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Thermo-mechanical Damage of Quenched and Tempered Carbon Steel for Railway Wheels

MASTER'S THESIS

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Supervisor

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Institute of Material Science, Joining and Forming

In cooperation with
Siemens AG

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Acknowledgements

At this point I would like to thank all of those who supported and motivated me during the preparation of this Master's thesis.

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Maier Kathrin,
Werndorf, March 2017

Abstract

This Master's thesis deals with different literature on block braked wheels. It has been prepared in cooperation with Graz University of Technology and the company Siemens AG in order to supplement current knowledge of block braked wheel systems.

This work is divided into three parts. The first contains a literature review, in which block braked wheels, wheel damage, finite element analysis (FEA), lifetime calculations, wheel material and other relevant concepts are defined. The second part concentrates on FEA, a numerical solution method. Various relevant parameters are determined for the calculation of wheel rim deformation, temperature change on the tread and residual stresses in the rim. These parameters are evaluated and compared with the current simulation model used by Siemens AG.
In the third part, selected aspects of the fatigue behaviour of block braked wheels are analysed in order to evaluate different damage models. The Manson-Coffin and Basquin models are often used for the wheel material and components without cracks. In cases with cracks, fracture mechanical methods, such as Paris´ law and modifications thereof are used.

The findings of this Master's thesis will allow the Siemens AG simulation model to be improved, with the aim of minimizing costs and development time as well as increasing the quality of the simulation.

Zusammenfassung

Diese Masterarbeit beschäftigt sich mit verschiedenen Literaturstellen über das klotzgebremste Rad. Sie wurde in Zusammenarbeit der Technischen Universität Graz und der Firma Siemens AG erstellt, um weitere Kenntnisse über das System der klotzgebremsten Räder zu gewinnen.

Diese Arbeit ist in drei Teile gegliedert. Im ersten Teil wurde sich ein Literaturüberblick verschafft, über klotzgebremste Räder, Radschäden, Finite Elemente Analyse (FEA), Lebensdauerbestimmung, dem Radmaterial und weitere Themen.
Der zweite Teil der Arbeit beschäftigt sich mit FEA, einem numerischem Lösungsverfahren. Es werden verschiedene relevante Parameter für die Berechnung der Verformung, der Temperaturänderung an der Lauffläche und der Eigenspannungen im Radkranz ermittelt. Diese Parameter wurden gewichtet und mit dem Simulationmodell von Siemens AG verglichen.
Im dritten Teil der Arbeit werden ausgesuchte Aspekte über das Ermüdungsverhalten von klotzgebremsten Rädern analysiert, um verschiedene Schädigungsmodelle für die Lebensdauerermittlung zu bewerten. Für das Rad sowie die Radwerkstoffe ohne Risse werden die Schädigungsmodelle von Manson-Coffin und Basquin in Betracht gezogen. Im Fall wenn Risse vorhanden sind werden bruchmechanischen Methoden, wie das Paris Gesetz aber auch dessen Modifikationen verwendet.

Anhand der Masterarbeit kann das bestehende Siemens AG Simulationsmodell erweitert werden. Ziel ist es, Kosten und Zeit bei der Entwicklung des klotzgebremsten Rades zu reduzieren und die Qualität der Simulation zu verbessern.

Motivation

Nowadays, block brakes are used in high-speed trains in combination with other brake systems. Therefore, a better understanding of the material behaviour of block braked wheels is necessary. Furthermore, the material behaviour should be included into the finite element simulations. This helps make simulations more realistic, minimizes costs and saves time during design. Currently, the lifetime of railway wheels is limited by thermal and mechanical loads. Better simulations and damage models will allow their lifetime to be precisely determined.

This Master's thesis is a part of a block braked wheels project led by Siemens AG. Subsequent Master's thesis and research build upon this work.

Thesis Objective

This Master's thesis deals with block braked wheel systems and fulfils three main objectives through its research. These are:

First of all, to find and review literature about systems, including the block braked wheel, the wheel material, the brake block influences, failures and bench tests.
Secondly, to determine several important phenomena for finite element simulations, railway wheel deformation, residual stresses and temperature fields. In the second part of this thesis, the results of the literature review are evaluated and compared with the model used by Siemens AG.
Thirdly, to describe different damage models used for the block braked wheel. These include damage models for cracked and non-cracked railway wheels.

Contents

Structure of the Master's thesis

This Master's thesis is a literature study about block braked wheels for Siemens AG. In the next two chapters a general literature review, about block brake-wheel systems, numerical simulations, and different damage models is presented. After these, in the following chapters the practical parts are presented, as seen in *Figure 0.1*.

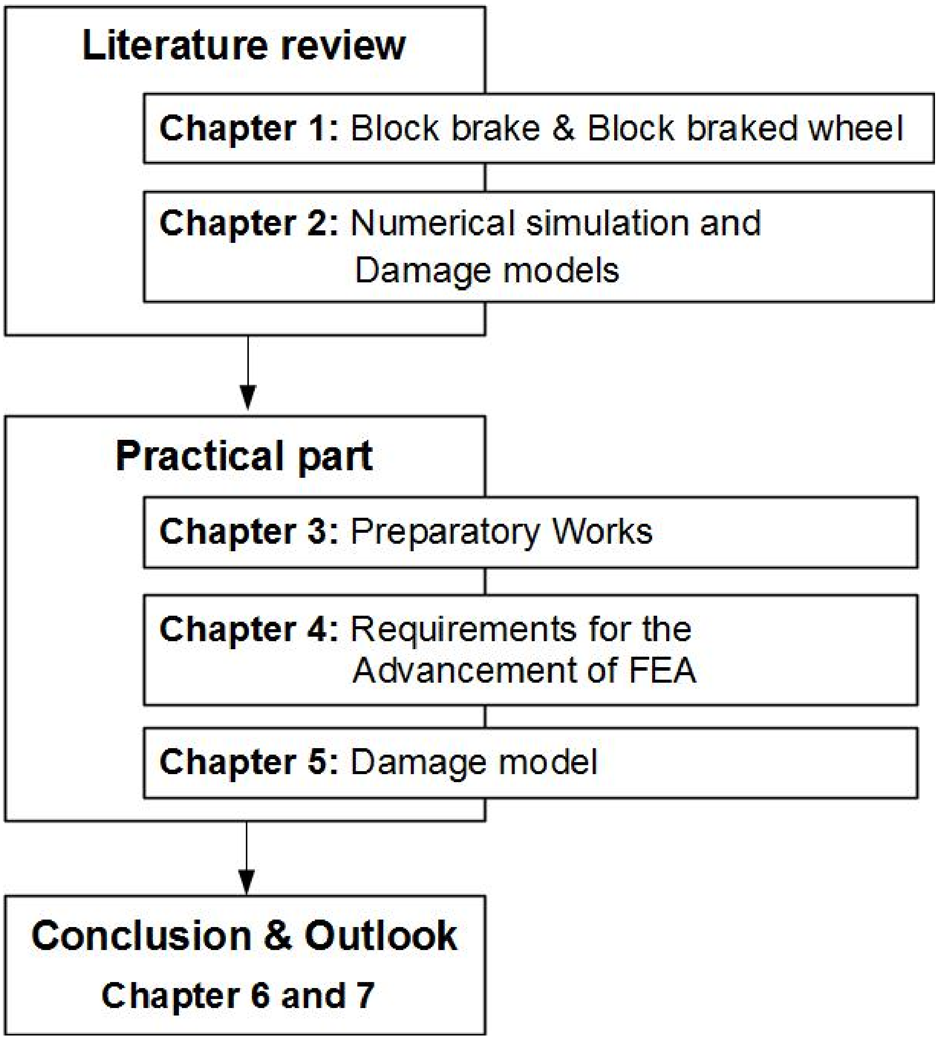
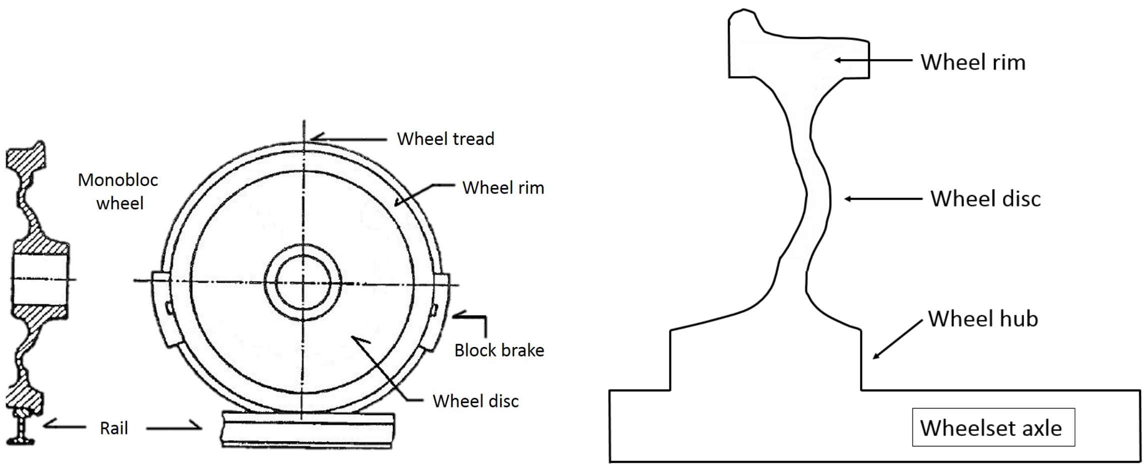


Figure 0.1: Overview of the structure of the Master's thesis.

1 Introduction

Braking is an action, which brings about a controlled reduction in velocity of an object, resulting a lower speed or a full stop. Railway vehicles are slowed by means of different brake systems, for example, with block, electro dynamic, or disc brakes. Generally, this result is achieved by converting the kinetic and potential energy of the train into the mechanical work of braking forces which turns into thermal energy. [1] [2]



(a) Block braked wheels [3]   (b) Monobloc wheel with wheelset axle. [4]

Figure 1.1: Block braked wheel system

Nowadays, in passenger trains and metros, a combination of the two systems is used. In block brake systems, a block made of a specific material is pressed against the wheel tread, as seen in *Figure 1.1*. Through friction with the brake block, the wheel is slowed down. The outcomes turn into heat and dissipate into the environment. These railway block braked wheels are made of quenched and tempered carbon steels, with a ferritic-perlite microstructure. In order to give these wheels a higher resistance to brake block induced thermomechanical loads, they are heat treated. In addition to the brake, the wheel is affected by the mechanical rail contact. Because of their thermo-mechanical loads, the wheel tread or disc often obtain damage. It is therefore important to investigate the mechanism between block brake and wheel. [1][2][5][6]

The next sections provide an overview of the block brake system in addition to its influence on the wheel. It also presents the block braked wheel itself, how it is manufactured, as well as its defects.

1.1 Block brakes

Block brakes are the simplest and least expansive brake systems used in railway trains. They reliably bring trains to a standstill at stations and signals. In contrast to other brake systems, block brakes are not only simpler, but also allows a wider application range for montage in terms of space requirements. This mechanical, friction block brake system has been used in freight trains for years, but there are also other brake systems, like electro dynamic and disc brakes. Modern, passenger trains and metros often use block brakes along with an electro dynamic and/or disc brake. In *Figure 1.2*, a freight train with two brake blocks is shown. [1][2][5]

Block brakes slow down the wheel by pressing the brake block against the wheel tread. Different numbers of brake blocks can be used, as seen in *Figure 1.3*. Normally there are one, two or four so-called brake shoes. These brake shoes are made of cast iron, organic composite, or sinter materials. The choice of the block matter is very important, because of its interaction with the wheel material. [1][2][5][7][8]

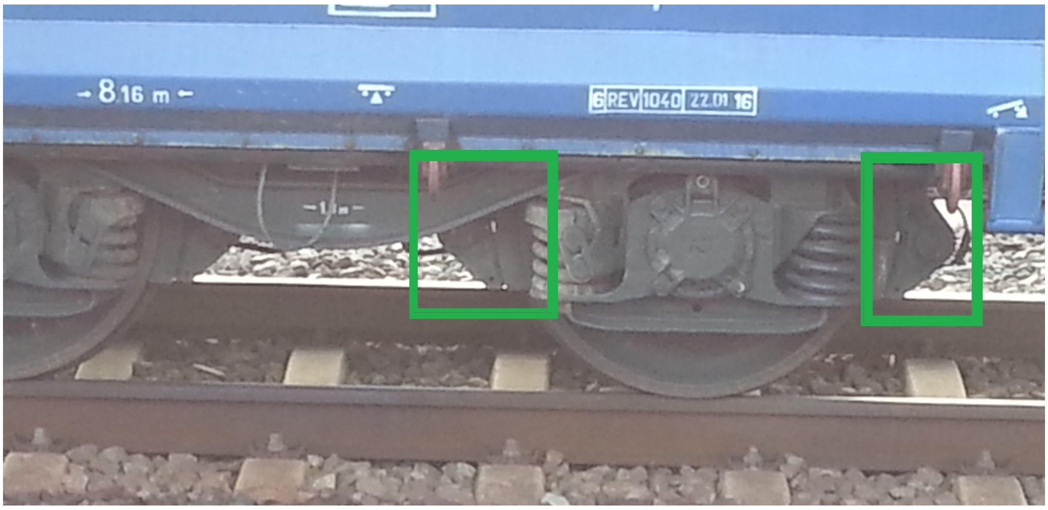


Figure 1.2: Freight trains with two brake blocks per wheel, indicated by the green boxes.

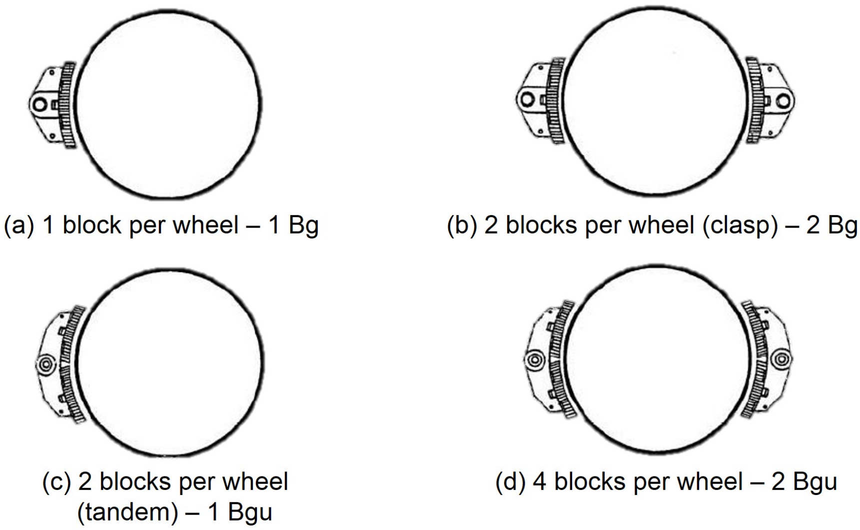


Figure 1.3: *"Four common block arrangements. Two blocks can be used either in (b) clasp or (c) tandem arrangement. Bg and Bgu stands for "'Bremsklotz geteilt"' and "'Bremsklotz geteilt unterteilt"', respectively."* [8]

While the train is being slowed down, numerous phenomena of different kinds occur, including mechanical and thermal processes. Furthermore, the transformation of kinetic energy and potential energy into thermal energy takes place. Thermal energy is transmitted between the two bodies and significantly raises their temperature. The temperature is generated due to the contact of the block and the wheel at a certain speed due to friction. The raised temperature of the braking system results in the heat transferred via convection and radiation to the surroundings. Nevertheless this is only possible up to a certain temperature which limits the braking system. In addition to the thermal effects of the block brakes, there are mechanical effects from the wheel-rail contact. The block braked wheel is also cooled by the rail contact. Block brakes also roughen the wheel tread and this roughness can increase the level of rolling noise, for example, on trains with cast iron brake blocks. [1] [2]

There are two braking actions to be defined: stop braking and drag braking. Stop braking means that the initial speed of the train significantly reduced or that the train stops. This braking causes a significant rise in the temperature of the wheel rim. Drag braking (downhill), on the other hand, will keep the train speed constant by applying a constant braking force for a long time. Excessive drag braking increases the risk of wheel failure, induced by residual stresses when the wheel cools down. Research on block braking systems focuses on several important topics, including wheel damage, wheel design, temperature field, thermo-mechanical aspects and brake blocks. [1] [2]

1.2 Block braked wheels

In railway systems, one of the main components is the wheel. After a certain time of operation, each wheel is examined for failures. However, there can be indistinguishable small or internal cracks, which are not detected in the tread or disk. If these cracks are not detected in time, they can lead to significant incidents, such as trains derailing. In recent years, such failures have been reduced by means of research and the development of new wheels, taking into account material, design and manufacturing processes. Over the years, different wheel designs have been developed in order to increase the track gauge stability and reduce high residual stresses in the disc, *Figure 1.4*. In the 1980s a new wheel design was developed with high track gauge stability and residual stresses below the critical limit. Today this block braked wheel design has been modified, and a variety of wheels are available. [9]

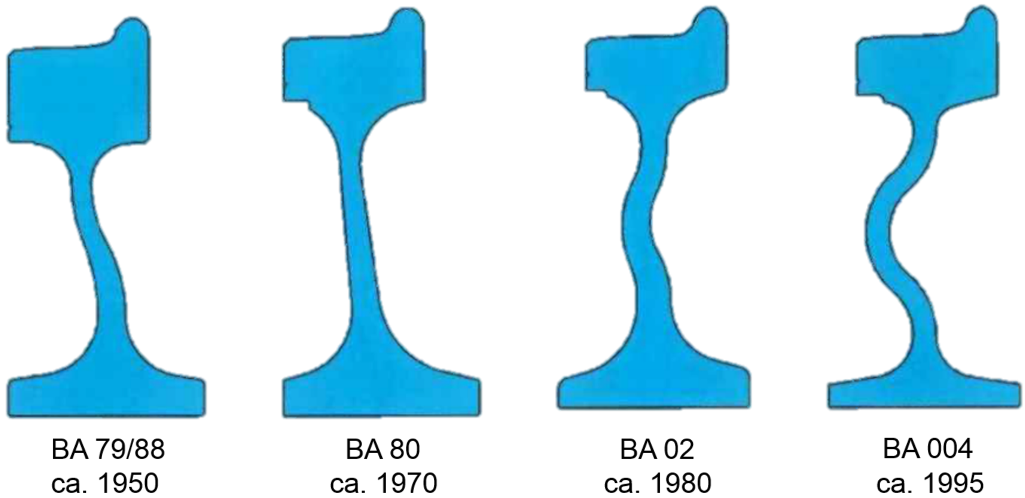


Figure 1.4: Development stages of block braked wheels [9]

1.2.1 Wheel material

In standard EN13262 [10], the characteristics of solid forged and rolled railway wheels for use in European networks are presented. In these four steel grades, ER6, ER7, ER8 and ER9, (E ... total quenching) are defined, see *Table 1.1*. Railway wheels are mainly made of ferritic-pearlitic, medium to high carbon steels, (0,4 to 0,7 wt.%). [10]

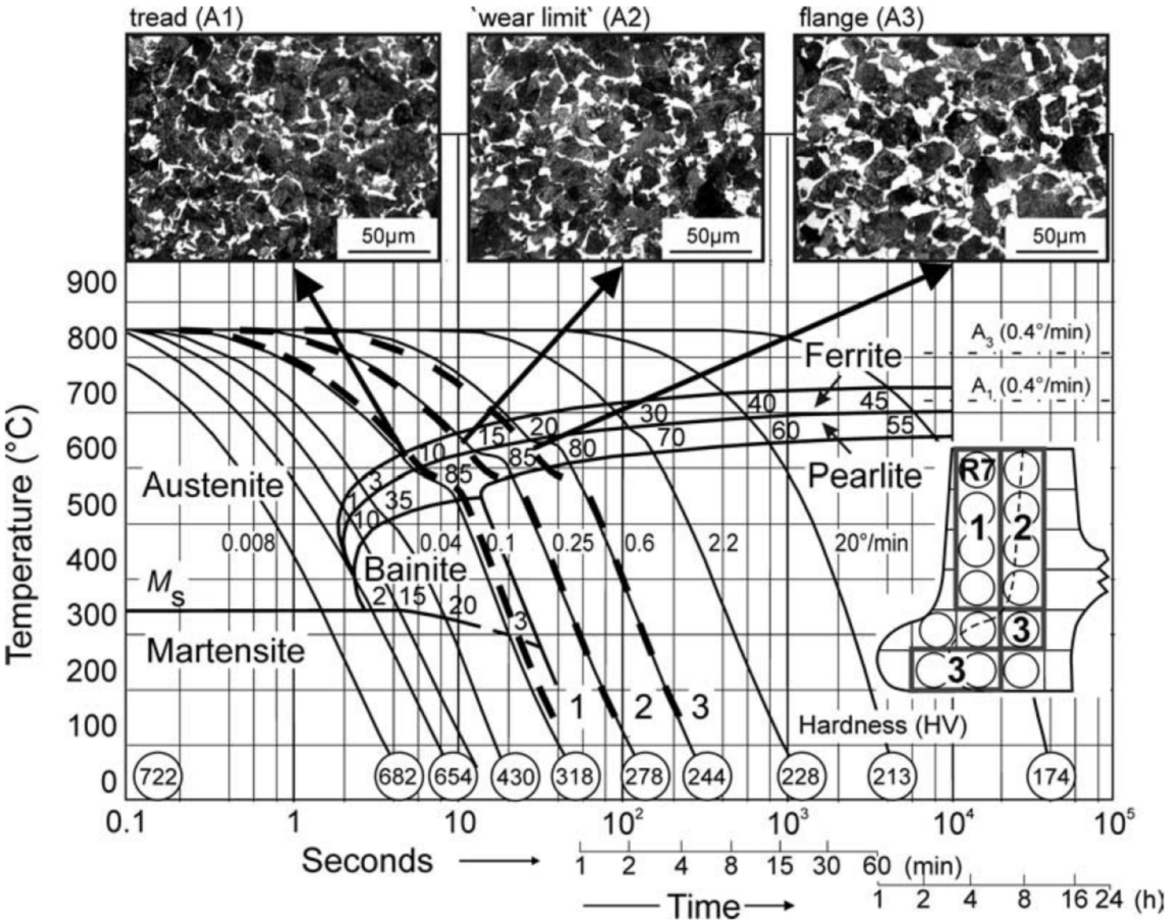
Table 1.1: Chemical composition of the four steel grades ER6, ER7, ER8 and ER9 [10]

	Maximum content in %							
Steel grade	C	Si	Mn	P	S	Cu	V	Cr + Mo + Ni
ER6	0,48	0,4	0,75	0,02	0,02	0,3	0,06	0,5
ER7	0,52	0,4	0,80	0,02	0,02	0,3	0,06	0,5
ER8	0,56	0,4	0,80	0,02	0,02	0,3	0,06	0,5
ER9	0,60	0,4	0,80	0,02	0,02	0,3	0,06	0,5

The cleanness, quality and consistency of the steel have been improved through better wheel manufacturing processes as well as inspection techniques. Non-metallic inclusions act as stress concentrators and potential crack initiation points. They are reduced mainly by controlling the chemical composition of the steel. Wheels defined by standard EN13262 are based on carbon steel grades. The carbon (C) content ranges from 0,48 wt.% to 0,60 wt.% and manganese (Mn) amounts to a maximum of 0,80 wt.%. In new block braked wheels, the structural transformation to martensite by quenching can be reduced by decreasing the C-content. Reducing the C–amount also decreases the strength, but, at the same time, increases the toughness of the steel. The proportion of ferrite in the microstructure depends on the C–content. The maximum silicon (Si) content is 0,40 wt.%. The sum of chromium (Cr), molybdenum (Mo) and nickel (Ni) is at most 0,50 wt.%. [6] [11]

In *Figure 1.5*, a continuous time–temperature–transformation diagram with exemplary cooling curves of different positions of a wheel rim R7 is shown.

The cooling curves are associated with the characteristic light microscope micrographs of the 'tread' (area A1), 'wear limit' (A2), and 'flange' (A3). The ferrite amount of the ferritic-pearlitic microstructure increases continuously with higher tread distance, as see in *Figure 1.5*. [12]



	Maximum content in wt%				
Steel grade	C	Si	Mn	Cu	Mo+Ni+Cr
R7	0.53	0.32	0.75	0.04	0.38

Figure 1.5: Time–temperature–transformation diagram of R7 steel [12].

The scanning electron microscope micrograph (*Figure 1.6*) shows a pearlite structure as well as the proeutectoid around the pearlite grains. The ferrite grain distribution and the size of the pearlitic lamellae distance is important for the fatigue behaviour. [12] [13]

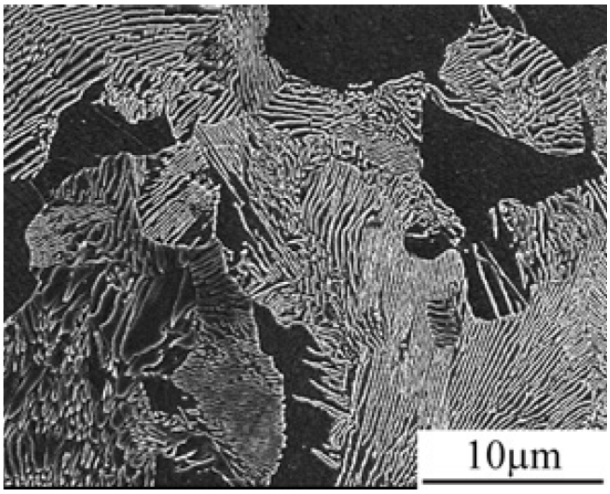


Figure 1.6: Characteristic microstructure close to the surface of the R7 monobloc wheel. [13]

1.2.2 Wheel heat treatment

The standard EN13262 [10] is valid for solid forged and rolled wheels, which are made of vacuum degassed steel. Through heat treatment the material properties can be modified. There are also two different conditions: total quenching (E) and rim chilling (T). During the wheel heat treatment process the tread and flange of the wheel harden, which improves wear resistance and generates large compressive residual stresses that limit fatigue and thermal crack growth. [10] [11]

During the manufacturing process, the wheel undergoes a three-phase heat treatment process, heating, differential quenching, and tempering. Differential quenching is the quenching of the tread surface, while the internal parts of the wheel (disc and hub) are cooled at a lower rate. In *Figure 1.7* a cross section of a wheel is shown. [14]

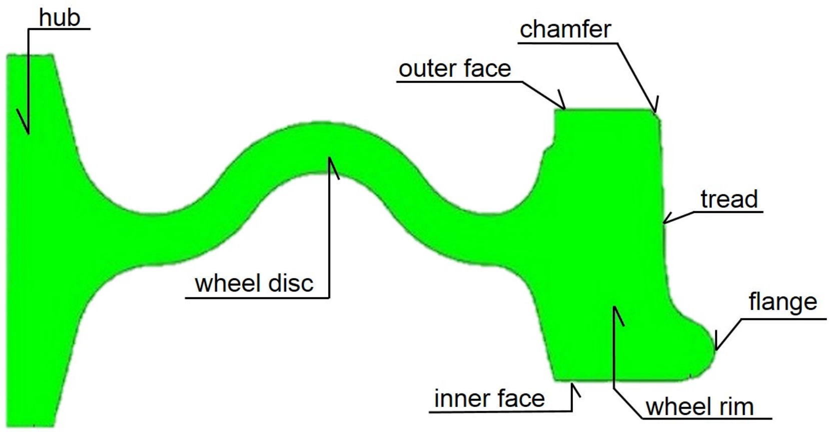


Figure 1.7: Cross section of a monobloc wheel

For rim chilling in particular, the first step is heating the wheel to a temperature of approximately 860 °C for one hour. This temperature is above the austenitization temperature for the wheel material. After that, the wheel rim is dipped into a bath of running water for 6 – 19 minutes and tempered. This is done in a furnace at a temperature of approximately 450 – 540 °C for around 5 – 6 hours, and followed by cooling in ambient air. The result is a tempered wheel rim and a normalized wheel disc. The heat treatment process also results in high mechanical properties (hardness in particular) and residual compressive stresses on the tread surface; the development of fatigue cracks is therefore impeded. In addition to impeding fatigue cracks, the process also improves wear resistance. In *Figure 1.8*, a general illustration of a wheel heat treatment can be seen. [6] [11] [14] [15]

In Europe, the steel grade ER7 is widely used. The wheel tread is well balanced between hardness (245 HB) and toughness (80 MPa$\sqrt{m}$). It is used for block brake applications in order to avoid brittle fractures. [10]

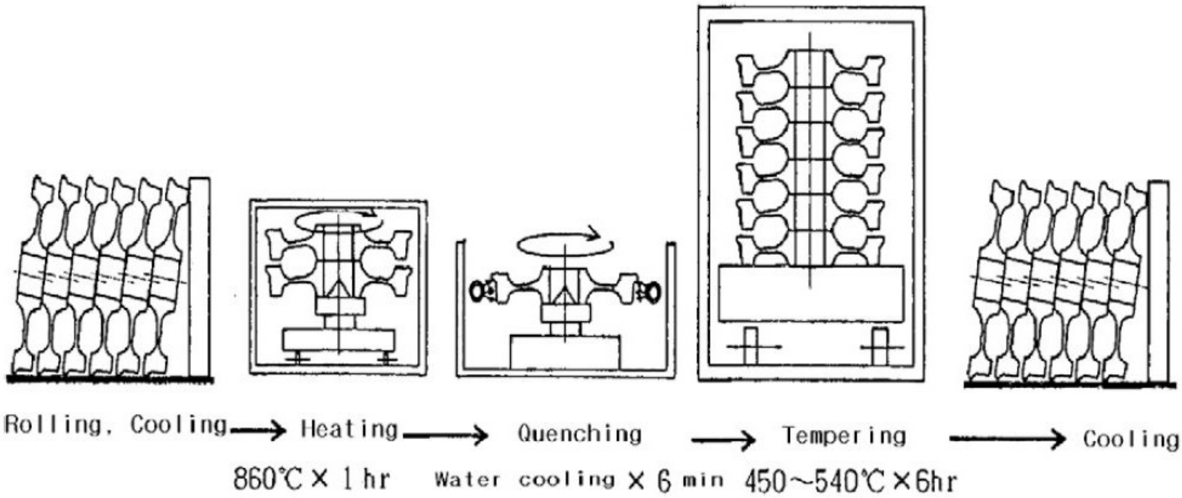


Figure 1.8: General illustration of a wheel heat treatment [15]

1.2.3 Influence of block brake and rail

During service, the wheel interacts with block brakes, the rail, and switches. The wheel material is influenced by the block brakes in two different ways, the first of which depends on the block material. Depending on the brake block material, the wheel is either heated quickly or slowly. The block brake also influences the cooling of the wheel. Secondly, the heat by brake systems include a risk of permanent deformation due axial deflection of the wheel rim. The braking processes induced very high compressive stresses in the wheel tread. This compression results in plastic yielding, which generates tensile stresses in the rim upon cooling. This can results in crack growth in the wheel rim [16]. This shows that in addition to friction, material properties of the wheel and the brake block, the thermal damage of the contacting bodies are also influenced by temperatures. Another factor that determines the influence of the brake block is its location on the wheel tread. The block-wheel contact can be in the centre of the wheel tread, near the flange or on the outer face of the wheel rim. In comparison with the standard position, centre of the wheel tread, the block brake generates much higher temperatures in the other positions. The highest temperature can be over the eutectoid temperature (A_1), which is the minimum temperature for austenite. If this is the case, the microstructure will be changed and the positive effects of heat treatment are nullified. [1][16][17][18]

In addition to the high local temperatures achieved through braking, the wheels are also influenced by wheel-rail contact. During the braking phase, and later, the cooling phase, the cold rail can conduct heat from the hot wheel. This effect is called rail-chill. The heat is transferred into the surroundings from the wheel, as well as from the brakes, by means of convection and radiation. [5]

1.3 Wheel defects

Wheel defects can occur as a result of the thermal effects of the block brake, mechanical effects of the wheel-rail contact, or a combination of both effects, apart from damage that occurs during manufacturing. The defective train wheels may cause damage to track and vehicle, and, in the worst case, lead to train derailment. This section will provide insight into different failures that occur on the wheel tread. The list below provides a short overview of several wheel defects [7][19]:

- Thermal cracks
- Hot Spots
- Rolling contact fatigue
- Fatigue cracks
- Wear
- Spalling or shelled tread
- Wheel rim deformation
- Flats
- Overheated wheels

In the following sub chapters, accurate descriptions of certain defects are provided, including thermal cracks, hot spots, rolling contact fatigue, fatigue cracks wear, and spalling or shelled tread. They are frequently occurring defects.

1.3.1 Thermal cracks

In the wheel tread and rim area, thermal cracks are the result of alternating heating and cooling. These cracks originate from metallurgical changes in the wheel material. Tread braking or wheel-rail frictional contact generate a large amount of heat, which is transmit to the wheel. Compressive stresses are created due to the constrained thermal expansion and thermal conductivity. The plastic deformation induced by compressive loading, produces tensile residual stresses during cooling. This can lead to continuous transverse tread cracks around the wheel circumference, as seen in *Figure 1.9*. Thermal cracks are the most serious form of defect in wheels and may develop in the form of fatigue cracks. Incorrectly placed brake blocks can bring about the appearance of these cracks. The main sources of tread thermal cracks are rolling contact in combination with cyclic thermal load and hot spots. Accordingly, the appearance of tread thermal cracks can be defined as a phenomenon affected by the interaction of low cycle thermal fatigue and rolling contact fatigue. [19] [20] [21] [22] [23]

Figure 1.9: Tread thermal cracking in an actual railway wheel. [24]

1.3.2 Hot spots

An uneven distribution of heat on the wheel and block surface due to the wheel and brake block interaction, causes banding and hot spots. These are visible by local changes in the colour of the tread. These coloured spots are uniformly distributed over the periphery of the wheel, as seen in *Figure 1.10*. These spots are regularly spaced, superheated areas, on the wheel tread which appear during braking and wheel sliding. [1] [21]

Figure 1.10: Part of wheel tread with hot spots during braking as the tread moves out of contact. The bright areas have higher temperature than the dark ones. The part shown is 70 mm in the axial direction and 700 mm circumferential direction.[25]

Hot spots depend on the block material. Vernersson [26] has found that cast iron brakes immediately generate hot spots on the wheel tread. In contrast, composite and sinter blocks cause hot spots only at high speeds over a longer time.

1.3.3 Rolling contact fatigue

Rolling motion causes rolling contact fatigue (RCF) cracks, which usually develop on the tread surface, and do not generally occur perpendicular to the running direction, *Figure 1.11*. This type of defect can lead to spalling. In contrast, thermal cracks occur radially on the tread and run parallel to the centre-line of the axle. [19]

Depending on the point of departure of the cracks, RCF can be classify as surface or sub-surface fatigue. The most common damage phenomenon is the "surface RCF". This is related to relatively high traction in the wheel-rail contact. [20]

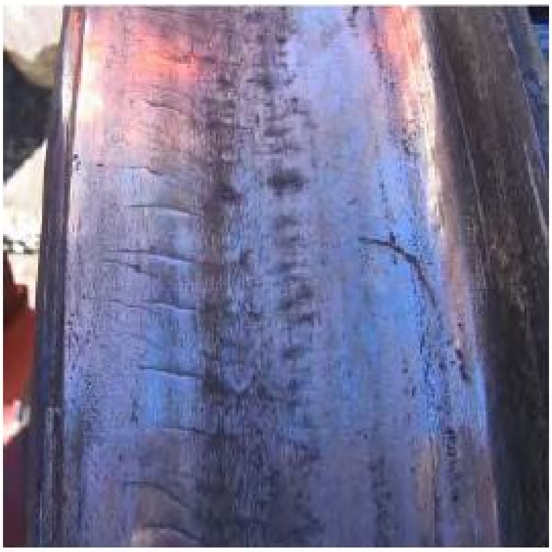


Figure 1.11: Rolling contact fatigue.
Cracks are angled across the wheel tread and may vary up to 45 degrees. [19]

1.3.4 Fatigue cracks

This defect is described in the Engineering Standard Rolling Stock - ESR 0330 - Wheel Defect Manual [19] as: "*Fatigue cracks generally originate from a defect in the wheel. These defects can be caused by either external damage or a manufacturing defect. Fatigue cracks usually appear as a solitary crack and may develop out of thermal cracks.*". An example for this defect is shown in *Figure 1.12*.

Figure 1.12: Fatigue crack originating from a thermal crack [19]

1.3.5 Wear

If two objects are in frictional contact, like wheel and brake shoe/rail, a loss of surface material occurs. This is defined as wear. Therefore a consequence of braking is that the diameter of the wheel tread decreases. Aside to the tread, wear occurs on the flange too. There are different conditions for minimizing wear, for example, by the correct alignment of the wheels, flange lubrication, using similar materials for the wheel and rail respectively, and operating equipment in proper mechanical condition. Another way is to increase the carbon content of the used material, as is promoting the morphology of the pearlite microstructure by altering the quench rate. [20] [27]

1.3.6 Spalling or shelled tread

Spalling or shelled tread, occurs, when pieces of metal break out of the tread surface. This may happen more or less continuously around the whole circumference, as depicted in *Figure 1.13*. This defect can brought about by thermal damage, skidding or over-stressing at the wheel-rail contact point. Spalling or shelled tread is due to a combination of the following factors: poor track and raised speed resulting in high impact stresses, vertical loads, overload braking (thermal damage and/or skidding) or the use of wheels of insufficient hardness. Furthermore spalling has a pronounced effect on wheel and brake block life, because many small craters may merge together. [7] [19]

Figure 1.13: Spalling of the tread area [19]

2 Numerical Simulation and Damage Models

For the safe design of a block braked wheel under cyclic load, it is important to know the lifetime behaviour of the material used. This behaviour can be directly measured through bench tests, but these are time-consuming and expensive. Therefore, efforts are being made to simulate lifetime behaviour based on models. In the last decades, different methods have been developed. The next sections provide a literature review of finite element analysis and damage models.

2.1 Finite Element Analysis

The method of finite element (FE) is a numerical solution method that uses differential equations for different technical and scientific tasks. Through finite element analysis (FEA), different physical effects, such as pressure, temperature, and magnetic field, can be simulated. Components are separated into various small and simple sub-problems (finite elements). Through splitting the components into sub-problems, the calculations of the equations are simplified. The result of the simulation is an approximate solution applicable to the real component. The advantages of FEA are, firstly, that using virtual prototypes of the parts minimizes the costs of development time. Secondly, faults and solutions for construction problems can be found. In general, FEA is a multipurpose tool that allows complex components to be simplified. In addition to structural element simulations, bench tests and total testing scenarios can be optimized by means of FE-simulation. There are two- and three-dimension models, *Figures 2.1* and 2.2. [28] [29]

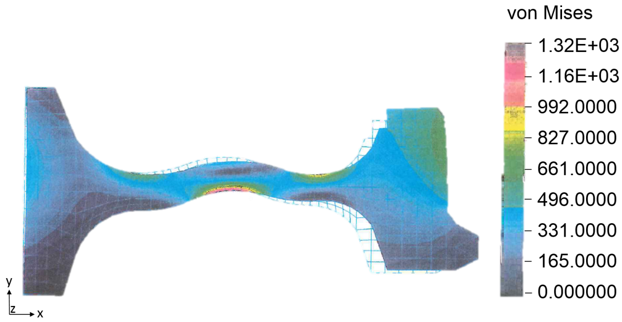


Figure 2.1: 2D FEM calculation of stress distribution and deformation of a wheel. [30]

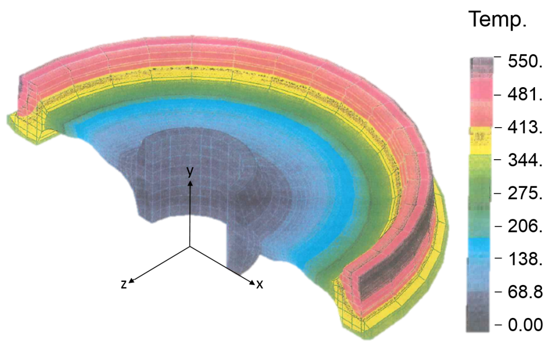


Figure 2.2: 3D FEM calculation of temperature distribution of a wheel sector [30]

The application of the finite element approach usually follows a standard step-by-step procedure, *Figure 2.3*. The first two steps involve modelling the component and dividing it into finite elements (*Geometry and Discretization*). In the next step, partial differential equations are developed in order to approximate the solution for each element. Material parameters and models are included in this step (*Element Equations*). Different material models are presented in more detail in *Section 2.2*. Next, those Element Equations must be put together to characterize the uniform behaviour of the whole system. Before the final equations can be solved, they must be modified to account for the system's boundary and initial conditions (*Boundary or Initial Conditions*);

then the equations of the model can be solved (*Calculation*). The solution of the simulation can be presented in tabular form or graphically. (*Postprocessing*). These steps are very rudimentary, but are often used for finite element applications. [28] [29] [31]

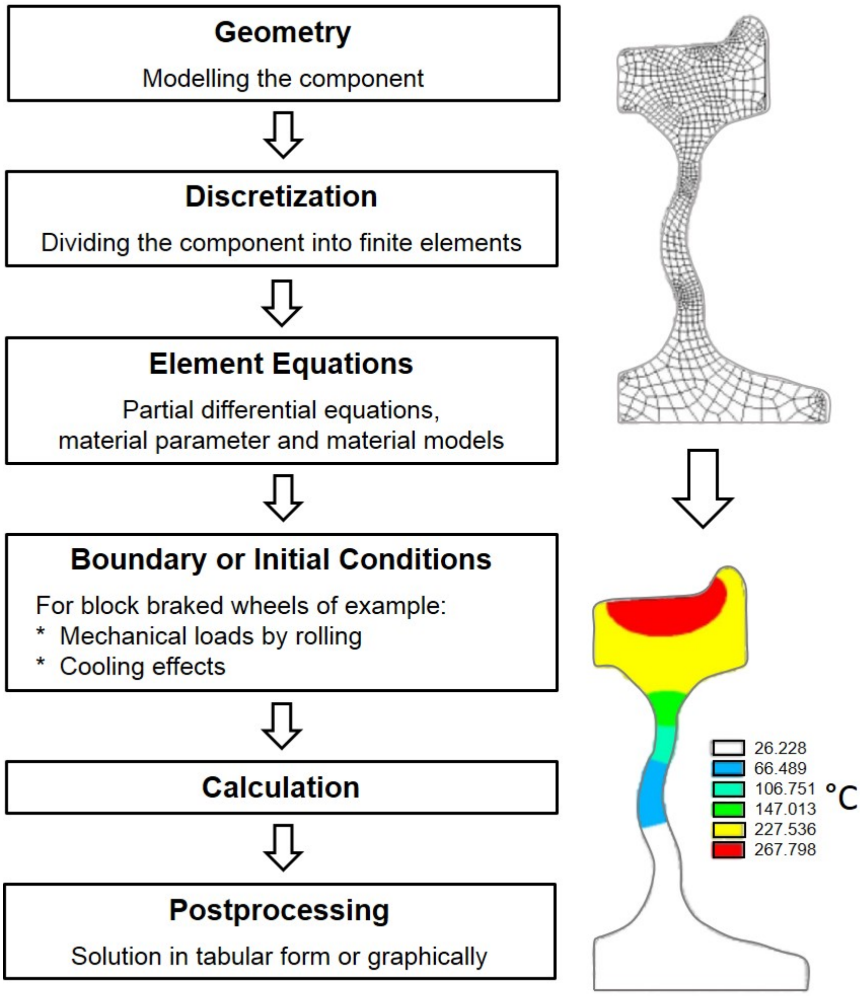


Figure 2.3: Finite element approach by a standard step-by-step procedure. At the bottom, part of the wheel is shown with finite elements and one possible solution for the temperature distribution. [30]

Geometry and Discretization

Geometric data is adopted from CAD-models or generated through preprocessing with lines, areas, or volume referred to coordinates. Thereby, essential characteristics of the components are recorded and idealized. The transition of the geometry of the component (CAD-Model) to the FE-model take place with finite elements. The choice of elements determine the quality of the FE-model. They can be different shapes, like triangles, squares, or rectangles as well as different sizes. [29]

Element Equations

Partial differential equations are developed to approximate the solution for the problem. For the calculation, the relevant parameters are material data, which describe the behaviour of the material mathematically. These depend on the problem and the formulation of the material laws. Further material models establish relation between stress, strain, temperature and/or time. Material data are, for example, the modulus of elasticity, the density, or the thermal conductivity. [29] [32]

Boundary or Initial Conditions

For a complete description of the simulation model, it is necessary to have information about the boundary conditions (BC) in addition to partial differential equations. The conditions are classified into three groups:

1. Geometrical or kinematic BC
2. Static BC
3. Mixed BC

For example, the position of the heat input, mechanical loads during rolling or cooling effects are all boundary conditions that can be considered. [33] Further initial conditions (IC) are defined, which are implemented at the beginning of the simulation. ICs for block braked wheels are, for example, production residual compressive stresses in the wheel rim or ambient temperature. [29]

2.2 Overview of Material Models

In order to construct the optimal components and to perform a realistic FEA, it is necessary to know the properties and the behaviour of the material used. The reason behind incorrect predictions is often insufficiently modelled material behaviour. Current FE-programs already include various finite elements, contact algorithms, and computational procedures, as well as a variety of different material models. Nevertheless, the parameters of the associated material are often unknown, since the material supplier cannot comprehensively provide them. [34] [35]

There are different kinds of classification for material behaviour, including elastic behaviour, plastic behaviour, and creep. Real components rarely show any of these behaviours. It is often a combination, like viscoelastic, viscoplastic, elastic-plastic models, as seen in *Figure 2.4*. In addition, all material models can be thermally coupled, and, therefore, the mechanical material properties will be a function of temperature. [35] [36] [37]

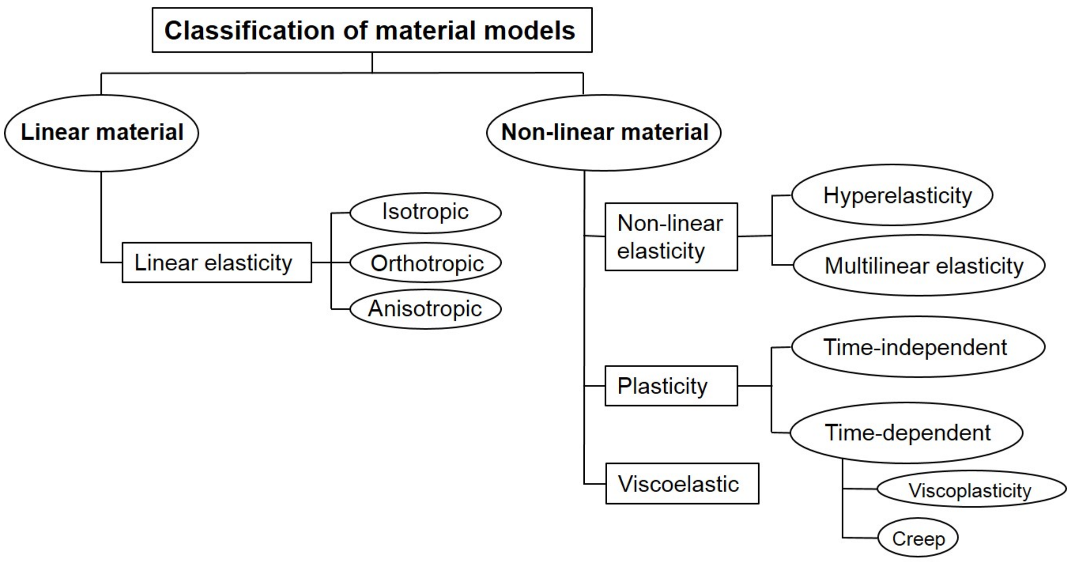


Figure 2.4: Overview of material models [38]

2.2.1 Elastic-plastic Model

When material is stressed, it will initially exhibit elastic behaviour: as the load increases, the deformation will grow proportionately. This applies until a specific reference value - the yield point A - as seen in *Figure 2.5*. From there on, the material starts to flow with increasing load and is deformed elastic-plastically. This signifies that after unloading, the deformation will partially remain. Only with a non-linear elastic-plastic material model can the behaviour of the material above the yield point be properly described. A simple linear-elastic approach produces inaccurate results. [39] [40] [41]

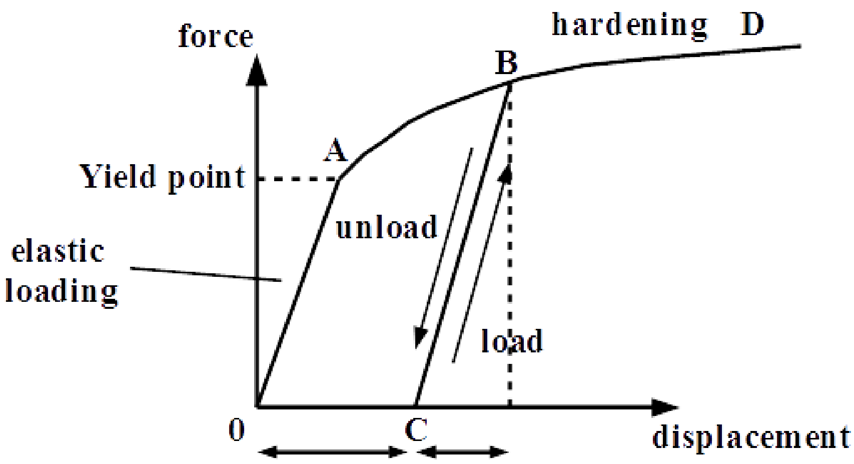


Figure 2.5: Force-displacement curve for metal at tension test. [40]

As mentioned, the model can be linear or non-linear. If the system depends on the direction or height of the load, the system is non-linear, but other conditions of contact can also lead to non-linear behaviour. For finite element simulations, it is necessary to use material models which represent real behaviour. The difference between the elastic - “perfectly” plastic and the elastic - “real” plastic model is that the ideal material model hardening is not considered, see *Figure 2.6*. If the material behaves in an isotropic/kinematic manner, or both, and the load is sufficiently high, the hardening must be included. [39] [40] [41]

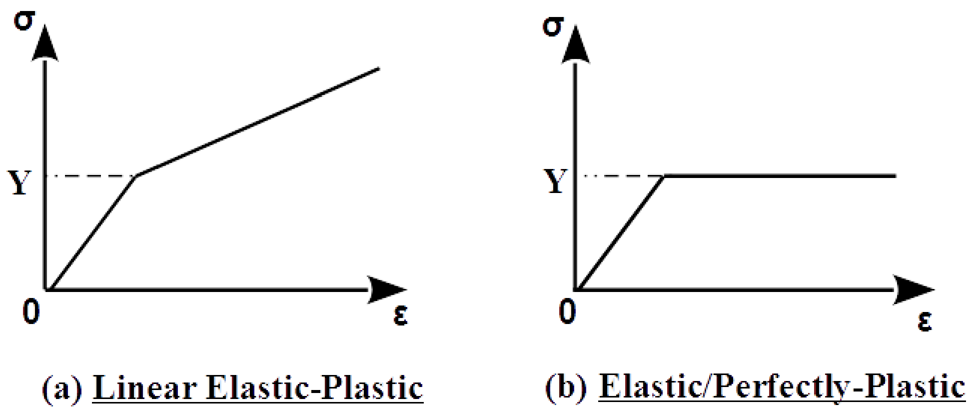


Figure 2.6: Comparison between (a) linear elastic-plastic and (b) elastic-perfectly plastic material model. Linear elastic-plastic include hardening above Y. [40]
σ ... stress, ϵ ... strain, Y ... yield point

2.2.2 Hardening Model

In the perfectly-plastic scenario, the yield surface stays unchanged, while in reality it may change in size, shape and position. The definition of how plastic deformation influences the yield surface, is called the hardening rule. There are different ways of schematically representing the hardening of materials induced by deformations. It is possible to distinguished between isotropic and kinematic hardening, or a combination of both of them. For the ideal plasticity model, hardening is not considered, *Figure 2.7*. Hardening can be considered in the uniaxiale case, as well as in the multiaxial one. In the first case, an initial yield surface is used, which is limited by two scalar values, tension stress and compression stress. In the multiaxial case next to the yield surface, the corresponding yield criterion is used, which can be expressed in higher-dimensional space. [40] [41] [42]

2.2.2.1 Isotropic hardening

Isotropic hardening describes a yield surface that expands the same in all directions. This implies that an increase in the tensile yield point due to

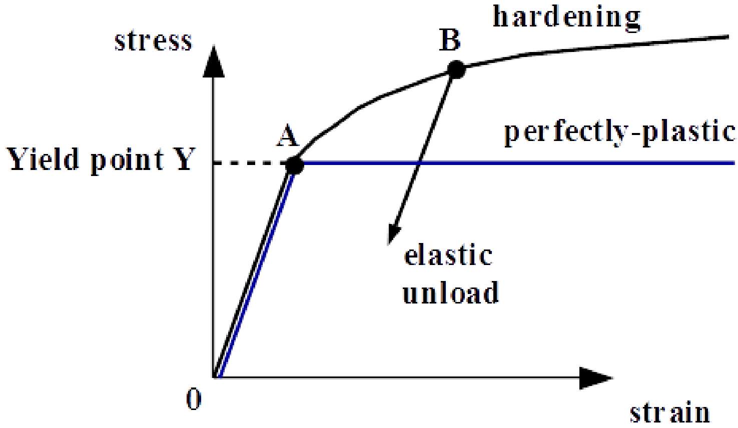


Figure 2.7: Uniaxiale strain-stress curve [40]

hardening results in an equal increase in the compressive yield point (see *Figure 2.10*). Looking at the yield surface shows that the surface remains the same shape in isotropic hardening, but expands with increasing stress (*Figure 2.8*). [40] [42] [43]

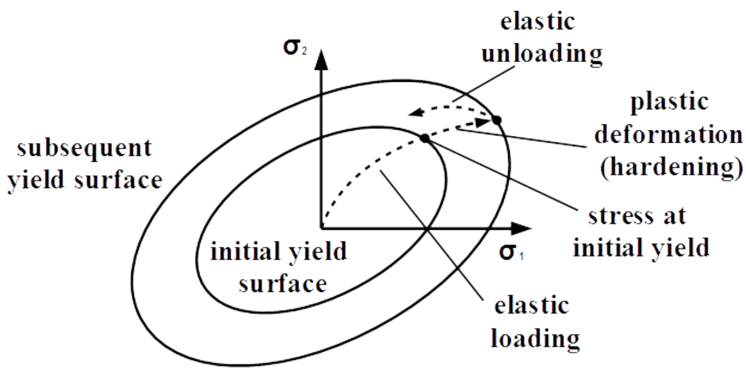


Figure 2.8: Yield surface of the isotropic hardening rule. [40]

2.2.2.2 Kinematic hardening

With kinematic hardening, the yield points in tension and compression are not identical. This means that the yield surface is not symmetrical around the stress axes. The kinematic hardening rule is used to model the Bauschinger effect and similar responses. Also the yield surface thereof remains in the same shape and size, only it changes position in the stress space. *Figure 2.9*. [40] [42]

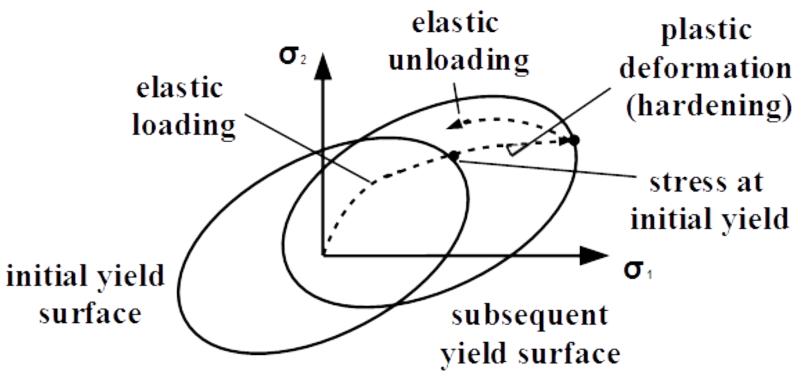


Figure 2.9: Yield surface of the kinematic hardening rule. [40]

Bauschinger effect

By loading a sample in tension over the yield point then unloading it and continuing until compression, the yield stress during compression is not the same as during tension. In fact, the yield point will be substantially lower than is during tension, which is known as the Bauschinger effect, *Figure 2.10*. The solid line represents the response of a real material. The dotted lines show two hardening models used in plasticity models: the isotropic and the kinematic hardening rule. [40] [42]

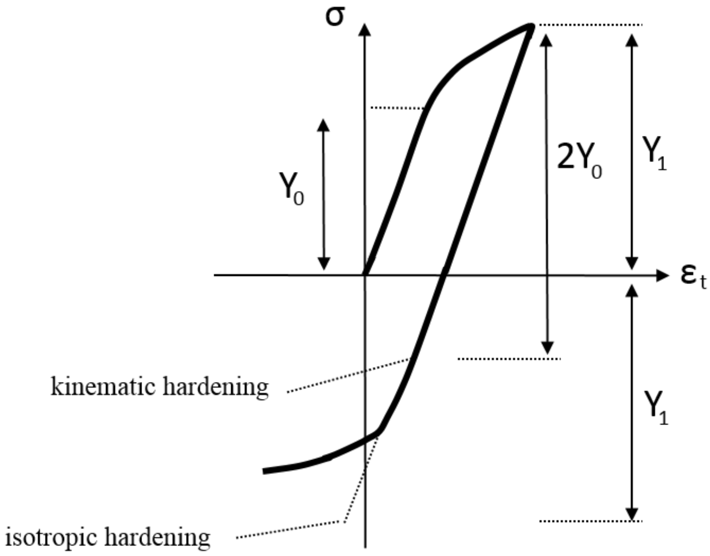


Figure 2.10: The Bauschinger effect: Comparison between isotropic and kinematic hardening [40]

2.2.3 Viscoplastic Material Model

Viscoelastic materials can undergo from irrecoverable deformations. Furthermore, they do not have any critical yield or threshold stresses, which are the characteristic properties of plastic behaviour. In contrast, while viscoplastic materials exhibit permanent deformations after the application of loads they continue to undergo a creep flow as a function of time under the influence of the applied load. Different mechanisms, such as the movement of dislocations in grains-climb, deviation, begin to arise as soon as the temperature is greater than approximately 30% of the absolute melting temperature. This is a schematic and indicative limit. In fact, certain materials, just as 304 stainless steel, show viscoplasticity at room temperature even though their melting temperature is greater than 1100 °C. For a broad range of temperature, the choice between plasticity and viscoplasticity depends on the type of application. [40] [41] [44]

2.2.4 Creep Model

Creep is a time-dependent, plastic deformation of a material under load. Aside from, the rate of creep is also dependent on stress and temperature. Also it is a material behaviour which appears at 30%∗melting point at constant stress. During creep at constant stress the strain rate increase with time.

The rate of creep is approximately constant over a long time, under the condition that the microstructure, stress and temperature stay the same. Towards the end of the service life and after a certain amount of deformation, the creep rate increases very rapidly and fracture follows. [37] [41] [45] [46]

2.3 Damage Model

Fatigue of railway wheels is a topic of growing importance because train technology is constantly to developing. Models for the description of their lifetime can be classified as either empirical or physical models. These two models can also be used in combination with mechanical damage models or fracture mechanical methods, as seen in *Table 2.1*. [47]

Table 2.1: Classification of models. Empirical methods and physical models can either be damage mechanical models or fracture mechanical methods. [47]

	Damage mechanical models	**Fracture mechanical methods**
Physical models	• Damage Parameter	• Tomkinsche Modell
Empirical methods	• Manson-Coffin • Basquin • Damage Parameter	• Paris • Frost Dugdale • Walker

Empirical methods provide a relation between measurable variables, like σ_a or $\epsilon_{a,p}$ and the lifetime. The first empirical model for the calculation of fatigue was developed by August Wöhler (1870). The results of lifetime measurements are displayed in Wöhler diagrams, which are named after him. The diagrams show the magnitude of load in relation to the number of cycles to failure (N_B). The double-logarithmic diagram has two areas: low-cycle (LCF) and high-cycle fatigue (HCF). [47] [48]

Physical models describe the material damage based on the movement of atoms, vacancies and displacements. [47] [48]

Damage mechanical models describe the development of pores and micro cracks with continuum mechanics methods. The damage rate is calculated by differential equations, which contain the actual damage. [47] [48]

Fracture mechanical methods are based on the growth of cracks, which grown until they reach a critical length and cause failure. The crack growth velocity is determined by inspection of the process around the crack tip. [47] [48]

This work focus on empirical methods in combination with damage mechanical models and fracture mechanical models.

2.3.1 Empirical Models

The empirical methods of lifetime prediction use damage parameters. These are defined by test result. Thereby, it is assumed that there is a definite correlation between the parameter and the number of cycles to failure. In combination with damage mechanical models, failures are not included in the calculation. [47]

2.3.1.1 Palmgren-Miner

Palmgren, Langer and Miner have suggested a linear part damage rule, also known under Miner-rule, for the damage accumulation with load with variable amplitude.

$$\sum_j \frac{N_i}{N_{B,i}} = 1 \tag{2.1}$$

N_i is the number of the cycles with the amplitude $(\Delta\sigma/2)_i$ and $N_{B,i}$ is the number of cycles to failure with the amplitude $(\Delta\sigma/2)_i$. After *Equation 2.1* the fracture occurs with a fatigue loading with different strain amplitudes $\Delta\sigma/2$ when the sum of the cycle numbers referring on the respective number of cycles to failure reaches the value one. [47]

2.3.1.2 Manson-Coffin model

The Manson-Coffin relation is an empirical damage mechanical model. In the Wöhler-diagram, the relation describes the LCF-range. This model anticipates that the plastic strain amplitude $\epsilon_{a,p}$ is relevant for the damage. It describes the plastic strain amplitude $\epsilon_{a,p}$ in dependence of the number of cycles to failure N_B, [41] [45] [48] [49]:

$$\epsilon_{a,p} = \epsilon_f N_B^{-\alpha} \tag{2.2}$$

ϵ_f is the ductility coefficient and α is the ductility exponent.

2.3.1.3 Basquin model

The Basquin-relation is an empirical damage mechanical model. The HCF-range of the Wöhler-diagram can be described by this relation. Here the elastic strain amplitude $\epsilon_{a,e}$ and the stress amplitude are relevant for the damage:

$$\epsilon_{a,e} = \frac{\sigma_a}{E} = \frac{\sigma_f}{E} N_B^{-\beta} \tag{2.3}$$

By combining the Manson-Coffin and the Basquin model, the result is the total strain amplitude $\epsilon_{a,t}$ in dependence of the number of cycles to failure N_B, *Figure 2.11*. [48]

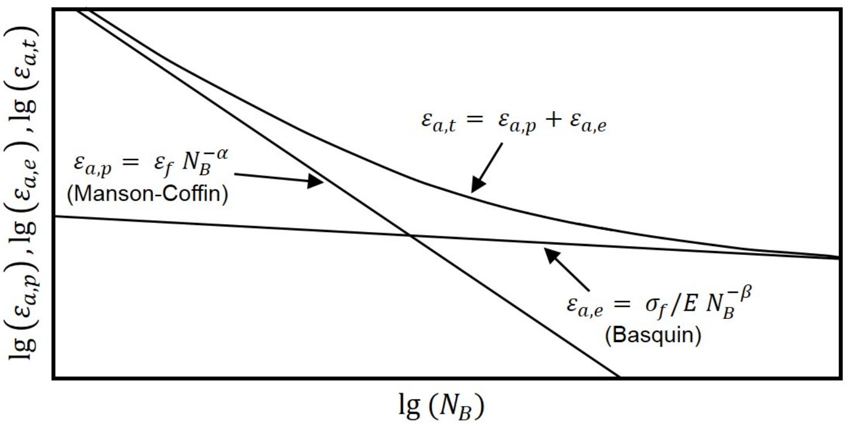


Figure 2.11: Schematic strain-Wöhler-curve with Manson-Coffin- and Basquin-relation [48]

2.3.1.4 Damage parameter by Smith, Watson and Topper

The Wöhler-diagram is only valid for alternating loads. Damage parameters characterize damage by fatigue based on individual load and stress cycles and their hysteresis loop. They also encompass the influence of stress amplitudes and mean stresses. Starting from the damage-parameter-Wöhler-line, if the variable amplitude and middle tension are unequal to zero, the damage contributions of the single cycles arise from the reciprocal values of the marking number of cycle, corresponding to the respective damage parameter values. The summation of the damage contributions results in the total damage D, which is defined by the number of cycle proportion. If the elective damage hypothesis applies, the fracture enters with a damage sum from D = 1, 0. [50]

The parameter P by Smith, Watson and Topper considers the product of tension σ and (total) strain amplitude $\epsilon_{a,t}$ as damaging, and the elasticity module E as additional (damage-irrelevant) factor is carried along [45] [49] [50] [51] [52]:

$$P = \sqrt{\sigma \epsilon_{a,t} E}. \tag{2.4}$$

2.3.2 Empirical Fracture Mechanical Method

The empirical fracture mechanical method considers initial cracks in the material. Therefore, the lifetime calculation examines the growth of the crack until the material fractures. For the calculation of the lifetime, the fracture toughness K_{IC} is used in addition to the threshold value ΔK_{th} and the crack growth curve, as seen in *Figure 2.12*. [52]

Under certain conditions, fatigue crack growth occurs in the material. This means a crack growth per load change of a small value, which adds up due to frequent repetitions of the cyclic load. The fatigue crack growth is determined by the crack growth during load change, which is defined by the crack propagation rate da/dN as a derivative of the crack length to the number of load cycles. If the crack velocity da/dN, which is determined experimentally, is plotted in dependence of the cyclic intensity of the stress intensity factor ΔK, the crack growth curve results. This curve is displayed in a double-log depiction and has a characteristic sigmoid course; see *Figure 2.12*. [45] [52]

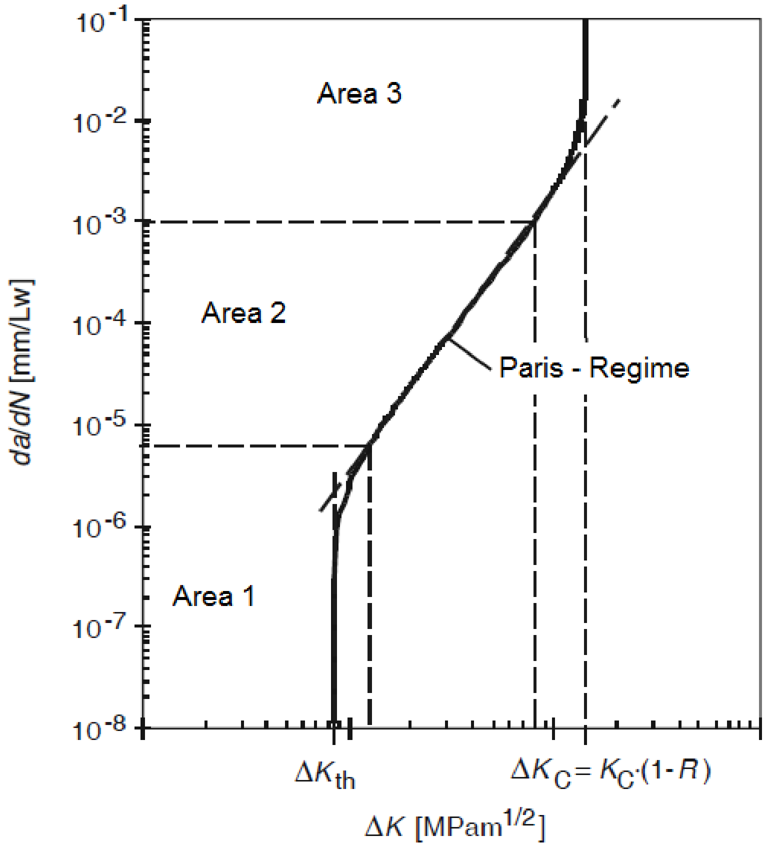


Figure 2.12: Crack growth curve [52]

The curve asymptotically approaches two limits. The first is the threshold value, ΔK_{th}, of the fatigue crack growth. If the cyclic stress intensity is above this threshold value, the fatigue crack is able to grow. The second limit, $\Delta K_C = \Delta K_{IC}$, represents the load at which the crack grows unstably (K_{IC}, the fracture toughness). The condition that must be fulfilled is $K_{I,max} = K_{IC}$ or $K_{I,max} = \Delta K_{IC}/(1-R)$. The crack growth curve can be split in to three areas. In the first area, the crack grows slowly while in the third it grows very fast. In the second, the curve is linear and is described by the Paris law, *Equation 2.5*, using the two material constants, C and m. [45] [52] [53]

$$\frac{da}{dN} = C(\Delta K)^m \tag{2.5}$$

This law is valid for long cracks only. For the computational prediction of the remaining service life of a component, different models and concepts have been developed. In addition to the knowledge of the stress characteristic, ΔK, for crack configuration, the basis for determining lifetime is the functional description of the crack growth curve, which is given by the crack velocity equation: $da/dN = f(\Delta K, R)$. The Paris law was one of the first functions of this kind and describes the second area of the crack growth curve. Originating from a certain initial crack a_i, the remaining service life before fracturing can be calculated by integrating of the crack velocity equation [52]:

$$\frac{da}{dN} = f(\Delta K, R) \Rightarrow dN = \frac{da}{f(\Delta K, R)} \Rightarrow N = \int_{a_i}^{a_B} \frac{da}{f(\Delta K, R)} \tag{2.6}$$

Other empirical fracture mechanical methods include, for example, a modified crack growth law of Paris. These models are separated in two equations, dependent on the temperature range. Other methods based on the Paris law are, for example, the Frost-Dugdale crack growth law and the crack growth law by Walkers. The Frost-Dugdale law is based on factors, which are included in the lifetime analysis, like rail-chill thermal and mechanical load on block braked wheels. Walkers' crack growth law shows that the crack growth rate is influenced by the stress ratio of the load applied. [54] [55]

3 Preparatory Works

Following the above literature review presenting block brake-wheel systems, numerical simulations, and different damage models, comes the practical part of this thesis. This section is split into three parts. The first seeks and present literature about block brake-wheel systems. The second selects sources with information about finite element simulations. With this information, the parameters to be used for the simulation are selected and compared with the current finite element simulation from Siemens AG. In the third section, different damage models are selected from the references. These damage models are based on both components without cracks and after crack initiation.

This chapter contains the first section of practical part of this thesis: the literature research. The other practical sections are presented in *Chapters 4* and *5*. The literature research has different aims. It should provide an overview of the state of art of the block brake-wheel systems. This includes the system itself, the block braked wheel, bench tests, and finite element simulations. Therefore, information about the wheel, including its material properties, manufacturer, and different damage cases, is investigated. An initial step in the course of this thesis was to examine what kinds of literature were already known to Siemens AG, and what other literature on the topic could be found. For this reason, an input source list was created, which can be found in the Appendix. This list shows the type of literature, source, and years of publication, which was available.

There are different kinds of literature dealing with the subject of block braked wheels, as seen in *Figure 3.1*. Papers, reports of bench tests and vehicle tests, standards, contributions to conferences, presentations, Master's thesis from students of different universities, technical articles, reports, and reference books. In addition to its different forms, the literature comes from different sources, such as Siemens AG itself, the standards database, international conferences, university libraries, journals, and scientific research databases.

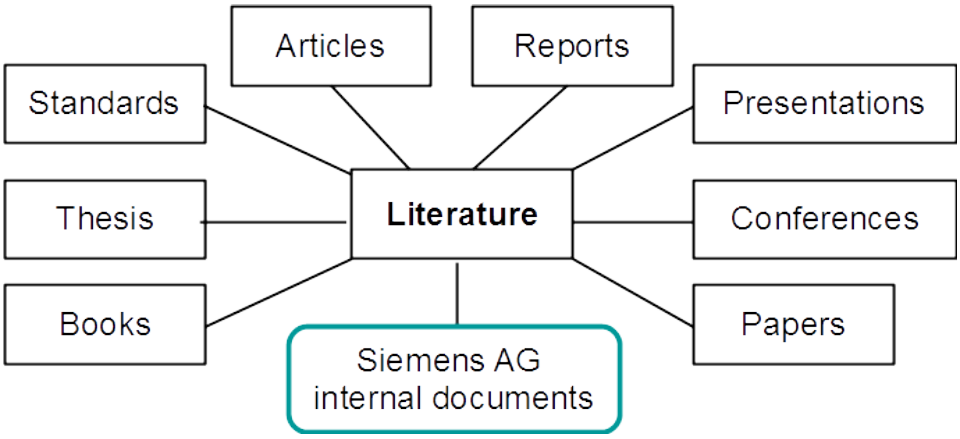


Figure 3.1: Different kinds of literature.

The next step was to collect literature from these sources and create a database; see *Figure 3.2*. This figure gives an overview of the different informations available about block braked wheels. The database has nine fields, which include author, title, publisher, issue of papers, journals or international conferences which consist of volume, number, place and pages. The issue is followed by the year of publication, the type, a short summary, several informative keywords, and, finally, the file name. The database includes 189 entries, which have been collected and stored internally by Siemens AG. The database can be found in the Appendix. With help of the literature list, an overview of the different topics can be gained; these topics include wheel material, brake block material, wheel damage, interactions between wheels and brakes or rails, tests, and finite element simulations.

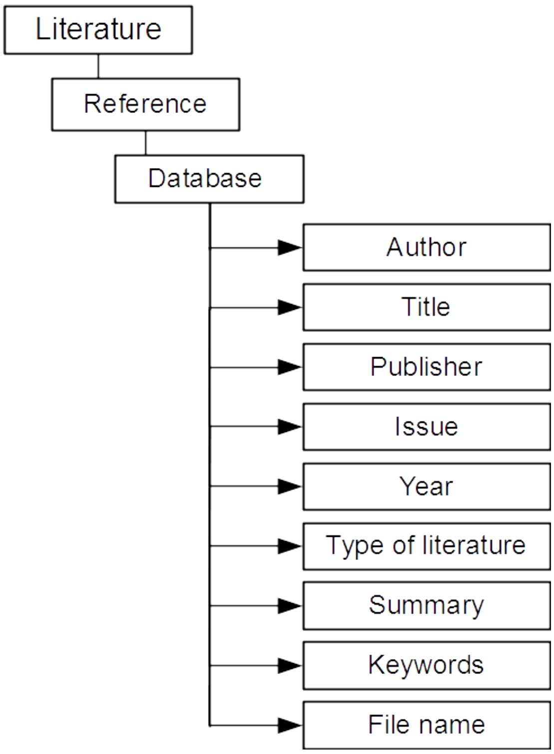


Figure 3.2: Collection of literature from references and creation of a database. The database include certain information of the literature.

The next two parts of the thesis were written based on information from the database. *Figure 3.3* shows a mind map of different topics which were found in literature. The main topics are the wheel material and the influence of the block brake, the finite element (FE) simulation, as well as different damage theories based on empirical damage mechanical models and empirical fracture mechanical methods.

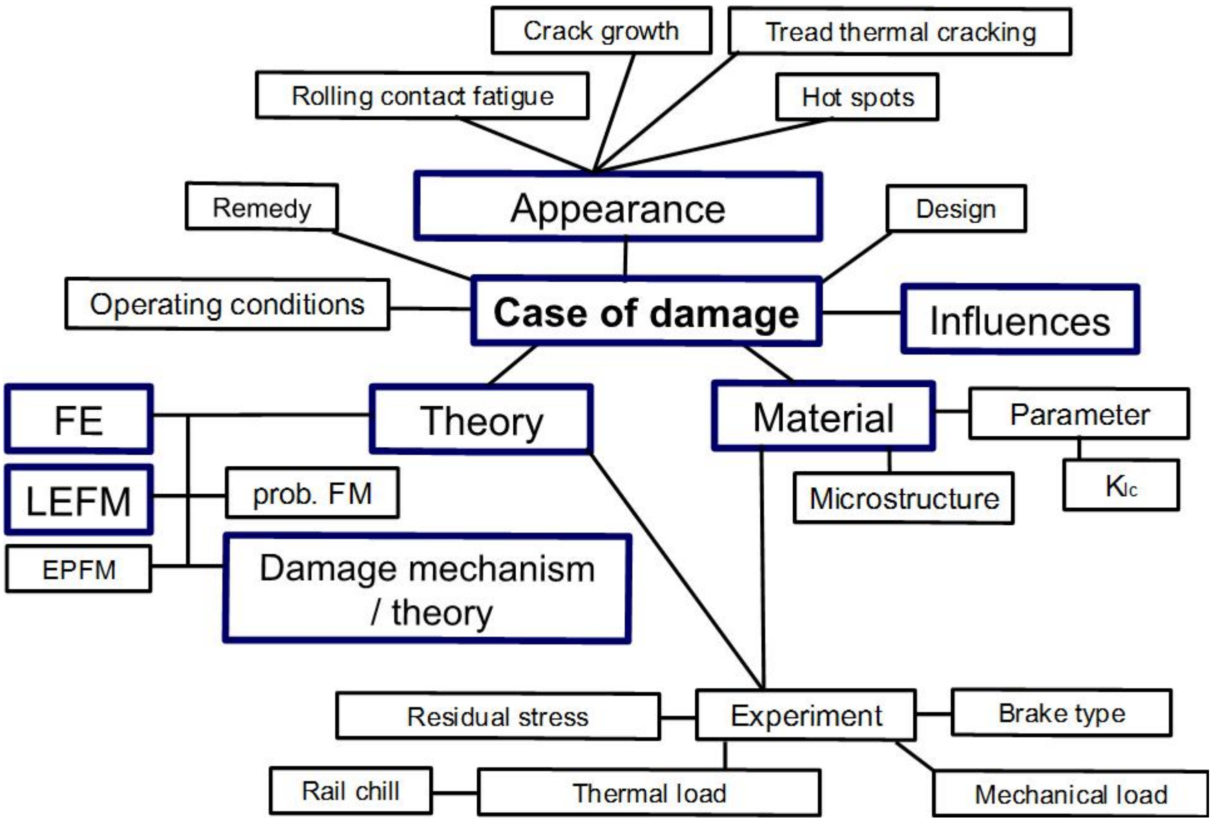


Figure 3.3: Overview of different topics relating to block braked wheels.

4 Requirements for the Advancement of FEA

In the previous chapter, a list of all of the references collected for this thesis on the topic of block braked wheel systems was presented. On the basis of this list, fifty-seven papers, technical reports, articles, presentations, and theses were selected, which deal with finite element simulations. The aim of this section is to identify, from literature, the phenomena that are important for finite element simulations of railway wheels in order to calculate the deformation D, residual stresses σ, and temperature field T, *Figure 4.1*. The initial conditions for monoblock wheels are established in the standard $EN13979-1$ [56] and $UIC510-5$ [57]. The results of the literature study are presented in an evaluation matrix. This matrix is compared with the actual finite element simulation used by Siemens AG and the phenomena from literature.

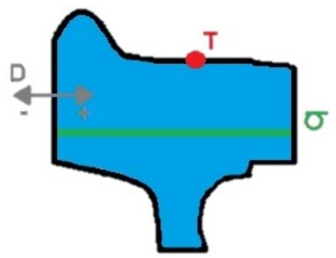


Figure 4.1: Railway wheel rim with three solutions: tread temperature T, residual stresses σ and wheel rim deformation D

In *Figure 4.2* an overview of the evaluation matrix is shown. Inside the circle, different phenomena are listed, which are used in the simulation model by Siemens AG. The other phenomena are not included. Details about the evaluation matrix can be found in the Appendix.

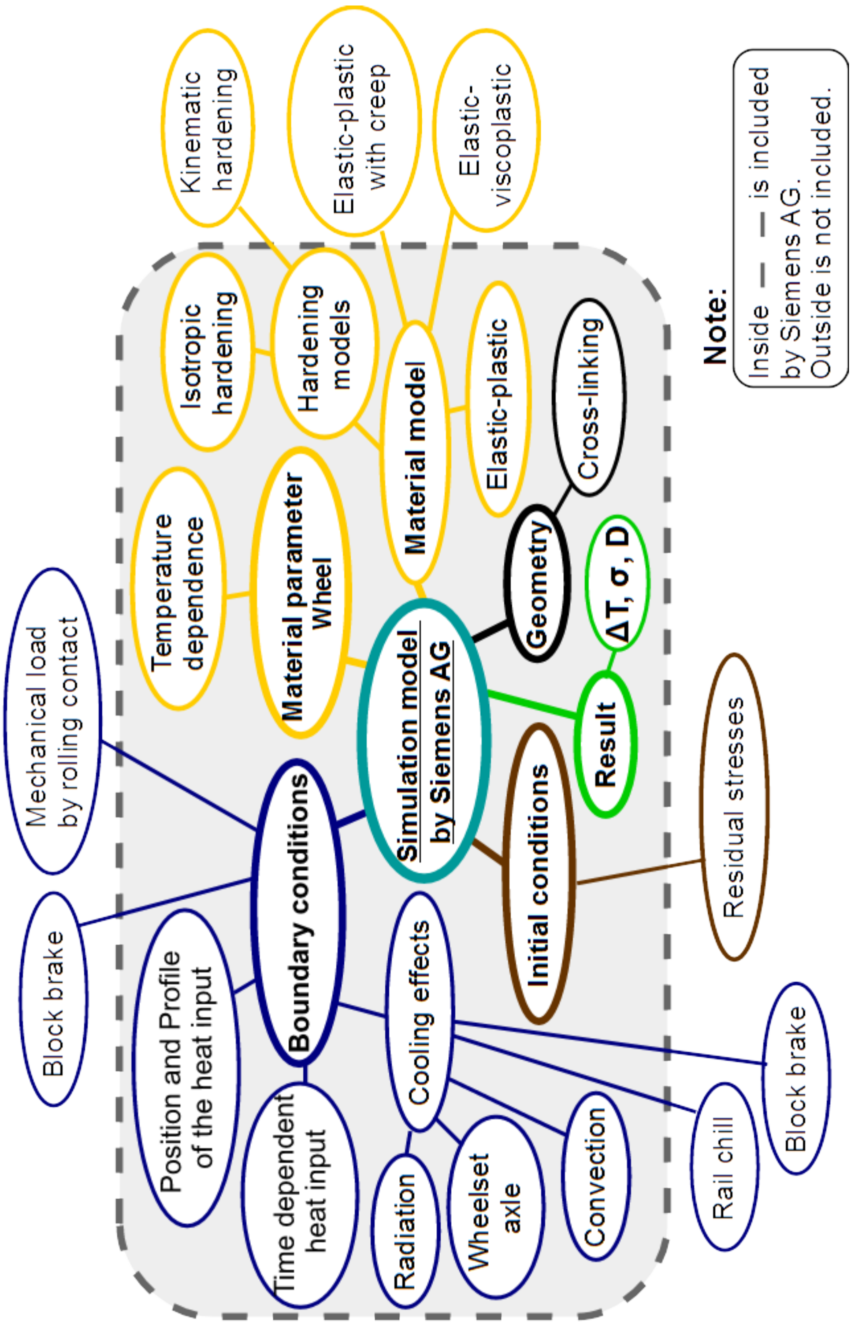


Figure 4.2: Overview of the content of the evaluation matrix. The point of departure are the actual simulation model and the phenomena which are used (grey range). Outside the grey range are the phenomena which are not included in the simulation.

At present, the simulation model used by Siemens AG serves to calculate temperature changes, residual stresses, and wheel rim deformation in an axisymmetric two-dimensional finite element simulation. The graphical result of the transient thermo-mechanical MARC model can be seen in *Figure 4.3*. This simulation model is based on material parameters found in reports [58] and contributions to conferences by Murawa [9]. It uses temperature-dependent material parameters, an isotropic hardening model, and an elastic-plastic material model. The boundary conditions include position, profile- and time-dependent heat input as well as cooling effects. In addition to radiation and convection, cooling effects occur through the wheelset axle.

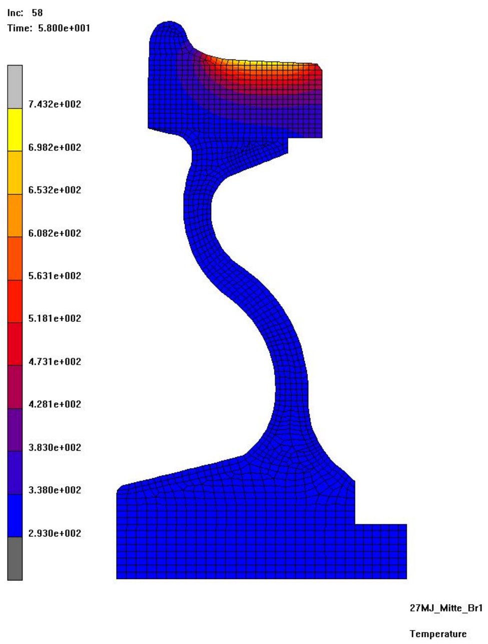


Figure 4.3: The graphical temperature result from the transient thermo-mechanical MARC model, [59]

4.1 Finite element mesh of the Wheel Geometry

Holowinski [60] and Caprioli [61], examine the behaviour of the results depending on the different finite element meshes, *Figure 4.4*. The results are significantly improved with a finer mesh for the wheel tread. On the other hand, this also results in extremely high computational costs, [62]. All sources use a fine mesh (finite element size = 1 mm) for the wheel tread.
Siemens AG uses fine meshes in the finite element model and will continue to do so in future models. For an efficient simulation, it is important to find a balanced relation between the finite element mesh and the computational costs.

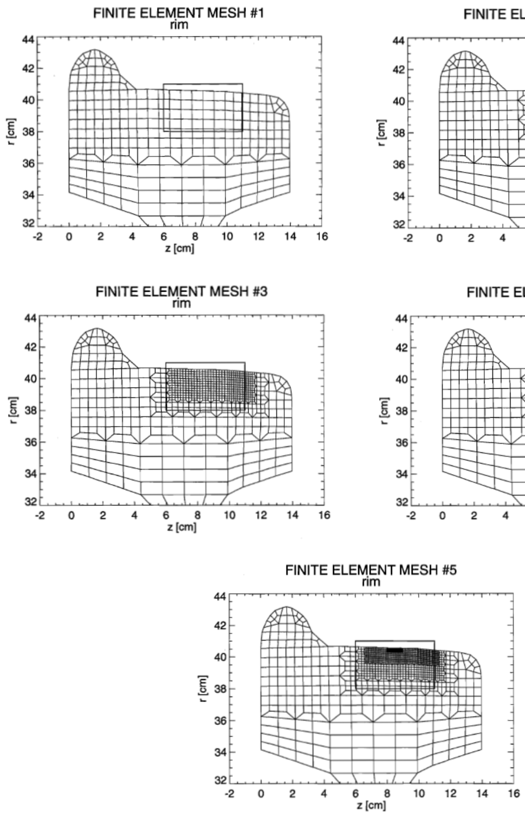


Figure 4.4: Different forms of meshes from the wheel tread. [60]

4.2 Material Parameters and Models

4.2.1 Temperature-dependent Material Parameters

Material properties change with temperature. Therefore, a number of references use temperature-dependent material parameters. Another aspect was found by Lundén [63]: during a simulation, he observed, that below 400 °C, there were no relevant differences between the results with or without temperature-dependence. *Figure 4.5* shows the properties as a function of temperature. Material parameters such as Young's modulus or yield strength can be seen to significantly depend on temperature. Siemens AG already uses temperature-dependent material characteristics for its current finite element simulation.

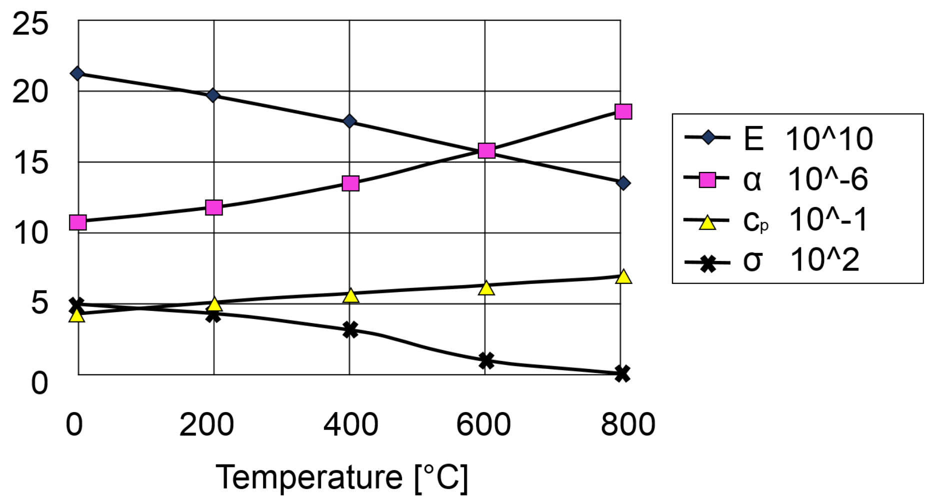


Figure 4.5: Material parameter as a function of temperature: Modulus of elasticity E [MPa], extension coefficient α [1/°C], specific heat c_p [kJ/kgK] and yield stress σ [MPa]. [64]

4.2.2 Material Models

Literature reports that a standard elastic-plastic model is used to simulate the block braked wheel. Besides the elastic-plastic model, there are also the elastic-viscoplastic model and the elastic-plastic model with creep effects. During simulation, the difference between the viscoplastic and the elastic-plastic-model with creep effects, is that the former considers the creep effect directly while the latter first considers the elastic-plastic part and then calculates the creep effect in a separate step. The elastic-plastic case is the most commonly used model for block braked wheels. Murawa [9] investigated whether there were any relevant differences between an elastic or an elastic-plastic model. They found that the elastic-plastic simulations were more realistic for residual stresses than the elastic-only. *Figure 4.6* shows the different models and their results with regard to residual stresses.

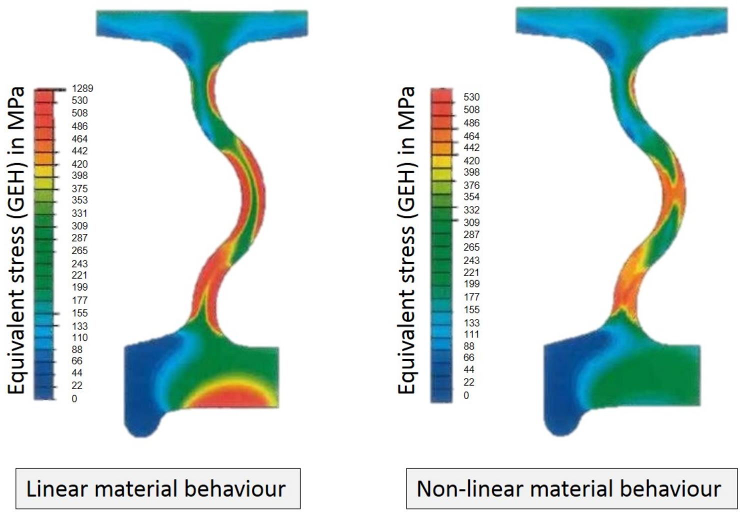


Figure 4.6: Comparison between the elastic and the elastic-plastic finite element models. [9]

The elastic-viscoplastic and the elastic-plastic model with creep effects are mentioned in literature, but they are not compared to the elastic-plastic case. Hence, it cannot be said if the results thereof are more realistic. Teimourimanesh [2], Caprioli [20] [62], Raninger [65] and Esmaeili [66] have all published that the elastic-viscoplastic model produces good results for simulation at high temperatures. Therefore, it would be useful to test whether or not, there is a large difference in comparison to the results produced by other models. The current finite element simulation by Siemens AG is elastic-plastic.

4.2.3 Hardening Models

Literature reports that there are two different hardening models: isotropic and kinematic hardening. Murawa [9] and Raninger [65] describe which load case requires the use of the isotropic, or kinematic models, as well as when a combination of the two is most useful. In case of monotonic loading, isotropic hardening describes the stress strain curve after yielding. For cyclic loading, it describes how the hysteresis loops change over multiple cycles. In contrast, kinematic hardening describes what happens during cycle loading and the description of cyclic $\sigma - \epsilon$-hysteresis are possible. Combined hardening can be modelled, but the change of the behaviour with increasing cycle number should be considered. Siemens AG uses the isotropic hardening rule in their model. In order to further develop their finite element analysis, it would be advantageous to test whether or not there are differences in their calculations.

4.3 Initial Conditions: Residual Stresses

During heat treatment, there is a certain amount of residual compressive stress on the rim. Through cooling after braking with block brakes, these stresses are converted into tensile stresses. These cause cracks and eventually lead to wheel damage. Murawa [9] describes how, after one drag braking with high power, the residual compressive stresses vanish. Wang and Pilon [67] tested which brake load and heat input, respectively, was necessary for no residual compressive stresses to be on the wheel rim. They found that the stresses vanish if the heating duration is longer than 57 minutes with about 34 kW heat input. Holowinski [60] shows the difference between cases with only thermal loads and thermal loads with the presence of initial residual stresses, which represented the as-manufactured stress state. Both cases were measured under the same conditions: the wheel was subjected to thermal loading during one stop-braking manoeuvre from 130 km/h at $1\,\mathrm{m}/s^2$. For the case with initial residual stresses, the measurement data was very similar to those without them. Furthermore the stresses resulted in a much bigger plastic zone than in the case with thermal load only. In the area of the tread surface, this could be explained because aside from thermal loadings high plastic strains occurred. Areas which are remote from the tread surface, are solely influenced by the initial residual stresses.

At present Siemens AG does not use stresses in its simulation, but plans to include it in a future model. The expectation is that the simulation of wheels will be more realistic once this is added.

4.4 Boundary Conditions

4.4.1 Block brake

The next step is the integration of the brake block part in to the model, as well as the use of a temperature-independent material model for the block. In literature, the block brake part is integrated into the models, as seen in *Figure 4.7*. The block is included in two-dimensional as well as three-dimensional finite element simulations, but there has been no comparison between the results with and without block brake. Models with a temperature-independent material model cannot be compared with temperature-dependent material parameters, because there is no clear agreement about whether the brake block component is necessary for the calculations.
In the finite element simulation used at Siemens AG, there are no brake blocks in the model. Siemens AG will examine if there are significant differences in the results. For this purpose, their model will integrate the brake block instead of the value of the heat input into the tread.

However, it should be kept in mind that friction is an important topic of simulating the block brake-wheel contact. Therefore, significant attention should be given to the frictional contact, as the subject is not to be underestimated. Effertz [68], Khosa [69] [70], Maalekian [71] and Vernersson [72] [73] deal with heat generation methods which consider that the heat is generated through frictional contact. The methods can be based on the coefficient of friction, thereby friction stress is a function of normal pressure or normal load. Furthermore, the methods can also be based on experimental power dissipation or the energy input. Another method is to estimate surface temperature and surface heat flux from temperature data at some locations inside the material.

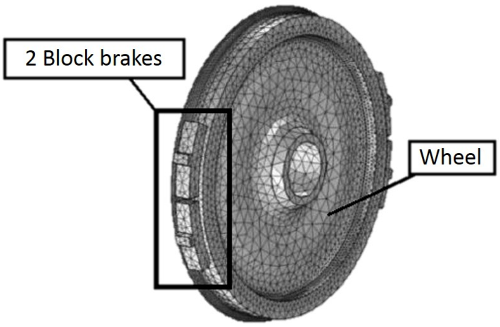


Figure 4.7: The three-dimensional model of the block-braked wheel. [17]

4.4.1.1 Position and Profile of the Heat Input

In *Figure 4.8*, results due to two different positions of heat input are shown. In the first, the block brake is in the centre of the wheel tread, which is the standard position of the block. The other position is the overhanging brake block position.

Kwon [22], Handa [24] and Milutinovic [74] show that the position of the block brake has an obvious influence on the wheel tread temperature. It was measured that the temperature difference is about 100 °C to 300 °C.

At present, Siemens AG uses both positions.

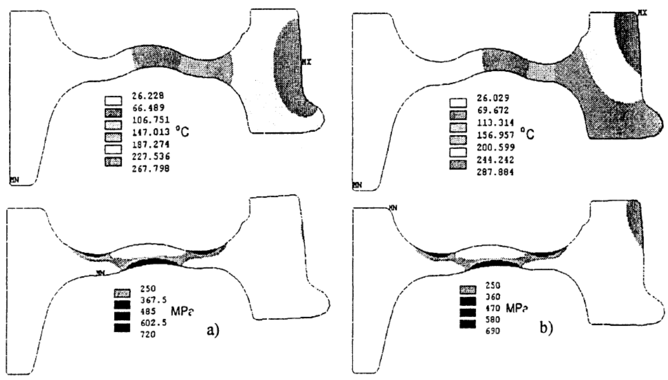


Figure 4.8: Temperature and stress states of the wheel with centred (a) and overhanging (b) block brake positions. [74]

In addition to the position, the profile of the heat input is another important parameter. The profile of heat input refers to the variation of the heat input on the wheel tread. There are different forms, as seen *Figure 4.9*. [75] [76]

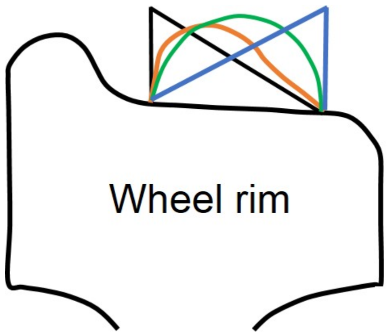


Figure 4.9: Different profile of heat input on the wheel tread. [75] [76]

4.4.1.2 Time-dependent Heat Input

Besides the position and the profile, the time-dependent heat input on the tread is investigated. This refers to the temperature change in relation to the time of train running, *Figure 4.10*. These diagrams are often created by applying a uniform heat flux along the tread surface, as in Teimourimanesh [7], Holowinski [60], Caprioli [62], Milutinović [64] and Gordon [77].
Siemens AG already uses time-dependent heat input in its models.

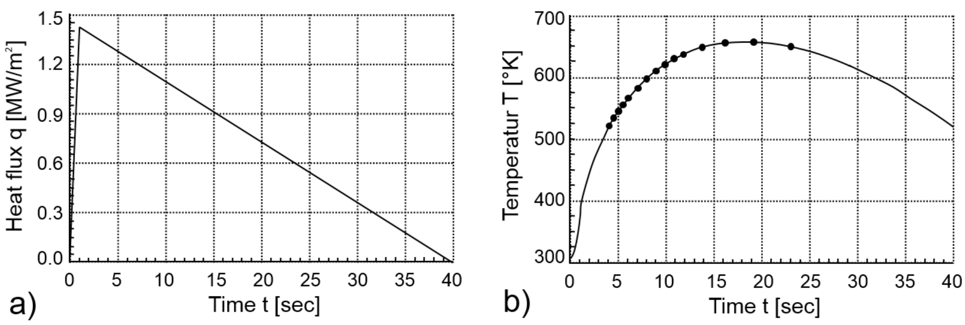


Figure 4.10: Heat flow-time curve (a) and temperature-time curve (b) on the wheel tread for one stop-braking. [60]

4.4.2 Mechanical Load by Rolling Contact

Along with the heat input of the block brake, rail contact is also considered in the finite element simulation. Caprioli [62], Lundén [63] and Vernersson [78] describe how the simulation with mechanical load only offers significant results in a three-dimensional model and when calculating lifetime measurements. Only Holowinski [60] describes a test with and without mechanical load by block braked wheels. The solutions for the cases of mechanical load and thermal loads are superimposed. There is no clear statement about the calculation of temperature, residual stresses and deformation. Along with the mechanical load, the rail cools the wheel, see *Section 4.4.3*.
At Siemens AG, the mechanical load is not considered because the current simulation is used to examine bench tests with heat input from block brakes only. Beside this examination of bench tests, they also consider the fulfilment of conditions as defined by the standards. For this reason, the mechanical load during rolling contact will not be included in the future bench test simulation model of Siemens AG.

4.4.3 Cooling Effects

Wheels are cooled during and after the braking phase by the brake block, the wheel-rail contact, convection and radiation, and by the wheelset axle, [18]. *Figure 4.11* shows different wheel rim temperatures as received from finite element simulation. The amount of heat loss to brake blocks (brown line) through radiation and convection (olive and green line) and rail-chill (blue line) is evident in the diagram. As seen in the diagram, in the case of frequent braking from high speed, convection and radiation have to be included as variables. Therefore, the avoidance of dirt and oil layer on the wheel surface is important to prevent high wheel temperatures. In addition to radiation and convection through ambient air, rail–chill effects and heat loss to brake blocks are essential.

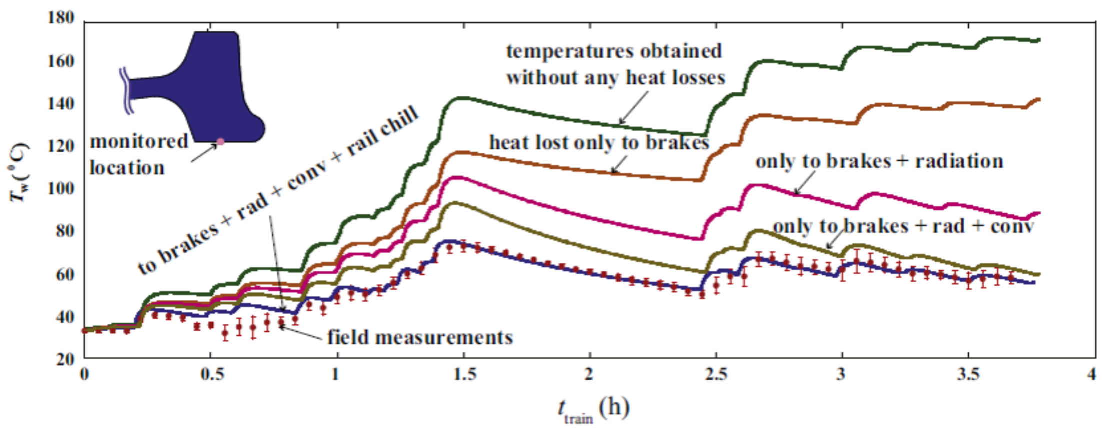


Figure 4.11: Different wheel rim temperatures received from finite element simulation. [18]

Teimourimanesh [5] [8], Vernersson [79] and Gupta [80] have observed that the rail-chill effect becomes significant important during braking when the tread temperature rises. The rail-chill effect depending on the brake block material during drag braking was also examined. The largest change of heat partitioning, while introducing rail-chill, was found for the composition brake block. The results for wheels with and without rail-chill vary by around 20 %. The smallest change appeared for cast iron blocks, with a 10 % distinction. The heat loss between the wheel tread and the rail is reliant on the temperature difference. Depending on the power of the stop braking, there is only a small temperature difference for a single braking action. Since the rail receives a minimum share of the generated heat, it is only necessary to consider the rail-chill effect in the phase after braking. However, for drag braking at constant brake power (or constant brake force), the rail-chill effect becomes increasingly significant, as the wheel tread temperature rises. In the braking phase, as well as in the phase after cooling, the rail-chill effect should be considered.

Vernersson [4] presents a model for cooling by convection. For the simulation, the wheel surface is divided into different areas, and for each area a separate expression is used to control the convection cooling, as depicted in *Figure 4.12*. The figure shows the three areas: the wheel tread (dashed line), the side faces of the wheel rim (solid lines), and the surface of the wheel disc.

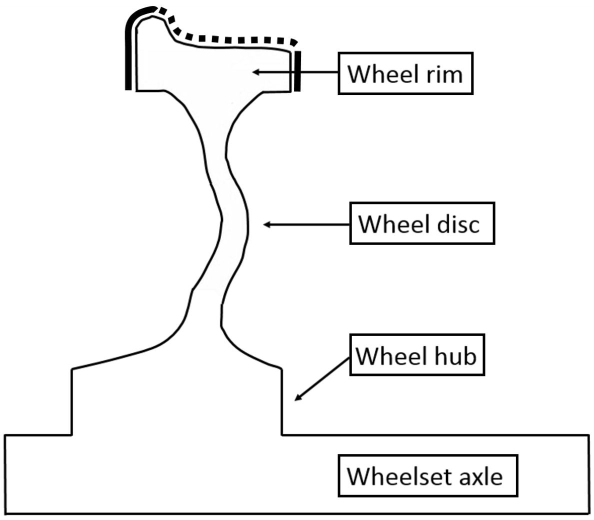


Figure 4.12: Three wheel areas for the convection cooling. The first area is the wheel tread (dashed line), the second is the side faces of the wheel rim (thick black lines) and the third is the surface of the wheel disc. [4]

Besides the rail-chill, the brake type is important. It is also necessary to differentiate between the braking itself and the cooling phase afterwards. For long drag braking, it is critical to consider cooling through convection and radiation during and after braking. In case of stop braking, it is only necessary to consider the two cooling effects after the braking phase.

The wheelset axle can also have a cooling effect; however, in literature, there is no information about this effect. The temperature of the hub has no relevant influence on the wheel tread, because of the large distance between them. Evidence shows that cooling effects are very important and should be included in simulations. Siemens AG uses three cooling effects at present: convection, radiation, and wheelset axle cooling. Because of the large distance between the wheel tread and the axle, the cooling effect of wheelset axle will be neglected in the future model. However, the cooling effect of the brake block will be integrated into the new model with radiation and convection. The new model will improve the bench test simulation of the wheel-brake block system without influence of the rail. Therefore, it is not relevant to integrate the rail-chill effect.

4.5 Microstructural Changes

The last point to be considered in the evaluation matrix, which can be found in the Appendix, is the microstructural changes resulting from the influence of heat on the wheel rim. In literature, bench tests have been run to examine the changes to the microstructure.

There are no conclusions about microstructure changes in cooperation with finite element simulation. At the moment, Siemens AG does not investigate the microstructure, but the future model will investigate these changes, not directly in the simulation, but during postprocessing. When the brake and cooling phases are known, the microstructural changes can be estimated from the simulation results. Further conclusions can be drawn about areas, which may have hard or brittle structural changes. Based on this knowledge, safety measures against crack initiation and crack growth can be defined.

4.6 Recommendations

To sum up, Siemens AG already uses a large number of relevant phenomena in their finite element model. For the simulation of temperature changes, residual stresses, and wheel rim deformations, the future model should include:

- Temperature-dependent material properties
- Elastic-plastic material models
- Mixed hardening rule
- Residual stresses in the wheel rim
- Different cooling effects:
  - Radiation
  - Convection
  - Block brake.

The elastic-plastic material model, the elastic-viscoplastic model, and the elastic-plastic model with creep effects were all found in the reviewed literature. Nonetheless, there was no clear agreement about which produces the most realistic results. It would be advantageous to test which material model best matches the bench tests. Next to the material model, the influence of the block brake should also be analysed, in order to clarify if there are significant differences in the results of the simulation. At present, Siemens AG uses three cooling effects in its simulations: convection, radiation, and wheelset axle cooling. Because of the large distance between the wheel tread and the axle, the cooling effect by wheelset axle can be neglected in the future model. However, the cooling effect of the brake block should be integrated into the new model, with radiation and convection. The new model by Siemens AG should improve on the current the model used to simulate bench test on the wheel-brake block system without the influence of the rail. Therefore, neither the mechanical load during rolling contact nor the rail-chill cooling effect are relevant, as seen in *Figure 4.13*. By the simulation of field measurements the influence of the rail is also to be considered. The grey space illustrates the phenomena which should be included, while those outside the grey area should not necessarily be included - further testing of their relevance being required.

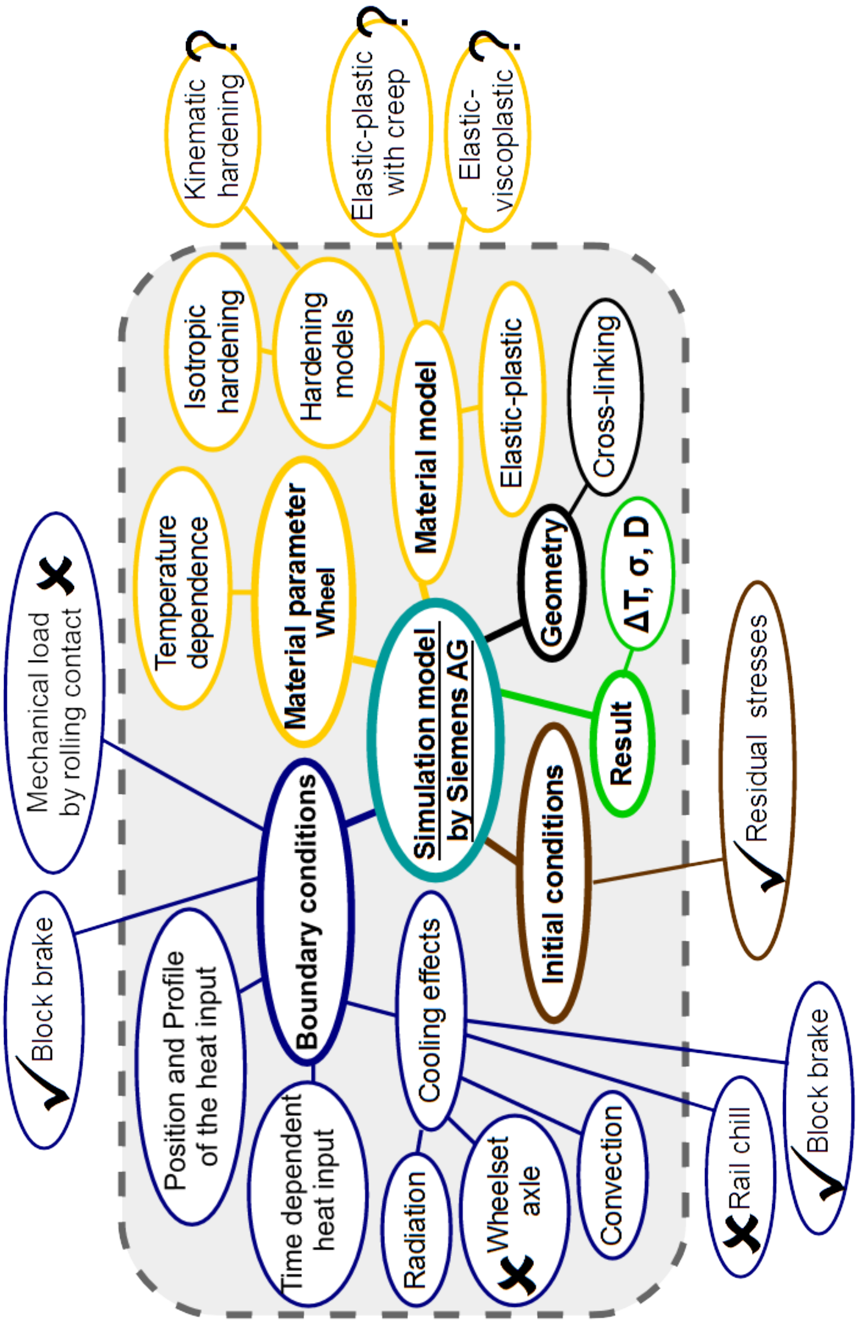


Figure 4.13: Overview of the evaluation matrix with the selection of the relevant parameters. The point of departures are the actual simulation model and the phenomena used (grey range). Outside the grey range are the phenomena which should not be included, indicated with an X, while the phenomena with a tick should be tested with regard to their relevance. Parameters, which are marked with a ?, have not shown a clear statement about their relevance.

5 Models for Lifetime Estimation

Fifty-seven different sources on damage models for lifetime estimation were identified in the references. *Table 5.1* presents different models of empirical damage and empirical fracture mechanical methods, used for the wheel material and its components.

The starting point for lifetime calculations is the analysis of the material; when the behaviour of the material is known, the lifetime of the component can also be calculated.

Table 5.1: Damage models Used by Siemens AG and in Literature

Models:	**References:**
Empirical damage methods:	
Basquin-model	[12] [81] [82] [83] [84] [85] [86] [87] [88] [89] [90] [91] [92] [93]
Manson-Coffin-Model	[12] [13] [63] [81] [82] [83] [93]
Basquin-Manson-Coffin-Model	[81] [82] [83]
Damage parameter P_{SWT}	[94]
Empirical fracture mechanical methods:	
Paris law	[53] [95] [96] [97] [98] [99]
Modified crack growth law	[97] [98]
Frost-Dugdale crack growth law	[100] [101] [102] [103]
Walker crack growth law	[104] [105]

The table shows that, in literature, the Manson-Coffin-model and the Basquin-model are often used, whether in tandem or separately, for the calculation of the lifetime of the material without cracks. For materials with cracks, the Paris law or modifications thereof are applied. The models are calculated with parameters from bench tests as well as from the finite element simulation. The next sections present the models from literature as well as how to establish the parameters from tests. In *Section 5.1* is shown an applied damage model by Siemens AG, which use the Basquin-Manson-Coffin Model.

5.1 Applied Model: Basquin-Manson-Coffin Model

Through internal tests, Siemens AG has found that, for the wheel material ER7, the Basquin-Manson-Coffin model is most useful for lifetime calculations. It applies for the material as well as for the component in the finite element simulation without cracks. For the finite element analysis (FEA), initial conditions like, stress σ, strain ϵ, and start temperature are used. For the material behaviour, it is necessary to know the thermophysical properties within the material model. These properties depend on the temperature T, and on the strain rate $\dot{\epsilon}$. For lifetime calculation, the relevant results of the simulation are the plastic and elastic strain amplitudes ($\epsilon_{pl,a}$, $\epsilon_{el,a}$).
In addition to FEA, low cycle fatigue (LCF) measurements for the railway wheel made of ER7 are also carried out, for which it is necessary to know the relevant parameters.
With the help of the results of the FEA and the LCF, different empirical damage models are tested. The models used are the Basquin-Manson-Coffin, Riedler-Unified Energy Approach, damage parameter by Smith-Watson-Topper, the parameter by Ostergren, and a simple life expectancy model by Winter, [81] [82].
The Manson-Coffin model has been found to best fit the measured data. With help of this model, the plastic strain amplitude $\epsilon_{pl,a}$ against cycle to crack initiation N_f can be plotted. The best damage model for the wheel can be used for the simulation of the block brake-wheel system. *Figure 5.1* shows the Siemens AG approach for finding the best damage model without cracks. Siemens AG has not yet investigated the lifetime of materials after crack initiation in detail. [83]

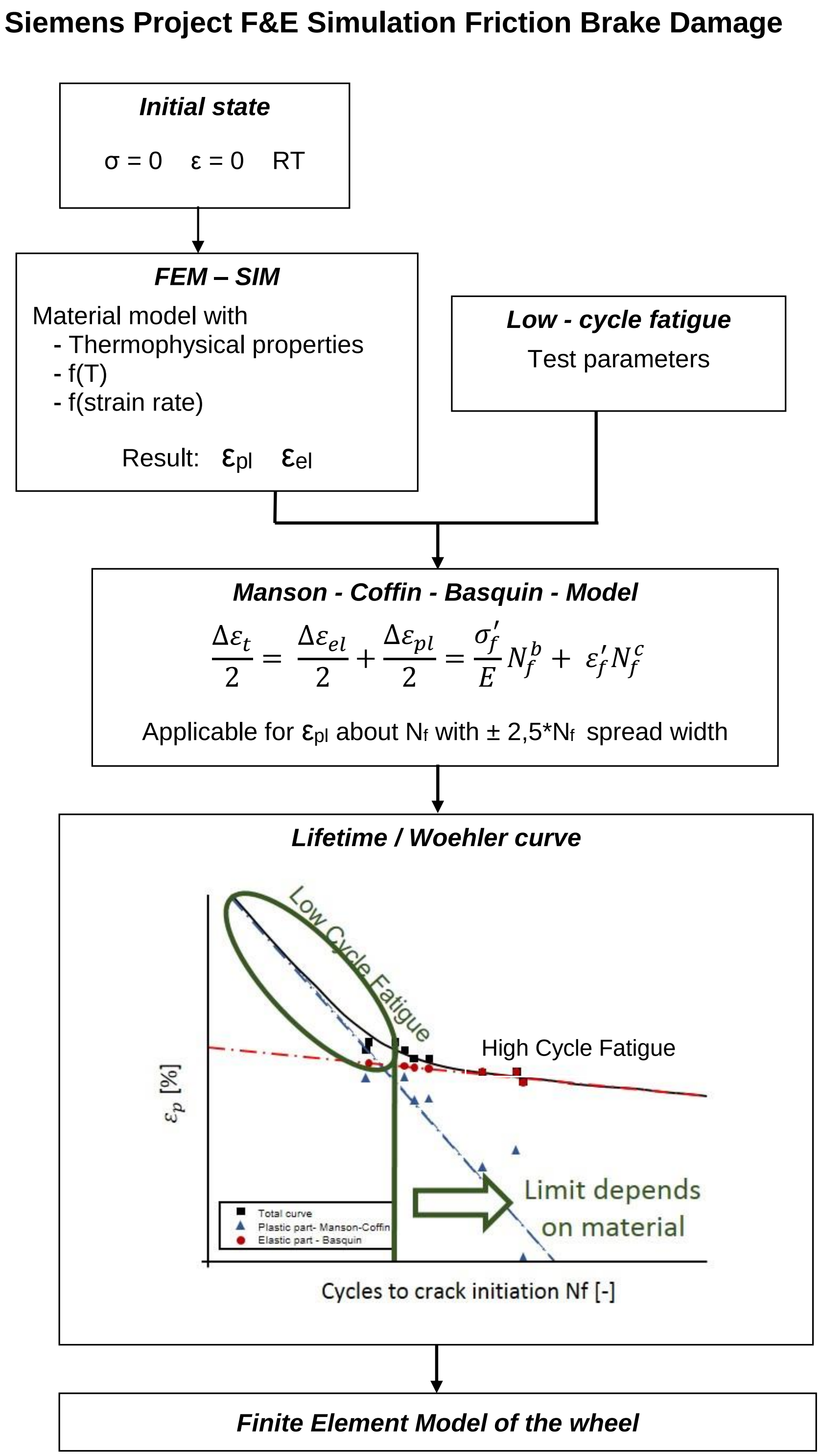


Figure 5.1: Damage model used by Siemens AG. [81] [82] [83]

5.2 Empirical Methods

Besides the applied model used by Siemens AG, lifetime measurements for railway wheels have also been investigated in literature. The lifetime calculation methods without cracks are addressed in this Section those for wheels with cracks are in *Section 5.3*.

5.2.1 Basquin-Model and Basquin-Manson-Coffin-Model

Starke, Walther and Eifler [84] describe a physical-based lifetime calculation method ($PHYBAL_{LSV}$). In this method the Basquin-model is used for the lifetime measurements. There are two variations of $PHYBAL_{LSV}$: one which only considers the Basquin-model for the lifetime measurement, and another which also includes the Manson-Coffin-model. [85] [86] [87] [88] [89] [90] [91]

The $PHYBAL_{LSV}$ method, with only the *Basquin-model* allows, on the basis of more general Morrow- and Basquin-equations, reliable calculations of Wöhler-diagrams, with only three endurance tests, as seen in *Figure 5.3*. With one load increase test (LIT) and two constant amplitude tests (CAT), it is possible to calculate Wöhler-diagrams, which match conventional approaches. In this way, the costs and experimental effort are massively reduced. Next to the calculation of the lifetime of the wheel material, this method can also be used to calculate the lifetime of the wheel component. The results of the tests are the plastic strain amplitude $\epsilon_{a,pl}$, the deformation-induced temperature change ΔT, and the electric resistance change ΔR. Those measured values are influenced by the microstructural changes in the volume of material, and are connected to the level of fatigue. The results can be used to transform the general Morrow-equation, which describes the cyclic stress-strain (CSS) curves. The equation shows the stress amplitude σ_a as a function of the plastic strain amplitude $\epsilon_{a,pl}$, with the cyclic hardening coefficient K' or K'_M and the cyclic hardening exponent n' or n'_M, *Equation 5.2*. Through the three measured values of the endurance tests, the equation can be transformed into a general form, where M can be ΔT, ΔR or $\epsilon_{a,pl}$. In addition to the Morrow-equation, the Basquin-equation can also be transformed into a general form, with the fatigue strength coefficient σ'_f or $\sigma'_{f,M}$ and the fatigue strength exponent b or b_M. [84] [85] [86] [87] [88]

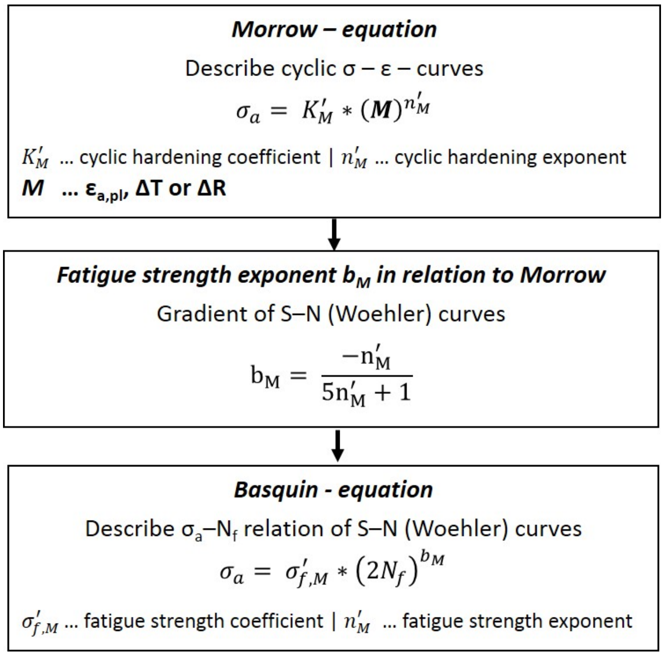


Figure 5.2: Relation between Morrow and Basquin-equation, which can be transformed into a general form, where M can be ΔT, ΔR or $\epsilon_{a,pl}$. [84] [85].

The fatigue strength exponent b_M, which refers to the gradient of the Wöhler-diagram can be calculated using the cyclic hardening exponent n'_M of the cyclic stress-strain curve. The fatigue strength coefficient $\sigma'_{f,M}$ can be determined with the known b_M, the stress amplitude σ_a and the number of cycles to failure N_f from one constant amplitude test. By transforming the Basquin-equation after N_f, the Wöhler-diagram can be determined on the basis of one LIT and two CAT. Therefore the diagram matches the measured values. *Figure 5.3* presents the sequence of PHYBAL$_{LSV}$.

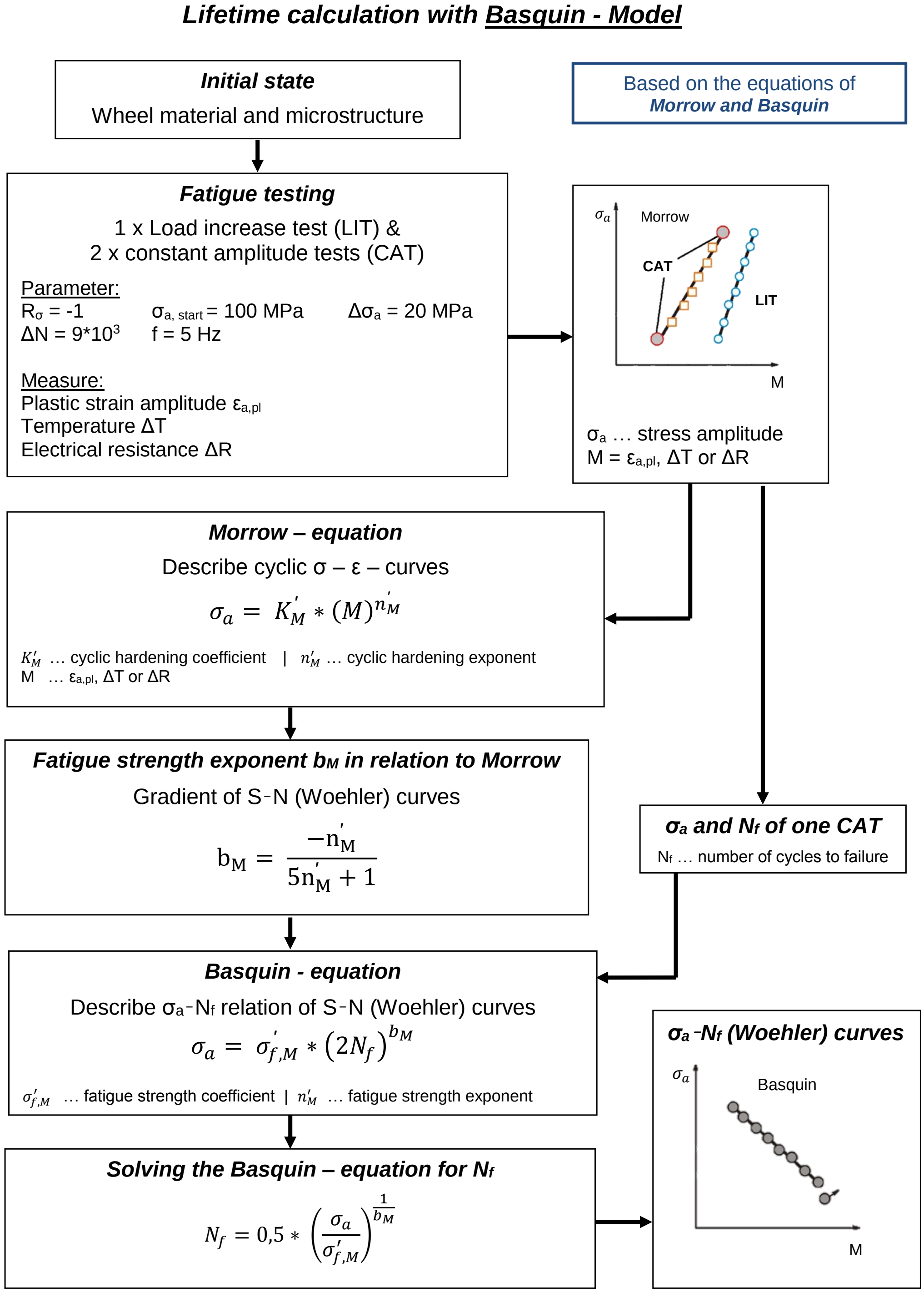


Figure 5.3: Lifetime calculation method based on the Basquin-model. [84] [85] [86] [87] [88].

The PHYBAL$_{LSV}$ method with the Basquin-Manson-Coffin-models additionally applies the Manson-Coffin-equation and uses single step tests (SST) as well as random loading tests (RLT) for the measurement of the plastic strain amplitude $\epsilon_{a,pl}$, the deformation induced temperature change ΔT, and the electric resistance change ΔR. Next to the Morrow-equation, the Manson-Coffin-equation, is transformed into a general form. The Manson-Coffin model describes the relationship between the plastic strain amplitude $\epsilon_{a,pl}$ and the number of reversals to failure $2N_f$. The general equation makes it possible to describe the relation between each measured value $M(N_f)$ at a defined number of cycles as well as the number of reversals to failure. In the following section, it is used to modify the general Morrow-equation and deploy the complete equation within the Basquin-equation. As in the first case, the $\sigma_a - N_f$ relation of Wöhler-curves is describable according to Basquin. This approach is presented in *Figure 5.4*. [89] [90] [91]

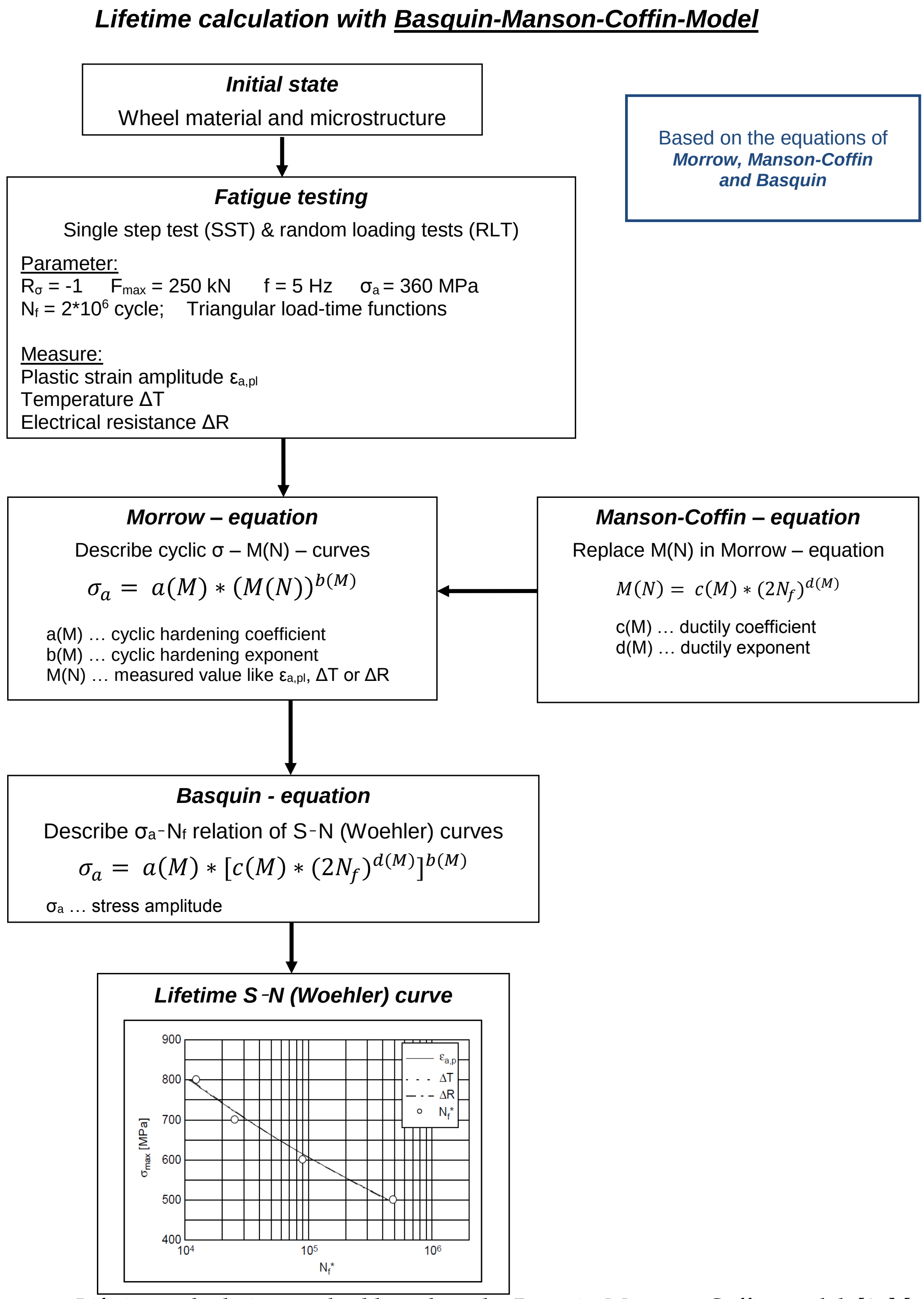


Figure 5.4: Lifetime calculation method based on the Basquin-Masnson-Coffin-model. [89] [90] [91].

5.2.2 Basquin, Manson-Coffin or Damage Parameter

The lifetime calculation method by Walther [12] is similar to PHYBAL$_{LSV}$ with the Basquin-Manson-Coffin model. Besides showing the cyclic deformation behaviour with special consideration of mean loadings, the microstructure is also investigated in the lifetime calculations. As mentioned above, PHYBAL$_{LSV}$ uses stress–strain (σ, ϵ) hysteresis measurements, thermometrical, and electrical measuring procedures. Giant-magneto-resistor measuring procedures and the microstructure are useful for calculating the lifetime, through they are rarely applied. As in the Section before the Basquin and Manson-Coffin-model is used, but not in combination. Furthermore the Smith-Watson-Topper damage parameter is used to the description of the influence of mean stresses. [13] [92] [93] [94]

This method is based on total-strain-controlled load-time function, and cyclic deformation experiments. The tests have been concluded when the specimen fails or after certain cycles are reached. To evaluate cyclic deformation behaviour, the bench tests integrate the conventional strain, thermometric, and Giant-Magneto Resistor (GMR) measurement setups [13]. Load dependent and number-of-cycle dependent changes to the microstructure of the wheel material are characterized and described by plastic strain amplitude $\epsilon_{a,pl}$, electrical change in voltage ΔU, temperature change ΔT, and GMR-Foucault current impedance Z_{GMR}. The measured values are based on physical processes, and therefore show a strong interrelation with the underlying fatigue process. ΔT and ΔU can, like $\epsilon_{a,pl}$, be used for lifetime prediction according to Manson-Coffin. With these data, in addition to Basquin, S-N-curves can be specified. Furthermore, the damage parameter according to Smith-Watson-Topper (PSWT) describes the influence of mean stresses on the lifetime. Light, scanning and transmission-electron microscopy enable the interpretation of the measured physical data using the microstructural details. In comparison to $PHYBAL_{LSV}$ the changes in voltage and GMR-Foucault current impedance are used instead of the electric resistance change. This lifetime calculation approach is presented in *Figure 5.5*

Load increase tests (LIT) and single-step push-pull tests with certain stress amplitudes have been done to investigate the interaction between the microstructure and the fatigue behaviour of the wheel material. Due the industrial heat treatment and the size of the wheels, the rims of railway wheels R7 are characterised by microstructural gradients. The microstructure of the components consists of a mixture of ferrite and pearlite regions. This has to be taken into account as the railway tread increases, and the surface distance to the ferrite fraction and cementite lamellae spacing growth. Furthermore, it is possible to apply $\epsilon_{a,pl}$ and σ_a over ΔT and ΔU to the stress-strain curve. These curves can be described by the power law of Morrow, with the cyclic hardening coefficient and the cyclic hardening exponent. The relation between the stress amplitude and the lifetime is presented in the form of S-N-curves. According to the Basquin and Manson-Coffin-relation, the best-fit straight lines can be described. The area-specific Wöhler curves shift to shorter lifetime, as the amount of ferrite and cementite lamellae spacing increases. Therefore, S-N-diagrams are able to show the dependence between the microstructure and the corresponding lifetime of the material. The discovery that $\epsilon_{a,pl}$, ΔU, ΔT and Z_{GMR} can be used for lifetime measurements is an additional benefit of this analysis [13] [92] [93] [94].

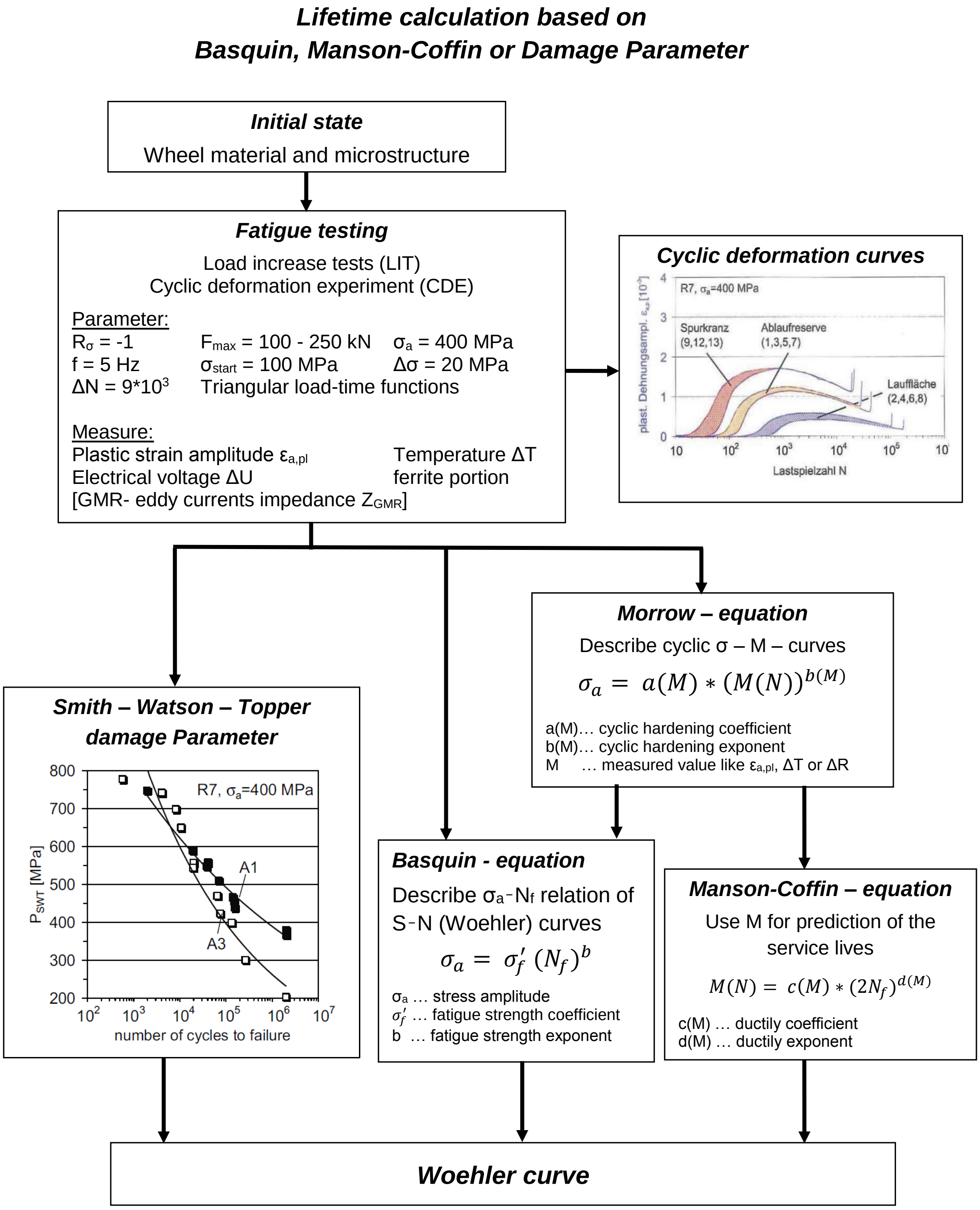


Figure 5.5: Lifetime calculation on the basis of Basquin-model, Manson-Coffin-model or Smith-Watson-Topper damage Parameter [13] [92] [93] [94].

5.2.3 Lifetime Measurement with Thermo-mechanical Load and Manson-Coffin

Lundén [63] investigated the block braked wheel during thermal and mechanical load, in which the component itself is assessed. The results of laboratory tests on the wheel are used for the model in the simulation. The finite element model uses a thermo-elasto-plastic material model with temperature-dependent material properties. The main focus is the fatigue of the wheel rim surface caused by mechanical and thermal loads. It describes how the plastic deformations are assumed to dominate the fatigue process. Therefore, effective plastic strains ϵ_{eff}^{pl} are used for the lifetime calculation at each integration point of the finite elements. Manson-Coffin diagrams render the critical plastic strain range as a function of the number of cycles until fracture (LCF). Using the strain data given from the finite element simulation, the relative durability (lifetime L_i) of the material at tread and the rim can be analysed. The plastic strains dominate the fatigue life, leading to *Equation 5.1*, in which Index 1 refers to as a reference case (lifetime $L_1 = 1$) and Index i as a studied case.

$$\frac{L_i}{L_1} = \left(\frac{\Delta\epsilon_{eff,1}^{pl}}{\Delta\epsilon_{eff,i}^{pl}} \right)^{1/0.6} \tag{5.1}$$

Figure 5.6 presents the operation of the lifetime calculation by Lundén.

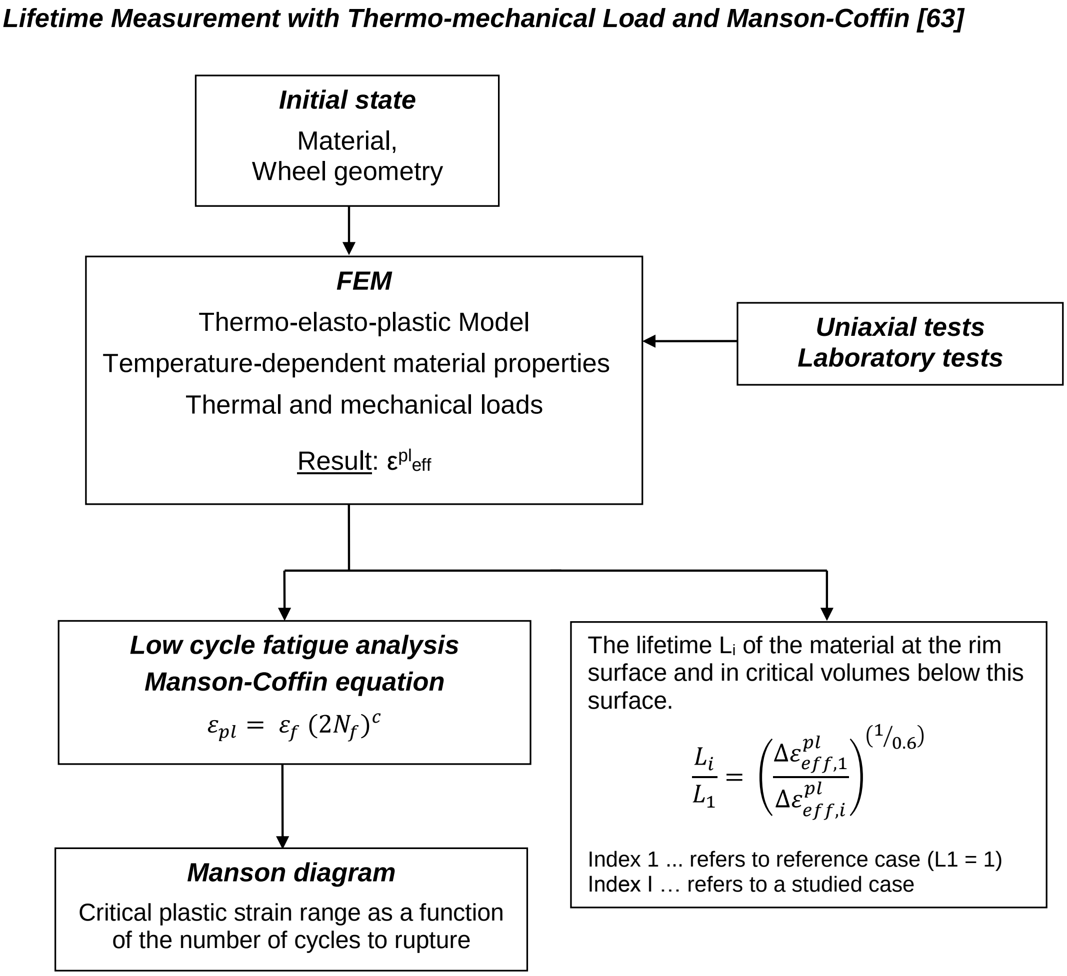


Figure 5.6: Lifetime measurement during thermo-mechanical load and based on Mason-Coffin-model [63].

5.3 Fracture Mechanical Methods

After a certain time, railway wheels can develop cracks on their surface or in the material. At that point, lifetime calculations are done by means of fracture mechanical methods. This means that the material contains a crack of a certain length. If the crack exceeds the critical length, the component is broken. [106] The methodology to predict the failure consists of five parts [105]:

1. Determination of critical crack size, a_c.
2. Calculation of the cyclic stress intensity factor, ΔK, at the crack tip.
3. Field data to simulate realistic brake loading conditions $\sigma(x, t)$.
4. Crack growth model
5. Residual life calculation.

In order to present a simple and complete set of experimental data for the determination of the crack propagation in the component, as well as its remaining lifetime, it is necessary to create a relation between the crack growth, da/dN, and the main influencing factors. These formulas have qualities of empiric regularities. The general crack growth law, which forms a relationship between da/dN and the cyclic fluctuations of the stress intensity factor ΔK, is formulated by Paris, *Equation 5.2*, with the material parameters C and m. This law is the basis of different models for fatigue crack growth and is used for block braked wheels, as seen in [53], [95], [96], [97], [98] and [99].

$$da/dN = C(\Delta K)^m \tag{5.2}$$

5.3.1 Modified Crack Growth Law

The crack growth of railway wheels under mechanical and thermal load is described by *Relation 5.3*. In this relation, C^* and ΔK^* are the coefficients of the modified crack growth law of Paris, in which n is the Paris-exponent and the factor C_{A1} is the increase in the crack growth rate when exceeding the eutectoid temperature (A_1), the minimum temperature for austenite. There are two equations. The first includes the service braking required crack growth for temperatures below T_{A1}. The second takes the crack growth during brake disturbances on the railway tread into account. Through the disturbances, the maximum temperatures are above 721 °C. [97] [98]

$$da/dN = \begin{Bmatrix} C^*(\Delta K/\Delta K^*)^n & for \quad T < T_{A1} = 721\,^{\circ}C \\ C_{A1}\, C^*(\Delta K/\Delta K^*)^n & for \quad T \geq T_{A1} = 721\,^{\circ}C \end{Bmatrix} \tag{5.3}$$

5.3.2 Frost-Dugdale Crack Growth Law

Peng and Jones, [100] [101] [102] [103], provide a method for solving thermal fatigue crack growth in the railway wheel under braking conditions. The analysis is done in three phases. In the first, a three-dimensional non-linear finite element model of the wheel is used for all braking operations. In the second section, the estimation of the stress intensity factor of thermal cracks is done by using a semi-analytical solution technique. This technique involves the use of an analytical solution aggregated with a numerical algorithm to evaluate fracture strength. In the third stage, a generalised Frost–Dugdale crack growth law, *Equation 5.4*, has been used on the basis of factors that are included in lifetime analysis: rail-chill, thermal load and mechanical load.

$$\frac{da}{dN} = Ca^{(1-m/2)}(\Delta K)^m \tag{5.4}$$

This law adapts the Paris based crack growth law, where C and m are constants. The advantage of calculating the fatigue crack growth with this methodology is that there is no need to explicitly model the crack. This allows a coarser mesh to be used for the wheel tread. The degree of freedom can be minimised, which reduces computation time. Solutions to stress intensity factors ΔK for different cracks can be obtained quickly and easily using the original finite element simulation.

5.3.3 Crack Growth Law by Walker

Haidari [104] studied the fatigue life of railway wheels under thermo-mechanical loads by using the Walker crack growth law. Therefore a model of a railway wheel, with two brake shoes and a part of rail was simulated. For the fatigue crack growth life prediction, the general crack propagation function by Walker, *Equation 5.5*, is used. ΔK_{eff} is the effective stress intensity factor range for mixed-mode loading, R is the stress ratio, and C, m and ς are material parameters. Through Walker's crack propagation function derivative, the number of required cycles to reach critical crack size can be determined. [104]

$$\frac{da}{dN} = C\left[\frac{\Delta K_{eff}}{(1-R)^{\varsigma}}\right]^m \tag{5.5}$$

In the following paragraphs, the Walker crack growth law is used for the probabilistic failure life prediction of the Master's thesis by Venkata Sasidhar [105]. A probabilistic methodology for the prediction of lifetime of cracked railway wheels under service conditions was developed. As in the case above, a three-dimensional finite element analysis and a mixed-mode crack model based on critical plane concepts was used. The wheel failure life is estimated using ΔK values, which are determined from the Gaussian process surrogate and Walker's crack growth law by operating cycle-by-cycle crack growth calculations.

Aside from the simple Paris law and the other presented methods other complex methods exist, for example, ESACrack, NASGRO or Forman. These methods fulfil a variety of requirements and include many parameters in the equation, for example material properties, stress ratio or crack closure effects. It must be kept in mind that the parameters can be difficult to obtain. [107]

To sum up, it can be said that the Manson-Coffin and the Basquin relations are used for the lifetime calculations of the wheel material, as well as for the component without cracks. The references describe different tests and parameters ($\epsilon_{a,pl}$, ΔU, ΔT, ΔR, Z_{GMR} and microstructures) for the calculation. In combination with this data, finite element simulations can also be run for the lifetime prediction. If the material contains cracks, the method most often used is the Paris law and modifications thereof.

6 Conclusion

Based on the list of references, different phenomena were selected for the finite element simulation. These are used to calculate the temperature changes, residual stresses, and wheel rim deformation in block braked wheel systems. These phenomena were subsequently compared with the model used by Siemens AG, and it was demonstrated that Siemens AG already uses most of them. The finite element simulation uses temperature-dependent material properties, the elastic-plastic material models, the isotropic hardening rule, as well as boundary conditions, such as the position, the profile- and time-dependent heat input, and different cooling effects, including radiation and convection. The simulations considered were also based on bench tests without rail contact. Therefore, it is not relevant to integrate the mechanical load during rolling contact, nor the rail-chill cooling effect. Along with the phenomena described above, the production residual compressive stress in the wheel rim and cooling through brake blocks are relevant for the calculations. No clear results were identified for the elastic-viscoplastic, elastic-plastic with creep, kinematic hardening, or the block brake as a component. These parameters should be tested as to their relevance, as shown in *Figure 6.1*.

Furthermore, the results of the simulation and the fatigue tests are used for the lifetime calculation with the help of different damage models. In references and at Siemens AG, the Manson-Coffin and Basquin relation are used for the lifetime calculations of block braked wheels. If the material contains cracks, the Paris crack growth law and modifications thereof are used.

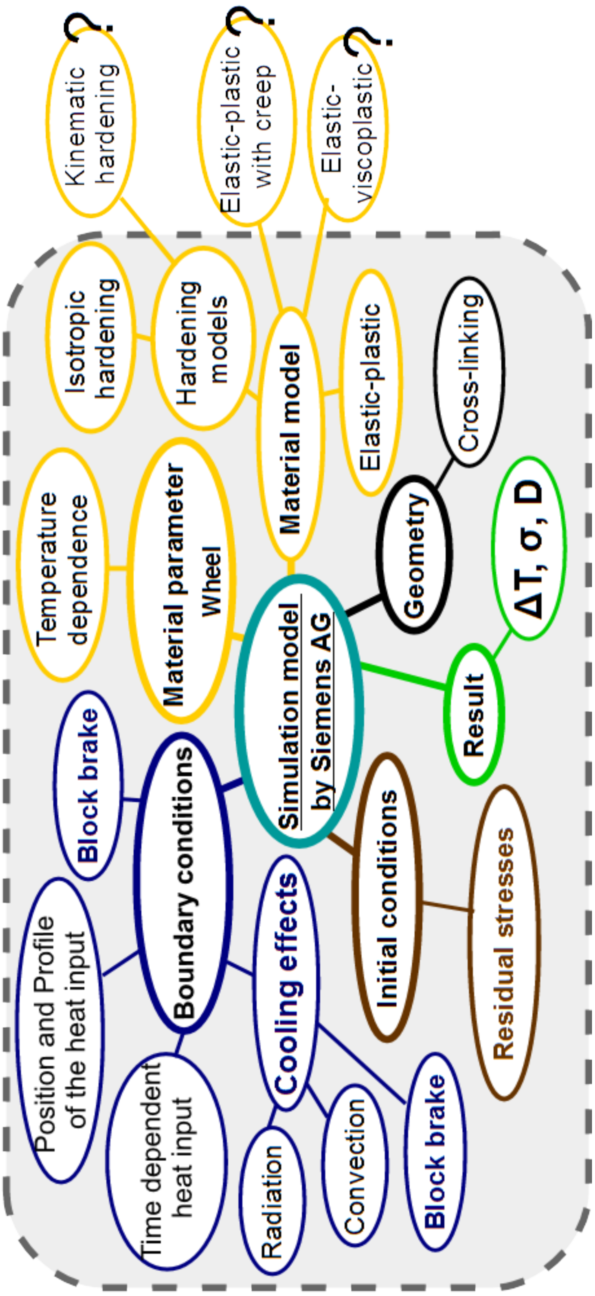


Figure 6.1: Overview of the evaluation matrix with the relevant parameters for the simulation model. Outside the grey range are the phenomena that should be tested regarding to their relevance.

7 Outlook

The finite element model used by Siemens AG will be improved based on the findings of this Master's thesis. The phenomena listed in the Overview of the evaluation matrix, *Figure 6.1*, should be included in the model, but the relevance of certain parameters describing the material models and the block brake components will have to be examined further. In addition to the model's current aims, which are to assess temperature change, residual stresses, and wheel rim deformation, the simulation could also be modified to include the mechanical loads from rail contact and the rail-chill effect. The model could also be enhanced by integrating damage models, such as the Manson-Coffin-Basquin-relation for wheels without cracks, or Paris' law for wheels with cracks.

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[103] D. Peng and R. Jones. "The development of combination mechanical contact and thermal braking loads for railway wheel fatigue analysis." In: *Theoretical and Applied Fracture Mechanics* 60.1 (2012), pp. 10–14 (cit. on pp. 56, 70).

[104] Azadeh Haidari and Parisa Hosseini Tehrani. "Thermal load effects on fatigue life of a cracked railway wheel." In: *Latin American Journal of Solids and Structures* 12 (June 2015), pp. 1144–1157 (cit. on pp. 56, 71).

[105] Venkata Sasidhar Sura. "Failure modeling and lfe prediction of railroad wheels." Dissertation. Faculty of the Graduate School of Vanderbilt University, 2011 (cit. on pp. 56, 69, 71).

[106] Uwe Zerbst, Katrin Mädler, and Hartmut Hintze. "Fracture mechanics in railway applications—an overview." In: *Engineering Fracture Mechanics* 72.2 (2005). Fracture Mechanics in Railway Applications, pp. 163–194 (cit. on p. 69).

[107] Frauenhofer IWM. *VERB: Failure Assessment Software Version 8.0; User's Guide*. Fraunhofer Institute for Mechanics of Materials, 2008 (cit. on p. 72).

List of Figures

Appendix

Input source list

Types of literature	Source (Journal, University, Conferences, etc.)	Available / searched years
Paper	Wear/Elsevier	1967 - 2016
	Engineering Failure Analysis	1994 - 2016
	Engineering Fracture Mechanics	1995 - 2016
	Periodica Polytechnica Transportation Engineering	1997 - 2016
	Periodica Polytechnica Mechanical Engineering	1998 - 2016
	Tribology in Industry	1979 - 2016
	Tribology International	1975 - 2016
	Key Engineering Materials	2006
	Thermal Science	2005 2010 - 2016
	Advances in Tribology Hindawi Publishing Corporation	2008 - 2016
	Buletinul AGIR	2009 - 2016
	Standard Steel highlight wheel manufacturing and inspection improvements at the Burnham	2001
	International Mechanical Engineering Congress and Exhibition, ASME RTD	1998
	Advanced Materials Research	2014
	Latin American Journal of Solids and Structures	2015
	Advances in Biology, Bioengineering and Environment Vouliagmeni	2010
	International Journal of Systems Applications, Engineering & Development	2011
	Theoretical and Applied Fracture Mechanics	1995 - 2012
	Technologic Papers of the Bureau of Standards	1910 - 1928
	International Journal of Mechanical Sciences	1998
	International Journal of Scientific & Engineering	1996 - 2016
	International Conference on Contact Mechanics	2003 2009 - 2015
	International Conference on Computers in Railways, Computers in Railways	1994 - 2015
	International Wheelset Congress	1988 - 2013
	International ANSYS Conference	2002
	International Heavy Haul Conference	2009 2015
	International Symposium on Dynamics of Vehicles on Roads and Tracks	2015
	XV International Scientific-expert Conference	2012
	Internationale Schienenfahrzeugtagung Dresden	1996 - 2015
	World Congress Railway Research	1999 - 2008
	World Tribology Congress III	2005 2013
	EuroBrake	2012 2014 2015
	European Conference on Braking	2010
	Tore Vernersson	1998 - 2015
	Siemens-Bibliothek in München	-

Input source list

Types of literature	Source (Journal, University, Conferences, etc.)	Available / searched years
Paper	Science Direct	1990 - 2015
	ResearchGate	2000 - 2015
	Moderne Schienenfahrzeuge Graz	2007 - 2016
	Eisenbahntechnische Publikationen - UIC	-
Presentation	Gleislauftechnik Müller	2016
	Siemens AG / Gruppe BR	2015
Article	Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit	2006 - 2014
	FME Transaction,University of Belgrade	2002 - 2016
	Department of Railway Engineering, Silesian University of Technology, Centre of Excellence TRANSMEC, Poland	-
	Vehicle System Dynamics	1972 - 2016
	ZEVrail Glasers Annalen	1988 - 1995 1998 - 2014
	DET - Die Eisenbahntechnik	1982
	ETR - Eisenbahntechnische Rundschau	1986 1987 1989 - 2015
	EI - Eisenbahningenieur	1998 - 2012
	Railway Gazette	1998 - 2004 2006 - 2012
	Material Testing	2003 - 2016
	Wissenschaftliche Zeitschrift der Hochschule für Verkehrswesen, "Friedrich List" Dresden	1984
	Journal of Tribology	2000
Books	Springer-Verlag	2013 2014
	Springer-Fachmedien	2010
	Lucchini RS	2008 2014
	Allrussischen wissenschaftlichen Forschungsinstituts Des Eisenbahntransports	2004
	CRC Press	2009
Reports	Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht	1979 - 1997
	FH Brandenburg; Brandenburg an der Havel	1998
	Bulletins - Engineering Experiment Station University of Illinois, Urbana	1904 - 1973
	U.S. Department of Transportation; Federal Railroad Administration; Office of Research an Development Washington	1996
	Deutscher Verband für Materialforschung und -prüfung e. v.	2003
	Detusche Bahn AG, DB Systemtechnik, Bremse und Kupplung T.TVI 12	2011

Input source list

Types of literature	Source (Journal, University, Conferences, etc.)	Available / searched years
Reports	Literaturliste F&E von BR	2015
	Abschlussberichte Siemens AG	2015
Standards	Europäisches Komitee für Normung; Brüssel	
	Internationale Eisenbahnverband	
Dissertations	Faculty of the Graduate School of Vanderbilt University Nashville, Tennessee	2011
	Department of Applied Mechanics, Chalmers University of Technology Gothenburg, Sweden	2012 2014
	Machine Elements; Department of Machine Design; The Royal Institute of Technology Stockholm, Sweden	1999
	Fakultät für Maschinenbau der Ruhr-Universität Bochum	2008
	Addis Ababa University Addis Ababa Institute of Technology School of Mechanical and Industrial Engineering	2014
	Werkstoffwissenschaften der Technischen Universität Berlin	1973
	Montanuniversitaet Leoben	2014
	Bibliothek TUGraz	1973

List of literature

Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
001	**M. Ertz, A comparison of analytical and numerical methods for the calculation of temperatures in wheel/rail contact** Wear/Elsevier 253, Seite 498–508; 2002; Paper	
		Methods for temperatur calculations, wheel - rail, brake block, semi-analytical and numerical methods
		Methods are presented for temperature calculation with smooth surfaces. The temperature distribution in wheel/rail contact will be investigated in detail. Convection and heat conduction through the contact patch are taken into account for the long-term behavior of the wheel temperature.
		2002_Paper_Ertz_A comparison of analytical and numerical.pdf
002	**D. Peng, A study into crack growth in a railway wheel under thermal stop brake loading spectrum** Engineering Failure Analysis 25, Seite 280 – 290; 2012; Paper	
		Thermal fatigue crack growth; thermal load; Stress intensity factor; FEM
		This paper provides a method for solving thermal fatigue crack growth in the rail wheel under stop braking spectrum. The analysis was performed in three stages: 1) finite element model; 2) calculate the stress intensity factor of thermal cracks 3) Frost–Dugdale approach
		2012_Paper_Peng_A study into crack growth in a railway wheel.pdf
003	**M. Akama, A study on the critical crack sizes that cause wheel fracture** World Congress on Railway Research; Deutschland; 2001; Paper	
		BM; FEM: stress intensity factor; thermal stress, mechanical stress, residual stress,
		In this study, the influence function method was applied to the analyses of K-value for surface cracks in various stress states of wheel rim together with the values of ΔKth and KIC for wheel steel to determine the critical crack sizes to start fatigue crack propagation and to cause brittle fracture in relation to the stress states in the wheel rim.
		2001_Paper_Akama_A study on the critical crack sizes.pdf
004	**D. Peng, An investigation of the influence of rail chill on crack growth in a railway wheel due to braking loads** Engineering Fracture Mechanics 98, Seite 1 – 14; 2012; Paper	
		Thermal fatigue crack growth; rail chill effect; thermal load; Stress intensity factor; FEM
		This paper provides a method for addressing thermal fatigue crack growth in railway wheels, allowing for rail chill effects under block braking. A 3D non-linear finite element model has been used to evaluate the thermal stress allowing for rail chill and for its influence on the crack growth in a rail wheel.
		2012_Paper_Peng_An investigation of the influence of rail chill.pdf
005	**A. Tudor, Analysis of heat partitioning in wheel/rail and wheel/brake shoe contact: An analytical approach** World Tribology Congress III, USA; 2005; Paper	
		Analytical model: temperatur + cooling wheel - rail - brake;
		In this paper, they present an analytical solution for the temperature distribution in a wheel subject to surface heating by rolling contact in the rail, heating by the action of the brake shoes, and nonuniform convective cooling with particular attention to zonal heat partitioning factors.
		2005_Paper_Tudor_Analysis of heat partitioning in wheel-rail.pdf
006	**P.M. Mohan; Analysis of Railway Wheel to study Thermal and Structural Behaviour** International Journal of Scientific & Engineering Research 3 (11); 2012; Paper	
		FEM: thermal, structural and combined loading; wheel;
		This paper is intended towards analyzing a CJ36 Griffin Freight Car wheel subjected to thermal, structural and combined loading.
		2012_Paper_Mohan_Analysis of Railway Wheel.pdf
007	**U. Zerbst Application of fracture mechanics to railway components - an overview** International Wheelset Congress 11th, France, Seite 69 – 76; 1995; Paper	
		Fracture; axles, wheels and rails;
		The paper gives an overview on the most relevant fracture mechanics issues for railway components (axles, wheels and rails).
		1995_Paper_Zerbst_Application of fracture mechanics to railway.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
008	**E. S. Oganyan, Approval of criteria of USA standards AAR S-660 and AAR S-669 to study rolling stock wheels strength** International Wheelset Congress 17th, Ukraine, Seite 192 - 198 2013 Paper	
		Static calculation - load, calculation of wheelset natural modes and vibration frequencies, thermal effects, residual stresses
		The objective of the present study is to research on comparability of requirements of locomotive wheels in respective standards of the USA and Russian Federation.
		2013_Paper_Oganyan_Approval of criteria of USA standards AAR S-660.pdf
009	**P. Piec, Aspects of Analysis of Reverse Friction - Caused Contact Phenomena** Tribology in industry 25 (3/4); 2003; Paper	
		Numerical analysis of brake shoe motion; wheel-brake shoe unit
		In the paper the contact phenomena caused by reverse friction “stick-slip” are discussed. To solve this complex problem, the authors have done the statistics, numerical computer simulation, bench tests as well as in-service tests on a real object.
		2003_Paper_Piec_Aspects of Analysis of Reverse Friction.pdf
010	**W. Rode, Beanspruchungskollektive an Rädern** Internationale Schienenfahrzeugtagung Dresden 1th (2), Dresden, Seite 185 – 191; 1996; Paper	
		Überblick; thermische Dimensionierung; Belastungskollektiv; Räder;
		Bei Bremsungen bei Gefällestrecken führen die Klotzbremse zu große Temperaturgradienten welche zu hohen tangentialen Zugeigenspannungen führen. Von Messungen erhaltene Ergebnisse und durchgeführten Berechnungen werden thermische Belastungen abgeleitet.
		1996_Paper_Rode_Beanspruchungskollektive an Rädern.pdf
011	**U. Villa, Berechnung von Eigenspannungen bei Eisenbahnrädern** Internationale Schienenfahrzeugtagung Dresden 1th (2), Dresden, Seite 221 – 231; 1996; Paper	
		FEM: Temperatur, Spannung; Materialverhalten; Rad Vergleich
		Klotzgebremste Eisenbahnräder unterliegen hohen Wärmebelastungen. (Temperaturberechnungen, Spannungsberechnungen, Eigenspannungen mittels FEM). Vergleich zwischen OE-Standardrad mit 920 mm Durchmesser und neuem Ilsenburger Rad.
		1996_Paper_Villa_Berechnung von Eigenspannungen.pdf
012	**F. Murawa, Betriebsbedingte Einflüsse auf das Festigkeitsverhalten von Vollrädern** ZEVrail Glasers Annalen 128 (Tagungsband SFT Graz), Seite 287 – 297; 2004; Artikel	
		Dauerfestigkeit. Rad-Schiene Kräfte, Zusatzeinflüse
		Festigkeitsverhalten von Vollrädern, Einfluss von Rad-Schiene, und Zusatzeinflüsse wie Bremse und Kräfte an Rad. Verschiedene Schadensakkumulations-Hypothesen kurz erwähnt.
		2004_Art_Murawa_Betriebsbedingte Einflüsse auf das Festigkeitsverhalten.pdf
013	**T. Vernersson, Braking Capacity of Railways Wheels - State-of-the-art-Survey** International Wheelset Congress 16th, South Africa; 2010; Paper	
		Temperatures, thermomechanical aspects, wheel damage, wheel design, brake blocks
		The objective of the paper is to provide an overview of design methods for tread braking systems with special focus in the braking capacity of the wheels. It will report on two interesting examples from ongoing research with results regarding the thermal behavior of tread braking systems.
		2010_Paper_Vernersson_Braking Capacity of Railways Wheels.pdf
014	**D. Jaenichen, Bremsarbeiten und -leistungen klotzgebremster Räder heterogen zusammengesetzter Güterzüge bei Gefällebremsungen** Internationale Schienenfahrzeugtagung Dresden 2th, Dresden, Seite 50 – 53; 1997; Paper	
		Bremsarbeiten und -leistungen; Simulationsrechnung;
		Zur Vermeidung von Radbrüchen und Radschäden bedarf es der Ermittlung der Bremsarbeiten und -leistungen an den Rädern, in einem heterogen zusammengesetzten Zug, unter den ungünstigsten Betriebsbedingungen.
		1997_Paper_Jaenichen_Bremarbeiten und -leistungen klotzgebremster.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
015	**D. Jaenichen, Bremsarbeiten und -leistungen klotzgebremster Räder heterogen zusammengesetzter Züge beim Gefällebremsungen** EI - Eisenbahningenieur 49 (2), Seite 59 – 64; 1998; Artikel	
		Rechenprogramm, Bremsarbeit, Bremsleistung, Bremseinfluss auf Rad
		Theoretische Betrachtung der Zugvariation, Bremsarbeit und -leistung durch ein Rechenprogramm. Mit diesem können verschiedene Bremsvariationen an verschiedenen Orten (Gefälle, Bremsart) und Zugvariationen dargestellt werden und somit auch teils Einflüsse der Fahrten auf die Räder gemacht werden (thermisch). Vergleich vom Programm mit einer Messfahrt.
		1998_Art_Jaenichen_Bremsarbeiten und -leistungen klotzgebremster Räder.pdf
016	**K. O. Edel, Bruchmechanische Analyse und Bewertung der Rissausbreitung im Radkranz von Eisenbahnvollrädern - Teil 1** ZEVrail Glasers Annalen 117 (8), Seite 262 – 268; 1993; Artikel	
		Bruchmechanische Analyse, Schäden Eisenbahn
		Teil 1: Für geschädigte Eisenbahnvollräder wurden bei der Deutschen Reichsbahn bruchmechanische Analysen in Form probabilistischer Berechnungen zur Bewertung der Rissausbreitung vorgenommen. Betrachtet: Phasen der Dauerfestigkeit, des stabilen Risswachstums unter zyklisch einwirkender Beanspruchung, Auslösung des Bruchs
		1993_Art_Edel_Bruchmechanische Analyse und Bewertung der Rissausbreitung Teil 1.pdf
017	**K. O. Edel, Bruchmechanische Analyse und Bewertung der Rissausbreitung im Radkranz von Eisenbahnvollrädern - Teil 2** ZEVrail Glasers Annalen 117 (9), Seite 308 – 315; 1993; Artikel	
		Bruchmechanische Analyse, Vollräder
		Teil 2 von Bruchmechanische Analyse und Bewertung der Rissausbreitung im Radkranz von Eisenbahnvollrädern
		1993_Art_Edel_Bruchmechanische Analyse und Bewertung der Rissausbreitung Teil 2.pdf
018	**W. Mombrei, Bruchmechanische Probleme an klotzgebremsten Eisenbahnrädern - Bruchzähigkeit von Radwerkstoffen** ZEVrail Glasers Annalen 115 (7/8), Seite 224 – 230; 1991; Artikel	
		Einflüsse und Erscheinung vom Bruch, Vollräder, Bruchmechanik,
		An klotzgebremsten Rädern zeigen sich unterschiedliche Formen der Ausbildung von Brüchen. Bruchmechanische Bewertungen zeigen Beeinflussungsmöglichkeiten.
		1991_Art_Mombrei_Bruchmechanische Probleme an klotzgebremsten.pdf
019	**M. Diener, Bruchmechanische und metallische Untersuchungen an Güterwagenrädern** ZEVrail Glasers Annalen 116 (6), Seite 179 – 191; 1992; Artikel	
		Bruchmechanik, Bruchzähigkeit, Vollräder, Versuch, Analyse gebrochener Räder, Materialkennwerte
		Die Bruchzähigkeit und seine Bedeutung als Werkstoffkennwert für bruchmechanische Untersuchungen werden erläutert und Methoden zu seiner Bestimmung werden beschrieben. Die Anforderungen an ein klotzgebremstes Vollrad nach UIC-Standard bezüglich einer verbesserten Bruchsicherheit werden aus metallkundlicher und bruchmechanischer Sicht dargestellt.
		1992_Art_Diener_Bruchmechanische und metallkundliche Untersuchungen.pdf
020	**V. Gupta, Calculations of the frictional heating of a locomotive wheel attending rolling plus sliding** Wear/Elsevier 191, Seite 237-241; 1995; Paper	
		FEM of frictional wheel heating
		Frictional heating, finite element analysis, locomotive wheel, rolling, sliding
		1995_Paper_Gupta_Calculations of the frictional heating.pdf

List of literature

Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
021	**P. Raninger, Characterization and Modeling of the Thermomechanical Fatigue Behavior of Brake Disks for High Speed Trains** Montanuniversitaet Leoben; 2014; Diplom- / Doktorarbeit	
		Temperatur auf der Reibfläche, Mechanismen: Initiieren & Wachstum von Rissen. FEM, Bremsprozess, viskoplastische Materialverhalten, Bremsscheibenmaterials, Schädigungsverhalten
		Das Hauptziel dieser Arbeit ist die Erarbeitung einer Simulationsmethodik, die sowohl die Entwicklung neuer Bremsscheiben-Designs, als auch die Planung des Bremsmanagements effizienter macht. Es werden sowohl eine umfassende Charakterisierung, als auch die Modellierung des thermomechanischen Ermüdungsverhaltens im Rahmen dieser Arbeit behandelt.
		2014_Diss_Raninger_Characterization and Modeling of the Fatigue Behavior.pdf
022	**R. Halama, Contact defects initiation in railroad wheels - Experience, experiments and modelling** Wear/Elsevier 271 (1/2), Seite 174 – 185; 2010; Paper	
		Defect types; tests under line rolling/sliding contact conditions; crack initiation phase; FEM to simulate the rolling/sliding contact test and a pure rolling contact case.
		Main results of comprehensive research of rolling contact defects initiation are presented.
		2010_Paper_Halama_Contact defects initiation in railroad wheels.pdf
023	**R. Lundén, Contact region fatigue of railway wheels under combined mechanical rolling pressure and thermal brake loading** Wear/Elsevier 144, Seite 57 – 70; 1991; Paper	
		FEM, mechanical, thermal load, Damage mechanics model
		The combined effect on railway wheels of a periodically varying contact pressure and an intermittent thermal brake loading is investigated in this paper. A commercial finite element model computer programme for thermo-elasto-plastic analysis is employed.
		1991_Paper_Lunden_Contact region fatigue of railway wheels.pdf
024	**N. Békési, Contact Thermal Analysis and wear simulation of a brake block** Advances in Tribology Hindawi Publishing Corporation; 2013; Paper	
		Experiment: wear; numerical modellng: wear, thermal expansions; FEM: mechanical and thermal
		The present paper describes an experimental test and a coupled contact-thermal-wear analysis of a railway wheel/brake block system through the braking process. During the test, the friction, the generated heat, and the wear were evaluated.
		2013_Paper_Békési_Contact Thermal Analysis .pdf
025	**T. Vernersson, Control of railway block braking - thermomechanical performance of wheels: a literature survey** Department of Applied Mechanics, Chalmers University of Technology Gothenburg, Sweden; 2002; Bericht	
		-
		The objective of the project is to achieve an optimum thermal behavior of the tread braked wheel system. An important aim is a better understanding and control of the heat partitioning between wheel rim and brake block. The focus will be on the wheel behavior in the block braking system.
		2002_Ber_Vernersson_Control of railway block braking.pdf
026	**S. J. Kwon, Damage evaluation regarding to contact zones of high-speed train wheel subjected to thermal fatigue** Engineering Failure Analysis 55, Seite 327 – 342; 2015; Paper	
		Experiment: material properties; failure mechanism, thermal fatigue damage, residual stress, FEM: heat treatment; braking process
		In the present paper, they study the failure analyses at the tread of the thermally damaged wheel by doing the metallurgical transformation analysis, hardness analysis, and the residual stress analysis to understand the failure mechanism of thermal fatigue damaged wheel.
		2015_Paper_Kwon_Damage evaluation regarding to contact zones.pdf

List of literature

Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
027	**S. J. Kwon, Damage Mechanism of Wheel for High Speed Train based on Fracture Mechanics** Key Engineering Materials 326-328, Seite 1047-1050; 2006; Paper	
		Tread damage, wheel for high speed, metallurgical analysis, mechanical analysis, field test
		In the paper, the combined effect on railway wheels of a periodically varying contact pressure and an intermittent thermal braking loading is investigated. To analyze the cause of tread damage to the wheel for high-speed, the measurements for replica of wheel surface and effect of braking application in field test are carried out.
		2006_Paper_Kwon_Damage Mechanism of Wheel for High Speed.pdf
028	**A. Bevan, Development and validation of wheel wear and rolling contact fatigue damage model** Wear/Elsevier 307 (1/2), Seite 100 – 111; 2013; Paper	
		Damage model; wear, rolling contact fatigue
		This paper summaries the development of a damage model to predict the deterioration rates of the wheel tread in terms of wear and rolling contact fatigue (RCF) damage.
		2013_Paper_Bevan_Development and validation of a wheel.pdf
029	**A. Ghidini, Development of testing methodologies according to fracture mechanics criteria applied to railways solid wheels** International Wheelset Congress 15th, Czech Republic, Seite 23 – 27; 2007; Paper	
		Bruchmechanik, material properties, experiment
		Starting from a discussion about the problems (fracture wheel) encountered in the development of testing methodologies in the field of LEBM the use of post yield fracture mechanics parameters is then exploited and the problems that may arise from their application either in laboratory testing or in solid wheel structural analysis.
		2007_Paper_Ghidini_Development of testing methodologies.pdf
030	**J. Raison, Die Paarung Rad/Verbundstoffbremssohle - Reduzierung des Rollgeräusches** ZEVrail Glasers Annalen 128 (10), Seite 474 – 497; 2004; Artikel	
		Experiment, Berechnung, Lärmreduzierung, Rad - Bremse, thermisch, Rad - Schiene
		Lärmreduktion. Anhand der akustischen Merkmale der wichtigsten Fahrzeuge der SNCF und der Ergebnisse aus den Entwicklungen der UIC werden konkrete technische Lösungen, ihre Leistungsfähigkeit sowie der derzeitige Stand der Technik aufgezeigt.
		2004_Art_Raison_Paarung Rad-Verbundstoffbremssohle.pdf
031	**J. C. Fortmann, Dimensionierung von Vollrädern für den Güterverkehr** ETR - Eisenbahntechnische Rundschau 52 (1/2), Seite: 32 – 38, 2003, Artikel	
		Erfolge durch ERRI-Berichte bezüglich Vollräderbrüche im Überblick
		Es werden die durchgeführten Arbeiten der ERRI B 169 vorgestellt, mit denen eine höhere Sicherheit für die Vollräder, insbesondere in Hinblick auf den alpenüberquerenden Güterverkehr, erreicht werden soll.
		2003_Art_Fortmann_Dimensionierung von Vollrädern für den Güterverkehr.pdf
032	**I. Zobory, Dynamic processes caused by track unevennesses in braked railway vehicles** Periodica Polytechnica Transportation Engineering 15 (2), Seite 171 – 183; 1987; Paper	
		Dynamic model - effects throught brake;
		In this paper, the formation of a dynamic model is described which is suitable for the examination of exciting effects transmitted through the brake suspension system and the description of the system is given as required for digital simulation taking into consideration a two-axle vehicle equipped with block-brakes.
		1987_Paper_Zobory_Dynamic Processes caues by track .pdf
033	**Min-Soo Kim, Dynamometer Tests of Brake Shoes under Wet Conditions for the High Speed Trains** International Journal of Systems Applications, Engineering & Development 5 (2); 2011; Paper	
		Brake dynamometer, tread brake test; dry + wet condition; friction coefficient;
		This paper discuss comparative studies of the wheel tread brake with composite brake blocks between under conditions with dry and wet using the dynamometer tests for the high speed trains.
		2011_Paper_Kim_Dynamometer Tests of Brake Shoes.pdf

List of literature

Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
034	**C. Lonsdale, Effects of increased gross rail load on 36-inch diameter freight car wheels** Standard Steel highlight wheel manufacturing and inspection improvements at the Burnham, PA 2001; Paper	
		Wheel defects; FEM: stress levels in wheel design, Mechanical loads, braking (thermal) loads;
		This paper discusses the effects of gross rail load (GRL) on the performance of 36-inch diameter freight car wheels in North American service. The root causes of several wheel defects are briefly described.
		2001_Paper_Lonsdale_Effects of increased gross rail load on.pdf
035	**C. Lonsdale, Effects of New Brake System Requirements on Freight Car Brake Shoes and Wheels** International Wheelset Congress 14th, USA; 2004; Paper	
		New brake block - wheel, wheel defects (thermally), FEM: stress and temperatur
		This paper explores the effects of new brake system requirements on the performance and life of brake shoes and wheels. Various service-operating scenarios are considered and the braking energy necessary for each case is calculated and used along with time as input parameters for finite element analysis (FEA) computer simulations.
		2004_Paper_Lonsdale_Effects of New Brake System Requirements.pdf
036	**J. Won Seo, Effects of residual stress and shape of web plate on the fatigue life of railway wheels** Engineering Failure Analysis 16, Seite 2493 – 2507; 2009; Paper	
		Railway wheel, Residual stress, Fatigue, FEM
		In this study, we evaluated residual stress of web plate by heat treatment due to the manufacturing process and changes of residual stress by braking using finite element analysis. The cyclic stress history for fatigue analysis is determined by applying finite element method. The fatigue strength evaluations of the web plate are performed to investigate the effect of the residual stress.
		2009_Paper_Won Seo_Effects of residual stress and shape of web.pdf
037	**F. Murawa, Eigenspannungen klotzgebremster Räder - Versuch oder Rechnung** EI - Eisenbahningenieur 59 (10), Seite 25 – 32; 2008; Artikel	
		FEM, Berechnung, Eigenspannung, thermisch
		Durch Bremsen mit Klotzbremsen kommt es zu hohen Temperatureinwirkungen, plastischen Verformungen und zu einbringen von neuen Eigenspannungen in das Rad. Es werden experimentelle und numerische (FEM) Ergebnisse verglichen.
		2008_Art_Murawa_Eigenspannungen klotzgebremster Vollräder.pdf
038	**F. Murawa, Eigenspannungen klotzgebremster Räder - Versuch oder Rechnung** Internationale Schienenfahrzeugtagung Dresden 9th, Dresden; 2008; Präsentation	
		FEM, Berechnung, Eigenspannung, thermisch
		Einfluss Klotzbremse auf Rad. Zu unterscheiden ist Stoppbremsung und Dauerbremsung. Rechenmodell und im Vergleich experimentell ermittelten Eigenspannungen.
		2008_Präs_Murawa_Eigenspannungen klotzgebremster Räder.pdf
039	**F. Murawa, Eigenspannungen klotzgebremster Räder - Versuch oder Rechnung** Internationale Schienenfahrzeugtagung Dresden 9th, Dresden, Seite 24 – 27; 2008; Paper	
		FEM, calculation, residual stresses, wheel
		Was passiert bei der Klotzbremsung mit den Rädern. Zu unterscheiden ist Stoppbremsung und Dauerbremsung. Rechenmodell und im Vergleich experimentell ermittelten Eigenspannungen.
		2008_Paper_Murawa_Eigenspannungen klotzgebremster Räder.pdf
040	**W. Mombrei, Einflüsse auf die Bruchneigung klotzgebremster Eisenbahn - Vollräder** DET - Die Eisenbahntechnik 30 (8), Seite 423 – 426; 1982; Artikel	
		Influence of failures, damage, wheel, material, residual stresses.
		Darstellung von Bruchformen und deren Einflüsse zur Entstehung, wie Eigenspannungen, Material, thermisch, Kerben. Und es werden mögliche Maßnahmen zur Verminderung der Bruchwahrscheinlichkeit diskutiert.
		1982_Art_Mombrei_Einflüsse auf die Bruchneigung klotzgebremster.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
041	**W. Mombrei, Einflüsse auf die Deformationsneigung klotzgebremster Eisenbahn - Vollräder** Wissenschaftliche Zeitschrift der Hochschule für Verkehrswesen, "Friedrich List" Dresden 32 (1), Seite 49 – 54; 1984; Artikel	
		Klotzbremsbedingte Raddeformation
		Es wird die Raddeformierung als Beeinträchtigung der klotzgebremsten Vollräder betrachtet. Und durch was es bestimmt ist.
		1984_Art_Mombrei_Einflüsse auf die Deformationsneigung.pdf
042	**DIN EN 13262:2004+A2:2011** **Bahnanwendungen – Radsätze und Drehgestelle – Räder – Produktanforderungen** Europäisches Komitee für Normung; Brüssel EN 13262; 2011; Norm	
		Eigenschaften der Räder; Qualifizierungsverfahren; Lieferbedingungen; Stahlgüten: ER6, ER7, ER8 und ER9;
		Produktqualifizierung des Rades; Diese Norm legt die Eigenschaften für Eisenbahnräder, die auf europäischen Streckennetzen verwendet werden, fest.
		2011_Norm_EN 13262_Bahnanwendungen – Radsätze und Drehgestelle.pdf
043	**DIN EN 13979-1: 2003+A2:2011** **Bahnanwendungen – Radsätze und Drehgestelle - Vollräder - Technische Zulassungsverfahren - Teil 1: Geschmiedete und gewalzte Räder** Europäisches Komitee für Normung; Brüssel EN 13979-1; 2011; Norm	
		Vollrad; Lastenheft; Radkonstruktion bewerten; Anwendungsbereich definieren
		Diese Norm beschreibt das Lastenheft und gibt an, wie die Radkonstruktion zu bewerten ist. Um das Lastenheft anzuwenden, ist es erforderlich, den Anwendungsbereich des Rades festzulegen. Auch wird festgelegt wie der Anwendungsbereich zu definieren ist
		Vollrad; Lastenheft; Radkonstruktion bewerten; Anwendungsbereich definieren;
044	**B. Volf, Erhöhung der Betriebssicherheit und Standzeit der Radsätze** EI - Eisenbahningenieur 60 (4), Seite 58 – 65; 2009; Artikel	
		Schäden, Rad, Lauffläche, Einflüsse, Rollkontaktermüdung, Experiment,
		Es wird die Aufmerksamkeit auf die Einflussfaktoren, welche die Kontaktspannung beeinflussen und als Ursache von Fehlern der Lauffläche betrachtet werden können.
		2009_Art_Volf_Erhöhung der Betriebssicherheit.pdf
045	**ERRI B 106 Standardisation of coaches; Report Nr. 15 Standardisation of a block-braked solid wheel designed for coaches operated at a maximum speed of 160 km/h - Mechanical rig tests** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B106 RP 15; 1991; Bericht	
		Experiment for stresses , Fracture in wheel
		Dieser Bericht beschäftigt sich einerseits mit grundlegenden Untersuchungen zur Definierung eines Testmodells zur Preisgebung der einfachst möglichsten Bedeutungen zur Bestimmung der Brauchbarkeit von Vollrädern vom DR Typ und ähnlichen Rädern und zweitens mit den Ergebnissen der Ermüdungstests welche an 5 DR Typ Rädern ausgeführt wurden.
		1991_Ber_ERRI B106 RP15_Standardisation of coaches.pdf
046	**ERRI EN 13979-1: 2003+A2:2011 Bahnanwendungen – Radsätze und Drehgestelle - Vollräder - Technische Zulassungsverfahren - Teil 1: Geschmiedete und gewalzte Räder** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 106.1 RP 13; 1990; Bericht	
		Experiment / Messfahrt mit Messung Spannungen und Kräfte, Lastkollektiv
		Der Bericht befasst sich mit Fahrversuchen, die an dem zur Standardisierung vorgeschlagenen DR-Radtyp durchgeführt worden sind. Zweck der Versuche war, die Vertikalkräfte, Führungskräfte und Spannungen, die für die Durchführung eines Ermüdungsversuchs auf dem Prüfstand benötigt werden, zu ermitteln.
		1990_Ber_ERRI B106 RP13_Standardisierung der Reisezugwagen-Radsätze.pdf

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000		**Keywords**
		Summary
		File Name
047	**ERRI B 126 RP 12: Fragen des Bremswesens. Bremse für Güterwagen mit 22,5 t Radsatzlast** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 126 RP 12; 1987; Bericht	
		Test / experiment; brake, wheel, temperature
		Um die Leistungsfähigkeit der Bremsanlage an den Güterwagen im Hinblick auf die Einführung der 22,5 t Radsatzlast zu ermitteln und Lösungsmöglichkeiten für deren Verstärkung bis zur S-Fähigkeit aufzuzeigen, wurden Bremsvesuche durchgeführt. Es wurde auch die Auswirkungen auf die Räder begutachtet.
		1987_Ber_ERRI B 126 RP 12_Fragen des Bremswesends.pdf
048	**ERRI B 136/RP 9: Radsätze mit aufgesattelten Achslagern: Konstruktion, Unterhaltung, Standardisierung. Bericht Nr. 9: Standardisierung der Radsätze mit aufgesattelten Rollenlagern von Güterwagen mit kleinen Rädern (Durchmesser 840-760-680 mm) (für Klotz- oder Radscheibenbremsen) Standardisierung eines aufgesattelten Radsatzes für Reisezugwagen mit Rädern von 920 mm Durchmesser.** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 136 RP 9; 1979; Bericht	
		Verhalten der Räder durch FEM (Spannung, Verformung) und Experiment, Bremsscheibe, Klotzbremse
		Im vorliegenden Bericht wird die Standardisierung der Radsätze mit aufgesattelten Rollenlagern von Güterwagen mit kleinen Rädern (Nenndurchmesser 680, 760 und 840 mm) behandelt.
		1979_Ber_ERRI B136 RP9_Radsätze mit aufgesattelten Achslagern.pdf
049	**ERRI B 169 / RP 14: Standardisierung der Radsätze. Verbesserung des mechanischen Widerstandes der Radwerkstoffe aufgrund erhöhter Radsatzlasten - Studie über die Stahlgüte R7T UCS** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 169 RP 14; 2005; Bericht	
		Test / experiment; material, wheel
		Neue Stählgüte R7T UCS entwickelt um Sicherheit zu erhöhen und Kosten zu senken. Verbessern bestimmter Kennwerte. Versuche (Härte, Gefüge, Eigensp., Bruchzähigkeit; Kerbschlag, etc.) mit der Stahlgüte werden durchgeführt und mit der Stahlgüte R7T verglichen.
		2005_Ber_ERRI B 169 RP 14_Standardisierung der Radsätze.pdf
050	**ERRI B 169/RP 12: Standardisierung der Radsätze: Erarbeitung einer für die Beschädigung eines Eisenbahnbauteils repräsentativen "globalen" Matrix zur Durchführung von Ermüdungsversuchen** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 169 RP 12; 1997; Bericht	
		Methode für Schädigung eines Eisenbahnbauteils, zur Durchführung von Ermüdungsversuchen bzw. Schadensberechnungen
		Beschreibung einer Methode zur Erarbeitung einer für die Beschädigung eines Eisenbahnbauteils repräsentativen globalen Matrix zur Durchführung von Ermüdungsversuchen.
		1997_Ber_ERRI B169 RP12_Standardisierung der Radsätze.pdf
051	**ERRI B 169: Thermische Grenzen der Räder und Bremsklötze; Bericht Nr. 1: Auswahl der Parameter für die Untersuchung von thermischen Grenzen der Räder und Bremsklötze** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 169 RP 01; 1987; Bericht	
		Experiment mit Temperaturmessung, Bremstypen, Verschleiß, Rad-Klotz, FEM für Temperatur und Spannung,
		Dieser Bericht dient um genaue Ziele der durchzuführenden Arbeiten und die für die Untersuchungen gewählten Parameter für die Untersuchung von thermischen Grenzen der Räder und Bremsklötze darzulegen.
		1987_Ber_ERRI B169 RP1_Thermische Grenzen der Räder und Bremsklötze.pdf

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000		**Keywords**
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		File Name
052	**ERRI B 169: Thermische Grenzen der Räder und Bremsklötze; Bericht Nr. 2: Auswirkung häufiger Bremsungen auf das Eigenspannungsfeld im Radkranz** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 169 RP 02; 1989; Bericht	
		Rad, Bremsung, Eigenspannung, zerstörungsfreie Messmethoden, Experiment Bremsung Spannung,
		In diesem Bericht sind die Versuche zur Überprüfung der Aussagefähigkeit der gewählten Messmethoden zur Messung der Eigenspannungen sowie die Prüfstands- und Streckenversuche, wo durch Bremsen Eigenspannungen im Rad erzeugt wurden, beschrieben. Auch ist die Spannungsverteilung im Radkranz, die man nach den Versuchen ermittelt hat, angegeben.
		1989_Ber_ERRI B169 RP2_Thermische Grenzen der Räder und Bremsklötze.pdf
053	**ERRI B 169: Thermische Grenzen der Räder und Bremsklötze; Bericht Nr. 3: Erforschung der Bruchschwelle** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 169 RP 03; 1991; Bericht	
		Experiment: Spannung + Bruch, Schaden durch thermische Beanspruchung, Rechenmodell: BM,
		Der Bericht beschreibt anhand von Bremsversuchen auf dem Prüfstand und Merkmalen von im Betrieb gebrochenen Rädern das Bruchverhalten von Monoblockrädern. Mit den gewonnenen Daten wird ein Rechenprogramm zur Vorhersage von Radbrüchen überprüft.
		1991_Ber_ERRI B169 RP3_Thermische Grenzen der Räder und Bremsklötze.pdf
054	**ERRI B169/RP 5 Standardisierung der Radsätze: Methoden zur Überwachung von Vollrädern (Sofortmaßnahmen zum Verhindern von Radbrüchen)** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 169 RP 05; 1993; Bericht	
		Maßnahmen für bestimmte Vollradschäden
		Es wird beschrieben welche Sofortmaßnahmen getroffen werden müssen, um den Bruch von Vollrädern zu verhindern, für thermischen und mechanischen Schäden. Schäden: Farbabbrand, Abstand der Rückenflächen der Radkränze, Überschleifender Bremssohlen, Einspannkerben
		1993_Ber_ERRI B169 RP5_Standardisierung der Radsätze.pdf
055	**ERRI B169/RP 7 Standardisierung der Radsätze; Thermische Grenzen der Räder und Bremsklötze - Überwachung der Vollräder im Betrieb; Zerstörungsfreies Verfahren zur Feststellung von Rissen in den Radkränzen** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI B 169 RP 07; 1995; Bericht	
		Zerstörungsfreien Prüfung, Risse im Radkranz, klotzgebremst
		Der vorliegende Bericht befasst sich mit dem Vergleich und der Bewertung der Methoden und der Arbeitsanweisungen zur zerstörungsfreien Prüfung zur Feststellung von Rissen in den Radkränzen der Vollräder
		1995_Ber_ERRI B169 RP7_Standardisierung der Radsätze.pdf
056	**ERRI E 162 / DT 155 Probleme der Anwendung der Linearelastischen Bruchmechanik in der Eisenbahntechnik** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI E 162 DT 155; 1983; Bericht	
		LEBM, Hinweis zur Anwendung an: Schienen, Schienenschweissungen, Eisenbahnvollradern, Radreifen und Achsen
		Die Grundlagen der linear-elastischen Bruchmechanik zur Bewertung des Wachstums und der kritischen Größe riss artiger Fehler in sprödbruchgefährdeten Konstruktionen werden dargelegt. Es werden Hinweise und Empfehlungen für Untersuchungen an Schienen, Schienenschweißungen, Eisenbahnvollrädern, Radreifen und Fahrzeugachsen gegeben.
		1983_Ber_ERRI E162 DT 155_Probleme der Anwendung der linearelastischen Bruchmechanik.pdf

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057	**ERRI E 162 / RP 5 Zerstörungsfreie Prüfung von Eisenbahnmaterialien im Betrieb. Bericht RP 5: Art und Größe kritischer Fehler in Rädern und Radsatzwellen** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI E 162 RP 05; 1987; Bericht	
		Erfahrungen aus Betrieb, BM Untersuchung, prob. BM Grenzgrößen für Risse
		Dieser Bericht enthält Angaben über Geometrie und Größe von Anrissen in Radsatzteilen aus betrieblichen Untersuchungen sowie aus bruchmechanischen Studien. Die Studien ergeben, dass die Eisenbahnen ihre bisherige Auffassung, wonach Risse in hochbeanspruchten Bauteilen unzulässig sind, unter bestimmten Bedingungen Überdenken könnten.
		1987_Ber_ERRI E162 RP 5_Zerstörungsfreie Prüfung von Eisenbahnmaterialien im Betrieb.pdf
058	**K. O. Edel, ERRI E 162 DT182: Die Festlegung zulässiger Radkranzquerrisse in laufflächengebremsten Vollrädern auf der Grundlage der probabilistischen Bruchmechanik** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI E 162 DT 182; 1987; Bericht	
		Vollrad; BM in- und stabiler Rissausbreitung, Spannungsintensitatsfaktor; Simulationsrechnung
		Auf der Grundlage der streuenden Werte der bruchmechanischen Eigenschaften und der Eigenspannungen überbremster Vollräder werden durch rechentechnische Simulation die Häufigkeitsverteilungen der Größen kritischer und vorkritischer Radkranzquerrisse ermittelt.
		1987_Ber_ERRI E162 DT182 Die Festlegung zulassiger Radkranzquerrisse.pdf
059	**ERRI E 162: Zerstörungsfreie Prüfung von Eisenbahnmaterialien im Betrieb; Bericht Nr. 3 Risse und Brüche, die im Eisenbahnbetrieb an Radreifen, Rädern und Radsatzwellen auftreten können** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI E 162 RP 03; 1986; Bericht	
		Risse und Brüche; zerstörungsfreie Prüfung,
		Es werden die Riss- und Bruchformen an Radreifen, -scheiben und -wellen und die möglichen Ursachen beschrieben.
		1986_Ber_ERRI E162 RP 3_Zerstörungsfreie Prüfung von Eisenbahnmaterialien.pdf
060	**M. Uhlig, ESR 0330 Wheel defect manual Version 1.2** RailCorp Engineering Standard - Rolling Stock ESR 0330; 2013; Norm	
		Wheel conditions, - defects, Thermal cracks, Rolling contact fatigue; Sub surface fatigue; Fatigue cracks; Spalling or shelled tread; etc
		Wheels with defective wheels may cause damage to both the track and the vehicle or lead to derailment. This standard provides staff with a summary of wheel conditions under which wheels may continue in service and operating restrictions imposed for defective wheels found on vehicles operating on the RailCorp network.
		2013_Norm_ESR 0330 Wheel defect manual.pdf
061	**M. Holowinski, Estimation of Actual Residual Stresses Due to Braking and Contact Loading of Rail Vehicle Wheels** U.S. Department of Transportation; Federal Railroad Administration; Office of Research an Development Washington; 1996; Bericht	
		FEM: residual stress; shakedown stress analyse, mechanical and thermal stresses, wheel
		This report summarizes the development of specialized finite element software for estimation of residual stresses in rail vehicle wheels subjected to combinations of mechanical stresses from wheel/rail contact and thermal stresses from frictional heating by tread brakes.
		1996_Ber_Holowinski_Estimation of Actual Residual Stresses.pdf
062	**K. Osuch, European and American wheels and their resistance to thermal damage** International Wheelset Congress 11th, France, Seite 77 – 86; 1995; Paper	
		Wheel thermal damage, experimen, comparison european - american
		Compare of European and American wheels. Analyze for damage limits. Make test rig.
		1995_Paper_Osuch_European and American wheels.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
063	**K. Handa, Experimental reproduction of wheel thermal cracks** World Congress on Railway Research 8th, Korea; 2008; Paper	
		Experiment: thermal cracks; wear of wheel tread; initiation;
		Thermal cracks on wheel tread have been experimentally reproduced on the full-scale brake test apparatus. Factors affecting the initiation of thermal cracks as well as the wear of wheel tread specified by observational analyses are briefly described on this paper
		2008_Paper_Handa_Experimental reproduction of wheel thermal cracks.pdf
064	**K. Handa, Experimental verification of influential factors on thermal cracking of tread braked wheels** International Wheelset Congress 17th, Ukraine, Seite 34 – 36; 2013; Paper	
		Tread thermal cracking, temperature, metallurgical investigation + numerical analysis: residual stress, experiment: thermal cracking mechanism
		In terms of the durability of carbon steel railway wheels, tread thermal cracking, one of the severe damages on tread surface, was investigated to understand the dominating factors. Based on the temperature conditions estimated by metallurgical investigation and numerical analysis, residual stress state during tread braking and after cooling was calculated.
		2013_Paper_Handa_Experimental verification of influential factors.pdf
065	**V. S. Sura, Failure modeling and life prediction of railroad wheels** Faculty of the Graduate School of Vanderbilt University, 2011, Diplom- / Doktorarbeit	
		Wheel failure; structural failure analysis; FEM: sub-surface cracking, stresses; fracture mechanics; reliability analysis methods; residual stresses; thermal brake load; wheel wear
		The current study develops an advanced analysis methodology to estimate the wheel failure life under realistic service conditions and considering multiple failure types. Also, probabilistic analysis is performed to consider uncertainties in service conditions.
		2011_Diss_Sura_Failure Modeling and life predcition of railroad wheels.pdf
066	**A. Ekberg, Fatigue of railway wheels and rails under rolling contact and thermal loading – an overview** Wear/Elsevier 258 (7/8), Seite 1288–1300, 2004, Paper	
		Rolling contact fatigue; mechanisms; prediction; influencing parameters; prevention
		An overview of rolling contact fatigue phenomena occurring at wheels and rails is given. The paper outlines mechanisms behind the various phenomena, means of prediction, influencing parameters and possible means of prevention.
		2004_Paper_Ekberg_Fatigue of railway wheels and rails.pdf
067	**H. Geijselaers, Finite Element Analysis of Thermoelestic Instability with Intermittent Contact** Journal of Tribology 122 (1), Seiten 42 – 46, 2000, Artikel	
		FEM, Wheel, hot spots, method to calculate thermoelastic instability
		In this paper it is demonstrated how the FEM may be used to simulate the development of hot spots on block braked wheel treads (calculate thermoelastic instability during braking). The brake blocks are modeled as rigid and nonconducting, which means, that their presence can be accounted for through the boundary conditions.
		2000_Art_Geijselaers_Finite Element Analysis of Thermoelestic Instability.pdf
068	**U. Zerbst, Fracture mechanics in railway applications – an overview** Engineering Fracture Mechanics 72, Seite 163 – 194; 2003; Paper	
		Fracture mechanics; fracture control concepts; safe-life; Fail-safe; damage tolerance; axles, wheels and rails
		This paper gives a general introduction to fracture mechanics application to railway components, like Railway axles, Railway wheels and Rails.
		2003_Paper_Zerbst_Fracture mechanics in railway applications.pdf
069	**G. Schinagl, H.4170 Simulation klotzgebremster Räder** Siemens AG 2015 Präsentation	
		Test / experiments, simulation
		Prüfstandversuche und Auswertung, Vergleich zur Simulation
		2015_Präs_Schinagl_H.4170 Simulation klotzgebremster Räder.pptx

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000		**Keywords**
		Summary
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070	**K. Handa, Identification of criteria of thermal cracking on wheel treads aiming at optimized brake system design** World Congress on Railway Research 9th, France; 2011; Paper	
		Experiment: tread thermal cracks; material analysis; FEM: residual stresses; thermal cracks;
		In the present study, full-scale experiments, material investigations and numerical analyses were used in combination in order to formulate the mechanism hypothesis which was then tested experimentally. The thermal cracking criteria would have been expressed based on the mechanism drawn from the hypothesis testing.
		2011_Paper_Handa_Identification of criteria of thermal.pdf
071	**N. Xiao, Influence law of braking heat load on wheel for railway heavy-haul freight car** International Heavy Haul Conference 11th, Australia; 2015; Paper	
		Residual thermal stress, wheel, calculation model, FEM, rim thickness, wheel - brake; wheel thermal fatigue damage
		The distribution of residual thermal stress for wheel due to braking was analyzed for different rim thickness.
		2015_Paper_Xiao_Influence law of braking heat load.pdf
072	**S. Caprioli, Influence of short thermal cracks on the material behaviour of a railway wheel subjected to repeated rolling** Advanced Materials Research 891-892, pp 1139-1145; 2014; Paper	
		Thermal crack, numerical model, FEM, crack length
		An analysis of whether and how the occurrence of shallow (radial) thermal cracks promotes additional plastic deformation of a mechanically loaded wheel tread is carried out. The study employs numerical simulations of a 2D slice of an elastoplastic railway wheel tread containing thermal (radial) cracks. The cracked wheel material is subjected to repeated passes of a frictional rolling contact load. The effect of the existing thermal cracks on bulk deformation and subsequent rolling contact promoted growth is quantified.
		2014_Paper_Caprioli_Influence of short thermal cracks on the material.pdf
073	**K. Handa, Influence of silicon carbide filters in cast iron composite brake blocks on brake performance and development of a production process** Wear/Elsevier 267 (5/8), Seite 833–838; 2009; Paper	
		Experiment: brake blocks; high speeds; thermal load wheel
		Cast iron composite brake blocks, which include silicon carbide (SiC) ceramic filters, have been developed for increased speeds in conventional trains. It has been found that the brake block temperature is related to the friction coefficient and that SiC inclusion in the brake block prevents an increase in temperature and increases the friction coefficient.
		2009_Paper_Handa_Influence of silicon carbide filters.pdf
074	**K. Handa, Influence of wheel/rail tangential traction force on thermal cracking of railway wheels** Wear/Elsevier 289, Seite 112 – 118; 2012; Paper	
		Tread thermal cracking; numerical analysis : temperature; microstructure, stress fields; full-scale brake dynamometer;
		The purpose of the present study is to distinguish the dominant factors of tread thermal cracking from among the factors reported previously, i.e. rolling contact with rails and heat input from a brake shoe.
		2012_Paper_Handa_Influence of wheel-rail tangential traction force.pdf
075	**K. Wang, Investigation Of Heat Treating Of Railroad Wheels And Its Effect On Braking Using Finite Element Analysis** International ANSYS Conference 2002; Paper	
		FEM: heat treatment process, residual stress after on-tread braking - temperatur + stress
		This paper studies the heat treatment process of a 36” freight car wheel manufactured by Griffin Wheel Company. Ideal and non-ideal heat treatment processing and the effect on the residual stress after on-tread braking are evaluated. Two models are developed to simulate both the heat treatment process and on-tread braking using ANSYS.
		2002_Paper_Wang_Investigation Of Heat Treating.pdf

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000		**Keywords**
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		File Name
076	**J.E. Gordon, Investigation of the Effects of Braking System Configurations on Thermal Input to Commuter Car Wheels** U.S. Department of Transportation; Federal Railroad Administration; Office of Research an Development Washington; 1996; Bericht	
		Braking, Heat transfer analysis, Rail vehicles, Wheels, FEM
		A heat transfer model, previously developed to estimate wheel rim temperature during tread braking of MU power cars and validated by comparison with operational test results, is extended and applied to cases involving several different blended brake system configurations.
		1996_Ber_Gordon_Investigation of the Effects of Braking System .pdf
077	**C. P. Zander Klotzbremsen mit Sintermetallbelägen - Betriebserfahrungen mit Hochleistungslokomotiven** ZEVrail Glasers Annalen 125 (4), Seite 157 – 165; 2001; Artikel	
		Brake block material, experiment, wheel - brake block, wheel damage,
		Die Einsatzmöglichkeiten von Klotzbremsen werden beschrieben, Vor- und Nachteile gegenübergestellt und die physikalischen Grenzen solcher Systeme aufgezeigt.
		2001_Art_Zander_Klotzbremsen mit Sintermetallbelägen.pdf
078	**S. M. Zakharov, Kontaktermüdungsradbeschädigungen der Güterwagen** Allrussischen wissenschaftlichen Forschungsinstituts des Eisenbahntransports namens Rotbannenorden, Moskau; 2004; Buch	
		Entstehung Kontaktermüdungsdefekten, Rad - Schiene, Haftwert,
		Es sind die Ergebnisse der Erforschungen zur Klärung der Gründe der Abspaltung infolge der thermomechanischen Beschädigungen der Radlauffläche, der Unterflächen- und der oberflächennahen Kontaktermüdung dargestellt.
		2004_Buch_Zakharov_Kontaktermüdungsradbeschädigungen.pdf
079	**M. R. K Vakkalagadda, Locomotive wheel failure from gauge widening/condemning: Effect of wheel profile, brake block type, and braking conditions** Engineering Failure Analysis 59, Seite 1 – 16; 2015; Paper	
		FEM: Wheel - rail - brake, thermo-mechanical analysis; wheel gauge; creep, failure
		FE simulations are used to investigate effect of wheel profile, wheel diameter, brake block type, nature of braking, braking frequency and braking cycles on wheel gauge with an aim to identify situations that can result in locomotive wheel failure from gauge widening or condemning and to identify wheel profiles and brake block types that are better suited for avoiding excessive gauge change.
		2015_Paper_Vakkalagadda_Locomotive wheel failure from gauge.pdf
080	**M. R. K Vakkalagadda, Locomotive wheel failure from gauge widening/condemning: Finite element modeling and identification of underlying mechanism** Engineering Failure Analysis 57, Pages 143–155; 2015; Paper	
		FEM, Heat treatment, brake block, two braking scenarios
		Wheel failure from gauge condemning/widening in straight plate, locomotive, railway wheels used by Indian Railways is studied using finite element analysis. The study accounts for residual stresses generated during wheel manufacturing and fitment on axle. A validated thermal model accounting for heat loss to rail, brake blocks and ambient air is considered for accurate prediction of wheel temperatures for a given train running and braking history.
		2015_Paper_Vakkalagadda_Locomotive wheel failure from gauge widening.pdf
081	**M. A. Dungan, Materials used in couplings mechanical friction braking system of high speed railway vehicles** Buletinul AGIR 2010 (2/3); 2010; Paper	
		Materials; friction torque components; braking;
		The paper presents a study on the materials used for friction torque components: brake shoe-binding-wheel, that the friction torque components: friction lining-disc brake. Elements of friction torque, the materials are made, to ensure an increased efficiency of mechanical braking system for all ranges of speeds.
		2010_Paper_Dungan_Materials used in couplings mechanical.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
082	**D. Nikas, Mechanical properties and fatigue behavior of railway wheel steels as influenced by mechanical and thermal loadings** International Conference on Contact Mechanics 10th, USA; 2015; Präsentation	
		Mechanical properties, thermal degradation, with and without plastic deformation; wheel steel, experiment
		Investigate the changes in properties that are induced by thermal degradation with and without prior plastic deformation
		2015_Präs_Nikas_Mechanical properties and fatigue behavior.pdf
083	**D. Nikas, Mechanical properties and fatigue behavior of railway wheel steels as influenced by mechanical and thermal loadings** International Conference on Contact Mechanics 10th, USA; 2015; Paper	
		mechanical properties, thermal degradation, with and without plastic deformation; wheel steel, experiment
		The aim of the present study is to investigate the changes in properties that are induced by thermal degradation with and without prior plastic deformation.
		2015_Paper_Nikas_Mechanical properties and fatigue behavior.pdf
084	**F. Walther, Mikrostrukturbasierte Ermüdungseigenschaften hochbeanspruchter UIC-Radwerkstoffe** EI - Eisenbahningenieur 55 (5), Seite 41 - 48 2004 Artikel	
		Experiment, wheel, failure behaviour, fatigue fracture, microstructure,
		Der Artikel beschäftigt sich mit der mikrostrukturorientierten Charakterisierung des Ermüdungs- und Schädigungsverhaltens hochbeanspruchter Vollräder und Radreifen der UIC-Güten R7 und B6. Anhand von Versuchen.
		2004_Art_Walther_Mikrostrukturbasierte Ermüdungseigenschaften.pdf
085	**M. S. Milosevic, Modeling thermal effects in braking system of Railway vehicles** Thermal Science 16 (2), Seite 515 - 526 2012 Paper	
		Thermal analysis, analytical and numerical modeling (FEM) of thermal effects;
		The thermal analysis of a block-braked solid railway wheel of a 444 class locomotive of the national rail-way operator Serbian Railways is processed in detail, using analyti-cal and numerical modeling of thermal effects during long-term braking for maintaining a constant speed on a down-grade railroad.
		2012_Paper_Milosevic_Modeling thermal effects in braking system.pdf
086	**M. S. Milosevic, Modeling thermal effects of the braking process at block-braked railway vehicles** XV International Scientific-expert Conference on Railways RAILCON ’12, Niš; 2012; Paper	
		Thermal analysis; analytical and numerical modeling (FEM) of thermal effects; damages of wheel;
		The thermal analysis of a block braked solid railway wheel of a locomotive of the type 444 of the national railway operator Serbian Railways using analytical and numerical modeling of thermal effects during braking until the locomotive stops, is processed in detail.
		2012_Paper_Milosevic_Modeling thermal effects of the braking process.pdf
087	**O. Krettek, Modellierung der Klotzbremse** ZEVrail Glasers Annalen 118 (6), Seite 315 – 323; 1994; Artikel	
		Brake block - wheel, FEM, Verriffelung, thermal instability
		Abläufe der Vorgänge zwischen Klotz und Rad liefern FE-Rechnungen, die allerdings eine exakte Modellierung der an Klotz und Rad angreifenden Kräfte und der durch sie hervorgerufenen Reibvorgänge voraussetzen. Auch wird auf thermische Instabilitäten eingegangen, welche aus der Modellrechnung folgen.
		1994_Art_Krettek_Modellierung der Klotzbremse.pdf
088	**T. Vernersson, Modelling of temperatures during railway tread braking: Influence of contact conditions and rail cooling effect** Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit 228 (1), Seite 93 – 109; 2012; Artikel	
		Numerical model, FEM, Hot spots, thermal, rail cooling effect, rail-wheel-brake
		The objective of this paper is to use a numerical modelling approach to study heat partitioning and the cooling effect of the rail during railway tread braking.
		2012_Art_Vernersson_Modelling of temperatures during railway tread braking.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
089	**M. Bonatrans, Neues Bewertungsverfahren für das Bruchverhalten von Vollräder mit vergüteter Oberfläche** Internationale Schienenfahrzeugtagung Dresden 4th, Dresden, Seite 18 – 20; 2000; Paper	
		Schäden; Bruchzähigkeit;
		Dieser Artikel behandelt die Bewertung der Bruchzähigkeit des Radkranzes aus der Stahlgüte R7T an Charpy Prüfkörpern bei statischer und dynamischer Belastung gemäß den Bestimmungen des Merkblattes UIC 812-3 und Korrelationsmöglichkeiten zwischen dieser Bewertung und den an den Prüfkörpern CT-30 ermittelten Ergebnissen.
		2000_Paper_Bonatrans_Neues Bewertungsverfahren für das Bruchverhalten.pdf
090	**W. Mombrei, Neutronendiffraktometrische Messungen von Gitterdehnungen zur Abschätzung der Eigenspannungsentwicklung im Einsatz von klotzgebremsten Vollrädern im Nahverkehr** Internationale Schienenfahrzeugtagung Dresden 8th, Dresden, Seite 42 – 44; 2006; Paper	
		Messung; Eigenspannungen, Rad;
		Vollradbrüche bzw. -anrisse an Rädern werfen die Frage auf, ob sich durch kurz hintereinander folgende Haltebremsungen ebenfalls ein zur Bruchausbildung ausreichendes Zugeigenspannungsfeld im Radkranz aufbauen kann. Es werden Gitterdehnungsmessungen zur Abschätzung der Eigenspannungsentwicklung im Einsatz der Räder vorgenommen.
		2006_Praper_Mombrei_Neutronendiffraktometrische Messungen.pdf
091	**W. Mombrei, Neutronendiffraktometrische Messungen von Gitterdehnungen zur Abschätzung der Eigenspannungsentwicklung im Einsatz von klotzgebremsten Vollrädern im Nahverkehr** Internationale Schienenfahrzeugtagung Dresden 8th, Dresden; 2006; Präsentation	
		Messung; Eigenspannungen, Rad;
		Es werden Gitterdehnungsmessungen zur Abschätzung der Eigenspannungsentwicklung im Einsatz der Räder vorgenommen.
		2006_Präs_Mombrei_Neutronendiffraktometrische Messungen .pdf
092	**T. Vernersson, Noise-related roughness on tread braked railway wheels-experimental measurements and numerical simulations** **Wear/Elsevier 253 (1/2), Seite 301–307; 2002; Paper**	
		Experiment: Temperatur wheel - brake; time-averaging FEM: thermoelastic interaction wheel - block; parametric study for block material; Transient FEM
		Block braking is studied experimentally and numerically with focus on the thermal phenomena, in particular on the development of localized temperature peaks: hot spots.
		2002_Paper_Vernersson_Noise-related roughness on tread braked.pdf
093	**A. Ekberg, Numerical evaluation of the material response of a railway wheel under thermomechanical braking conditions** Wear/Elsevier 314 (1/2), Seite 181 – 188; 2013; Paper	
		Thermomechanical rolling contact + loading, Models, FEM
		A computationally efficient finite element mesh of a wheel subjected to thermomechanical loading has been developed. The influence of loading schemes in terms of discretisation of load traversals and mechanical loading during heating and cooling on the thermomechanical material response has been assessed and quantified.
		2013_Paper_Ekberg_Numerical evaluation of the material response.pdf
094	**K. O. Edel, Oberflächendefekte im Scheibenbereich** Abschlußbericht zum DFG-Projekt FH Brandenburg; Brandenburg an der Havel; 1998; Bericht	
		Scheibenbereich, BM: Dauerfestigkeit und Risswachstum, FEM: Spannung; Werkstoffeigenschaften, Temperatur, Eigenspannung
		Um die Betriebssicherheit der mit BV1-Vollrädern ausgerüsteten Güterwagen unter den dynamischen Beanspruchungen des Eisenbahnbetriebes gewährleisten zu können, werden Analysen und Bewertungen mittels der Bruchmechanik durchgeführt. Kap 2: Die Beanspruchung der BV1-Vollräder
		1998_Ber_Edel_Oberflächendefekte im Scheibenbereich.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
095	**P. Piec, On study of phenomena in the wheel - brake shoe contact area** Periodica Polytechnica Transportation Engineering 21 (3), Seite 229-238; 1992; Paper	
		Wheel - brake brake; experiment and numerical simulation - dry friction
		The paper comprises the results of experimental investigation and of numerical simulation on the phenomenon of the wheel corrugation generated during braking with a brake shoe.
		1992_Paper_Piec_On study of phenomena in the wheel.pdf
096	**M. R. K Vakkalagadda, Performance analyses of brake blocks used by Indian Railways** Wear/Elsevier 328 - 329, Seite 64 – 76; 2015; Paper	
		Experiment: stop braking; friction characteristics brake shoe, heat generat
		This work investigates friction characteristics of cast iron and composite brake blocks, used by Indian Railways, with an aim to understand their performance under different running conditions and to understand the effect the brake block characteristics would have on heat generated in locomotive and wagons wheels.
		2015_Paper_Vakkalagadda_Performance analyses of brake block.pdf
097	**W. Mombrei, Probleme der Bruchneigung klotzgebremster Eisenbahnvollräder** Dem Wissenschaftlichen Rat der Hochschule für Vehrkehrswesen "Friedrich List" Dresden; 1984; Diplom- / Doktorarbeit	
		Bruchformen, Radmaterial -Kennwerte; Temperatur, Eigenspannungen Rad - Klotz; Abkühlgeschw. Experimente: Klc, BM Betrachtung
		Im Ergebnis der Betrachtungen der Bedingungen der Bruchausbildung sollen Vorschläge erarbeitet werden, auf deren Grundlage eine Verminderung der Bruchwahrscheinlichkeit klotzgebremster Vollräder - speziell für die Beanspruchungsbedingungen an Eisenbahnwagen - erreicht werden kann.
		1985_Diss_Mombrei_Probleme der Bruchneigung.pdf
098	**W. Mombrei, Probleme der Bruchzähigkeit an Eisenbahnvollrädern** Internationale Schienenfahrzeugtagung Dresden 1th (2), Dresden, Seite 232 – 235; 1996; Paper	
		Untersuchung: Bruchzähigkeit
		Bestimmung der Bruchzähigkeit von Vollrädern
		1996_Paper_Mombrei_Probleme der Bruchzähigkeit.pdf
099	**P.Raninger, Project overview A6.15 - Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014; Präsentation	
		Overview: Laboratory tests, Simulation, Damage analysis
		Präsentation / Bericht mit der Übersicht über das Vorgehen und der Inhalte einzelner Berichte.
		2014_Präs_Raninger_Projekt Overview A6 15 Modeling of the in-service.pdf
100	**P.Raninger, Project report A6.15 A-P1: Thermophysical data - Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014; Präsentation	
		Laboratory tests: Thermophysics
		Präsentation / Bericht der thermophysiklischen Charakterisierung von 5 Materialien (15CDV6; GJS500; ER7; GJL250; GS22)
		2014_Präs_Raninger_Project report A6 15 A-P1: Thermophysical data.pdf
101	**P.Raninger, Project report A6.15 A-P2: Tension-Tests - Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014; Präsentation	
		Laboratory tests: Tension tests
		Präsentation / Bericht über Zugversuche für 5 Materialien (15CDV6; GJS500; ER7; GJL250; GS22)
		2014_Präs_Raninger_Project report A6 15 A-P2: Tension-Tests.pdf
102	**P.Raninger; Project report A6.15 A-P3: LCF-Tests - Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014; Präsentation	
		Laboratory tests: LCF
		Präsentation / Bericht über die LCF-Charakterisierung von 5 Materialien (15CDV6; GJS500; ER7; GJL250; GS22)
		2014_Präs_Raninger_Project report A6 15 A-P3: LCF-Tests.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
103	**P.Raninger, Project report A6.15 A-P4: TMF Untersuchungen an Stahl- und Gusseisenwerkstoffen** Montanuniversität Leoben Lehrstuhl für Allgemeinen Maschinenbau; 2014; Bericht	
		Laboratory tests: TMF
		TMF-Charakterisierung an 5 unterschiedlichen Werkstoffen (15CDV6; GJS500; ER7; GJL250; GS22). Bei den Versuchen handelt es sich um reine „out-of-Phase“ TMFVersuche.
		2014_Ber_Raninger_Project report A6 15 A-P4: TMF.pdf
104	**P.Raninger, Project report A6.15 A-P5: Crack propagation - Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014; Präsentation	
		Laboratory tests: Fracture mechanics
		Präsentation / Bericht über die Charakterisierung des Rissfortschrittsverhalten von 4 Materialien (15CDV6; GJS500; ER7; GS22)
		2014_Präs_Raninger_Project report A6 15 A-P5: Crack propagation.pdf
105	**P.Raninger, Project report A6.15 B-P1: Material models - Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014; Präsentation	
		Simulation: FE-sample level Material modelling
		Präsentation / Bericht mit einer Übersicht über Materialmodelle
		2014_Präs_Raninger_Project report A6 15 B-P1: Material models.pdf
106	**P.Raninger, Project report A6.15 B-P2: Verification on Sample Level with Single Element Test - Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014; Präsentation	
		Simulation: FE-sample level Verification
		Präsentation / Bericht mit einem Überblick über Ergebnisse (TMF, LCF, mit Vergleich der Ergebnisse). Eine Einführung in Single Element Test (SET),
		2014_Präs_Raninger_Project report A6 15 B-P2: Verification.pdf
107	**P.Raninger, Project report A6.15 B-P3: BrakeCalc - Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014, Präsentation	
		Simulation: FE-component level
		Präsentation / Bericht mit einer Übersichtsdarstellung der Simulation der Bremsberechnung, Parameter und deren Ergebnisse
		2014_Präs_Raninger_Project report A6 15 B-P3: BrakeCalc.pdf
108	**P.Raninger, Projekt A6.15 Modeling of the in-service behavior of wheel-mounted brake disks for railway applications** Material Center Leoben - Forschung GMBH; 2014; Bericht	
		Scheibengebremste Räder, Material 15CDV6, GJS500, ER7, GS22 and GJL250
		Bericht mit einer Übersicht über das Vorgehen und der einzelnen Berichte über das Verhalten von scheibengebremsten Rädern
		2014_Ber_Raninger_Projekt A6 15 Modeling of the in-service.pdf
109	**DB AG Prüfbericht HGV - Klotzversuche; Dokument: 10-P-14280-T.TVI 12-103302-PR01_V02** Deutsche Bahn AG, DB Systemtechnik, Bremse und Kupplung T.TVI 12; 2011; Bericht	
		Temperatur, Eigenspannungen, Verformung, Verschleiß
		Überprüfung des thermischen Verhalten eines klotzgebremsten Rades im Hochgeschwindigkeitsverkehr. Die Versuchsreihe besteht aus einfachen Stoppbremsungen aus unteschiedlichen Ausgangsgeschwindigkeiten. Es werden die verbleibenden Eigenspannungen mittels Ultraschall ermittelt.
		2011_Ber_DB AG_Prüfbericht HGV - Klotzversuche.pdf
110	**R. Müller; Radsätze** Gleislauftechnik Müller; 2016; Präsentation	
		Model for verification
		Thermomechanische Lastannahme der Räder, Temperaturverlauf, Radbruch, akustisches Verhalten, thermomechanische und mechanische Überprüfung / Modell der Räder
		2016_Präs_Gleislauftechnik Müller_Radsätze.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
111	**S. Teimourimanesh, Railway Tread braking Temperatures - Numerical simulation and experimental studies** Department of Applied Mechanics, Chalmers University of Technology Gothenburg, Sweden; 2012; Diplom- / Doktorarbeit	
		Literature studies, brake rig experiments and field tests, in addition to numerical modelling and simulations, FEM
		Extensive Literature survey with special focus on the braking capacity of wheels. Two different railway wheel design have been numerically studied.
		2012_Diss_Teimourimanesh_Railway tread braking temperatures.pdf
112	**M. Diener, Reliability and safety in railway products - Fracture mechanics on railway solid wheels** Lucchini RS Series LRS-TECHNO 01; 2008; Buch	
		Material properties, Bruchzähigkeit, production, wheel, experiment,
		Es werden Versuche durchgeführt um den Einfluss der Vollräder bezüglich Schäden und Brüche zu analysieren. (Bruchzähigkeit !) Auch wird der Herstellungsprozess der Räder dargestellt.
		Büro WS
113	**M. A. Dungan, Research concerning thermal stress in case of stop and duration braking of electric locomotives EA-060 type** International Journal of Systems Applications, Engineering & Development 5 (3), Seite 428-435; 2011; Paper	
		Calculation temperature; brake shoe; stop braking
		The aim of the paper: Determine by calculation the maximum temperature incurred during braking on friction members, both for new and for used bandages for the case of stop braking and for the case of duration braking.
		2011_Paper_Dungan_Research concerning thermal stress.pdf
114	**L. I. Dungan, Research concerning thermal stress of bandages on block braking in case of braking stop** Advances in Biology, Bioengineering and Environment; Greece, Seite 168 – 171; 2010; Paper	
		Maximum temperature incurred during braking; calculation
		The aim of the paper is to determine by calculation the maximum temperature incurred during braking so as to tread depth and tire, both for new and for used bandages for the case of stopping when breaking.
		2010_Paper_Dungan_Research concerning thermal stress.pdf
115	**S. M. Zakharov, Rolling contact fatigue defects in freight car wheels** Wear/Elsevier 258 (7/8), Seite 1142 – 1147; 2004; Paper	
		Defect formation, rolling contact fatigue: wheel spalling, shelling, thread checking, initiation
		Three types of rolling contact fatigue are prevalent. All these defects and mechanisms are generally known, however, there are many particularities that should be studied. Theoretic studies and modeling of the defect formation are presented and discussed in the paper.
		2004_Paper_Zakherov_Rolling contact fatigue defects.pdf
116	**S. Caprioli, Short rolling contact fatigue and thermal cracks under frictional rolling - A comparison through simulations** Engineering Fracture Mechanics 141, Seite 260 – 273; 2015; Paper	
		Rolling contact fatigue; FEM: Thermal and RCF cracks; wheel tread;
		The relative severity of radial (thermal) and inclined rolling contact fatigue surface cracks of equal depth in a railway wheel is investigated by three-dimensional elastoplastic finite element analyses of a cracked wheel sector subjected to contact loading.
		2015_Paper_Caprioli_Short rolling contact fatigue and thermal.pdf
117	**A. Ghidini, Special Wheels for Mass Transit** Lucchini RS Series LRS-TECHNO 07; 2014; Buch	
		Wheel, material properties, transportation, damage
		It describes steel grades for wheels, tyres and wheel centers for mass and rapid transit and describes the various solutions offered today for the use in critical applications.
		Büro WS

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
118	**Q. Wu, Study on curving performance of heavy haul train under braking condition** International Symposium on Dynamics of Vehicles on Roads and Tracks 24th, Graz; 2015; Paper	
		Train curving performances; dynamics model by numerical method
		In this paper, dynamic models of 1D and 3D train are established by numerical method, in which dynamic behaviors of draft gear and brake shoe are both considered. The assessment of train curving performance is more focused on making a comparison between idling and braking conditions.
		2015_Paper_Wu _Study on curving performance of heavy.pdf
119	**K. Handa, Surface cracks initiation on carbon steel railway wheels under concurrent load of continuous rolling contact and cyclic frictional heat** 268 (1/2), Seite 50 – 58; 2009; Paper	
		Durability wheel; experiment: tread thermal cracks (focus), residual stress
		In the paper they have demonstrated that tread thermal cracks can be experimentally reproduced under the condition of concurrent loading of continuous rolling contact with rails and cyclic frictional heat from brake blocks.
		2009_Paper_Handa_Surface cracks initiation on carbon steel.pdf
120	**D. Milutinovic, Temperature and Stress State of the Block-Braked Solid Wheel in Operation on Yugoslav Railways** FME Transaction, University of Belgrade 31 (1), Seite 15 – 20; 2003; Artikel	
		Calculation of temperature and stress states by FEM, brake block - wheel,
		The paper gives the analysis calculation results of the thermal load of the railway vehicle block-braked solid wheel on characteristic selected line on Yugoslav Railways network. Thermal analysis was done using the FEM, which was also used for obtaining wheel temperature and stress states in the simulated operation conditions.
		2003_Art_Milutinovic_Temperature and Stress State.pdf
121	**T. Vernersson, Temperature and thermoelastic instability at tread braking using cast iron friction material** Wear/Elsevier 314 (1/2), Seite 171 – 180; 2013; Paper	
		2 Methods, thermomechanical interaction, pin-on-disc experiment
		In this paper, two approaches are adopted to analyze the thermomechanical interaction in a pin-on-disc experimental study of railway braking materials. First, the thermal problem is studied, Second: the frictionally induced thermoelastic instabilities at the pin-disc contact are studied using a numerical method.
		2013_Paper_Vernersson_Temperatures and thermoelastic instability.pdf
122	**T. Vernersson, Temperatures at railway tread braking. Part 1: modelling** Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit 221, Seite 167 – 182; 2006; Paper	
		Thermal model, wheel - brake block temperatur, rail chill, FEM, heat partitioning
		The aim is to develop an efficient engineering tool for analysis of temperatures at railway tread brakes. One objective is to find performance limits of tread braking. The focus is on the wheel behavior. The thermal behavior of the block - wheel - rail system will be studied. Base on: Modelling
		2006_Paper_Vernersson_Temperatures at railway tread braking Part 1.pdf
123	**T. Vernersson, Temperatures at railway tread braking. Part 2: calibration and numerical examples** Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit 221, Seite 429 – 442; 2006; Paper	
		Thermal interaction wheel - brake, brake rig experiment.
		The aim is to develop an efficient engineering tool for analysis of temperatures at railway tread brakes. One objective is to find performance limits of tread braking. The focus is on the wheel behavior. The thermal behavior of the block - wheel - rail system will be studied. Base on: Calibration and numerical examples
		2006_Paper_Vernersson_Temperatures at railway tread braking Part 2.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
124	**T. Vernersson, Temperatures at railway tread braking. Part 3: wheel and block temperatures and the influence of rail chill** Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit 221, Seite 443 – 454; 2006; Paper	
		Rail chill, brake rig test, field test, experiment,
		The aim is to develop an efficient engineering tool for analysis of temperatures at railway tread brakes. One objective is to find performance limits of tread braking. The focus is on the wheel behavior. The thermal behavior of the block - wheel - rail system will be studied. Base on: wheel and block temperatures and the influence of rail chill
		2006_Paper_Vernersson_Temperatures at railway tread braking Part 3.pdf
125	**N. Lakota, Temperaturwechselverhalten ein- und mehrphasiger metallischer Werkstoffe in der Rissinitiierungs- und Rissfortschrittsphase** Fakultät für Maschinenbau der Ruhr-Universität Bochum, 2008, Diplom- / Doktorarbeit	
		Exp.: Temperaturwechsel - prüfung mit Nd-YAG Laser; Quantifizierung Risswachstums an der Oberfläche & in die Tiefe; versch. Werkstoffe
		In dieser Arbeit soll der Einfluss der herstellungsbedingten Spannungen und Oberflächenbeschaffenheit auf die Temperaturwechselbeständigkeit von Werkstoffen im Stadium der Rissinitiierung geklärt werden.
		2008_Diss_Lakota_Temperaturwechselverhalten ein- und mehrphasiger metallischer.pdf
126	**Z. Pengpai, The application of fatigue performance to optimal design for wheel of railway freight train** International Wheelset Congress 17th, Ukraine, Seite 91 – 95; 2013; Paper	
		Fatigue assessment method, stress cyclic models, wheel design, tread-brake, method for fatigue strength calculation,
		Compared with the general design method, optimal design of wheel considering fatigue performance can make the design more reliable. However, for the existing evaluation standards of wheel strength, it is difficult to assess the wheel's fatigue strength for case of continuous tread-brake.
		2013_Paper_Pengpai_The application of fatigue performance.pdf
127	**D. Peng, The development of combination mechanical contact and thermal braking loads for railway wheel fatigue analysis** Theoretical and Applied Fracture Mechanics 60 (1), Seite 10 – 14, 2012, Paper	
		Crack growth; braking loads, FEM: mechanical loads, thermal loads; Stress intensity factor;
		This paper presents the results of a study into methods for estimating the residual lifetime of the rail S-shape plate rail wheel due to cyclic mechanical loads and thermal loads.
		2012_Paper_Peng_The development of combination mechanical.pdf
128	**G. Donzella, The effect of block braking on the residual stress state of a solid railway wheel** Institution of Mechanical Engineers; Part F Journal of Rail and Rapid Transit 212 (2), Seite 145 – 158;·1998; Paper	
		FEM, block braking, residual stresses, thermal fatigue
		A finite element, numerical model of a solid railway wheel was perfected permitting the simulation of a block braking operation. The analyses performed, backed by experimental tests, permitted the degree of variation in the residual stress state caused by particularly heavy braking to be evaluated. The thermal fatigue strength of the component, although in an approximate way, was checked on the basis of the calculated stress state
		1998_Paper_Donzella_The effect of block braking.pdf
129	**H. R. Wetenkamp, The effect of brake shoe action on thermal cracking and on failure of wrought steel railway car wheels** Bulletins - Engineering Experiment Station, University of Illinois, Urbana 47 (77), No. 387; 1950; Bericht	
		Experiment - 2 types of tests, wheel - brake shoe, carbon contant (wheel), heat treatment, wheel design, stresses
		Investigation of steel car wheels. Laboratory tests were made on 369 wrought steel railway car wheels. Two types of tests were performed: (1) the wheels were stopped from high speed by using high brake shoe pressure, and (2) the wheels were tested under long-continued applications of the brake shoes.
		1950_Ber_Wetenkamp_The effect of brake shoe action on thermal cracking .pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
130	**I. S. Cole, The effect of localised cyclic heating on railway wheel steels - an investigation into the effects of tread braking** International Wheelset Congress 10th, Australia, Seite 319 – 324; 1992; Paper	
		4 damage pattern, experiment, damage critical to wheel life
		Critical damage pattern, laboratory simulation
		1992_Paper_Cole_The effect of localised cyclic heating.pdf
131	**D. Peng, The tool for assessing the damage tolerance of railway wheel under service conditions** Theoretical and Applied Fracture Mechanics 57 (1), Seite 1–13; 2011; Paper	
		Stress field; mechanical -, brake load; residual stress; crack growth; FEM
		This paper aims to provide a prediction of the crack growth in the rail wheel – due to cyclic braking loads, mechanical loads and residual stress from manufacture process. Simulation FEM has been used.
		2011_Paper_Peng_The tool for assessing the damage.pdf
132	**M. Sitarz, Theory and research of composite brake shoe** Department of Railway Engineering, Silesian University of Technology, Centre of Excellence TRANSMEC, Poland – Artikel	
		Thermal and tribologic phenomena, brake shoe - wheel, braking. modeling of thermal and mechanical phenomena,
		In this article it is described mainly the thermal and tribologic phenomena concerning the cooperation between brake shoe and rail wheel proceeding during braking. It was described the researches of new composite materials and new construction.
		0000_Art_Sitarz_Theory and research of composite brake shoe .pdf
133	**A. Sulti, Thermal and Stress Analysis of AALRT Wheel when braking with block brake** Addis Ababa University, Addis Ababa Institute of Technology, School of Mechanical and Industrial Engineering; 2014; Diplom- / Doktorarbeit	
		Analytical modeling of thermal and mechanical loads on wheel, mathematical model for interface temperatur rise, FEM of the wheel
		In this thesis, the thermal and stress analysis of the AALRT wheel is studied assuming that if it uses tread brake which is imposed due the braking action on different gradients and some resistance factors.
		2014_Diss_Sulti_Thermal and Stress Analysis of AALRT.pdf
134	**S. Teimourimanesh, Thermal Capacity of Railway Wheels - Temperatures, residual stresses and fatigue damage with special focus on metro applications** Department of Applied Mechanics, Chalmers University of Technology, Gothenburg, Sweden; 2014; Diplom- / Doktorarbeit	
		Literature studie; hot spots, experiments; thermomechanical behaviour; thermal models: temperatures + heat partitioning between block, wheel and rail;
		In the thesis, important aspects of the thermal capacity of tread braked wheels have been assessed in literature survey. Then two different railway wheel designs have been numerically studied (freight and metro wheels). The influence of brake block materials, thermal parameters and brake pressure distribution on the wheel temperatures has been investigated.
		2014_Diss_Teimourimanesh_Thermal capacity of railway wheels.pdf
135	**T. Vernersson, Thermal capacity of tread braked railway wheels - Part 1: Modelling** Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit; 2014; Paper	
		Model, FEM: thermal loads, mechanical loads, Wheel - rail - brake block,
		In the paper, a model is proposed and developed that represents typical conditions in metro and suburban operations, in particular during sequential stop braking. The analysis also considers drag braking, mechanical loading, residual stresses and wheel-axle interference fit.
		2014_Paper_Vernersson_Thermal capacity of tread braked Teil 1.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
136	**T. Vernersson, Thermal capacity of tread braked railway wheels - Part 2: Applications** Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit; 2014; Paper	
		Parametric study, loading, temperatures, axial flange deflection, residual stresses, fatigue life of wheel
		In this paper, application examples are given employing a modelling framework which has been developed in a companion paper. The examples represent typical conditions in metro and suburban operations, in particular during sequential stop braking. Also results for drag braking, mechanical loading, residual stresses and wheel-axles interference fit are given.
		2014_Paper_Vernersson_Thermal capacity of tread braked Teil 2.pdf
137	**O. Orringer, Thermal cracking in railroad vehicle wheels subjected to high performance stop braking** Theoretical and Applied Fracture Mechanics 23 (1), Seite 55-65; 1995; Paper	
		Fracture wheel; experiment: metallurgical; stop braking; residual stress
		An investigation of thermal cracks observed in the wheels of certain electric multiple unit (EMU) locomotives in North American commuter rail service is summarized.
		1995_Paper_Orringer_Thermal cracking in railroad vehicle wheels subjected.pdf
138	**T. Vernersson, Thermal cracking of a railway wheel tread due to tread braking–critical crack sizes and influence of repeated thermal cycles.** Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit 227 (1), Seite 10 – 18; 2012; Artikel	
		Two-dimensional FEM + resulting stress intensity factors, thermal loading - cracking, Bruchmechanik
		The paper presents a numerical study (2D- & 3D- FE Model) of the impact of thermal loading imposed by block braking on the resulting wheel tread cracking.
		2012_Art_Vernersson_Thermal cracking of a railway wheel tread.pdf
139	**T. Vernersson, Thermal cracking of railway wheels: Towards experimental validation** Tribology International 94, Seite 409 – 420; 2015; Paper	
		Experiment: temperature; FEM: Heat partitioning, thermomechanical;
		Experiment: It was found that thermal cracks equivalent to those observed on operating railway wheels could only be generated under combined loading from braking and wheel – rail rolling contact. Numeric: The effect of combined thermal and mechanical loading is investigated. (FE) simulations
		2015_Paper_Vernersson_Thermal cracking of railway wheels.pdf
140	**W. Nong, Thermal Damage Test research of speed increased freight cars' wheel tread** International Wheelset Congress 13th, Italy, Seite 1 – 9; 2001; Paper	
		2 kinds of brake blocks influence thermal the wheel, experiment,
		Freight cars, thermal damage of wheel tread, test: temperature, residual stress, metallographic
		2001_Paper_Nong_Thermal Damage Test research of speed.pdf
141	**A. Tudor, Thermal Effect of the Brake Shoes Friction on the Wheel /Rail Contact** Tribology in industry 25 (1/2), Seite 27 – 32; 2003; Paper	
		Friction heat transfer model of wheel, heat rolling friction temperature,wheel - rail - brake; temperatur, calculation
		An analytical solution for the temperature distribution in wheel/ brake shoe contact is presented. The wheel of locomotive or wagon is simultaneously heated by the friction due to wheel/ contact and two brake shoe contacts. The analyses were applied to calculate the partition heat coefficients between wheel and rail and between wheel and left or right brake shoe.
		2003_Paper_Tudor_Thermal Effect of the Brake Shoes Friction.pdf
142	**G. Fekete, Thermal FE analysis of a one side brake block test equipment (Part 1)** Periodica Polytechnica Mechanical Engineering 57 (1), Seite 27–33; 2013; Paper	
		FEM: thermal, friction; heat generation by friction; thermal contact resistance
		This paper includes the first part of an investigation of the complex braking process during the braking of railway vehicles, using transient thermal FE models with temperature dependent material properties.
		2013_Paper_Fekete_Thermal FE analysis P1.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
143	**G. Fekete, Thermal FE analysis of a one side brake block test equipment (Part 2) Periodica** Polytechnica Mechanical Engineering 57 (1), Seite 35 – 40; 2013; Paper	
		Temperaturverteilung: heat load; FEM: thermal elastic deformation; brake block
		The paper includes the second part of an investigation of the braking process of railway vehicles, dealing with the temperature distribution of a brake block in various load cases and the FE analysis of the phenomenon of thermal elastic deformation.
		2013_Paper_Fekete_Thermal FE analysis P2.pdf
144	**S. Caprioli, Thermal impact on rolling contact fatigue of railway wheels** Department of Applied Mechanics, Chalmers University of Technology; Gothenburg, Sweden; 2014; Diplom- / Doktorarbeit	
		Rolling contact fatigue, tread braking, thermal fracture,
		This thesis investigates the influence of combined thermal and mechanical loading on RCF of railway wheels on the basis of numerical predictions
		2014_Diss_Caprioli_Thermal impact on rolling contact fatigue.pdf
145	**A. Haidari, Thermal load effects on fatigue life of a cracked railway wheel** Latin American Journal of Solids and Structures 12, Seite 1144 – 1157; 2015; Paper	
		Wheel - brake - rail: FEM: thermal, mechanical; Fatigue crack growth
		In this paper, fatigue life of a cracked railway wheel under thermo-mechanical loads is studied. For this purpose a FE model of a wheel, with two brake shoes and a portion of rail are created and suitable loads and boundary conditions are applied to the model.
		2015_Paper_Haidari_Thermal load effects on fatigue life.pdf
146	**D. Milutinovic, Thermal load of block-braked solid wheel on Yugoslav Railways** International Conference on Computers in Railways 7th, VII, Seite 737 – 746; 2000; Paper	
		FEM: stress state, temperatur, wheel model; wheel tread - brake block
		The paper gives results of an analysis of thermal load of railway vehicle block-braked solid wheel on characteristic section of the line in the Yugoslav Railways network. Thermal analysis was done using the FEM which was also used for obtaining wheel temperature and stress states in simulated operating conditions.
		2000_Paper_Milutinovic_Thermal load of block-braked.pdf
147	**F Demilly, Thermal mechanical limits of railway wheels: What solutions for a braking with chilled disks or tread brake shoes?** European Conference on Braking 6th, Lille, Seite 131 – 138; 2010; Paper	
		Brake technologies, thermo-mechanocal wheel design, thermal defects, wheel lifespan, life cycle cost,
		Depending of the braking configuration and of the required performance, different solutions can be imagined for the wheel depending of the cost and LCC approach.
		2010_Paper_Demilly_Thermal mechanical limits of railway wheels.pdf
148	**G. Bódai, Thermal simulation of a pin on a rotating cylinder jacket system** Periodica Polytechnica Mechanical Engineering 56 (2), Seite 117 – 124; 2012; Paper	
		FEM: thermal load; Experiment: force, temperature;
		In this paper specimen level measurements and finite element simulations are introduced in order to study the thermal behavior of a pin and wheel sliding contact configuration. The pin-like specimen is processed from cast iron and models the local contact of a railway brake block and wheel tire.
		2012_Paper_Bódai_Thermal simulation of a pin.pdf
149	**G. K. Burgess, Thermal stresses in chilled iron car wheels** Technologic Papers of the Bureau of Standards 16 (209), Seite 193 – 232; 1922; Paper	
		Experiment of the wheel: drop test, thermal test, thermal stress test
		A method is described for electrically heating car wheels in the laboratory which produce effects similar to that encountered though long application of the brakes on heavy grades.
		1922_Paper_Burgess_Thermal stresses in chilled iron car wheels.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
150	**G. K. Burgess, Thermal stresses in steel car wheels** Technologic Papers of the Bureau of Standards 17 (235). Seite 367 – 403; 1923; Paper	
		Experiment of the wheel: thermal stress test
		19 steel wheels were tested by using the method described for testing chilled iron car wheels in the laboratory under conditions approximating those encountered in service caused by heavy brake application.
		1923_Paper_Burgess_Thermal stresses in steel car wheels..pdf
151	**T. Vernersson, Thermally induced roughness of tread braked railway wheels** International Wheelset Congress 12th, China, Seite 68-75; 1998; Paper	
		Roughness, experiment, microstructure, mathematical model, hot spots, Brake block material, brake parameter
		Initiation and development of wheel roughness as caused by tread braking. The study aims at an optimization of the existing tread braking systems for reduced radiated noise from the railway system.
		1998_Paper_Vernersson_Thermally induced roughness.pdf
152	**T. Vernersson, Thermally induced roughness of tread braked railway wheels Part 2: modelling and field measurements** Wear/Elsevier 236 (1/2), Seite 106–116; 1999; Paper	
		FEM, theoretical and numerical model, brake block - wheel rim,
		In the present paper, a theoretical and numerical model of the interaction between wheel rim and brake block has been developed. Simulations with this model demonstrate the principal phenomena occurring at the wheel/block contact.
		1999_Paper_Vernersson_Thermally induced roughness of tread-braked P2.pdf
153	**T. Vernersson, Thermally induced roughness of tread-braked railway wheels Part 1: brake rig experiments** Wear/Elsevier 236 (1/2), Seite 96 – 105; 1999; Paper	
		Thermomechanical interaction brake block - wheel, experiment, hot spots, wheel wear and roughness
		In the present paper, full-scale tread braking experiments on an inertia dynamometer are reported. Mainly cast iron but also composition and sinter material brake blocks are tested. A stationary pattern of temperature rises (hot spots) on the wheel tread is recorded which is found to correlate well with the measured roughness.
		1999_Paper_Vernersson_Thermally induced roughness of tread-braked P1.pdf
154	**T. Vernersson, Thermomechanical cracking of railway wheel treads: A combined experimental and numerical Approach** International Conference on Contact Mechanics 10th, USA; 2015; Präsentation	
		rolling contact fatigue, thermal cracks; experiment: temperature, FEM: thermomechanical
		Thermal cracking of railway wheel treads is studied by full-scale brake rig tests and FEM. The focus is on thermal mechanical rolling contact fatigue (RCF) life predictions.
		2015_Präs_Vernersson_Thermomechanical cracking.pdf
155	**T. Vernersson, Thermomechanical cracking of railway wheel treads: A combined experimental and numerical Approach** International Conference on Contact Mechanics 10th, USA; 2015; Paper	
		rolling contact fatigue, thermal cracks; experiment: temperature, FEM: thermomechanical
		Thermal cracking of railway wheel treads is studied by full-scale brake rig tests and finite element simulations. The focus is on thermal mechanical rolling contact fatigue (RCF) life predictions.
		2015_Paper_Vernersson_Thermomechanical cracking.pdf
156	**L. Ramanan, Thermo-mechanical finite element analysis of a rail wheel** International Journal of Mechanical Sciences 41 (4/5), Seite 487 – 505; 1998; Paper	
		Mechanical -, contact -, coupled forces; temperatures, thermal stress, FEM: Wheel mode
		The rail wheel, which is acted upon by mechanical forces also experiences thermal stresses due to braking, during service. The coupled nature of these forces is analyzed using a 3D elasto-plastic FEM. Contact stresses at the rail-wheel interaction location are analyzed using a global-local approach on a 3D elasto-plastic FEM.
		1998_Paper_Ramanan_Thermo-mechanical FEA of a rail wheel.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
157	**J. Raison, Thermomechanisches und akustisches Verhalten der Räder von Eisenbahn-Fahrzeugen** ZEVrail Glasers Annalen 122 (9/10), Seite 375 – 384; 1998; Artikel	
		Rad, Modellrechnung, Experiment, Ermüdungsverhalten, mechanisch -, thermomechanisches - und akustisches Verhalten
		Es wird die Entwicklung und Optimierung neuer Räder beschrieben, die auf der Grundlage einer engen Verknüpfung von Modellrechnungen, Prüfstands- und Streckenversuchen durchgeführt werden.
		1998_Art_Raison_Thermomechanisches und akustisches Verhalten der Räder.pdf
158	**T. Vernersson, Train–Track Interaction and Mechanisms of Irregular Wear on Wheel and Rail Surfaces** Vehicle System Dynamics 40 (1/3), Seite 3 – 54; 2003; Artikel	
		Wheel - rail - brake; wear; literatur study; damage mechanisms; hot spots;
		The aim of the present survey is to provide an overview of the current knowledge about wheel-rail and wheel-block interaction when related to mechanisms of irregular wheel/rail wear.
		2003_Art_Vernersson_Train Track Interaction and Mechanisms.pdf
159	**T. Vernersson, Tread Braking - Fatigue Life of Railway Wheel Webs** EuroBrake France, Seite 102 – 103; 2014; Paper	
		Fatigue damage, thermomechanical loading, mechanical load, wheel design, thermal model
		The fatigue life of the wheel web is studied in detail when loaded by a combination of thermomechanical loading from tread braking and mechanical loading from wheel-rail contact forces.
		2014_Paper_Vernersson_Tread Braking - Fatigue Life of Railway.pdf
160	**T. Vernersson, Tread Braking of Railway Wheels – Noise-Related Tread Roughness and Dimensioning Wheel Temperatures: Field Tests, Rig Measurements and Numerical Simulations** Department of Applied Mechanics, Chalmers University of Technology Gothenburg, Sweden; 2006; Diplom- / Doktorarbeit	
		Roughness, hot spots, brake material, brake type, literature studies, experiment, numerical modelling, rail chill,
		The mechanism behind the development of roughness on wheel treads, as caused by different brake block materials, is studied using brake rig experiments supported by numerical modelling. The partitioning of heat between wheel and blocks is the studied, taking the influence of cooling from the rail into account.
		2006_Diss_Vernersson_Tread Braking of Railway Wheels.pdf
161	**T. Vernersson, Tread Braking of Railway Wheels - State-of-the-art Survey** European Conference on Braking 6th, Lille, Seite 293 – 302; 2010; Paper	
		Temperatures, thermomechanical aspects, wheel damage, wheel design, brake blocks,
		The objective of the present paper is to provide an overview of design methods for tread braking systems with special focus on the braking capacity of the wheels.
		2010_Paper_Vernersson_Tread Braking of Railway Wheels.pdf
162	**T. Vernersson, Tread braking of railway wheels - temperatures generated by a metro train** Institution of Mechanical Engineers; Part F: Journal of Rail and Rapid Transit 228 (2), Seite 210–221; 2012; Paper	
		Experiment: tread braking temperatures; simulation model; cooling model for rim and web part
		This paper is part of a project which is aimed at the development of methods and the provision of data for the assessment of the thermal capacity of tread braked wheels that can be used as a basis for future design guidelines.
		2012_Paper_Vernersson_Tread braking of railway wheels - temperatures.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
163	**J. Kalousek, Tribological interrelationship of seasonal fluctuations of freight car wheel wear, contact fatigue shelling and composition brakeshoe consumption** Wear/Elsevier 191 (1/2), Seite 210 - 218 1995 Paper	
		Model of metal “pick-up”, wheel shelling; wheel tread wear; brake shoe damage; seasonal fluctuations
		This paper proposes a novel theory which explains the strong linkage between brake shoe metal pick-up and a corresponding increase in wheel tread wear and shelling during the wet winter months.
		1995_Paper_Kalousek_Tribological interrelationship of seasonal fluctuations.pdf
164	**W. Mombrei, Typische Schäden an Eisenbahnrädern** Internationale Schienenfahrzeugtagung Dresden 1th (2), Dresden, Seite 127 – 139; 1996; Paper	
		Schadensformen; Rad; Einfluss; Entstehung; Materialverhalten;
		Schäden an Eisenbahnrädern. Thermisch bedingte Vollradbrüche; Unrund werden der Räder sowie Ausbildung von nicht thermischen bedingten Laufflächenrissen und Laufflächenausbröcklung.
		1996_Paper_Mombrei_Typische Schäden an Eisenbahnrädern.pdf
165	**UIC - B 126.13: Fragen des Bremswesens: Bremsfahrten eines mit Verbundstoffbremssohlen ausgerüsteten inhomogenen Güterzuges auf der Tauern Südstrecke** Internationale Eisenbahnverband UIC - B 126.13; 2008; Norm	
		Bremsversuche, Gefällefahrten, Verbundstoffbremssohlen
		-
		Büro BR
166	**Dörsch, UIC - B 126/ DT 420: Fragen des Bremswesens. Bremsfahrten eines mit Verbundstoffbremssohlen vom Typ LL ausgerüsteten inhomogenen Güterzuges auf der Tauern Südstrecke** Internationale Eisenbahnverband UIC - B 126 / DT 420; 2008; Norm	
		Test / experiment; brake, wheel; temperature; residual stress
		Untersuchung von Bremssohlen, hinsichtlich dessen diese keine Schäden am Rad beim Bremsen (Gefälle) verursachen. Es werden dafür Versuche durchgeführt. Es wird dabei auch das Rad beobachtet (Temperaturverlauf, Eigenspannungen)
		2008_Norm_UIC B 126 DT 420_Fragem des Bremswesens.pdf
167	**UIC-Kodex 510-2: Bedingungen für die Verwendung von Rädern verschiedener Durchmesser in Laufwerken unterschiedlicher Bauart** Internationale Eisenbahnverband UIC – 510-5; 2002; Norm	
		Räder, Grenzwerte
		Dieses Merkblatt enthält die Bedingungen für den Bau und die Unterhaltung der Räder für Reisezug- und Güterwagen, die im internationalen Verkehr eingesetzt werden. Es umfasst die Raddurchmesser und gibt hierfür die hinsichtlich der Werkstoffbeanspruchung von Rad und Schiene zulässigen Radsatzlasten an. Außerdem werden die Überprüfungsmaßnahmen für die Räder der Stahlsorten R2, R3, R8 und R9 angegeben, sowie die zulässigen Restspannungen im Radkranz der Räder der Stahlsorten R7 und R6.
		2002_Norm_UIC 510-2_Bedingungen für die Verwendung von Rädern verschiedener.pdf
168	**UIC-Kodex 510-5: Technisches Zulassung von Vollrädern - Anwendungsdokument für die EN 13979-1** Internationale Eisenbahnverband UIC – 510-5; 2007; Norm	
		Ergänzung zu EN 13979-1; Räder;
		In diesem Merkblatt werden die Vorschriften der Norm EN 13979-1 erläutert bzw. ergänzt, welche bei der technische UIC-Zulassung eines Rades einzuhalten sind
		2007_Norm_UIC 510-5_Technisches Zulassung von Vollrädern.pdf
169	**A. J. Opinsky, Understanding rim thermal failures in freight car wheels** International Wheelset Congress 9th, Canada, Seite 5.5.1 – 5.5.11; 1988; Paper	
		Failures, Brake shoe, wheel, residual stresses, design
		Failures on the back rim face of freight car wheels, brake block, calculated: residual stress, mechanical stress effect
		1988_Paper_Opinsky_Understanding rim thermal failures.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
170	**J. Deputat, Untersuchung der Eigenspannungsänderungen in Eisenbahn-Vollrädern nach Bremsungen** ZEVrail Glasers Annalen 115 (7/8), Seite 231 – 235; 1991; Artikel	
		Experiment, residual stress - brake, Spannungsänderung
		Es werden Ultraschall-Eigenspannungsmessmethoden, die auf der Abhängigkeit der Schallgeschwindigkeit von der mechanischen Spannung beruht, sowie einige Messergebnisse zu Spannungsänderungen infolge von Bremsungen auf dem Bremsprüfstand und im Betrieb vorgestellt.
		1991_Art_Deputat_Untersuchung der Eigenspannungsänderungen.pdf
171	**E. Pahl, Ursache der Rillenbildung in Rädern klotzgebremster Schienenfahrzeuge und deren Vermeidung** Werkstoffwissenschaften der Technischen Universität Berlin; 1973; Diplom- / Doktorarbeit	
		Exp.: Werkstoffübergang Rad - Klotz und Rillenbildung (RB); Temperatur; Vermeidung RB; Berechnung: Reibwärme, Spitzentemp. an Reibfläche & Temperaturverteilung
		Die vorliegende Arbeit bezieht sich auf eine Störung im Verschleißverhalten zwischen Rad und Bremsklotz, die zu einer Rillenbildung in der Lauffläche des Rades führt. Ziel war es den Mechanismus der Rillenbildung in Rädern unter Einwirkung gußeisener Bremsklötze zu klären und Maßnahmen zu deren treffsicheren Vermeidung zu erproben und vorzuschlagen.
		1973_Diss_Pahl_Ursache der Rillenbildung in Rädern klotzgebremster.pdf
172	**K. Anders, VDI-Wärmeatlas** Springer-Verlag Berlin, Heidelberg, 11 Auflage; 2013; Buch	
		-
		Geschrieben von Spezialisten aus Industrie und Wissenschaft, ermöglicht das Standardwerk die Auslegung technischer Apparate und Anlagen, z. B. in der Verfahrens- und der Energietechnik. Dafür werden Daten bereitgestellt, Berechnungsmethoden eingehend erläutert und Konstruktionen vorgestellt.
		2013_Buch_VDI-Wärmeatlas
173	**R. Müller, Veränderungen von Radlaufflächen im Betriebseinsatz und deren Auswirkungen auf das Fahrzeugverhalten - Teil 1** ZEVrail Glasers Annalen 122 (11), Seite 675 – 688; 1998; Artikel	
		Formen von unrunden Räder, Lauffläche, Schäden
		Betrachtung der Veränderung der Radlaufflächen und das unrund werden der Räder. Verschiedene Einflüsse.
		1998_Art_Müller_Veränderungen von Radlaufflächen im Betriebseinsatz Teil 1.pdf
174	**R. Müller, Veränderungen von Radlaufflächen im Betriebseinsatz und deren Auswirkungen auf das Fahrzeugverhalten - Teil 2** ZEVrail Glasers Annalen 122 (12), Seite 721 – 738; 1998; Artikel	
		Rad - Schiene, Radprofil, Rollgeräusch, Klotzbremse
		Teil 2 von Veränderungen von Radlaufflächen im Betriebseinsatz und deren Auswirkungen auf das Fahrzeugverhalten
		1998_Art_Müller_Veränderungen von Radlaufflächen im Betriebseinsatz Teil 2.pdf
175	**K. Sommer, Verschleiß metallischer Werkstoffe: Erscheinungsformen sicher beurteilen** Springer-Fachmedien Wiesenbach, 2 Auflage; 2010; Buch	
		Tribologische Grundlagen, Methodik der Analyse tribologischer Schäden, Verschleißformen
		Das Buch bietet mit der Behandlung zahlreicher Schadensbeispiele konkrete Hilfestellung bei der Analyse und Beurteilung von Verschleißproblemen und ermöglicht geeignete Maßnahmen für die Optimierung von Sicherheit und Zuverlässigkeit beim Betrieb von Anlagen und Maschinen.
		2010_Buch_Sommer_Verschleiss metallischer Werkstoffe.pdf

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Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
176	**P. von Böckh, Wärmeübertragung Grundlagen und Praxis** Springer-Verlag Berlin, Heidelberg, 5 Auflage; 2014; Buch	
		Wärmeübertragung , -leitung, -strahlung; Strömungsdynamik; Thermophysikalische Stoffeigenschaften;
		Grundlagen der Wärmeübertragung. Man wird in die Lage versetzt, Wärmeüberträger auszulegen sowie Wärmeübertragungsaufgaben aller Art zu analysieren und praktische Lösungen dafür zu finden. Auf ausgedehnte theoretische Herleitungen wird verzichtet, stattdessen werden die wesentlichen Zusammenhänge anhand zahlreicher Beispiele aus dem Ingenieuralltag verdeutlicht.
		2014_Buch_Böckh_Wärmeübertragung.pdf
177	**T. Vernersson, Wear of Block Brakes and Disk Brakes for Repeated Brake Cycles** European Conference on Braking 6th, Lille, Seite 19 – 27; 2010; Paper	
		Numerical study, temperature-dependent wear model, brake block / disc, FEM of block, contact pressure, temperature,
		A numerical study is presented where the wear of the brake block / brake pad is estimated for railway tread brakes / disc brakes employing an implemented temperature-dependent wear model. The influence of the stiffness of the interacting parts on the wear of pad / block is studied by use of finite element simulations.
		2010_Paper_Vernersson_Wear of Block Brakes and Disk Brakes.pdf
178	**T. Vernersson, Wear of brake blocks for in-service conditions - Influence of the level of modelling** Wear/Elsevier 314 (1/2), Seite 125 – 131, 2013, Paper	
		Wear brake block, thermal model + thermoelastic model,
		In the present work, a numerical study is presented where the wear of the brake blocks is estimated for different train routes using wear rates from controlled wear experiment. Two different models are utilized in this study, a thermal model with a prescribed contact pressure between block and wheel and a thermoelastic model where the contact pressure variations are calculated as part of the simulation.
		2013_Paper_Vernersson_Wear of brake blocks for in-service conditions.pdf
179	**T. Vernersson, Wear of disc brakes and block brakes - Influence of design on modelled wear for repeated brake cycles** International Wheelset Congress 16th, South Africa; 2010; Paper	
		FEM: braking – wheel, brake block, disc brake, wear, temperature, thermoelastic interaction
		A numerical study is presented where the wear of the brake block / brake pad is estimated for railway tread brakes / disc brakes employing an implemented temperature-dependent wear model. The influence of the stiffness of the interacting parts on the wear of pad / block is studied by use of FE simulations.
		2010_Paper_Vernersson_Wear of disc brakes and block brakes.pdf
180	**I. Poschmann, Werkstoffe für rollendes Eisenbahnmaterial Gefüge und mechanische Eigenschaften** EI - Eisenbahningenieur 53 (8), Seite 47 – 51; 2002; Artikel	
		Werkstoffkennwerte, Rissfortschritt, Rad, Experiment
		Ein Werkstoffkonzept wird speziell für thermisch hoch belastete Räder und die Entwicklung der zugehörigen Wärmebehandlungstechnik vorgestellt.
		2002_Art_Poschmann_Werkstoffe für rollendes Eisenbahnmaterial.pdf
181	**C. Heermant, Werkstoffentwicklungen für thermisch beanspruchte Eisenbahnräder** Deutscher Verband für Materialforschung und -prüfung e. v. DVM-Bericht 670, Berlin, Seite: 153 – 162; 2003; Bericht	
		Rad, Werkstoffprüfung: Temperaturabh. bezüglich Temperatur, Kerschlagarbeit und Bruchzähigkeit; Vergleich Stähle,
		Durch den Bochumer Verein wurden neue niedrig-legierte, perlitisch-ferritische Stähle mit reduziertem Kohlenstoffgehalt für thermisch beanspruchte Räder und Reifen entwickelt. Werkstoffprüfungen ergaben, dass die mechanischen Kennwerte der neuen Werkstoffe trotz der geringen C-Gehalts denen der Referenzstähle für Räder (R7, R8) und Radreifen (B1, B4) entsprechen.
		2003_Ber_Heermant_Werkstoffentwicklungen für thermisch.pdf

List of literature

Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
182	**C. Lonsdale, Wheel Rim Residual Stress Measurement Using Ultrasonic Testing** Standard Steel highlight wheel manufacturing and inspection improvements at the Burnham, PA; 2001; Paper	
		Residual compressive stress formed; wheel - brake; experiment: wheel rim residual stress
		This paper provides a description of how the residual compressive hoop stress is formed in the rim and reviews relevant railway service environment issues. Conventional destructive testing and ultrasonic methods for evaluation of the residual stress state of the wheel rim are compared.
		2001_Paper_Demilly_Wheel Rim Residual Stress Measurement.pdf
183	**T. Vernersson, Wheel Tread Damage - a Numerical Study of Railway Wheel Tread Plasticity Under Thermomechanical Loading** International Heavy Haul Conference 9th, China, Seite 465 – 472; 2009; Paper	
		FEM; wheel tread stresses, rolling contact, thermal loading
		A numerical study (2D & 3D FES) is presented where the impact of simultaneous thermal and mechanical loading on a railway wheel tread as imposed by braking and rolling contact is reported.
		2009_Paper_Vernersson_Wheel Tread Damage - a Numerical Study.pdf
184	**T. Vernersson, Wheel Tread Profile Evolution for Combined Block Braking and Wheel-Rail Contact – Results from Dynamometer Experiments** International Conference on Contact Mechanics 10th, USA; 2015; Paper	
		Full-scale tread braking experiment, rail chill, wheel tread, plastic deformation wear.
		In this study, a series of full-scale tread braking experiments, including wheel-rail rolling contact, were conducted in order to clarify the influencing factors of evolution of wheel tread profile. The experiments focused on plastic deformation and wear caused by rolling contact and tread braking.
		2015_Paper_Vernersson_Wheel Tread Profile Evolution.pdf
185	**R. Lewis, Wheel-rail Interface Handbook** CRC Press; 2009; Buch	
		Disparate strands of relatively recent research and practical experience; state-of-the-art of scientific and engineering knowledge of the problems with the wheel–rail interface
		Many of the engineering problems of particular importance to railways arise at interfaces and the safety-critical role of the wheel/rail interface is widely acknowledged. Better understanding of wheel/rail interfaces is therefore critical to improving the capacity, reliability and safety of the railway system.
		2009_Buch_Lewis_Wheel-rail interface handbook
186	**M R K Vakkalagadda, Estimation of railway wheel running temperatures using a hybrid approach** Wear/Elsevier 328–329, Seite 537–551, 2015, Paper	
		Temperature, brake block, rail, convection, radiation.
		A three step approach employing a train running model, boundary element method, and finite element model is proposed to estimate railway wheel temperatures. The approach is validated using data from a field trial. A detailed study of heat loss to brake blocks, rail and ambient air (through convection and radiation) under different conditions is also conducted.
		2015_Paper_Vakkagadda_Estimation of railway wheel temperatures.pdf
187	**ERRI E 162 / RP 7: Zerstörungsfreie Prüfung von Eisenbahnmaterialien im Betrieb Bericht Nr. 7: Zerstörungsfreie Prüfung von Rädern, Radsatzwellen und Zughacken im Eisenbahnbetrieb: Stand der Technik, Erfahrungen und Empfehlungen** Forschungs- und Versuchsamt des Internationalen Eisenbahnverbandes, Utrecht ERRI E 162 RP 07;1988; Bericht	
		Räder, Wellen, Zughaken, Prüfverfahren, Prüfen der Objekte
		Der Bericht schlägt zur Erleichterung der Verständigung eine einfache und zweckmässige Kodierung der Prüfobjekte und der Verfahren vor, die für ihre Prüfung geeignet sind. Er enthält systematisch gegliedert und detailliert dargestellt die Ansichten und Urteile der Sachverständigen vieler europäischer Eisenbahnen über wichtige Aspekte zur zerstörungsfreien Prüfung von Rädern, Radsatzwellen und Zughaken.
		1988_Ber_ERRI E 162 RP 7_Zerstörungsfreie Prüfung von Eisenbahnmaterialien im Betrieb.pdf

List of literature

Nr.	Author, Title Publisher; Issue (Journal), Page Year; Types of literature	
000		**Keywords**
		Summary
		File Name
188	**D. C. Grundy, Fatigue and Fracture of a Railway Wheel Steel** University of Pittsburgh, Massachusetts Institute of Technology; 1994; Diplom- / Doktorarbeit	
		Wheel, tensile test, charpy impact, fracture mechanic, fatigue test,
		Federal Railroad Administration (FRA) inspections of three commuter railroads serving the greater New York area found high rates of cracking in the wheels of multiple unit locomotive wheels. The FRA initiated an engineering study to derive long term solutions to the cracking problem which safeguard against catastrophic fracture of a wheel yet are economically reasonable for the railroads.
		1994_Diss_Grundy_Fatigue and Fracture of a Railway Wheel Steel.pdf
189	**F. McMaster, Fatigue Behavior of Railcar Wheel Steel at Ambient and Elevated Temperature** U.S. Department of Transportation; Research and Special Programs Administration; Office of Research an Development Washington; 2003; Bericht	
		Material behavior, fatigue performance, TC128, railcar wheels, forgings
		This report presents the results of a material property test program undertaken on a Class B railcar wheel steel.
		2003_Ber_McMaster_Fatigue Behavior of Railcar Wheel.pdf

Evaluation matrix

Literature	Phenomena	Relevance	Implemented until now by Siemens	Important for future Siemens model?
[47] [48]	Temperature - dependent material model for the wheel **	3	✓	*Yes*
[7]	Elastic - plastic material model for the wheel	3	✓	*Yes*
[2] [17] [49] [50] [51]	Elastic - plastic material model with *visco* effect for the wheel	0	×	*No**
[50]	Elastic - plastic material model with *creep* for the wheel	0	×	*No**
[7] [50]	Material model for the wheel with isotropic hardening	0	✓	*Yes*
[7] [50]	Material model for the wheel with kinematic hardening.	0	×	*No**
[20] [22] [52]	Position and profil of the heat input into the tread	2	✓	*Yes*
[5] [49] [48] [53] [54]	Time course of the heat input into the tread	2	✓	*Yes*
[7] [54] [55]	Production residual compressive stress in the wheel rim *	2	×	*Yes*
[47] [49] [54] [56]	Mechanical load by rolling contact	1	×	*No*
[1] [57] [58] [59]	Temperature - independent material model for the brake block	0	×	*Yes*
[1] [57] [58] [59] [60]	Integrate brake block part in the model	0	×	*Yes*
[59]	Cooling by brake block	2	×	*Yes*
[1] [6] [61] [62] [59]	Cooling by wheel - rail - contact ***	2	×	*No*
[59] [63]	Cooling by convection ***	3	✓	*Yes*
[59]	Cooling by radiation ***	3	✓	*Yes*
[-]	Cooling by wheelset axle	0	✓	*No*
[49] [54] [64]	Cross-linking of wheel geometry	1	✓	*Yes*
[-]	Microstructural changes under the influence of heat in the wheel rim	0	×	*Maybe*

Relevant:
0 … No statement
1 … Less important
2 … Important
3 … Very important

Implemented:
✓ … considered
× … excluded

Future Siemens model

Yes	Be expected to integrate into the model
Maybe	Examine the valuation target relevant
No	Not integrate into the model
*No**	It will be maybe relevant by damage mechanism. Relevant by calculate strain rate.

** Production residual compressive stress in the wheel rim:*
Rather irrelevant by stop braking and irrelevant by drag braking

**** Cooling by wheel - rail - contact; convection and radiation:*
Relevant after braking by stop braking and drag braking.
During braking only relevant by drag braking.
During stop braking rather irrelevant

*** Temperature - dependent material model for the wheel:*
Relevant by temperatures at 400°C, below irrelevant