benefit of using RVEs is to capture the variability of the material and especially the fiber arrangement [85]. RVEs can also consider defects, e.g., fiber undulations [86] and voids [87].

In the present doctoral thesis the fiber distribution in an RVE is generated based on experimental data extracting the first and second nearest neighbour for the fibers in a composite laminate. In **Paper C** an RVE generation algorithm that continuously places fibers within the RVE based on the experimental data is implemented. Utilizing an RVE model and computational homogenization, the effective macro-mechanical properties, or lamina properties, can be calculated based on the constituent properties. In **Paper C** a void is implemented in the RVE such that defects and their effect on the effective macro-mechanical properties can be investigated. The results conclude that it is important to consider the void statistics of the true material when moving to the macro-mechanical modeling, not missing

the effects of a local void volume fraction and the effect that large voids might have on the material properties. Figure 2.18 illustrates the typical micro-modeling setup. In **Paper D** the investigation and statistical analysis of micro-geometrical details are investigated further. To extract data used as input for numerical modeling, a neural network is used to analyze micrographs and extract the data more efficiently.

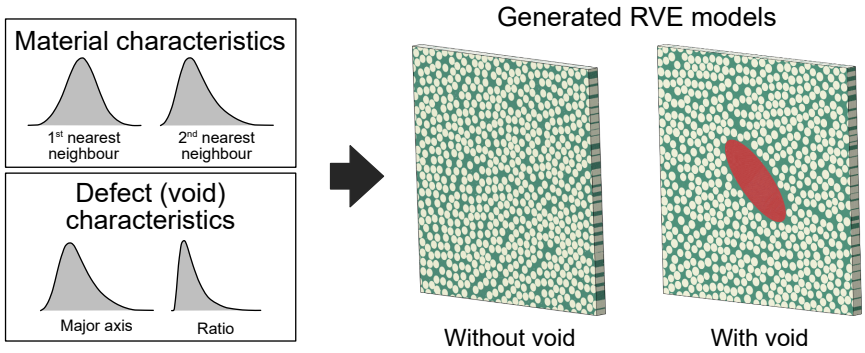


Figure 2.18: *Experimental RVE modeling approach for CFRP laminate (**Paper C**).*

2.5.3 Macro-Scale Modeling

The MSM in this doctoral thesis is carried out by transferring information between different length scales rather than by coupling the different length scale simulations. By only transferring information between the different length scales, the simulations can be rerun without updating simulations from all length scales. This maintains the advantages of each length scale such as the time-efficient macro models and the detailed micro models. The micro-mechanical simulations provide the macro-mechanical simulations with effective material properties that are based on experimental data (Figure 2.19). In **Paper E** and **Paper F** the stress fields obtained from the macro model simulations are the basis for the probabilistic fatigue assessment using the weakest link theory (Section 2.4.1). The macro-scale modeling represents a specimen with the same geometry as the fatigue test specimen.

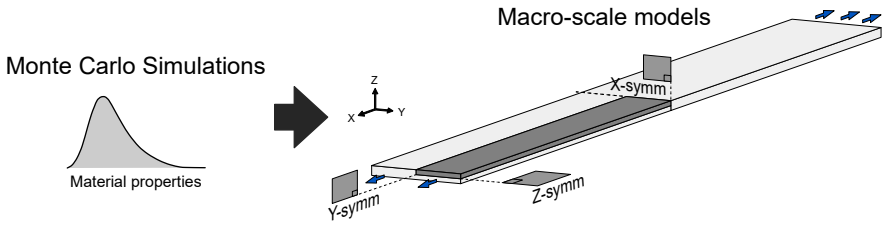


Figure 2.19: *Macro-modeling approach for CFRP laminate (**Paper E-F**).*

Utilizing experimental data to capture material variability the results from the RVE simulations will vary. To capture an overall behavior or trend Monte Carlo Simulations (MCS) are conducted. Using MCS, variations of the macro-mechanical properties based on extracted experimental data can be captured. By randomly varying material properties, best- and worst-case scenarios can be explored and identified in a design process. This is explored further in **Paper F**.

Chapter 3

From Research to an Industrial Modeling Approach

Continuous advancements have been made in the last decades for composite material research. Years of research have led to the understanding of composite material behavior; however, there is still no unity in how to assess the integrity and fatigue life of composite structures. Disruptive technologies such as BEVs generate an opportunity to make innovative changes to an industry working hard to meet climate goals. Meeting the demands for a more sustainable transport industry is not only met by developing the powertrain; it is as important to advance the implementation of new technologies and material research. New advanced lightweight materials, such as CFRP, can reduce weight and impact the complete life cycle of the vehicle. Knowledge and experience from research need to be transferred to those involved in the development so that new innovative solutions and methods can reach the market and challenge the existing technology.

To make composite materials a natural part of the automotive design process, there is not just one encumbrance. There is the challenge of finding its position in the circular economy for a sustainable transport industry [88], the sensitivity of manufacturing methodology on mechanical properties [89], and the many defects that can arise [20]. A step towards enabling the use of composite materials in the commercial vehicle design process is to define a fatigue modeling framework accounting for the uncertainties of composite materials. With a framework, the damage modes can be assessed where or when they are critical.

The composite material variability affects the fatigue behavior and needs to be considered at individual length scales, and by utilizing MSM combined with a probabilistic approach; the material variability can be assessed. The weakest link theory can be used to assess and evaluate the combined effect of randomly distributed defects on the material fatigue strength. The different length scales and how they are defined in a numerical implementation are

presented in Figure 3.1. The complexity of modeling the behavior of composite materials is evident, and the industry needs a generalized approach where in-depth research can be applied further or adapted for different material combinations.

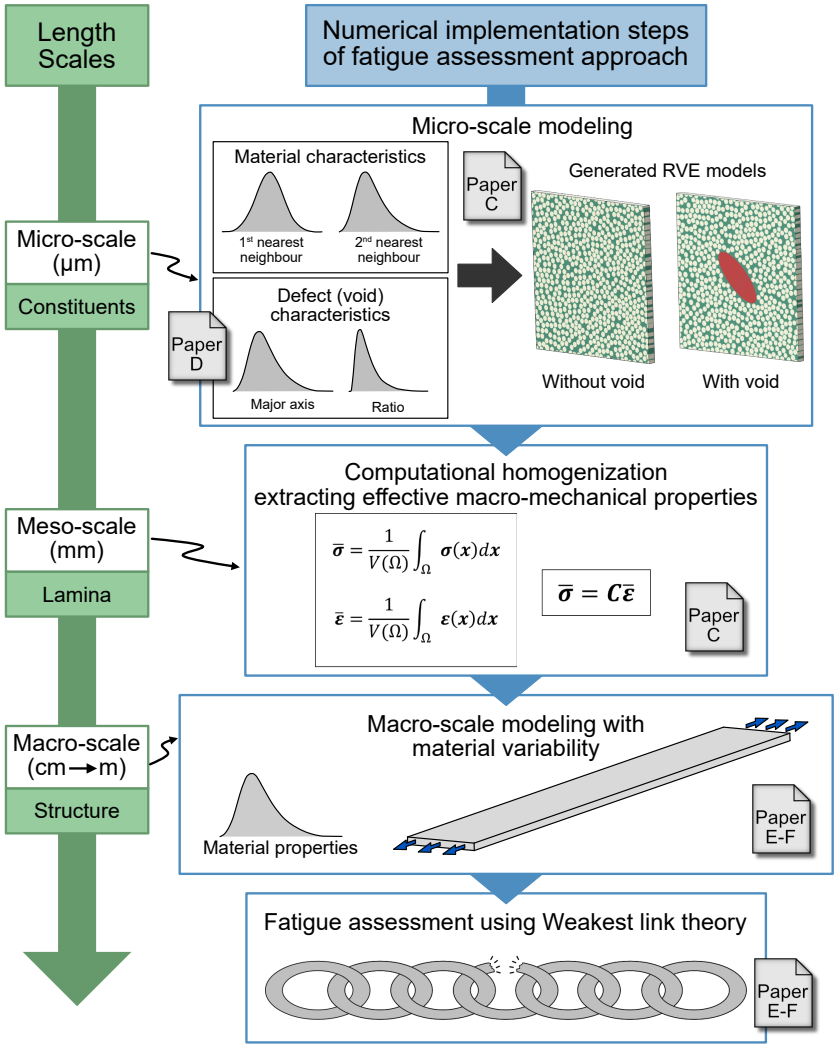


Figure 3.1: *The numerical implementation steps of the probabilistic fatigue modeling framework and how it connects to different length scales of a composite material.*

Chapter 4

Summary of Papers

Paper A

Development of fatigue testing procedure for unidirectional carbon fiber composites

Sara Eliasson, Svenja Wanner, Zuheir Barsoum and Per Wennhage

Procedia Structural Integrity, 2019, Vol. 19, Pages 81-89. International Conference on Fatigue Design 2019, 8th Edition.

Increasing the use of fiber reinforced polymer materials mechanical properties are important to characterize. Characterizing the anisotropic materials in the stronger material property directions might be limited by the weaker material property directions; therefore, setting up a fatigue testing procedure for the strongest material direction maximizes the usefulness of a test procedure. In **Paper A** fatigue testing of a UD CFRP laminate in the fiber direction (0° direction) is conducted and an approach to set up a systematical fatigue testing procedure to find an optimal specimen design for the provided lab environment is proposed. The fatigue testing results are affected by tab configuration, clamping force, choice of adhesive, temperature increase, and more. The proposed test procedure results in fatigue failure of the CFRP material rather than tab failure. A step-by-step procedure is outlined to set up a fatigue testing procedure. A result of the study was a specimen design used throughout the current thesis with failure achieved in the gauge length. Fatigue specimens tested and their respective mode of failure are presented in Figure 4.1.

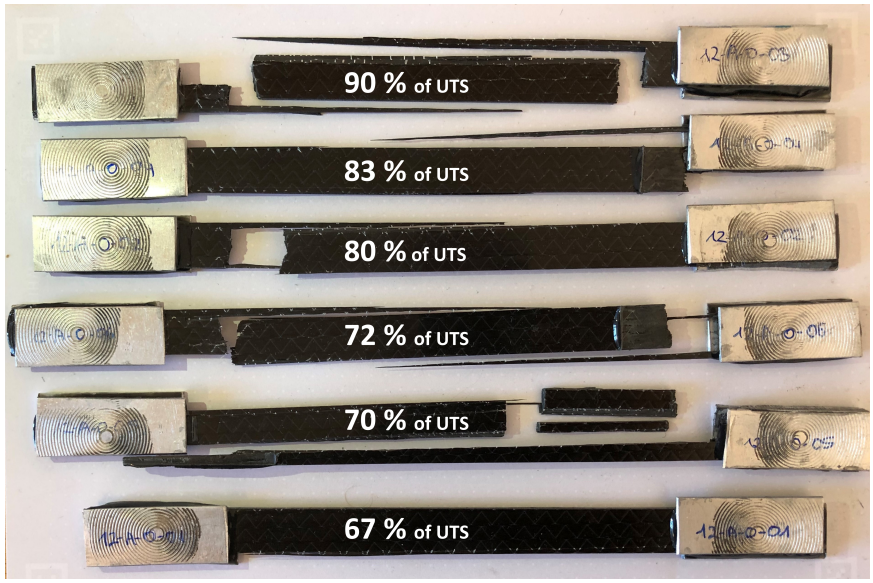


Figure 4.1: *Failure modes for fatigue test specimens loaded at different percentage of UTS.*

Paper B

Fatigue and damage assessment of CFRP material using digital image correlation

Sara Eliasson, Lars Johan Wenner Berg, Per Wennhage and Zuheir Barsoum

Procedia Structural Integrity, 2022, Vol. 38, Pages 631-639. International Conference on Fatigue Design 2021, 9th Edition.

Since fatigue damage development in CFRP can be measured through stiffness loss, a systematic approach is set up to characterize fatigue damage development in a UD CFRP. In-situ surface strain measurements are conducted utilizing a high-speed camera and DIC, investigating the gradual elongation of the specimen during fatigue loading. An automated trigger mechanism activates the high-speed camera at desired cycle counts and the images representing the peak loads are analyzed and compared. The strain measurements reveal that a difference in strain development over time can be connected to a high spread in fatigue testing results and varying failure modes. The strain development is presented in Figure 4.2, showing an initial stiffness degradation of up to 15 % for one of the specimens. The fatigue testing results reveal that the fatigue limit of the UD CFRP can be in the magnitude of 80 % of the material's UTS.

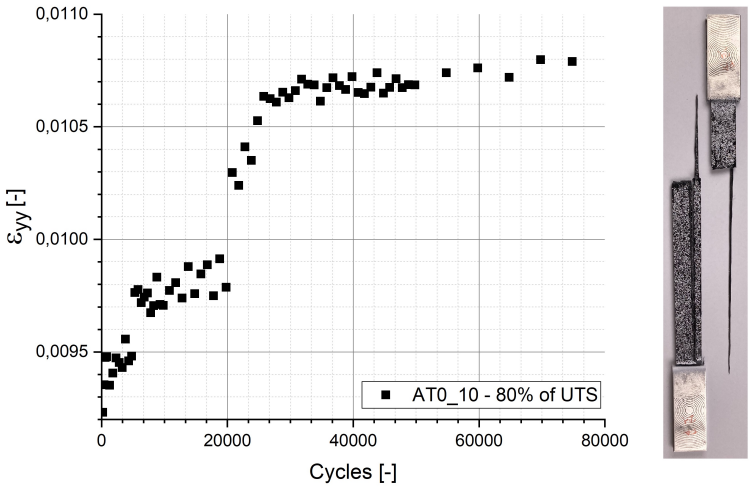


Figure 4.2: *DIC results for average strain in the fiber direction (Y-direction) for specimen loaded at 80 % of UTS.*

Paper C

An experimentally based micromechanical framework exploring effects of void shape on macromechanical properties

Sara Eliasson, Mathilda Karlsson Hagnell, Per Wennhage and Zuheir Barsoum

Materials, 2022, Vol. 15, no. 12

A micro-mechanical simulation approach in a MSM framework is proposed and the main steps of **Paper C** are outlined in Figure 4.3. Using image processing techniques the RVE generation is derived from true micro-mechanical geometry extracted from micrographs. The generated RVE models are used to extract the effective macro-mechanical properties. Manufacturing defects, i.e., voids, are considered in the RVE modeling to investigate the interaction of void shape, void size, void volume fraction, and fiber distribution. The study employs the concept of RVE to bring results from a detailed micro-scale model into an efficient engineering macro-level approach, bridging the gap between manufacturability and micro-mechanical simulations. The implementation of voids is based on extracted statistical data from actual voids in the CFRP laminate. The voids are implemented such that the effects of fiber distribution and voids on the effective macro-mechanical properties can be evaluated. It is important to consider the phenomena of local void volume fraction, void size, and void shape and how they affect the effective macro-mechanical properties considering the overall void volume fraction of an RVE and the actual laminate. The proposed framework has a good prediction of the macro-mechanical properties and shows great potential to be used in a full MSM framework for industrial implementation where weak spots and critical areas for a laminate can be identified by combining the variation of results from the RVE simulations.

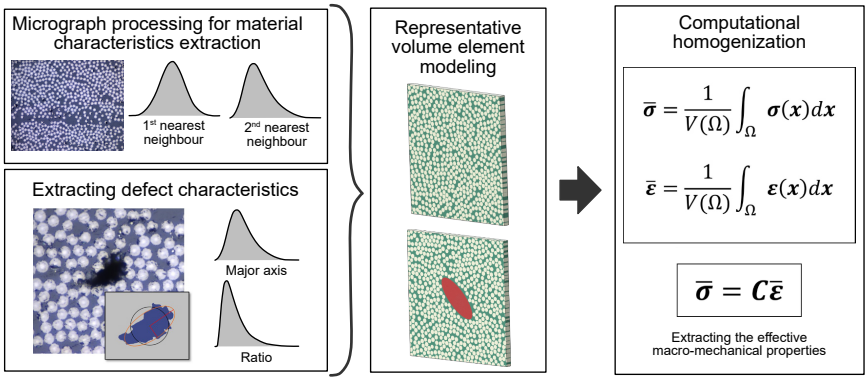


Figure 4.3: *The main steps of the micro-modeling framework.*

Paper D

A statistical porosity characterization approach of carbon-fiber-reinforced polymer material using optical microscopy and neural network

Sara Eliasson, Mathilda Karlsson Hagnell, Per Wennhage and Zuheir Barsoum

Materials, 2022, Vol. 15, no. 19

Manufacturing defects such as voids can dramatically impact the mechanical properties of composite materials and work as initiation sites for damage. To understand the material behavior it is essential to characterize the micro-mechanical composition of the material, both with regards to fibers and defects. An accurate characterization is essential to predict and analyze the mechanical properties. In **Paper D** optical microscopy is utilized to capture the micro-geometrical features, and a neural network is used to extract the material characteristics. The neural network can efficiently segment micrographs and label the constituents: void, matrix, and fiber (Figure 4.4). A neural network minimizes manual labor by automating the process and shows great potential to replace repetitive tasks in a design process saving time. By analyzing the segmented images the constituent fractions can be determined, and a constituent characterization can be performed with high accuracy for a low number of training images. The extracted data are statistically analyzed and if significant differences are found, they could support understanding differences in the material behavior. The global and local void volume fractions show significant differences for the composite laminate used in **Paper D** and are good candidates for explaining material behavior differences.

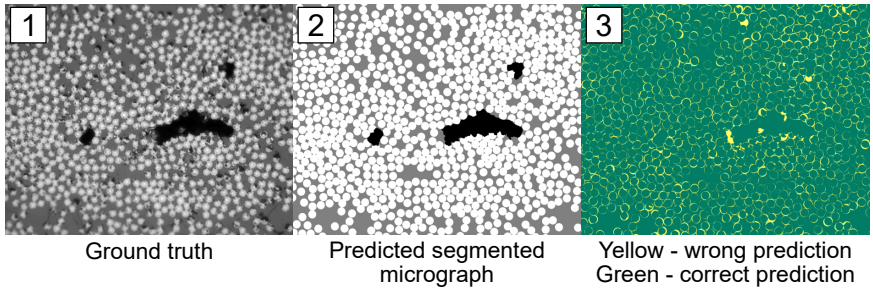


Figure 4.4: *(1) The original micrograph referred to as the ground truth. (2) Results from the neural network, and how it labels the ground truth and identifies voids, matrix, and fibers. (3) How well the network labels the ground truth where green pixels are a correct prediction and the yellow pixels a wrong prediction.*

Paper E

Probabilistic fatigue strength assessment of carbon fiber laminate: exploring effects of manufacturing defects through a two-scale modeling approach

Sara Eliasson, Gustav Hultgren, Zuheir Barsoum, and Per Wennhage

Submitted to international research journal

The study presents a two-scale modeling approach allowing for an efficient fatigue strength evaluation on a macro-scale considering a micro-mechanical defect characterization of a CFRP laminate. The modeling approach integrates a macro model with the effective elastic properties from micro-mechanical simulations considering voids. Maintaining the global void volume fraction of the CFRP laminate and using a probabilistic weakest link approach enables the analysis of defects' influence on material fatigue strength. A CFRP laminate with a cross-ply layup was investigated and the material variability was modeled and captured at the macro-scale (Figure 4.5). A fatigue testing investigation was conducted to verify the predicted numerical behavior and the numerical models identified a difference in the characteristic fatigue strength consistent with the fatigue test results. It is numerically concluded that the investigated CFRP material's fatigue strength is affected by the presence of voids. Even with only a slight difference in the global void volume fraction a scatter in fatigue strength is identified.

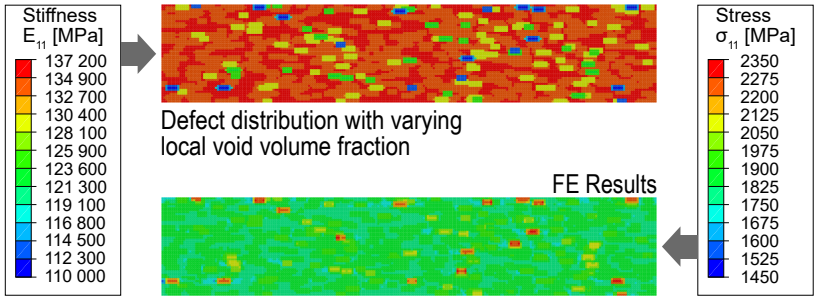


Figure 4.5: *Implementation of the material variability in the macro model using defect volumes that represent local defects. The material stiffness, E_{11}, and stress, σ_{11} is presented for one of the 0° layers in the FE macro model.*

Paper F

Numerical fatigue assessment of carbon fiber reinforced polymers using a probabilistic framework

Sara Eliasson, Gustav Hultgren, Per Wennhage and Zuheir Barsoum

Submitted to international research journal

A probabilistic framework is developed utilizing a two-scale modeling approach to efficiently consider the material variability typical for composite materials. The modeling integrates a macro-scale model with effective elastic properties extracted from micro-mechanical simulations. Using a weakest link modeling approach for fatigue assessment the combined effects of defects on fatigue strength in a CFRP laminate can be investigated. A full fatigue test program is presented and used to calibrate the probabilistic fatigue model. Three simulation Case Studies (CS) are analyzed where simulations are ranked and matched with experimental data points based on three different Weibull moduli for the equivalent stress calculations. A reduction of scatter is desirable when scaling the nominal stress from the experimental data to get the equivalent stress. The standard deviation, $\zeta_{\log C}$, is optimized and for the first case study, CS-I, a minimum is found within a reasonable range of β, while the other case studies move towards a single value problem formulation (Figure 4.6). The calibrated model shows a reduction in scatter of the fatigue results and the developed probabilistic modeling framework reveals promising results of being effective and streamlined for industrial implementation.

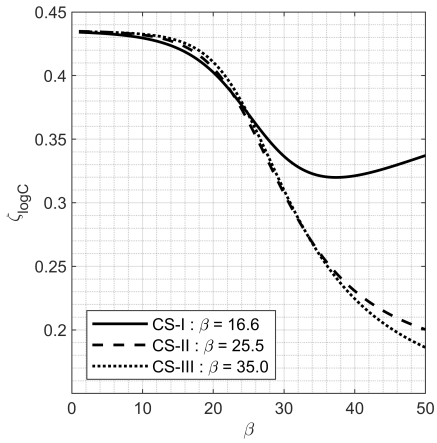


Figure 4.6: *The Weibull modulus, β, as a function of the standard deviation, ζ_{logC}, for three simulation case studies.*

Chapter 5

Conclusions

CFRP has been introduced as an advanced lightweight material with a high strength-to-weight ratio and great fatigue properties. The impressive material properties make it easy to be optimistic about the implementation possibilities for this material. Nevertheless, in metal-dominated industries such as the commercial vehicle industry, composites need to demonstrate the advantages in the competition against metal design. An ideal design should exploit the best characteristics of materials for a given application and use the right material in the right place. A vital requirement to evaluate different materials in a time-critical design development process is numerical simulation methods.

Commercial vehicle components are mainly designed and dimensioned for fatigue loading. Therefore, the current doctoral thesis is centered around developing a framework for fatigue life modeling and analysis of composite materials. The framework should encourage the use of composite materials in engineering designs and structures. The numerical models must be efficient, accurate, and straightforward to use early in the design process. The research presented in this thesis aims to answer the posed research questions and objectives and is the basis for the developed framework.

To model a specific material behavior, the typical behavior needs to be characterized. Commencing the development of a fatigue modeling approach of composite materials necessitates an initial investigation of fatigue mechanisms and the degradation of fatigue-induced damage. This is addressed in **Paper A** and **Paper B**, which aim to provide broader conclusions for **RQ4** listed below.

- When characterizing composite materials, choosing a robust specimen configuration is important. For fatigue testing of anisotropic materials, weaker material directions must be carefully addressed not to affect the testing of the stronger material directions. The specimen configuration involves accurately selecting tab configuration, tab material, adhesive, and clamping pressure. With a stable testing procedure, failure in the gauge length can be achieved.

- Testing a unidirectional CFRP at a load level of 80 % of UTS results in a high scatter in the fatigue test data. The high variability can be connected to the damage development and damage modes. The damage can also be related to the initial stiffness loss of the specimens.

- For a unidirectional laminate that is loaded in the fiber direction the scatter is remarkable. The influence of the variation in fiber strength has an important role, and the behavior could be connected to Region I in the typical fatigue life curve (Figure 2.7) where fibers carry the load. Loading laminates in this region comes with great risks.

Paper C and **Paper D** contribute with conclusions for **RQ3**. A methodology to analyze the mechanical properties utilizing numerical simulations is attempted. The conclusions are listed below.

- Utilizing RVE models the effective macro-mechanical properties of composite materials can be determined using only the constituents' properties. Generating the RVE based on experimental data makes it possible to consider the micro-geometrical variations that could be important for the behavior of the composite laminate.

- Considering a composite laminate's global void volume fraction, the individual voids are important and can greatly affect the local mechanical properties. The phenomena of local void volume fraction, void size, and void shape and how they affect the effective macro-mechanical properties are important in investigating design limitations and material quality demands.

- Statistical investigations and conclusions regarding the porosity of composite materials can help explain the mechanical behavior and can be used in numerical modeling to predict material characteristics. It can also be used for deciding material quality regulations. The global and local void volume fractions can be used to explain differences in material behavior.

- A micro-scale modeling framework supports the characterization of material properties numerically and has the potential to be used in a larger MSM framework. Utilizing RVE simulations connected to experimental investigations helps to bridge the gap between manufacturability and micro-mechanical simulations for industrial implementation.
- A continuous development and improvement of numerical methods is important to keep up with the short development times. Utilizing neural networks can help streamline work requiring a large amount of data processing, and repetitive manual processes can be made more efficient.

Experimental investigation and material characterization simulations underlie the continuation of addressing **RQ1** and **RQ2**. The final studies in **Paper E** and **Paper F** apply a probabilistic modeling approach for fatigue assessment of a CFRP laminate. Conclusions that can be drawn from the studies are listed below.

- It can be numerically concluded that the investigated CFRP laminates are affected by defects, i.e., voids. Considering the voids as defect volumes in a macro model maintaining a given global void volume fraction and using a probabilistic approach, the fatigue strength for randomly generated specimens can be predicted.
- By incorporating uncertainty into the numerical model to capture the typical variability of composite materials, design criteria can be identified that consider defects and support the manufacturing quality demands that are set for composite materials in a design development process.
- Utilizing a Weibull distribution in a weakest link formulation to consider the combined effects of the material variability of CFRP, the fatigue life can be evaluated using a characteristic fatigue strength in an MSM framework. Considering voids as a material variation in a macro model, the scatter of the numerical results can be significantly reduced compared to the experimental data supporting the fatigue life prediction methodology.
- A probabilistic modeling framework for fatigue assessment shows great potential; it is efficient and captures a variation in the behavior of typical anisotropic materials. Utilizing the two-scale modeling approach offers many modeling possibilities. Numerical simulations and experimental investigations at each scale can be exchanged or extended to consider more or other types of defects and damage modes.

Chapter 6

Contribution to the Research Field

The current work puts special attention on presenting a fatigue modeling framework that is applicable and accessible for the industry. It shall be modular and easily adaptable to specific material combinations and loading conditions. In order to formulate a modeling framework many studies are conducted and the main work is present in the appended papers. The major contributions to the research field are highlighted below.

- Development of a modeling framework for fatigue assessment of composite materials. The framework is developed to be suitable for industrial implementation and is a basis for continuous development.
- The implementation of numerical probabilistic modeling and the novel use of the weakest link theory for composite materials.
- Development of a two-scale modeling approach that transfers information between length scales and captures the material variability of typical composite material.
- The production of fatigue test data and material characterization through experimental investigations are available for the international research community.

Chapter 7

Future Work

The next step of the research would be to utilize the developed methodology and framework for an actual composite component. When implementing the framework a natural part of the development process would be to investigate and find out what is missing and what information would be necessary for the given problem formulation. Further developments would be to investigate more defects, other damage modes, and other loading conditions and continue to develop the modeling approach.

Since sustainability is escalating through the industries it is important to consider the sustainable aspects of design and materials. With regard to material choice, there are better options than carbon fiber/epoxy from a sustainability perspective. Thermoplastics are more suitable based on recyclability and natural fibers are less energy demanding to produce. Considering other material combinations than CFRP it could be investigated if they could be applicable to the developed framework.

The continuous improvement and development of simulation methods are important. Computational power increases and as the computational time is reduced it leaves room for more and more advanced simulations. A proposal for improvement is the RVE modeling. The analysis of varying the RVE model parameters and interpreting the results demands many simulations and large amounts of information to process. This process can be enhanced by using a metamodel to replace the RVE simulations, saving a great amount of computational resources. The results can be analyzed using global sensitivity analysis to interpret the variation of the results, as proposed in [90]. With evolving technology it is important to explore and not limit the development to what is familiar. There are great possibilities to automate repetitive tasks and use machine learning in simulation methods to increase efficiency and accuracy.

With the new technology being developed and the transport industry moving towards digitalization, automation, and electrification, it is essential not to get stuck in innovation and consider only one part of the system. Future aspects can include, e.g., cost, circularity aspects, or other areas of applications. There is a growing significance to conscientiously preserve the planet's resources. It is important not to take the same steps as last time in the development process and instead introduce new techniques that open up new opportunities and new innovative designs. If we limit ourselves, we disconnect from the opportunity to learn more and to move with the forefront of material research.

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Appended Papers