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# Abstract

The understanding of damage progression in dynamic-cyclically tested short-fibre reinforced plastics can be improved by the development of damage accumulation models that consider the load history and sequence of loads subjected to the material. In this paper, the nature of damage progression is analysed with the help of dynamic-cyclical fatigue tests conducted on specimens made of polybutylene terephthalate with 30 wt. - % glass fibres. Using the data, a new strain-based damage accumulation model is developed which aims to make good service life predictions while considering the effect of load history and sequence of loads. Subsequently, damage accumulation tests with four separate load phases are conducted, the new model is evaluated, and suggestions for improvement based on the analysis and evaluation are made.

# Zusammenfassung and Summary

## Zusammenfassung

Deskriptoren:

Schlagworte:

## Summary

Descriptors: Short-fibre reinforced plastics, fatigue, damage accumulation, dynamic testing, Wöhler curves, strain

Keywords: ...

At least one picture!

Problem –

When designing components made of out short-fibre reinforced plastics (SFRP), the best possible compromise between durability and safety and lightweight construction is sought. It is therefore important to understand how damages accumulate in the material and when the material is likely to fail. Since damage accumulation in SFRPs is non-linear and the sequence of load phases has an influence on the service life of the material, this should be considered in the damage accumulation model.

Goal –

The first goal of this work is to better understand the nature of damage progression

The second goal is to develop a new damage accumulation model which delivers accurate service life predictions for material samples subjected to varying load conditions within the same test.

Path towards goal –

Literature review

Fatigue tests

Damage accumulation tests

Most important results –

Strain correlating with the maximum stress

Frequency had an effect on the specimen temperature and the viscoelastic behaviour of the material

Stress, or rather, maximum force primary factor in determining the service life.

Damage accumulation tests with high loads later in the test broke earlier than when the high load was at the beginning

Purely based on strain does not work – speculation that critical strain bzw. A certain line plays a deciding role

Use and Application of the Results –

Model developed fell short in terms of results

but suggestions made with the help of the data analysis and model evaluation. New ideas

Goal, research here helps develop a more accurate damage accumulation model – a energy- and strain-based suggestion is made.

# Introduction

Das Ziel von Leichtbau ist es, das Gewicht eines Bauteils maximal zu reduzieren und gleichzeitig die Sicherheit und Leistungsfähigkeit zu gewährleisten. Es gibt Material mit einer geringen Dichte, Bauteiloptimierung, Verfahrensoptimierung

Vorteile bzw. Begründung von kurzfaserverstärkten Kunststoffen

Um auf die Vorteile von kurzfaserverstärkten Kunststoffe aufzubauen, wird eine effiziente Bauteilauslegung angestrebt. (⅓ einer Seite sollte ausreichen)

Materialuntersuchung, Verständnis der makroskopischen Versagensursache = Lebensdauerprognose. Da aber nur im Labor dauerhaft die selbe Kraft bei selber Frequenz, Schadensakkumulation - wie die Reihenfolge der Belastung eine Auswirkung hat auf die Lebensdauer.

Ansatz - mechanisch/mathematisches Modell um die Lebensdauer abschätzen zu können unter Berücksichtigung der Frequenz, Spannung, Temperaturerhöhung, vorherige Schadenspunkte.

Basiert auf 90 Grad Daten, bei dem die Kräfte durch das Matrixmaterial geleitet werden. Anschließend ein Vergleich mit 0 Grad - Kraft anders durch das bauteil geleitet. Anpassung basierend auf Faserorientierung (Ergebnissen eines CT Scans) als möglicher Vorfaktor.

Abgleich mit Versuchen eines anderen Materials?

Ergebnisse auf mehr Bauteile uübertragen zu koönnen, Bauteile - 3D Rippenbauteil im 3 Punkt Biegeversuch. Simulation - sowohl die Stellen des Versagens (Tsai-Hill Kriteriums), als auch die Anzahl der Zyklen, basierend darauf wie die Kraäfte in der Simulation durch das Bauteil geleitet werden, wie die Faserorientierung im Bauteil ist und an welchen Stellen das Bauteil mit einer maximalen Spannung konfrontiert wird.

[1-2 Seiten]

Die Einleitung als Erläuterung zur Problemstellung ist je nach Art der Arbeit (Literaturrecherche, praktische oder konstruktive Arbeit) mehr oder weniger ausführlich, jedoch grundsätzlich in kurzer, prägnanter Form abzufassen. Ziel ist es, dem Leser den Einstieg in das Problem zu ermöglichen.

|  |  |  |
| --- | --- | --- |
| **Kennwert** | **Material 1** | **Material 2** |
| A | 10 | 100 |
| B | 20 | 200 |
| C | 30 | 300 |
| D | 40 | 400 |

*Tabelle 3.1: Beispieltabelle*

|  |  |
| --- | --- |
|  | *(Gl. 3.1)* |

# State of the Art

The main challenge in laying out load-bearing mechanical components is ensuring that the component can safely and durably withstand the loads and conditions to which it is likely to be subjected while being as light as possible. Since the load conditions for most components vary during use and material fatigue is non-linear, the load history and sequence of load phases should be considered when predicting the service life and describing the fatigue progression of a material or component. The following section highlights the properties of and explains the need for reliable fatigue and damage accumulation models for components made of short-fibre reinforced plastics (SFRP).

## Material Properties of Short Fibre Reinforced Plastics (SFRP)

Fibre-reinforced plastics have been gaining importance for many years. Before the spread of the COVID-19, a 6% global year-over-year growth was forecast for thermoplastic composites for the year 2020 (a 6% higher growth than in the previous year) [Tec19]. Fibre-reinforced plastic have a high potential for lightweight construction due to their good mechanical properties and comparatively low density [KVI Buch].

### Classification and Mechanical Properties

A fibre-reinforced plastic consists of fibres embedded in a polymer matrix material. The fibres absorb the majority of the force introduced into the component and are responsible for the high stiffness and strength of the composite [FLM09]. The Young's modulus of glass fibres is similar to those of aluminium and titanium – R-glass: 86-87 GPa, aluminium: 70 GPa, titanium: 110 GPa [Hop16], [HM17], [Kuc11].

The functions of the matrix are to hold the fibres in place, to transfer force to the fibres, to provide stability to the composite under compressive loading, and to protect the fibres from environmental influences [Hop16]. To model a composite, elastic behaviour is attributed to the fibres and viscoelastic behaviour to the matrix material [Kai13].

At the boundary of matrix and fibres there is a small interphase, a thin layer of matrix material with a higher Young’s modulus than the rest of the matrix [Sch17]. The interphase is formed when the material freezes after the component has been shaped. The fibres act as a nucleating agent, resulting in increased degree of crystallinity close to the fibre (shown in figure 6).

The material properties depend on the fibre and matrix material, the fibre orientation, the fibre volume content, the fibre length distribution, the fibre/matrix adhesion, and the manufacturing conditions [FLM09]. The fibre length also plays a decisive role and influences the stiffness, strength, and impact resistance [HM17]. A distinction is made here between short fibres (< 1 mm or < 5 mm, depending on the source), long fibres (1 or 5 - 50 mm) and continuous fibres (fibre length corresponds approximately to the component length) [HM17]. A higher aspect ratio (ratio between length and diameter of the fibre) leads to higher strength [HopKVII]. Different manufacturing processes are used to make components of different fibre lengths. Generally, the longer the fibres, the more expensive the component becomes due to less automatable and more time-consuming production methods [HM17]. A small overview of the properties of different fibre lengths is shown in figure 7.

Short-fibre reinforced plastics (SFRP) have the significant advantage that they can be injection moulded. All the advantages of the injection moulding process – low cycle time, high functional integration, high reproducibility, and high automation – reduce the price of the components and make SFRPs practical and profitable for large-scale production (e.g., in the automotive industry) [HM17]. (The composite used for this paper will be introduced in section 5).

### Anisotropic Properties

Fibre-reinforced plastics have anisotropic mechanical properties due to locally different fibre orientations – strength and stiffness are higher parallel to the fibre orientation than perpendicular to it. [AT87, Hop16]. The relationship between the material strength and the angle between force direction and fibre orientation is shown in figure 8. When making more complex components with long or continuous fibres, fibres can be placed in predominantly one direction, thereby optimising the component mechanically and maximising the lightweight potential. In components with short fibres, the fibre orientation is created during injection moulding. Three characteristic layers are formed (as shown in figure 9). In the middle layer (core zone), the fibres are oriented perpendicular to the flow direction because the shear rate in this area is almost zero. In the outer layers near the wall of the mould (shear zones), the fibres are predominantly oriented in the flow direction due to the steep velocity gradient [Kai13, Sch17]. In the immediate vicinity of the wall, the melt freezes very quickly on contact with the mould wall, resulting in a very thin layer with no discernible orientation on the component surface [HopKVII]. The relative size of the middle layer can be influenced by changes in the injection moulding parameters, but generally decreases with increasing distance from the injection point [Kai13, Sch17]. By means of filling simulations and micromechanical material models, it is possible to estimate local mechanical properties as a function of fibre orientation and fibre length. Nevertheless, fibre composites are often homogenised or modelled with a global fibre orientation for simplification. Alternatively, the locally different fibre orientations of SFRPs can be determined numerically with good prediction quality with the help of fibre orientation tensors according to Advani and Tucker [AT87].

### End of Life Options

It is important to justify the selection of a material environmentally as well as technically and economically. The processing temperature of fibre-reinforced plastics is several hundred degrees lower than the processing temperature of aluminium or magnesium alloys, two materials often used in lightweight production, thus requiring less energy during production. Since injection-moulded components usually require little to no post-processing, the production of a component is often completed after one step. \*\*\*

SFRPs can be economically mass produced. This makes it possible to use components made of SFRPs in cheaper cars, among other things. This makes the lightweight construction potential of SFRPs more accessible and suitable on a larger scale. Components made of SFRPs are not short-lived disposable products and can help save resources and energy over the course of their use.

The images of oceans littered with plastics are well known and show how important concrete end-of-life solutions for plastic products are. Take-bake legislation and various recycling laws are increasing the likelihood that technical components made of plastics will not simply be thrown away but will be professionally reprocessed [Hop16]. In this respect, there is still a need for research and development for the reuse and recycling composites containing glass fibres. An example of material recycling can be found in cement plants, where fibreglass composites are used both energetically as a coal substitute and materially as a sand substitute. The development of new recycling possibilities is slowed down by the fact that it is not financially lucrative to use recycled plastics, as virgin plastics and raw fibres remain cheap. Theoretically, fibre-reinforced plastics are well suited to be used as fuel in waste incineration plants. However, the glass fibres are a burden on the plants' filter systems and can vitrify the combustion chamber. It is also difficult to burn 100% of the material and unburnt residues often remain in the ash [Neo18]. Overall, the use of SFRPs can be ecologically justified when compared to similar materials. However, there is still a need for research and development on end-of-life recycling solutions.

## Modelling and Predicting Material Fatigue

Components made of SFRPs are typically exposed to cyclical, dynamic loads in use. In order to simplify, accelerate, and optimize the design of a new component, it is helpful to be able to make estimates about the fatigue and damage progression. The aim is to design components safely without compromising the lightweight potential.

### Setup of Fatigue Testing

To collect fatigue data, standardised specimens are subjected to fatigue tests under a series of stress conditions. For anisotropic materials such as fibre-reinforced plastics, specimens with at least two fibre orientations are tested [Dah17]. The (maximum) stress [N/mm2] is plotted against the logarithm of the number of cycles to failure (NB) in what is known as a Wöhler curve.

Fatigue testing is divided into three sections: short-term strength, fatigue strength, and endurance strength. The three sections are separated by the number of oscillations until material failure, as shown in figure 10. The area of short-term strength represents stress levels that would result in exceeding the yield point during tensile testing. In the area of fatigue strength, a correlation between maximum testing force and the number of oscillations until failure can usually be observed. Given a constant stress amplitude, the material will eventually fail. As of roughly 106 load cycles (depending on the source consulted and material being tested), the material is in the area of endurance strength, where it is said not to break given the load conditions. The stress at which 106 load cycles are reached is considered the fatigue limit [Stu15].

As a rule, specimens are tested with stresses that result in fracture load cycles between 103 and 106 – the area of fatigue strength [Dah17, FMK15]. Wöhler curves are helpful in making sure a component is designed with an appropriate safety factor. However, it makes it difficult to maximize the lightweight potential [Stu15]. The safe dimensioning of thermoplastic components is further complicated by the fact that the load conditions, manufacturing process, as well as external influences and boundary conditions have varying, non-linear influences on the service life. Figure 11 shows some of the key properties and external conditions that influence the number of expected loads until failure [Dah17].

### Specimen Heating during Testing

When interpreting fatigue test results, attention must be paid to the type of failure and a differentiation must be made between a break caused by mechanical damage and a thermal fracture. Fatigue tests require that failure be caused by mechanical fatigue. In the case of a thermal fracture, there is a rapid increase in the temperature of the specimen, which causes the plastic to ‘soften’ [Dah17]. According to [FMK15], the chance of a thermal fracture increases sharply from a temperature increase of about (assuming ambient temperature is 23°C). The test conditions should be chosen so that the heat can be removed by convection and the temperature can stabilise at a . In [FMK15], two formulas are presented that allow an estimation of temperature rise depending on either the frequency and the hysteresis or stress and strain amplitude. In [MHM+11], a similar approach is presented in the form of a heat balance for calculating the amount of heat dissipated to the environment based on testing variables and material properties. The three formulas are shown in image 12.

### Types of Fatigue Models

[Bau17] lists three types of fatigue models: time strength models, phenomenological models and fracture mechanical models. Time strength models only consider the number of cycles until failure, NB. The non-linear nature of damage progression is not taken into account [Bau17]. This non-linear progression of the mechanical properties during a fatigue test can be observed in the form of strain relaxation, a 'softening' of the material and, under some conditions, a changed strain behaviour due to self-heating [SSS17].

In phenomenological models, the stiffness and strength degradation of the material are taken into account on a macroscopic level (order of magnitude: 10-2 m). Such models are oriented towards measured mechanical properties such as strain, stress, dynamic stiffness, and viscoelasticity – these can usually be measured during the ongoing test [Bau17]. The new damage accumulation model developed in this paper is a phenomenological model.

Fracture mechanical models attribute material failure to an accumulation of microscopic damages. At the microscopic level (order of magnitude: 10-6m), material behaviour can be modelled by creating small representative volume elements (RVE), where fibres, interphase, and matrix are differentiated [Bau17]. Each RVE is assigned mechanical properties dependent on the local fibre orientation and is mechanically and thermally coupled to the neighbouring RVEs. Such models are of great scientific interest – they make it possible to analyse deformation, fatigue, and failure in more depth and to localise possible failure locations more precisely [Kai13, Bau17]. Fracture mechanical models require a higher understanding of materials and are often associated with more complex simulations. Some interesting examples of micromodels of short-fibre reinforced plastics in recent years are [Gün13], [Kai13], [Bau17] and [Sch17].

Furthermore, there a many different hypotheses as to when material failure occurs. These can be separated into models based on fracture mechanics and models based on stress and strain. The models based on stress and strain can further be divided into models with lump sum failure criteria and models with more differentiated failure criteria. Among the models with lump sum failure criteria, the Tsai/Hill and Tsai/Wu criteria have proven most reliable, partly because they consider the influence of the fibre orientation and fibre-matrix interactions on material failure [Vog16].

### Examples of Fatigue Models

[SSS17] compares different phenomenological life models in tests using a PEEK thermoplastic. The strain-based Coffin-Mason model uses the elastic and plastic strain components at the midpoint of the life (n = NB/2). It shows a correlation between the strain amplitude and the logarithmic number of loading cycles until failure but is not suitable for tests with varying loads. The SWT fatigue model uses the information from the stabilised hysteresis at n = NB/2, but in addition to strain, stress is also considered.

Two energy-based models achieve the most accurate predictions in the tests conducted by [SSS17]. The first model applies strain energy density data at n = NB/2 (as in the Coffin-Mason and SWT models). The information is taken from the middle of the test where the progression of measured data such as strain or dynamic stiffness is quasi-linear. Thus, it does not take into account the non-linear degradation stages at the beginning and end of the test. One way the non-linear nature of fatigue manifests itself is in what [SSS17] call the ‘mean stress relaxation phenomenon’, whereby the hysteresis shape changes during the course of the test as the material dissipates more energy per load cycle. (The non-linear nature of fatigue progression will further be discussed in section 5). The second model takes into account the non-linear progression of degradation by summing up the strain energy density of all loading cycles until failure. In the tests of [SSS17], the highest prediction quality was achieved with this summation model. The main advantage of the energy-based systems is that the entire load cycle is considered with the help of hysteresis and not only the stress and strain extremes.

Further strain, stress, and energy-based models are compared in [SMS+20], on the basis of tests conducted with short-fibre reinforced PA66 with 50% glass fibre content. As in [SSS17], the energy-based models generally perform slightly better than the strain-based models. The Raphael et al. model looks at the energy density from the hysteresis as well as the mean value of the strain. It shows that certain ranges can be represented differently well by the two variables considered. [SMS+20] then presents the IDAFIP model developed in that paper. This model takes into account creep energy density and cyclic energy density. It is relatively simple and does not require much experimental data (one test temperature, two fibre orientations) to achieve very good predictions.

With tests on a PA6-GF35 and a PBT-GF30, [FMK15] investigates the influence of frequency, self-heating, anisotropy, humidity, temperature, strain amplitude, strain concentration, stress ratio, and notch effect on fatigue behaviour and service life. [FMK15] develops its own model for fatigue tests under constant test conditions, which includes the stress conditions, fibre orientations as well as adjustable material parameters.

A limiting factor for many fatigue models is that they only provide good predictions for specimens experiencing tensile testing (R > 0) [SMS+20]. The Walker formula makes it possible to quantify the influence of the strain average and stress ratio R [FMK15].

## Damage Accumulation

The previous section discussed the difficulties in making accurate service life predictions over a wide range of testing conditions. Wöhler curves help display the relationship between the maximum dynamic stress and the decadic logarithm of the number of load cycles until failure NB. Even under controlled laboratory conditions with the same stress, loading frequency, and chamber temperature, the results (cycles until failure) scatter. The Wöhler curve is the result of the best possible compromise of all test data and should not be viewed as more than a reasonable estimate.

The test conditions under which the data for Wöhler curves are collected are not what a SFRP can realistically expect to be subjected to. A SFRP component installed in, for example, an automobile is exposed to fluctuating temperatures, varying stresses and load amplitudes, as well as notch effects and much more. This leads to a non-linear accumulation of damage in the material.

### Necessity of Damage Accumulation Models

The aim of a damage accumulation model is to predict the service life of components under varying test conditions. In particular, the influence of the loading history and the sequence of loading phases on the service life should be taken into account. A damage accumulation model works by summing up all individual damage factors di. A model predicts failure when the sum of all the damage factors reaches 1, as shown here:

|  |  |
| --- | --- |
|  | *(Eqn. 4.1)* |

If the actual number of cycles achieved is calculated in the model with a D > 1, the sample or component has withstood more cycles than predicted. This is known as a safe (or conservative) estimate and is generally preferable to an overestimation of the service life (if the number of cycles until failure results in a D < 1).

The fatigue behaviour of fibre composite plastics is non-linear even under constant loading conditions. The need to consider the loading history and sequence of loading phases is demonstrated in experiments described in [RCR12]. In these experiments, steel specimens are loaded at a constant frequency of 5 Hz in five phases with different levels of stress (5000 cycles each per loading phase). The results show that the samples stabilised at a higher temperature at the same stress and frequency when they had undergone a larger preload. The sequence of loads was also shown to have an effect on the temperature change of the specimen compared to ambient temperature [RCR12]. Small temperature differences can have a noticeable difference on the number of cycles to failure, especially with temperature-sensitive materials such as thermoplastics. Furthermore, gradual temperature changes indicate changes in the viscoelastic behaviour of the material, which in turn indicates material fatigue. It is therefore apparent that the sequence of load phases has an impact on the rate of fatigue.

### Examples of Damage Accumulation Models

In the following, some linear and non-linear damage accumulation models are presented and briefly explained. In section 6, the new damage accumulation model will be compared with a few of the models introduced in this section.

The best-known and simplest damage accumulation model is the Palmgren-Miner model from 1945. It is based exclusively on the results of Wöhler tests and is described by the following formula:

|  |  |
| --- | --- |
|  | *(Eqn. 4.2)* |

ni are the cycles the material is tested at a given stress and NB,i are the cycles until failure at the same stress (shown in figure 13). This model makes no use of material-dependent properties and does not take into account the loading history or the sequence of loading phases. The prediction quality is unreliable [Vog16]. As a linear model, it is not suitable for capturing the complex non-linear fatigue behaviour of a thermoplastic. In most cases, the Palmgren-Miner model estimates the service life rather conservatively (the service life is underestimated). For lower loads, acceptable predictions can be made with the Palmgren-Miner model, according to [RCR12], and it is precisely because of its simplicity that the Palmgren-Miner model is often used as a means of roughly estimating service life.

Several adapted versions of the original Palmgren-Miner formula have been introduced since. Models such as the 'Miner elementary' and the model according to Haibach follow the same course as the original model until the fatigue limit is reached. For stresses above the fatigue limit, the results do not differ. Like Palmgren-Miner, these models should not be used in the hope of obtaining highly accurate results [Vog16].

Another linear model is the Folge-Wöhler-Kurven model (FWK) developed by Schott. In contrast to Palmgren-Miner, the FWK model takes into account that a component has a different damage behaviour if it has already been dynamically loaded or damaged. Using the original Wöhler curve as a basis, a new Wöhler curve is calculated for each loading phase using the following formula:

|  |  |
| --- | --- |
|  | *(Eqn. 4.3)* |

Failure of the specimen/component is expected when the number of cycles has reached N = 0. The importance of the loading history is recognised, but the loading sequence is still neglected [Vog16].

The simplest non-linear damage accumulation model is the 'Miner general' model.

|  |  |
| --- | --- |
|  | *(Egn. 4.4)* |

As with the Palmgren-Miner model, the Wöhler curve is taken as a basis, this time with a material-specific parameter b, which can be adapted to existing data. This allows acceptable to very good estimates of the service life, although the predictions tend to overestimate the service life (D < 1). Marco and Starkey modified 'Miner general' so that the material parameter b is re-determined for each loading phase. This modified version is significantly more complex, and the results are unreliable [Vog16].

The non-linear model of Owen-Howe is one of the earliest models developed with a fibre-reinforced plastic. Parameters A and B are presented for this model:

|  |  |
| --- | --- |
|  | *(Eqn. 4.5)* |

These can be adapted to the test data. The model delivers useful results, especially in comparison to Palmgren-Miner, and is numerically well suited for damage accumulation. However, the loading sequence is not taken into account and that the model often overestimates the service life (D < 1). Bond-Farrow developed a more general version of the Owen-Howe model using tests on carbon fibre reinforced plastics:

|  |  |
| --- | --- |
|  | *(Eqn. 4.6)* |

The only difference compared to the original version is the replacement of the square by a third adjustable material parameter, C [Vog16].

Broutman-Sahu published a model which was also based on experiments with glass fibre reinforced plastics. In this model, the tensile strength () and the experienced stress () of each loading phase are mathematically recorded [Vog16].

|  |  |
| --- | --- |
|  | *(Eqn. 4.7)* |

The Hashin-Rotem model from 1978 is the first model presented here in which the damage Di is recursively influenced by the damage of the previous load phases.

|  |  |
| --- | --- |
|  | *(Eqn. 4.8)* |

Although the recursive approach is interesting, the forecasting quality of this model is very low, and the lifetime is often strongly underestimated (D > 1). There is also a lack of parameters that allow the model to be adjusted to fit existing data. However, the loading history and the sequence of load phases are considered. In a modified version of the Hashin-Rotem model, parameters A and B are introduced.

|  |  |
| --- | --- |
|  | *(Eqn. 4.9)* |

This allows the model to be adapted to existing experimental data. This narrows the range of the forecast and significantly improves the forecast quality [Vog16].

Like the Palmgren-Miner model, the 1976 Subramanyan model does not contain any material-specific constants.

|  |  |
| --- | --- |
|  | *(Eqn. 4.10)* |

Since only the data from the Wöhler line is used, the model is comparably simple and can be applied quickly and the results are of a higher prediction quality compared to Palmgren-Miner. However, the model tends to underestimate the lifetime (D > 1) and is not well suited for multiphase loading. In recent years, Rege et al. and, building on this, Zhu et al. have developed models with additional damage exponents based on the work of Subramanyan [ZLL+19]. Especially the model of Zhu et al. achieves a high prediction quality.

|  |  |
| --- | --- |
|  | *(Eqn. 4.11)* |

The model was developed using damage accumulation tests with alternating loading phases and contains both the respective strain amplitude of the individual loading phases () and parameters l and s, which are used to weight the loading sequence. Thus, this model takes the order of the load phases into account.

The Damage Curve Approach (DCA) and Directive Cumulative Damage (DCD) approaches were also developed using multiphase damage accumulation tests. In DCA, the complete sequence of loading phases is mathematically recorded and supplemented with the material parameter .

|  |  |
| --- | --- |
|  | *(Eqn. 4.12)* |

The model overestimates the service life in most cases and the prediction quality is in a similar range to that of Hashin-Rotem [SSS17]. The DCD developed by Shrestha in 2016, on the other hand, provides very constant predictions in the range D = 0.5 for multiphase dynamic tensile tests. This is an overestimation and thus a prediction on the uncertain side. Due to the very low scatter of the results, the addition of an additional pre-factor could be considered to achieve results in the range D = 1.

The table in figure 14 summarizes the damage accumulation models introduced in this section. The model names in bold are the models that will be used later in evaluation the new damage accumulation model.

To summarize, a damage accumulation model should ideally do the following:

1. Consistently predict the number of cycles until failure.
2. Be as simple as possible.
3. Not require vast amounts of data to calibrate.
4. Reflect the non-linear nature of material fatigue.
5. Regard the load history and sequence of load phases.

# Setup and Analysis of Fatigue Tests

To better understand the fatigue and damage progression of short fibre reinforced thermoplastics, fatigue tests were conducted. In the following section, the manufacturing process of the specimens, the material used, and the experimental setup will be described. The results from the fatigue tests will then be analysed.

## Test Specimens

### Specimen Fabrication

The specimens used were 1BA specimens, as laid out in figure 16. These are commonly used in tensile testing and cyclical fatigue testing. To create the specimens, flat plates were injected (also shown in figure 16). After removing the sprue of the plate, the remaining part of the plate was fixed in place using a 3D-printed clamp and the outside contour of the specimen was milled. The ends of each specimen were then separated from the rest of the plate using a belt saw.

Specimens were created at both 0° and 90° angles relative to the flow direction of the moulding process. Having specimens with different fibre orientations is necessary due to the anisotropic mechanical properties of composite material. During the injection process, the injection speed and shear rate are not constant across the thickness of the injection mould while it is being filled. Due to this velocity gradient, the fibres are pushed into different orientations in the middle of the specimen compared to close to the wall of the injection mould, as explained in section 4. For the purpose of simplicity, the specimens will be referred to by the angle relative to the flow direction, as shown in figure 16.

### Material

The material used for the specimens in the following experiments is called Pocan B3235 000000 (made by Lanxess Corporation). It is a composite of the semi-crystalline thermoplastic polybutylene terephthalate (PBT) with 30 wt. - % short glass fibres. PBT is used both in technical components such as plain bearings and roller bearings as well as in household items such as hairdryers and vacuum cleaners. Its chemical structure and mechanical properties are similar to those of polyethylene terephthalate (PET). It is especially well suited for injection moulding, as the material crystalizes quickly. The material data sheet can be seen viewed in the appendix of this paper.

## Fatigue Test Setup

The fatigue tests were performed using a servo-hydraulic testing machine made by Zwick/Roell. The setup of the machine is shown in figure 17. The machine consists of one anchored and one movable clamp. A 3D-printed holder was used to ensure each specimen was always positioned vertically and centrally before being clamped in at both ends. To ensure that each specimen experienced the same clamping force, special clamps were developed - instead of applying force by tightening a screw, a screw was loosened allowing two sets of disc springs to expand and apply the force. To measure the specimen's surface temperature, an infrared pyrometer was placed aiming at the specimen. To measure the specimen strain, an extensometer was clipped onto the specimen. The 3D-printed holder ensured that the extensometer was always clipped on at the same position on each specimen. The actual stress experienced by the specimen was measured using the load cell at the at the bottom of the machine. The specimen being tested was contained within a testing chamber whose temperature was regulated and held constant at 23°C.

The fatigue tests consisted of dynamically pulling each specimen with a specific stress amplitude at a specific frequency until the specimen broke. The nature of one load cycle is shown in figure 18. The aim was to subject the specimens only to tensile and not compressive loads. To ensure this and give the controlling a margin of error, a minimum stress of 2 MPa was selected for each test. \*\*\*

For the fatigue tests conducted, the maximum stress (stress amplitude) was varied in order to obtain specimens that failed throughout the fatigue strength area (in the range between 103 and 106 cycles). This was repeated at frequencies of 2 Hz, 5 Hz, and 15 Hz in order to be able to analyse the impact of the testing frequency on the mechanical properties of the material during fatigue progression. This was repeated for both specimen fibre orientations (0° and 90°). After each specimen broke, the location of the failure was analysed. Specimens which broke at one of the two clips used to hold the extensometer in place were marked as ‘not valid’ and are not included in the data as it could not be ruled out that they had broken as a result of notch effects caused by the extensometer clips.

## Fatigue Test Analysis

The data collected during the fatigue tests was analysed with the goal of finding and better understanding the correlation between the testing parameters and the progression of selected mechanical properties and conditions such as the specimen temperature, strain and dynamic stiffness, as well as the viscoelasticity (energy stored vs. energy dissipated). Figure 19 gives a rough overview of the relationships between the independent and dependent variables.

### Analysis of Wöhler Curves

The Wöhler curves (as introduced in section 4.2) for the 0° and 90° specimens are shown in figures 20 and 21. The lines of best fit (calculated using curve fitting software) are included in the images and are of the format:

|  |  |
| --- | --- |
|  | *(Eqn. 5.1)* |

This format was selected because it consistently delivered the highest R-squared value, indicating the least amount of variance. These lines of best fit are purposely only depicted in the range of forces tested and are not to be extrapolated. The logarithmic scale of the x-axis understates the difference between two data points, especially towards the right of the diagram. Nonetheless, both the 0° and 90° Wöhler curves show clear correlations between the maximum force selected for the test and the number of cycles endured until failure.

Due to material inhomogeneities, the data points scatter, indicating an element of unpredictability as to when a material will fail – this is the main reason multiple tests at each load level are necessary. To accommodate this statistical uncertainty, engineers calculate the probability of failure for a given load after a given number of load cycles [Sturm Sascha] [MG Skript]. This is often presented similarly to a Wöhler curve with three quasi-parallel lines representing a 10 %, 50 %, and 90 % probability of failure (as shown in figure 22). The placement of the lines is determined by the statistical distribution of specimens and their points of failure and follows a Gaussian distribution. Due to time constraints, not enough specimens were tested at each load level be able to produce such a diagram. This statistical uncertainty is one of the main reasons why components are designed with a certain safety factor S. This makes it difficult to make maximum use of the lightweight potential of materials such as SFRPs.

### Analysis of Temperature and Viscoelastic Behaviour

A sense of how the mechanical properties correlate with the testing conditions can be gained by looking at the measured average over the course of a test. As seen in the Wöhler curves, the 15 Hz specimens withstand the most load cycles and the 2 Hz specimens the fewest at a given maximum stress, indicating a higher rate of fatigue per load cycle, despite the higher frequency tests reaching higher temperatures. Figures23 and 24 show the relationship between the average and maximum temperature and maximum force of a test. The average and maximum temperature (= temperature at failure) correlate with both the maximum force and the test frequency. The specimens are able to withstand more load cycles at the higher frequencies tested, despite the higher temperature experienced by the material. The influence of the increased temperature cannot easily be gauged because it is counteracted by the more elastic behaviour displayed by the material at higher test frequencies.

During each load cycle, a certain amount of energy is transferred into the specimen. A large percentage of this energy is stored elastically. The rest of the energy goes into material damage, plastic deformation, or is converted to heat energy. The energy stored and the energy dissipated can be shown using a hysteresis loop, shown in figure 25.

Figures 26 and 27 show the average and maximum temperatures plotted over the ratio stored to dissipated energy per cycle. The ratio of stored to dissipated energy is significantly higher at 15 Hz at the same specimen temperature. This alludes to a more elastic, less viscous material behaviour at the higher frequencies tested (= smaller area inside the hysteresis loop). The increase in temperature is caused by the fact that although a smaller proportion of the energy supplied to the specimen is converted to heat for each load cycle, the energy supplied per second is higher, leading to a higher temperature at which thermal equilibrium is reached. To compare, all three formulas for estimating temperature increase during testing (introduced in section 4) regard the frequency as very influential.

As of a certain threshold, the temperature increase would be high enough to significantly affect the viscoelastic behaviour and cause thermal fracture instead of failure due to mechanical fatigue, thereby also decreasing the number of load cycles needed until failure. The Wöhler curves (especially for the 0° specimens) show that the gap between the 15 Hz and other specimens narrows the higher the maximum stress, because the average and maximum temperatures experienced during these tests are significantly higher and the viscoelastic behaviour is therefore more viscous.

### Analysis of Strain

The analysis of the strain data shows a relationship between the maximum stress and strain-at-failure. Figures 28 and 29 show the maximum strain (at failure), averaged out for all specimens of each force/frequency combination, respectively for 0° and 90° specimens. Although the data for the 90° specimens scatter more, a linear relationship between the maximum force and the strain-at-failure is visible.

Furthermore, the data points of all three investigated frequencies overlap. This suggests that the strain-at-failure is not dependent on the frequency tested. Given the fact that the minimum stress applied for each test was kept constant at 2 MPa, the strain-at-failure can be defined as a function of the maximum stress in each fatigue test.

The idea of a strain-at-failure is related to the concept of critical strain. Each plastic material has a critical strain level . In the case of fibre reinforced plastics, the critical strain level is further dependent on the fibre orientation. The critical strain represents a border, below which a material will only experience reversible (elastic) deformations no matter how long the material is subjected to a load. If a material experiences strains in excess of the critical strain ( irreversible (plastic) deformations can occur. Critical strains have been shown to be independent of the type of load (static, cyclical, uni- or multiaxial) as well as the temperature and other environmental influences. A graph depicting the critical strain line as well as the flow strain line is shown in figure 30. The flow strain line is based on the same concept as the critical strain line, except for the fact that it is dependent on the load conditions, time, temperature, and environmental influences. Figure 31 depicts the strain progression of a cyclically tested material compared to a statically tested material. The critical strain is the same, but dynamically tested materials are likely to reach the critical strain more rapidly due to specimen heating [MHM+11].

During fatigue tests, mechanical properties such as strain or dynamic stiffness tend to follow a pattern similar to the creep progression seen in quasi-static tests. In creep tests, three characteristic stages of creep are observable (shown in figure 32). In the primary stage, the rate of creep decreases. The rate of creep is constant in the secondary stage before increasing again in the tertiary stage. The time-strain curves for quasi-static tests according to [WK I Skript] are shown in figure 33. They indicate that a material will have achieved a higher strain at the point of failure the higher the load is.

Although this theory describes quasi-static material testing, the strain progression of a sample of fatigue tests display very similar tendencies. Figures 34 and 35 show a selection of strain progressions from the fatigue tests (5 Hz specimens were selected). The strain progressions are noticeably similar to those shown in figure 33 – the strain-at-failure is highest for the highest loads. The time axis was normalized to allow a side-by-side comparison of the strain progression depending on the maximum stress. The degree to which the temperature increase due to high stress and frequency affects the strain progression is not regarded, as there is no comparative data from isothermal tests.

Besides the correlation between strain-at-failure and maximum stress, the increase in strain appears to be an indication for an accumulation of plastic deformations and micro-damages to the material. Furthermore, the strain-at-failure seems to be independent of the frequency (in the range of frequencies tested). Based on the observable, load-dependent strain-at-failure as well as analysis of the strain progression of fatigue tests, strain was selected as the basis for the new damage accumulation model (NDAM). The development of the model as well as its validation are described in the following section.

# Development and Evaluation of New Damage Accumulation Model

One disadvantage of the fatigue tests introduced and analysed in the section 5 is that the independent testing variables (force amplitude, frequency) are kept constant until the specimen breaks. Most dynamically stressed components are unlikely to be subjected to constant conditions such as those replicated by the testing machine. A damage accumulation model should be able to predict when a material which has been subjected to varying testing conditions will fail as well as be able to model the damage/fatigue progression until that point of failure. This is the goal of the strain-based damage accumulation model introduced and evaluated in this section. This model will be referred to as the NDAM (new damage accumulation model) in diagrams.

## Model Development

As described in section 5.3, there is visible correlation between the maximum force of the tests and the strain-at-failure (). **Images** 6.1 and 6.2 show this linear correlation between the maximum stress and strain-at-failure, including the strain-at-failure **for the quasistatic tests**. The data points collected from the 90° specimens scatter more than those collected from the 0° specimens, but a correlation remains recognisable. Two linear lines of best fit were created using curve fitting software.

To take the viscoelasticity of plastics as well as the cyclical nature of the tests into account, the strain is separated into two parts. The first part is the minimum strain recorded by the testing machine. Although the minimum stress used was 2 MPa instead of 0 MPa (to give the controlling a margin of error so that the specimens are always subjected to tensile stress and never compressive stress), this represents a small fraction of the maximum force used for the tests. The assumption is made that the increase in minimum strain during a test is equatable to the creeping effect experienced by plastics under quasi-static stress.

|  |  |
| --- | --- |
|  | *(Eqn. 6.1)* |

Subtracting the minimum strain from the maximum strain results in the difference in strain from the points of maximum and minimum stress for a given cycle. This dynamic part of the total strain increases over the course of a test due to material fatigue and the accumulation of microscopic damages such as fibre-matrix-detachment, cracks in the matrix, fibre pull-out, and fibre breakage [FE07]. The two strain components are shown by means of a hysteresis loop in figure 6.3.

|  |  |
| --- | --- |
|  | *(Eqn. 6.2)* |

The superposition of the static and dynamic parts of the strain equal the total strain (), shown in figure 6.4. The new damage accumulation model predicts material failure when this total (maximum) strain reaches the maximum strain-at-failure obtained from the fatigue tests. The maximum strain obtained from the linear fit line is defined as the material failure criteria (D = 1).

To have damage progression diagrams that accommodate the logarithmic correlation between the maximum stress and time until failure, the static and dynamic strain components will be described as functions of the normalized time, . is defined as the time at failure, which is obtained with a modified version of the Wöhler curve, in which the x-axis represents the time until failure instead of the cycles until failure (figure 6.5). The line of best fit for each frequency is taken to be the point at which is reached. Specimens that exceed this time until failure break at .

The static strain component is based on the Maxwell model. The Maxwell model is one of several models used for viscoelastic materials and consists of an elastic spring (described using Hooke's law) and a viscous damper (described as a Newtonian fluid) connected in series. An illustration of the model as well as a typical stress-strain diagram are shown on **image** 6.6. Both elements experience the same stress (2 MPa). The total strain is equal to the sum of the strains experienced by the spring and damper. The elastic spring allows for an instantaneous jump in strain (whereby the material behaves as an elastic solid). While the stress at the minimum point remains constant at 2 MPa, the strain gradually increases. This increase in strain after the initial jump is modelled using the viscous damper, which represents material creep. The material displays viscous qualities in this phase. This basic viscoelastic model is applicable in this case because the deformations at 2 MPa are small compared to the maximum stresses applied in the fatigue tests (62 – 92.5 MPa for 0°, 46 – 61 MPa for 90°). The total creep function of the Maxwell model is:

|  |  |
| --- | --- |
|  | *(Eqn. 6.3)* |

Examples of the progression of the minimum strain over the course of a fatigue test are shown in figure 6.7. The strain progression is not perfectly linear, especially at the beginning of the test. It resembles the progression of the dynamic strain, which will be discussed later in this section. Despite this, the function type of the creep function of the Maxwell model is used to describe the static strain:

|  |  |
| --- | --- |
|  | *(Eqn. 6.4)* |

Both factors a and b are obtained using the progression data for each orientation and maximum stress level with the help of curve fitting software. (Since factors a and b are derived from the data, they were not called 1/E and , respectively). Factor a, which represents the elastic jump due to the 2 MPa minimum tensile stress, is constant for each orientation. It must also be at level, so that the sum of the static and dynamic strain components at is equal to the strain-at-failure . This means that factor a is not exactly equal to the inverse of the material’s Young’s modulus (0°: a = …, 1/E =…; 90°). Figure 6.8 shows each factor b obtained from the curve fitting software plotted against the maximum force. A correlation is visible for the 0° specimen. The 90° appear to scatter more, however, the range of values for b is smaller than for the 0° specimens. Factor b is defined as a function of the maximum stress for both orientations. Figure 6.9 summarizes how the individual factors from the static strain are derived and shows an example of how the model fits over the actual data.

The dynamic strain component is based on the inverse of a model used to describe the progression of the dynamic stiffness under tensile fatigue testing []. The dynamic stiffness is shown using a hysteresis loop in **image** 6.10, along with the formula.

Since the maximum and minimum stress ( are constant, the dynamic stiffness becomes inversely proportional to the difference between the maximum and minimum strain, which is equal to . Only the framework of the original dynamic stiffness function from [] was adopted for the damage accumulation model, as there were issues with the continuity of the formula beyond tn = 1 and because the original model includes factors based on types of data not measured during the fatigue tests. The dynamic strain progression can be described using a geometric function with the format:

.

As with the static strain component, factors a, b, c, and d were determined by running curve fitting software on the progression data for each orientation/stress combination. **Image** 6.11 shows the correlation between the calculated factors and the maximum force. With the exception of factor c for the 90° specimens, a correlation is visible. Thus, factors a, b, c, and d are described as functions of the maximum force. **Image** 6.12 shows examples of edyn progression with the corresponding model.

**Image** 6.13 summarizes the four main components of the damage accumulation model and gives an overview of how each component is derived.

In addition to predicting the point of failure, the model should chart the progression of damage. Each stress phase inflicts an amount of damage di to the material. Since the point when is defined as the failure criteria, the nonlinear progression of the strain is defined as being equivalent to the fatigue/damage progression.

D = sum of di

Whereas di =

However, both strain components experience a jump in strain at the beginning. The jump in the static strain component is equal to the factor a and is by definition perfectly elastic. It should thus not be considered as part of the damage experienced. The jump in the dynamic strain component exists because of the mathematical nature of the function. By design, Edyn(tn=1) = 0. While the function type does well replicating the dynamic strain progression, as seen in **image** 6.12, the quasi-instaneous jump for from edyn(tn = o) to edyn(tn = 0+) does not reflect the actual data and should also not be considered as part of the damage experienced. To eliminate this jump, the change in dynamic strain of the first five cycles of the first load phase is subtracted. An overview of the steps described in this paragraph are visualized in **image** 6.14. The revised version of formula … is:

Formula for di, first phase, all subsequent phases

Since the dynamic strain component is nonlinear, it is necessary to make sure the model takes the damage history as well as the order of load phases into account. The strain progression has been defined as equivalent to the damage progression. Therefore, the sum of all previous dis are important in order to determine at which tn the next load phase mathematically starts. To calculate the starting tn for a subsequent load phase, the sum of all dis is inserted into formula… and then calculated backwards using a fixed-point iteration. This is shown in **image** 6.15.

## Damage Accumulation Tests

To assess the new model, damage accumulation tests were conducted. These tests were performed and analysed before the model introduced and described in section 6.1 was developed, so the analysis presented in the following section was available in the development phase. However, the data from the model is solely derived from the fatigue tests described in section 5.

### Setup and Concept

The damage accumulation tests were performed with the same specimens on the same testing machine as the fatigue tests. Each test consisted of four load phases with varying combinations of three maximum forces and three test frequencies. These are shown in the following **table**:

Table with Top: 0, 90. Then Force, Frequency Force Frequency

The frequencies selected for the damage accumulation tests are the same as those used for the fatigue tests. The forces selected were in between the forces used for the fatigue tests. The extreme forces were avoided in an attempt to shorten the amount of total time needed for all the tests – lower maximum forces take exponentially longer to test. For comparison, the range of forces tested in the fatigue tests were 620 N – 925 N (with one 1000 N specimen) for the 0° specimens and 460 N – 610 N for the 90° specimens. The second and fourth loading phase of each test were constant for each orientation, with a frequency of 5 Hz and the middle force of 760 N for 0° and 540 N for 90°. The frequency and force were varied for the first and third phases to see what effect the order of load phases has on the damage progression. On overview of the different tests is shown in **images** 6.16.

The Palmgren-Miner model was used to determine the number of cycles in each phase. It was determined that di = 0.2 (according to Palmgren-Miner) for the first three phases (shown in **image** 6.17). The idea was to let each specimen break in the fourth and final load phase. Thus, the specimens are subjected to identical load histories – merely the sequence of the load phases is different. This enables an analysis of what effect the load sequence has on the damage progression, which is the topic of the following section.

### Analysis

The damage accumulation tests were designed so that, theoretically, each test should be able to endure the same number of load cycles in the fourth load phase. This is based on assumptions of linear fatigue and a lack of data scattering. Images … and … show the averages of the number of phases in the fourth load phase for 0° and 90°, respectively. The variance in results clearly shows that the load history and sequence of load phases have an impact on the fatigue progression and therefore the service life of the material.

For both fibre orientations, the tests in which the first load phase had the highest maximum force lasted longer than their counterparts with the highest maximum force in the third load phase. This suggests higher loads cause more damage when a material has already experienced a certain amount of fatigue. An analysis of the strain progression (images … and … constant frequency to negate frequency influence) shows that because of the higher preload, the strain level of the phase with the highest maximum force is higher in the third load phase than in the first load phase. This could imply that more irreversible damage (which can also be referred to as plastic deformation) is caused at higher strain levels, especially when the maximum force is higher. This ties into the theory of critical strain, introduced in section 5.3.3. As shown in image …, the bottom of each load cycle is not involved in plastic deformation. Below a critical strain, all deformations are considered to be elastic. As the plastic deformations accumulate and lead to material fatigue, the strain gradually increases as the dynamic stiffness decreases. Therefore, the same maximum force at the same frequency does more damage to the material when a larger part of the load cycle/hysteresis loop is above the critical strain (shown in image …). This understanding gained through the analysis of the damage accumulation tests indicate that the damage criteria for the NDAM need to be adapted (this will be discussed in section 6.3).

The damage accumulation tests where the force was kept constant and only the frequency was varied show similar results for both orders of load phases, both for the 0° and the 90° specimens. The error bars show that the results are within the same range. This suggests that the frequency (at least in the range of frequencies tested: 2 Hz – 15 Hz) has a negligible influence on the fatigue behaviour when compared to the maximum force.

Image … (same as before) additionally shows that the Palmgren-Miner model systematically overestimates the service life of the 0° specimens and underestimates the service life of the 90° specimens (with few exceptions). This suggests that the nature of fatigue and damage progression differs based on the fibre orientation of the specimens. This could be explained by the fact that the damage mechanisms in fibre-reinforced plastics differ based on the direction of force compared to the fibre orientation.

When a load is applied parallel to the direction of the fibres, the main damage mechanisms observed are fibre-pull-out and fibre breakage. Loads perpendicular to the main fibre orientation on the other hand cause fibre-matrix-detachment as well as cracks in the matrix [FE07]. The damage mechanisms are shown in image …. In dynamically tested SFRPs, the propagation of individual crack in the matrix material are the main cause for material failure [HM80, Dem08, BDA10]. The propagation of cracks is dependent on the fibre orientation – materials with more fibres perpendicular to the direction of the crack propagation direction show a higher resistance to the growth of cracks [Gün13]. It is possible that the load phases with lower maximum forces have a smaller influence in damaging the material on the 90° specimens than on the 0° specimens. This could be attributed to a proportionally higher critical strain.

An analysis of the progression data from the damage accumulation tests reinforces the idea that although the expected service life of a material is directly dependent on the frequency, the maximum force is the primary factor upon which the fatigue progression depends. By looking at the strain progression of the experiments with a constant maximum force in all four load phases (images … and …), it is noticeable that the strain progression increases without any jumps. As shown earlier, the frequency affects the viscoelasticity of the material as well as change in specimen temperature. However, the analysis of the damage accumulation tests has indicated that the level of strain above the critical strain and/or the area inside the hysteresis loop above the critical strain are measured indicators of fatigue and damage progression.

Overall, the progression data from the damage accumulation tests showed similar patterns to the data from the fatigue tests. The progression of temperature, dynamic stiffness, and strain follow similar patterns, albeit with sizable jumps between the load phases.

Image … shows the average damage *D* for the different damage accumulation tests according to Palmgren-Miner. As previously mentioned, Palmgren-Miner tended to overestimate the service life of the 0° specimens and underestimate the service life of the 90° specimens. Images … and … show the average damage *D* for the Bond-Farrow and modified Hashin-Rotem damage accumulation models. Bond-Farrow was selected for comparison because it too was developed using experimental data from fibre-reinforced plastics. The modified Hashin-Rotem was selected due to its recursive nature – the order of load phases is considered in the model. The results …

Images … and … present the quality of prognosis of the new damage accumulation model (NDAM). For comparison, the predicted damage *D* of the other three models are shown side by side. The evaluation of these results will be discussed in the next section (6.3).

## Model Evaluation

Given the range of results (load cycles until failure), both during the fatigue tests and the damage accumulation tests, it cannot be expected that each individual experiment is accurately predicted by the model. This is due to the scattering of data and the use of averages and lines of best fit. Ideally, a damage accumulation model is able to get as consistently close to achieving *D* = 1 as possible.

As shown in images … and …, the … model gives the best predictions. The NDAM displays very similar predictions to the Palmgren-Miner model. NEED TO ACTUALLY DO THE REST OF ANALYSIS BEFORE WRITING THIS PART

Image … displays two examples of the damage progression according to Palmgren-Miner and the NDAM. It contrasts the linear nature of the Palmgren-Miner with the non-linear nature of the NDAM. According to the NDAM, the material experiences proportionally more damage right at the beginning of the first load phase, reflecting the course of the strain data. The two damage progression lines end up failing close to each other. It is likely that the damage progression during the first load phase is proportionally lower than in the subsequent load phases – the NDAM therefore inflates the damage of the first phase and subdues the damage of the second and third phases.

Unfortunately, the NDAM has not proved to be an improvement on the far more basic Palmgren-Miner model. It was not able iron out the irregularities in prediction quality caused by the effect of the sequence of load phases.

In developing the NDAM, the attempt was made to base the damage criteria and progression purely on the data from the fatigue tests. Having analysed the damage accumulation tests, it is apparent that although the NDAM is non-linear and takes the preload as well as sequence of load phases into account, it is fundamentally too similar to the Palmgren-Miner model. Although Wöhler curves are a commonly used tool in predicting service life, they may not be an ideal database for modelling fatigue progression [MHM+11]. Having more fatigue test data allowing more accurate averages and lines of best fit to be calculated might improve the quality of prediction, but would likely not address the model’s flaws.

The correlation between the maximum load force and the strain-at-failure as well as the concept of critical strain support the choice of strain as the basis for the NDAM. An improved, strain-based solution might be a weight factor by which each increment of damage is multiplied, depending on the maximum force, preload, and current strain experienced. This weight factor would take the critical strain into account and decrease the impact of load cycles at the beginning of testing and increase the importance of load cycles at the end of testing.

Alternatively, the model could make use of the area inside the hysteresis loop above the critical strain level – a combination of energy- and strain-based model. As mentioned in section 4.2, the energy-based fatigue models were able to achieve the highest prediction quality, in part because the entire load cycle is considered and not just the maximum and minimum stress and strain.

A damage accumulation model based on both energy and strain might therefore resemble the model developed by Raphael et al., which looks at both the energy density from the hysteresis as well as the mean value of the strain. Given the comparative accounts of various fatigue models described in [SSS17] and [SMS+20] as well as the analysis of the damage accumulation tests, a model which adds the area inside the hysteresis (of strains larger than the critical strain) of each load cycle might offer a more accurate depiction of damage progression as well as better service life prediction results. An idea of what this might look like including a basic framework for a formula may is shown in images … and ….

Returning to the five criteria points of what a damage accumulation model should do, the evaluation concludes that the prediction quality of the NDAM is unfortunately not an improvement on the prediction quality of far simpler models such as the Palmgren-Miner model. Furthermore, the modelling of the damage progression likely exaggerates the damage caused at the beginning of a fatigue test and underestimates the damage later on in the test.

CRITICAL STRAIN AS BASE OR the other line discussed earlier perhaps!!!

0 degrees: raw results – most similar to palmgren miner, all other models offer better prediction results. systematic overestimation of damage – however, low scatter of results (from 0.59 – 0.82), comparable to the model that does best on this data, Hashin Rotem.

Multiplying by or adding a certain factor to the sum of damages calculated by the model would improve prediction results, but might render the depiction of damage progression less logical. 0 degrees could be adjusted to achieve good results.

90 degrees: Again, Hashin Rotem modified with the best results. 6/8 of the test patterns with decent results – F\_LH and HH\_LL with large variance.

Look at strain at failure for 0 degrees and 90 degrees damage accumulation experiments vs time and vs the maximum stress in the 4th load phase

Show the

Hashin Rotem includes Material Parameters that allow the data to be adjusted, whereas the NDAM is based purely on data, averages, and lines of best fit. A 1:1 comparison is therefore not possible. Weighted to play down beginning and play up end, depending on di and previous D.

# Conclusion and Outlook

Does not cover pauses, in which material could ‘recover’.

Only covers tensile testing with R values close to 0. To apply this model to phases with higher R values, perhaps making the strain components depenedent on the stress amplitude. As is often proven in plastics, there is no one model to that would cover everything

As is the case with many models describing plastic, one material tested, only tensile, only ne glass fibre content

Might be interesting to investigate material properties at constant temperature and factor in the effect of temperature increase at a later point – make sure the convection is able to carry away the heat quickly enough.

Open questions:

[ca. 1 Seite]

In dem Fazit sollen die wesentlichen, neu erarbeiteten Erkenntnisse der Arbeit dargestellt werden und im Ausblick soll darauf aufbauend aufgezeigt werden

* welche offenen Fragen noch bestehen und
* welche weiterführenden Arbeiten noch durchgeführt werden sollten.

Fazit & Ausblick sollten auf eine DIN A4-Seite beschränkt werden.

Es wäre sehr wünschenswert, wenn die Vorteile und energetischen Ersparnisse, die durch den Leichtbau gewonnen werden, nicht durch das einbauen solcher Bauteile in SUVs überflüssig gemacht werden. Es ist die Meinung des Autors, dass neben den technologischen Fortschritten auch ein gesellschaftliches Umdenken der Rolle der Automobile in unserem Leben benötigt werden.

WHAT WE DID - PAST TENSE

WHAT WE KNOW ABOUT THE MATERIAL - PRESENT TENSE

# Abbreviations, Formula Symbols, and Indices

Abkürzungen

|  |  |
| --- | --- |
| **Abkürzung** | **Bedeutung** |
| CFK | Kohlenstoffaserverstärkter Kunststoff |
| CLT | Klassische Laminattheorie (Classical Laminate Theory) |

## Formula Symbols

|  |  |  |
| --- | --- | --- |
| **Formelzeichen** | **Einheit** | **Bedeutung** |
| A | [mm2] | Querschnittsfläche |
| B | [mm] | Breite |

## Indices

|  |  |
| --- | --- |
| **Index** | **Bedeutung** |
| A | Abklingstrecke |
| A | außen |

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# Appendix

Der Anhang enthält Aussagen, die für das grundsätzliche Verständnis der Arbeit verzichtbar, für den im Detail interessierten Leser oder für weitere Arbeiten im IKV jedoch wichtig sind. Dies sind insbesondere:

* Programmdokumentation, Listings (bei Softwarearbeiten),
* (Details) Versuchsaufbau,
* Versuchsprotokolle,
* Ergebnisse umfangreicher Versuchsreihen,
* (längere) mathematische Herleitungen.

Der Anhang sollte nicht unnötig aufgebauscht werden. Er sollte auch keinen Text enthalten, den man eigentlich im Hauptteil erwarten würde.