THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Influence of wheel tread damage on wheelset and track loading – Field tests and numerical simulations

MICHELE MARIA MAGLIO

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
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MICHELE MARIA MAGLIO

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Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover: A railway wheel with severe tread damage.

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ABSTRACT

Wheel tread damage leading to high magnitudes of vertical wheel–rail contact forces is a major cause of train delays in the Swedish railway network, in particular during the coldest months of the year. According to regulations, vehicles generating contact forces exceeding the limit value for allowed wheel–rail impact loads must be taken out of service for wheel maintenance. This may lead to severe traffic disruptions and higher costs. Increased wheel–rail impact loads also cause elevated stress levels in wheels, axles and bearings and may shorten the life of track components, resulting in higher costs for vehicle and track maintenance. Wheel tread irregularities also lead to increased levels of rolling noise, impact noise and ground-borne vibration.

The aim of the thesis is to enhance the understanding of wheel tread damage and its consequences and to identify better means of addressing them. To achieve this aim, the ability for numerical simulations to investigate different operational scenarios is crucial. A versatile and cost-efficient method to simulate the vertical dynamic interaction between a wheelset and a railway track, accounting for generic distributions and shapes of wheel tread damage, has therefore been extended and improved. The wheelset (comprising two wheels, axle and any attached equipment for braking and power transmission) and track with two discretely supported rails are described by three-dimensional finite element (FE) models. The dynamic coupling between the two wheel–rail contacts (one on each wheel) via the wheelset axle and via the sleepers and ballast is considered. The simulation of dynamic vehicle–track interaction is carried out in the time domain using a convolution integral approach, while the non-linear wheel–rail normal contact is solved using Kalker's variational method. Non-symmetric wheelset and track designs, as well as non-symmetric distributions of wheel tread damage or rail irregularities can be studied. Based on Green's functions, a post-processing step has been developed to compute time-variant stresses at locations in the wheelset axle which are prone to fatigue. In an extensive parameter study, wheel–rail impact loads and axle stresses have been computed for different shapes and sizes of wheel tread damage.

The simulations need to be calibrated and validated by tests. To this end, field tests with two different Swedish passenger trains with severe wheel tread damage have been carried out. Time histories of numerically evaluated axle stresses have been compared to measured data from an instrumented wheelset. Simulations have been used to demonstrate that variations in rail roughness level, and the angular position of a strain gauge with respect to that of a discrete wheel tread defect, may lead to a significant influence on predicted axle stresses.

Developed numerical routines to predict stresses at critical locations in the wheelset from condition monitoring data will improve understanding and possibilities to handle wheel tread deteriorations. A discussion on future applications in terms of improved wheelset maintenance procedures is initiated.

Keywords: wheel tread damage, dynamic wheel–rail interaction, impact loads, axle stress, instrumented wheelset, wheelset maintenance.

Preface

The work presented in this thesis was accomplished at the Division of Dynamics at the Department of Mechanics and Maritime Sciences, Chalmers University of Technology, between February 2018 and September 2020. It was conducted as part of the activities within the National Centre of Excellence in Railway Mechanics CHARMEC (CHAlmers Railway MEChanics, www.charmec.chalmers.se) within the project TS20 – "Wheel tread damage – identification and effects". Parts of the research have been funded within the European Union's Horizon 2020 research and innovation programme in the Shift2Rail project In2Track2 under grant agreement No. 826255. The project has been supported by CHARMEC's industrial partners. In particular, the support from Bombardier Transportation, Faiveley Transport, Green Cargo, Lucchini RS, Lucchini Sweden, SJ and Trafikverket is gratefully acknowledged.

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Thank you to all the members of the project reference group, to my co-authors and to all the people in CHARMEC for the fruitful discussions we have had during these years. Thank you to the administrative personnel on the third floor for always being available, helpful and cheerful. A special thank you to all the colleagues and friends at the divisions of Dynamics and Material and Computational Mechanics for having made the third floor of the M-building such a pleasant work environment. Meeting you for coffee, lunch or for evenings out in Gothenburg has made these years at Chalmers great!

Finally, I want to express my gratitude to my parents Maria Rosaria and Massimo, as well as to my sister Martina, for always being there for me and for really making me feel your love and support. Thank you to my uncle Zio Do. A big thank you to all my friends in Maglie and to those from my years in Torino. I am always looking forward to spending time with you and I am grateful for having had you all by my side during these years.

Gothenburg, September 2020

Michele Maglio

THESIS

This thesis consists of an extended summary and the following appended papers:

Paper A	M. Maglio, M. Asplund, J.C.O. Nielsen, T. Vernersson, E. Kabo and A. Ekberg. Digitalisation of condition monitoring data as input for fatigue evaluation of wheelsets, *Proceedings of the XIX International Wheelset Congress (IWC2019)*, Venice, Italy, 5 pp, 2019.
Paper B	M. Maglio, A. Pieringer, J.C.O. Nielsen and T. Vernersson. Wheel–rail impact loads and axle bending stresses simulated for generic distributions and shapes of discrete wheel tread damage. *Submitted for international publication*, 26 pp, 2020.
Paper C	M. Maglio, T. Vernersson, J.C.O. Nielsen, A. Pieringer, P. Söderström, D. Regazzi and S. Cervello. Railway wheel tread damage and axle bending stress – Instrumented wheelset measurements and numerical simulations. *To be submitted for international publication*, 24 pp, 2020.

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work including taking part in planning the papers, developing the theory and the numerical implementations, running the simulations and writing the papers.

CONTENTS

Part I

Extended Summary

1 Introduction

1.1 Background and motivation

In order to achieve a fair and more sustainable future for the world population, the United Nations (UN) have developed a call for action in the form of 17 Sustainable Development Goals (SDG), see Figure 1 [1]. These interconnected goals are aimed at promoting prosperity while protecting the planet. All nations, independently of their wealth and size, are supposed to collaborate in order to accomplish these goals by 2030.

The work presented in the thesis relates to several of the SDGs. For example, goal number 9 that includes “build resilient infrastructure, promote sustainable industrialisation and foster innovation”, and goal number 13 “Climate action”.

Railways is an environmentally friendly means of transportation. Thereby, investing in railways aid in achieving both SDGs 9 and 13. Essential reasons why railways are environmentally efficient are the high stiffness, and the low friction in the wheel–rail contact, which leads to low rolling resistance [2]. However, the wheel–rail contact is also subjected to very high stress levels that can cause material deterioration which leads to needs for maintenance.

In order to facilitate a shift of travellers to railways from other means of transport, trains have to be perceived as punctual and reliable. Since 2012, the punctuality rate (i.e. the share of trains

Figure 1: The seventeen sustainable development goals [1]

that arrive at their final destination with a delay of at most 5 minutes) for passenger trains in Sweden is steady at around 90%. The aim agreed upon by the industry is to raise this rate to 95% [3]. To achieve this goal, improvements are required on both infrastructure and vehicle side. In particular, maintenance planning is of vital importance to increase the fleet availability and avoid operational disruptions.

Maintenance also carries additional costs for both the train operator and the track owner. It is estimated that the degradation of the vehicle–track system corresponds to up to 60% of the maintenance costs for the track, and almost all of the maintenance costs for the running gear [4]. With the increasing demands on railway transportation of both goods and passengers, more trains are expected to run on the same infrastructure, and possibly at higher speeds and with higher axle loads. Unless actions are taken, this will increase deterioration of vehicles at the same time as the number and size of available maintenance windows decrease. The increased loads and number of vehicles leads (unless actions are taken) to higher probabilities of wheel and rail failures. These failures usually do not pose major safety issues but can cause significant traffic disruptions which are costly for the industry and cause annoyance to passengers. In addition, derailments that occur can in some cases have very severe consequences. One example is the derailment of a wagon carrying liquefied petroleum gas in Viareggio (Italy) in 2009, which caused 32 deaths [5]. This derailment was claimed to be caused by an axle rupture [6], which is the most common cause of derailments in Europe [7].

A better knowledge of root causes and the mechanisms that cause the deterioration of wheels and rails is needed in order to reduce wheel and rail damage and thereby reduce the risk of traffic disruptions, increased maintenance costs and safety issues. This knowledge should be employed to improve condition monitoring using data from sensors installed in the tracks or on the trains. In combination with numerical predictions, such data can be used to better understand the current status of the railway assets and adapt future operations, as well as improve the design of new components, to the needs of the industry.

Another challenge for the railway industry is related to noise emissions. Although environmental noise from railways can sometimes be perceived as less disturbing than that from road or air traffic [8], trains often travel on tracks that are close to dwellings and can cause severe annoyance to residents. Railway noise is generated by different sources [9]. The power unit is the main source of noise at standstill and at speeds lower than about 60 km/h, while at speeds higher than 300 km/h, aerodynamic effects due to the passing of the train are predominant. In the range of speeds in between, the main source of noise emission is the dynamic interaction between wheels and rails [9]. In particular, rolling noise is caused by roughness of the running surfaces of wheel and rail, while impact noise is generated by discrete irregularities, such as wheel flats. Both surface roughness and discrete irregularities are causes of material deterioration.

In summary, the work on wheel tread damage presented in the current paper relates to (subsequent) component deterioration and to increased noise generation. The core aim of the work – to better prevent, understand consequences of, and maintain wheel damage – serves to improve safety, environment, economy, reliability and punctuality. This relates to a competitive advantage of the railway, as well as a mean to fulfil the UN sustainable development goals.

1.2 Overview

Defects on the running surfaces of train wheels lead to dynamic wheel–rail contact forces with magnitudes that depend on train speed, axle load, the geometric shape of the irregularity and the dynamic characteristics of the vehicle–track system. For the wheelset, high vertical loads may imply an increased risk of wheel and axle fatigue and damage of bearings. To limit the risk of a catastrophic failure of the running gear (and track), there are operational limits on allowed wheel impact loads.

Based on results from field measurements and a model of dynamic vehicle–track interaction, the research presented in this thesis allows for a prediction of the vertical wheel–rail contact forces that are generated by different types of wheel tread damage. These results are used to calculate amplitude spectra of stresses occurring in the wheelset.

More in detail, **Paper A** is focused on the measurements of wheel–rail impact loads generated by a given case of discrete tread damage at different vehicle speeds. The discrete damage has been scanned and is modelled and employed in simulations of dynamic vehicle–track interaction. In **Paper B**, a numerical procedure for the prediction of wheel–rail contact forces and axle stresses due to a generic distribution and shape of wheel tread damage is presented. The dynamic coupling between the two contact points (one on each wheel) via the wheelset axle and via the sleepers is accounted for. Using the procedure implemented in the in-house software, an extensive study is made on the influence of different forms of tread damage and operational conditions on wheel–rail contact forces and axle stresses. In **Paper C**, the measured evolution of wheel tread damage over time is used as input in the in-house software to compute stresses in a wheelset. In parallel, the physical wheelset has been instrumented with strain gauges on the axle. The measured and calculated spectra of dynamic stresses under operational conditions are compared. The relative effects of the measured wheel out-of-roundness (OOR) and simulated levels of rail roughness on axle bending stresses are investigated.

In future work, models to assess long-term damage of critical components in the running gear caused by the operational stresses will be developed. This allows to study fatigue damage caused by different combinations of wheel tread defects and operational conditions, such as variations in train speed and track stiffness.

1.3 Outline of the thesis

The extended summary of this thesis is structured as follows:

In Chapter 2, different forms of wheel tread damage and rail surface deterioration are described. Some aspects of maintenance planning are discussed.

Chapter 3 deals with vertical wheel–rail contact forces and how the magnitudes of these are affected by discrete damage on the running surfaces of wheels and rails. Methods to measure or numerically predict such loads are described.

Chapter 4 introduces axle stresses and techniques that are used to monitor these. Procedures to numerically predict stress levels in the wheelset are also discussed.

Chapter 5 discusses the on-going shift towards optimised maintenance procedures in the railway industry and how the presented work fits in this context.

A summary of the appended papers is presented in Chapter 6. Finally, Chapter 7 concludes the work and presents some ideas for future research.

2 Wheel tread and rail surface damage

2.1 Wheelset and track components

The wheel–rail contact is the interface between the running gear and the track. The running gear consists of the wheelsets (axle and wheels), the bogie, the suspensions and the bearing boxes. The running gear supports the carbody, guides the vehicle, is used for braking and (in some cases) provides traction to the vehicle [10]. The wheelset includes two wheels, which in almost all cases are rigidly connected by an axle. As a consequence, the whole wheelset spins around its axial axis with a uniform angular velocity. The wheelset steers based on the conicity of the wheel running surfaces, which are denoted wheel treads. If the centre of the wheelset is displaced in the lateral direction, the two wheels make contact with the rails at points with different rolling radii. The difference in rolling velocity between the two contact points allows the vehicle to steer. Figure 2 illustrates the terminology used to refer to some sections of the wheelset and the track.

The components of the track are separated into a superstructure and a substructure. The rails, sleepers and ballast (or slabs), as well as their connections, are part of the superstructure. The substructure usually consists of the subgrade, which in some cases is replaced by a bridge or tunnel structure, etc. [11]. The rails are mounted by fastenings and rest on rail pads on sleepers with an inclination which allows for a better fit with the wheel profile. The profile match

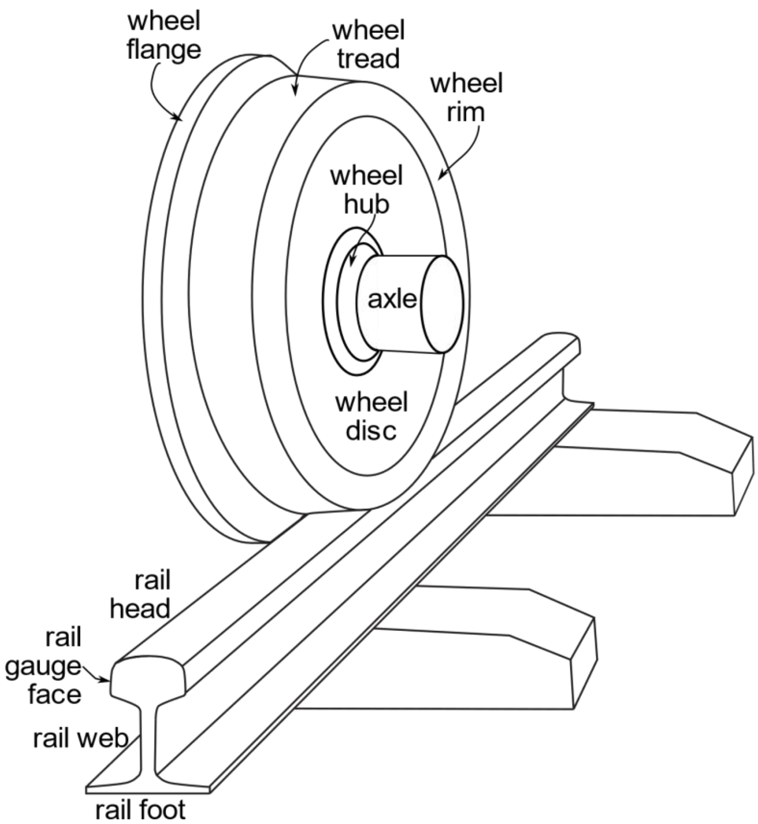


Figure 2: Terminology used to refer to some parts of the wheelset and of the track

between the wheel tread and the rail running surface determines the guiding performance of the train.

2.2 Surface damage on wheels and rails

A comprehensive guide on different forms of wheel tread damage has been presented by Deuce [12]. High wheel–rail contact forces may lead to plastic deformation, in particular when the contact is close to the side of the wheel or rail. The wheel tread is affected by wear, which is a gradual removal of material due to (frictional) wheel–rail contact [13]. In most cases, the tread wear is fairly benign, but wheels mainly rolling on straight routes and/or equipped with tread brakes may develop hollow tread wear. The wear is in this case concentrated to the centre of the tread, see Figure 3. This leads to changes in the conicity of the wheel tread and possibly to the formation of a “false flange” towards the field side of the wheel [12].

Regular contact between the wheel flange and the rail gauge corner due to poor steering or (lateral) track geometry irregularities may lead to severe wear of the wheel flange. If this happens, the contact position on the opposite wheel during curving may shift to a position closer to its field side. As a result, the steering performance of the train is impaired.

Wear of the wheel tread can also generate radial out-of-roundness (OOR), which can be periodic or stochastic [14]. The latter case can be a consequence of the presence of a mixed microstructure on the wheel tread generated by inadequate heat treatment during production [12].

The tangential creep forces that are generated in the wheel–rail contact contribute to the initiation of cracks on the wheel tread. If networks of fatigue cracks grow and interact, material

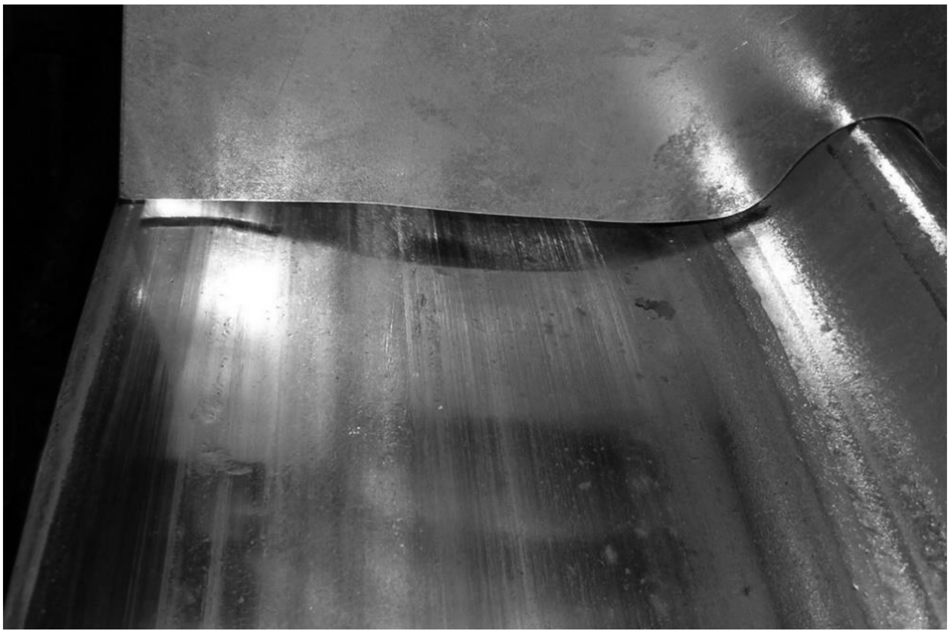


Figure 3: Hollow wear on a locomotive wheel. Picture courtesy of A. Ekberg

Figure 4: Wheel from a passenger train with severe RCF damage

Figure 5: Wheel with indentations on the tread. The black and white dots were used as markings during the 3D scanning activities of **Paper A**

fall-out may occur, so-called rolling contact fatigue (RCF) defects, see Figure 4. In this thesis, wheels with RCF damage have been studied in **Paper A** and **Paper C**.

Figure 6: Wheel with a long wheel flat

Clusters of RCF defects may occur on the wheel tread. They form as cracks that start at a shallow inclination from the surface before typically deviating to a more radial growth direction. If the cracks interact and there is material fall-out, defect clusters, so-called RCF clusters may form quickly. Crack growth can be enhanced by the penetration of liquids or snow in between the crack faces. RCF clusters are particularly common during the winter season. Indentations are another type of discrete defects. These are usually caused by indentation of sand or other loose particles on the rail. Their effect is often mostly cosmetic, see Figure 5 [12].

Thermal overloads due to braking can overheat the wheels and generate thermal cracks. This mainly occurs on vehicles equipped with tread brakes [15]. These cracks represent a safety issue, as they can grow radially through the wheel rim and the wheel web causing wheel fractures.

Prolonged braking with locked wheels that results in the wheel sliding on the rail may lead to overheating of the wheel material followed by a rapid cooling (when the wheel starts to roll again) of a specific section of the wheel. This results in a characteristic form of wheel tread damage denoted wheel flat. Newly formed wheel flats tend to have sharp edges, which round off over time due to the effect of repeated impacts on the rail [16]. Some examples of wheel flats are shown in Figures 6 and 7. If the steel in the heat affected zone on the wheel is subjected to martensite formation, it becomes harder and more brittle. Subsequent mechanical loads on the wheel may lead to crack formation and further material fall-out or spalling of the martensitic steel.

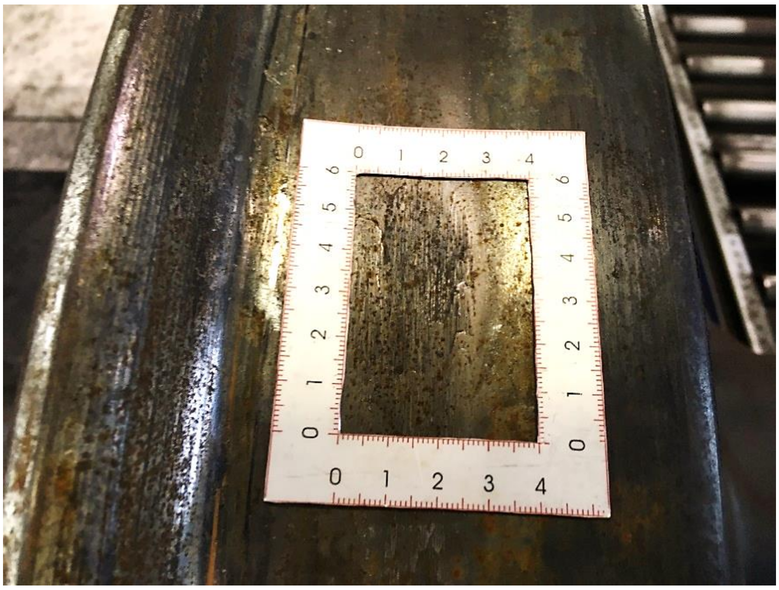


Figure 7: Wheel with a small wheel flat

Also rails are affected by wear, especially at the gauge corners and at locations where there is a significant tangential motion between the wheel and the rail [17]. Rail wear affects the contact geometry, which under some conditions can have beneficial effects as initiated short rail cracks can be worn off before they start to propagate.

Rails are also subjected to fatigue damage. Especially critical locations are welded sections, where residual tensile stresses from the welding process can be combined with the negative effects from voids, inclusions or other welding defects in the material [18]. Surface initiated rolling contact fatigue (RCF) can occur in the form of head check cracks on rails in curves. These cracks tend to propagate driven by traffic loading and the presence of fluid that gets trapped into the crack [19].

The formation of martensite at certain locations on the rail surface, or the presence of discrete defects, can trigger the formation of isolated forms of RCF damage on the rail surface. This is enhanced by the repeated application of traction and braking forces. The resulting defects take the name of squats or studs. Squats are characterised by the presence of a v-shaped crack and typically consist of an area where the plastic deformation is combined with a network of subsurface cracks. Studs are squat-type defects that are generated by heat fluxes due to slip in the wheel–rail contact. Studs are not related to excessive plastic deformation, and while studs develop faster than squats, they are less likely to cause rail breaks [20].

Rails are often affected by (more or less) severe plastic deformation at rail joints and in switches & crossings [21]. This may lead to an increase of vertical and lateral wheel–rail contact forces and the initiation of rail cracks.

2.3 Monitoring of wheel tread damage

The studies in this thesis are mainly aimed at assessing the influence of the deterioration of the wheel tread on wheel–rail contact forces and resulting stresses in the axle. The presence of wheel tread damage can be detected by means of condition monitoring and visual inspections. For example, wheel flats and severe RCF damage can be detected using data from wayside wheel impact load detectors (WILDs), from acoustic sensors mounted on the train or on the track, or by visual inspections.

Flange wear and hollow tread wear can be quantified by means of wheel tread profile measurements, such as those performed in **Paper C**. Overheating of the wheels can be observed by temperature detectors or by covering the wheels with a paint that changes colour or flakes off from the wheel web at higher temperatures.

3 Wheel–rail contact forces

The forces generated in the wheel–rail contact must be limited as they can cause fatigue and damage to track and vehicle components. Excessive track forces may also increase the risk of derailment. Contact forces can be separated into static forces (due to the vehicle weight including loads), quasi-static forces (for example those due to curving) and dynamic forces (mainly due to irregularities in the track geometry, on the running surfaces of rails and wheel, in track stiffness, etc.) [22]. In this thesis, the focus is on the dynamic contribution to the wheel–rail contact forces.

3.1 Influence of wheel tread damage and rail irregularities

Damage on the wheel tread and/or on the rail running surface generates dynamic variations in the vertical wheel–rail contact force. Depending on the type of damage, the time history of the contact force can have characteristics. For example, a wheel flat initially generates a brief period of unloading of the rail or even a temporary loss of wheel–rail contact for a large wheel flat. As the flat impacts on the rail, a sudden increase in contact load is generated followed by oscillations around the static value of the contact force [16].

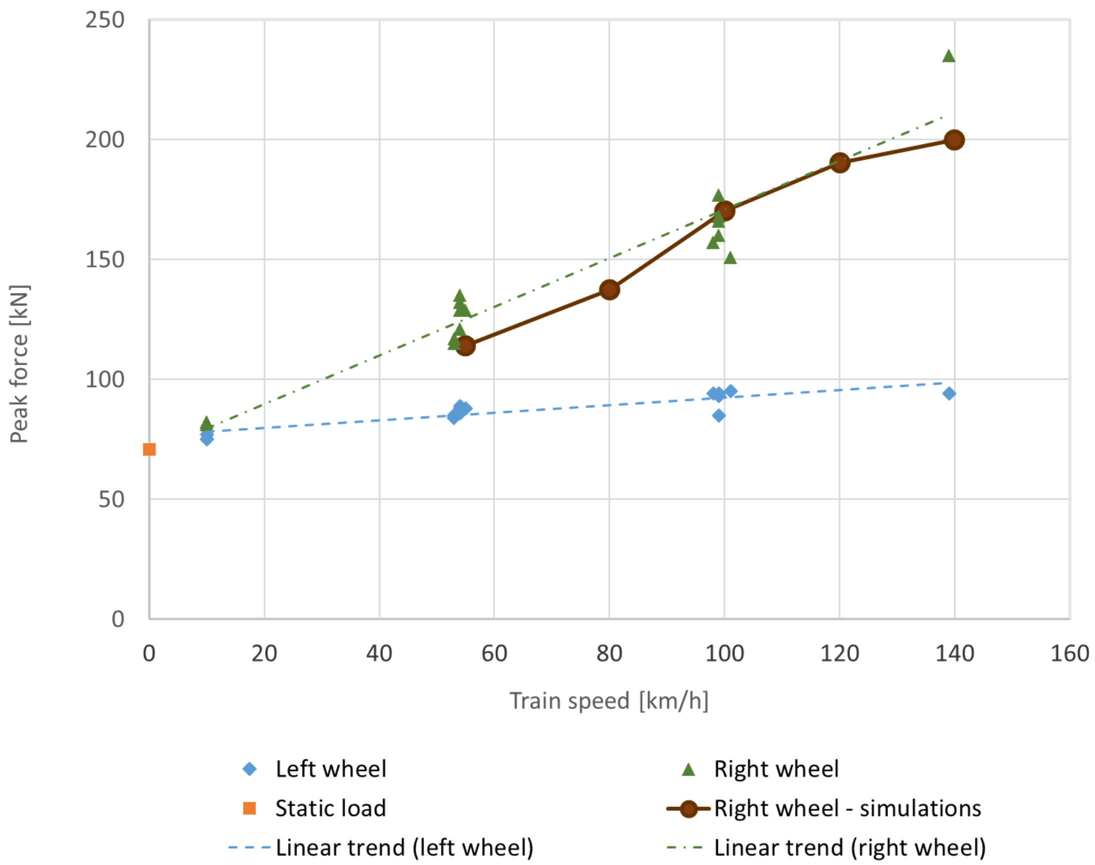


Figure 8: Peak loads measured during the field test described in **Paper A** *and maximum predicted wheel–rail contact force for the most damaged wheel, denoted "right wheel". Source: Presentation of* **Paper A** *at IWC2019*

Clusters of RCF defects may generate a more irregular signature of the vertical contact force depending on the distribution and shape of the discrete defects. According to the field test carried out in **Paper A**, the peak force (maximum contact force over time) generated by a wheel with severe RCF is proportional to the train speed up to velocities of 100 km/h, see Figure 8 [23]. The field tests were performed to increase the understanding of wheel tread defects that trigger the alarm load limits in a WILD. The results can be used to improve regulations regarding restricted operations and maintenance of trains after an alarm has been triggered.

The results from the field test have been used to validate an in-house software for the simulation of dynamic wheel–rail interaction. In this version, the software only considers the contact conditions at one wheel–rail contact point. Simulations were performed for the same operational conditions as those of the field test of **Paper A**. The largest RCF cluster present on the damaged wheel tread during the field test was modelled by superposing an ellipsoid-shaped discrete defect on the wheel tread according to the formulation in [24]. The defect had a maximum depth of 0.5 mm and semi-axis lengths of 60 mm in the longitudinal direction and 40 mm in the lateral direction. The results in terms of maximum values of simulated wheel–rail contact forces for different speeds are superposed to the plots in Figure 8. The results imply that the effect on wheel–rail contact forces from an RCF cluster closely resembled that of a rounded wheel flat.

Wheel OOR lead to oscillations in vertical wheel–rail contact forces and to the increase of rolling noise levels [25]. A particular type of periodic OOR is wheel polygonisation, which regularly has been found on wheels used in the Chinese high-speed network. Polygonisation leads to a deterioration of the vehicle stability as well as to an increase of vibration levels in the bogie [26].

The influence of rail roughness level on vehicle–track dynamics, and especially on the output in terms of rolling noise, has been investigated in several research projects, see e.g. [27] and [28]. The standard ISO 3095 [29] specifies rail roughness that is accepted in type testing of new vehicles in terms of their generated rolling noise levels. This is corresponding to a low-roughness rail that has been newly installed or recently acoustically ground. In **Paper C**, rail roughness spectra inspired by the spectrum in ISO 3095 are employed to compute vertical wheel–rail contact forces at different roughness levels. The results are also used to estimate the increase in axle stresses due to increasing levels of rail roughness, as described in Chapter 4.

The effect of squats, as well as of discrete rail irregularities in general, on contact forces and local stresses has been investigated in depth in [24]. It was concluded that, while variations in contact pressure are mainly dependent on the three-dimensional shape of the defect, the tangential forces and shear stresses are highly affected by friction and creepages. It was also concluded that squats are more likely to be initiated by ellipsoid-shaped discrete defects rather than from corrugations on the rail.

3.2 Measurements

Wheel–rail contact forces can be measured in different ways. Since the 1960s, instrumented wheelsets developed in Sweden have been capable of measuring both vertical and lateral contact forces [30]. Contact forces can also be measured using wayside WILDs. These are capable of registering the mean and peak loads generated by the passage of each wheel. These data can be identified using the number of the vehicle and the date and time of the measurement and classified according to the direction of travel, the number of the axle in the vehicle and the speed of the train. By means of statistical analyses, WILD data can be used e.g. to draw conclusions about the deterioration rate of a specific axle [31].

Measured contact forces can be used to provide relevant information on the status of trains and track. The influence of wheel–rail impact loads on the bending moment of rails has been evaluated in [32]. It was concluded that a limit on measured wheel–rail contact force represents a better criterion than the wheel flat length to determine whether a vehicle has to be removed from traffic for maintenance. In a subsequent study [33], the contact forces were related to crack growth in rails. The influences of variations in track stiffness, rail temperature and the presence of hanging sleepers were assessed. These studies contributed to the formulation of an updated recommendation for allowable dynamic wheel loads [34], depending on the difference between the current temperature of the rail and its stress-free temperature.

3.3 Simulations

Several models and algorithms for the simulation of wheel–rail contact forces have been presented in the literature, see e.g. the overview in [35]. A general approach for solving the rolling contact problem, where discrete irregularities on wheels and rails are considered, is to use the finite element (FE) method in the time domain. However, such FE simulations are time demanding, in particular if a dense mesh of the wheel is employed and a long stretch of track needs to be considered. Computational times can be reduced substantially if the analysis is performed using a frequency-domain model. However, such models need to be completely linear. In studies where the variation in contact force is large with respect to the static wheel load, such as for the impact loads generated by the tread damage studied in the present work, a non-linear contact model and calculations in the time domain are necessary [36].

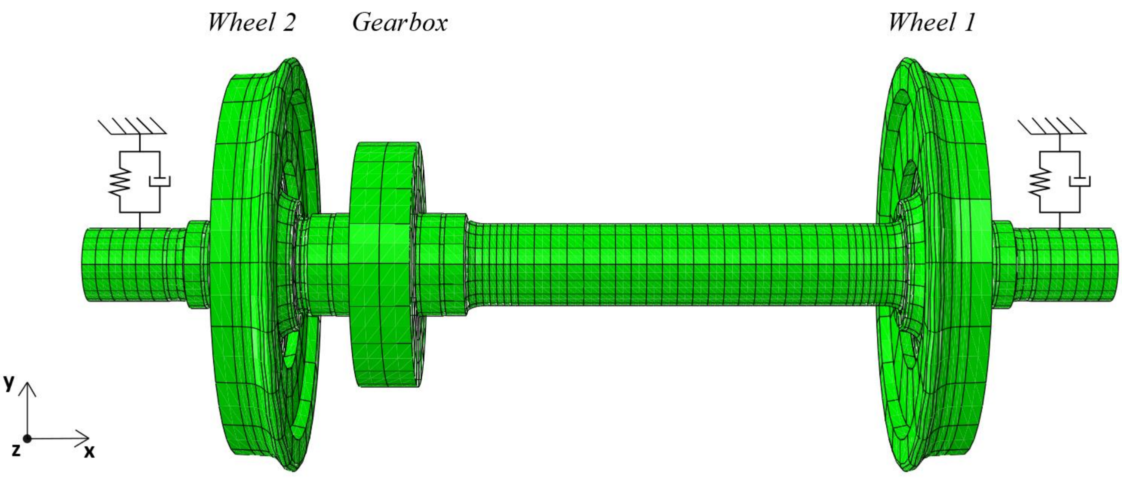


Figure 9: FE wheelset model used in **Paper B** *and* **Paper C**

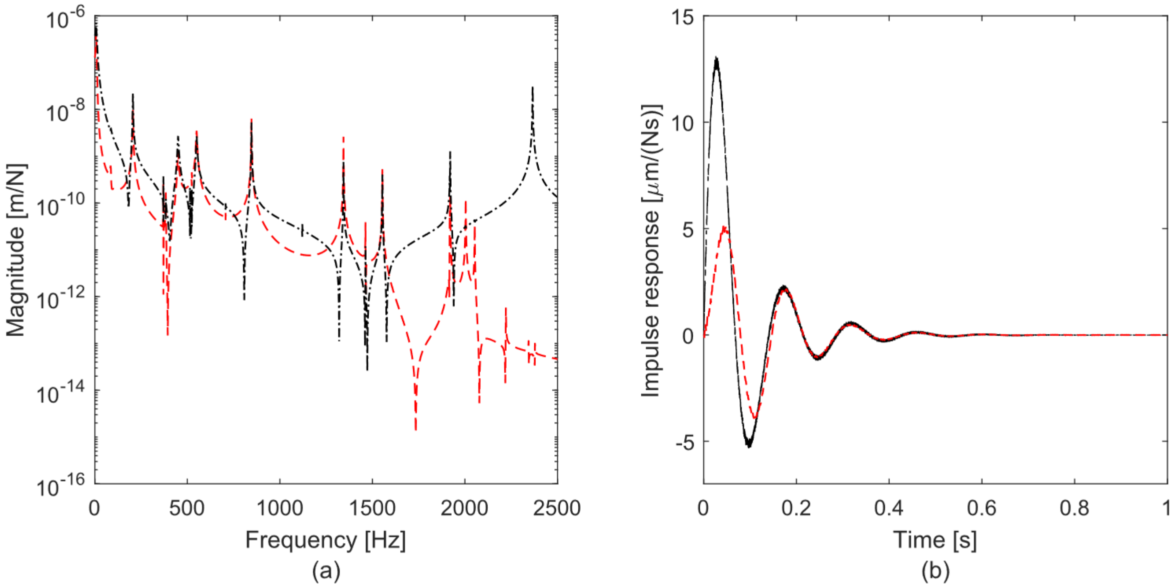


Figure 10: (a) Frequency response functions and (b) corresponding Green's functions for the wheelset model in **Paper B** *and* **Paper C**. *The direct receptance and its Green's function obtained for the wheel on the opposite side of the gearbox (named Wheel 1 in the papers) are plotted in black. The cross receptance on the contact point of the opposite wheel and its Green's function are plotted using a red dashed line*

In the three papers appended to this thesis, the in-house MATLAB software WERAN (WhEel/Rail Noise) has been used for the simulations of dynamic wheel–rail interaction. More details on the software, as well as the theory behind the simulations, can be found in [9]. The wheelset and the track are modelled by means of so-called Green's functions. In this thesis, the Green's functions for the wheelset and the track are obtained based on calculated frequency response functions using 3D FE models of the wheelset and the track.

For the wheelset model in Figure 9, the complex-valued (including information about both magnitude and phase) direct and cross receptances (displacement over force) are evaluated at both contact points to account for the dynamic cross-coupling (generated via the wheelset axle) between the two contact points. Each Green's function is calculated by means of the inverse Fourier transform of the corresponding receptance. Some examples of receptances and Green's functions for the wheelset of Figure 9 are plotted in Figure 10.

A different mathematical formulation is necessary for the modelling of track dynamics to account for the relative motion between the wheelset and the track. In a first step, ordinary Green's functions are computed from the direct and cross receptances at several track positions to capture the response of the track up to a sufficient distance from the contact point. These receptances also account for the dynamic cross-coupling between the two rails by the sleepers and the ballast and are obtained from a 3D track model whose cross-section is shown in Figure 11. For a given train speed, samples from the set of ordinary Green's functions are then combined to form the discrete moving Green's functions for the track. These account for the motion of the contact points along the rail. This second step is described in detail in [9].

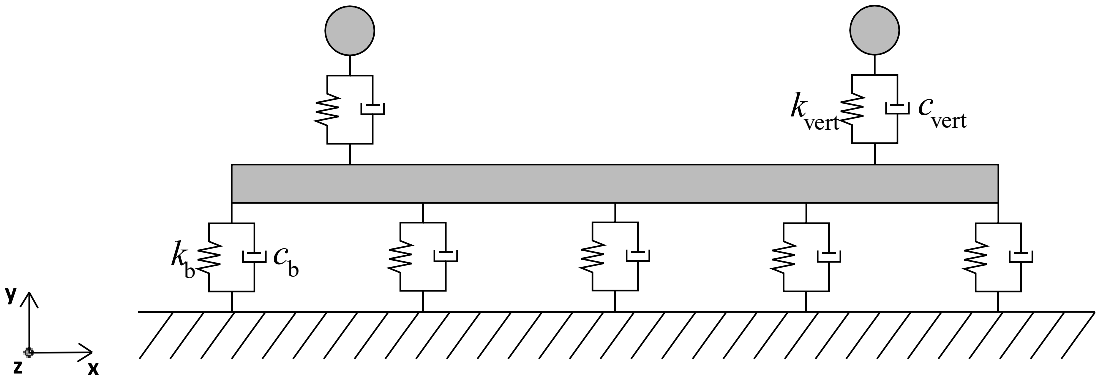
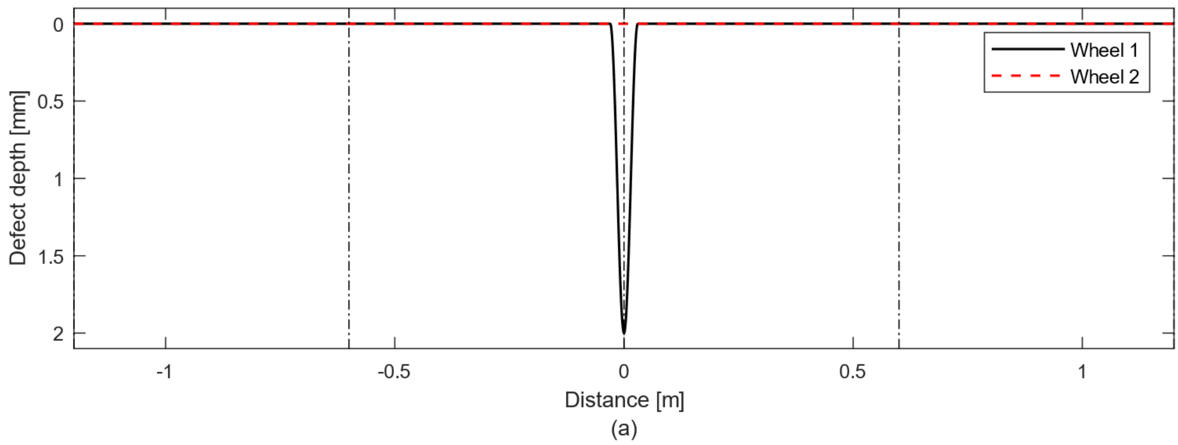


Figure 11: Cross-section of track model used in **Paper B** *and* **Paper C***. The view features one sleeper (the horizontal rectangle) and two rails (circles). The sleeper is connected to the ground by non-interacting springs and dampers coupled in parallel. Rail pads are modelled by accounting for both vertical and rotational (with respect to x) stiffness and damping*

The in-house software solves the normal contact problem using the active set algorithm proposed by Kalker [37]. At the interface between the two bodies, a potential contact area is defined and discretised into a mesh of rectangular elements. In each time step, the elements that are in contact and their contact pressures are determined using an iterative procedure. The total vertical contact force acting between wheel and rail is computed by summing the contributions from the contact pressure values in all elements of the contact patch. The forces at the two contact patches are convoluted with their respective Green's functions to obtain the wheel and rail displacements. The iteration proceeds to the next step if the displacements are in agreement with the kinematic constraints for the wheel–rail contact, see **Paper B**. The cross-coupling between the two contact patches is accounted for in the Green's functions. It is also possible to account for the influence of discrete surface defects or other types of deviations from the nominal wheel/rail geometry, such as wheel and rail roughness or wheel out-of-roundness.

In the studies of **Paper B**, a discrete defect has been superposed on the tread of one wheel (labelled "Wheel 1" in Figure 9). No defects were located on the opposite wheel or on the rail surfaces. The discrete defect had an ellipsoidal shape with maximum depth 2 mm, circumferential semi-axis length 30 mm and lateral semi-axis length 24 mm. The defect was placed such that its longitudinal semi-axis was aligned with the wheel nominal rolling circle. For a speed of 100 km/h, Figure 12(b) shows the calculated time history of the wheel–rail contact forces for the two wheels. The time history of the damaged wheel resembles the oscillation in contact force due a wheel flat, as described in Section 3.1. As the wheel–rail contact reaches the leading edge of the tread defect, the wheel is subjected to an unloading phase. For this combination of train speed and defect size, the contact force on the wheel with the tread defect is reduced to zero over a short time interval, implying that loss of contact has occurred. At the far end of the defect, the contact force for the damaged wheel increases abruptly to 358 kN. After the occurrence of the maximum force, a transient characterised by minor oscillations in magnitude is observed, before the contact force returns to its original magnitude.



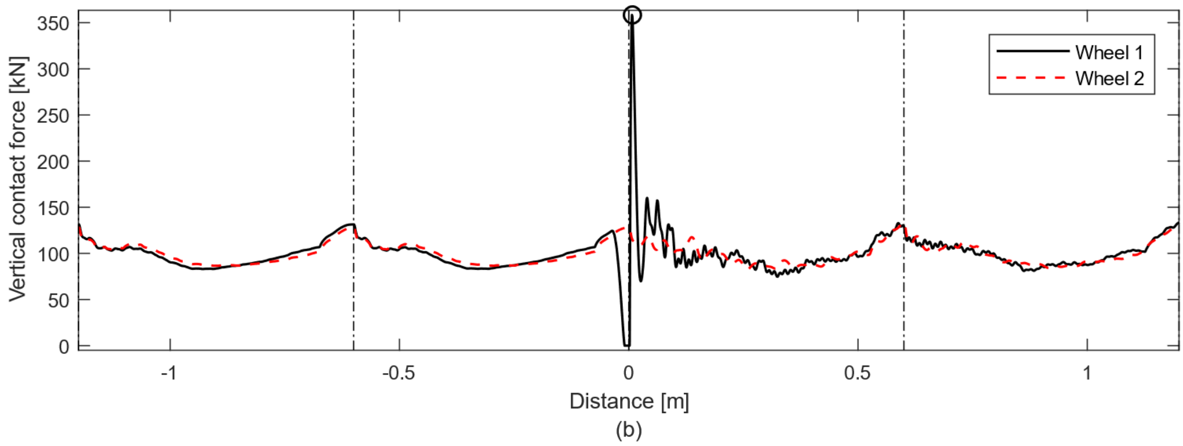


Figure 12: (a) Modelled irregularity at the nominal rolling circle of wheel 1 and (b) calculated time history of vertical wheel–rail contact forces for both wheels. Distance is measured from a point where the circumferential centre of the defect is aligned with a position on the rail directly above a sleeper. Axle load 20 tonnes and train speed 100 km/h. The vertical dashed-dotted lines indicate sleeper positions along the track. Maximum contact force is marked with a circle. Source: **Paper B**

Note that the wheel without the defect is only subjected to a minor variation in contact force, indicating that the cross-coupling between the contact points on the two wheels is rather weak.

4 Stresses in the wheelset

Wheelset components can sustain damage or fracture due to high stresses emanating from the wheel–rail contact. Wheels, for example, are subjected to the combined effects from mechanical dynamic loads during service, centrifugal loads from wheel rotation and from residual stresses due to the heat treatment in the production and subsequent operational loads. In [38], the growth of fatigue cracks in mono-block wheels was studied for different vertical loads, crack lengths and wheel–rail friction coefficients. As the initial length of a crack has a great effect on fatigue life, it was concluded that a more careful manufacturing process can increase the fatigue life of wheels remarkably.

As shown in the studies of **Paper B** and **Paper C**, axles are subjected to high bending stresses due to the static weight of the vehicle as well as the lateral and vertical dynamic loads resulting from the dynamic wheel–rail interaction. In addition, torsional stresses due to braking or traction, and stresses generated by the shrink- or press-fit of the wheels on the axle and subsequent fretting contact between the axle and the wheel hub, contribute to the stress state.

In Europe, axle design is regulated by the standard EN 13103-1 [39] (for axles with external journals). This standard has replaced the former standards EN 13103 [40] (for non-powered axles) and EN 13104 [41] (for powered axles). The calculations in standard [39] are based on static design loads acting on the wheelset. Magnification factors are employed to account for the dynamic variation in loads (e.g. due to the effects of irregularities in track geometry and stiffness, braking, curving, traction, and switches & crossings). The standard defines how fatigue stresses shall be calculated at different sections of the axle (based on the axle geometry, information on vehicle dimensions, operating conditions and braking or traction system) and comparisons can be made with allowed stress levels for specific axle steel grades at specified axle zones. In standard EN 13103-1, the employed design forces are independent of the actual train operating conditions, and dynamic variations in the wheel–rail contact forces due to tread damage and out-of-round wheels are not accounted for.

4.1 Measurements

The evolution of stresses in the wheelset due to wheel tread deterioration can be investigated using field measurements. For example, measurements can be performed using instrumented wheelsets with strain gauges mounted on the axle or on the wheel web [42].

Research on instrumented wheelsets has been performed for wheelsets operating in the Chinese high-speed network. In [43], a system of strain gauges placed on both the axle and on the wheel web was developed with the objective to increase the signal-to-noise ratio and to obtain more precise measurements. In Italy, research has been carried out to increase the measurement accuracy of wheel–rail contact forces for a wheelset running in critical conditions. A calibration procedure is proposed to account for significant lateral displacements of the wheel–rail contact point. This can be appropriate for example when the derailment coefficient, i.e. the ratio of lateral force to vertical force acting on a wheel at a certain moment in time, is found to be high [44].

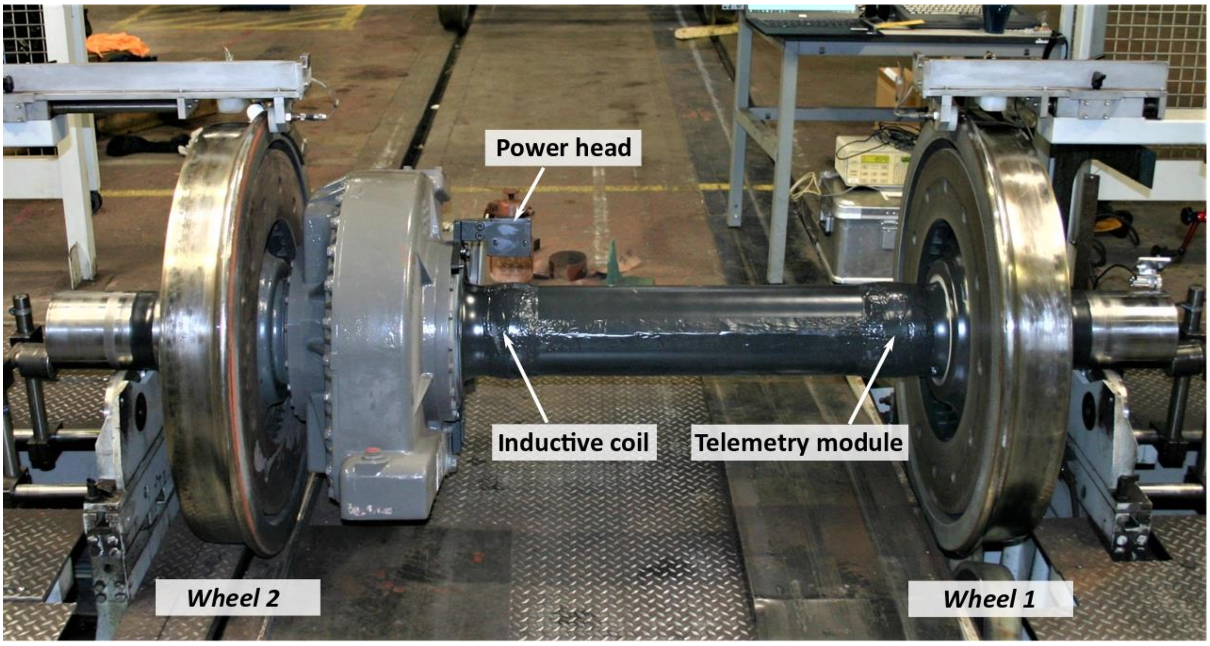


Figure 13: The instrumented powered wheelset used during the field test reported in **Paper C**

In **Paper C**, a system for the measurement of bending stresses at four different locations of the axle is presented. The system consists of strain gauges and a telemetry transmitter installed on the axle body, as well as a telemetry receiver, a telemetry inductive power supply and an embedded data acquisition computer installed in the bogie or on the vehicle body, see Figure 13. The strain data, which are processed on-board, are stored in the form of rainflow count data computed according to [45] stored in a matrix of pre-defined combinations of intervals of mean values and amplitudes. The strains can be transformed to stresses by multiplication with a calibration coefficient. The rainflow data are uploaded to a remote server and can then be analysed e.g. using a crack-growth algorithm, such as the one presented in [46].

The downloading of matrices at specific locations allows to assess the influence of track (and wheel) quality on measured axle stresses for specific stretches of the track. Moreover, stress amplitude spectra collected at different times of the year can be used to investigate the effect of seasonal variations (such as if there is a variation in track stiffness between winter and summer) and/or the effect of performed maintenance (such as the influence of a decrease in running surface roughness after wheel reprofiling or rail grinding).

4.2 Simulations

Different approaches have been used for numerical simulations to evaluate stresses in the wheelset, and in particular in the axle. In [47], axle stresses have been computed by means of FE analyses based on the wheel–rail contact force magnitudes prescribed in [40]. A detailed FE model of a complete wheelset was used. Results in terms of stresses were post-processed using a crack propagation model based on Paris' law.

In **Paper A**, axle stresses have been computed according to the quasi-static procedure described in the former standard for non-powered wheelsets [40]. For the studied axle, this procedure is the same as the one performed according to the current standard [39]. For different vehicle speeds, the average values of measured wheel–rail impact loads were used to calculate stresses at critical locations of the axle. It was concluded that when the contribution from the dynamic loads was not accounted for, the most critical section of the axle from a fatigue point of view was located at the fillet area near the brake disc. Accounting for the dynamic loads (but not the dynamics of the wheelset), other sections were subjected to higher stresses. At a speed of 100 km/h, the most critical sections were at the collar groove (the fillet located between the axle journal and the wheel seat) and at the wheel seat, where the fatigue limit according to the standard is reduced because of the effect of fretting.

In **Paper B**, a post-processing routine to compute time-variant stresses at critical locations of the wheelset based on pre-calculated contact force time histories (and the dynamics of the wheelset) is presented. Stress frequency response functions are computed using a 3D FE model of the wheelset, applying a similar procedure as the one used to obtain displacement frequency response functions briefly described in Section 3.3. The stress frequency response functions are transformed to stress Green's functions by means of inverse Fourier transforms. The time history of the bending stress at a specified location in the wheelset is determined by convoluting the time histories of the contact forces at the two wheel–rail contact points with their respective stress Green's functions. In **Paper C**, time histories of bending stresses in the axle were computed, while (in a simplified way) accounting for the effect of the wheelset rotation. This was achieved by multiplying the time history of the stress amplitude with a time-variant cosine function having the same wavelength as the circumference of the rolling circle. These time histories have been post-processed with a rainflow count algorithm to compute mean stresses and stress amplitudes at selected locations of the wheelset.

In **Paper C**, bending stress amplitudes have been computed at the location of the axle where the telemetry system was installed. Simulations were performed using the wheel OOR measured

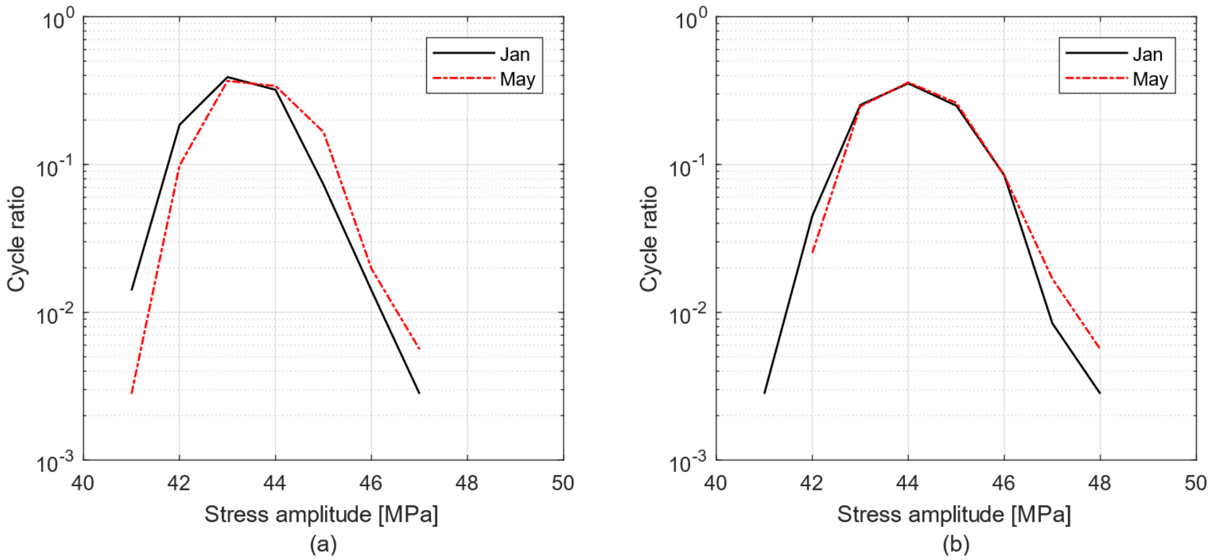


Figure 14: Simulated ratio between number of cycles at different stress amplitudes versus total number of cycles for OOR measured in January 2019 and May 2019 (a) 'Tangent track' and (b) 'Curved track' (R=500 m). Rail roughness based on ISO 3095 spectrum.
Source: **Paper C**

during the field tests performed in January 2019 and May 2019 for the cases of running on tangent track and running on curved track. Results have been collected in histograms showing the occurrence of different stress amplitude values. Figure 14 compares stress amplitudes obtained for the different levels of wheel OOR (the peak-to-trough values of wheel OOR increased between January and May) and for the cases of running on tangent or curved track. More details on the simulation method are available in **Paper C**.

Figure 14 shows that an increase in the number of cycles at higher stress amplitudes can be observed for the cases representing 'Curved track' compared with the cases for 'Tangent track'. Further, the simulations employing OOR from May 2019 lead to an increase in number of cycles at higher stress amplitudes compared with the simulations reflecting the OOR in January 2019. However, it is observed that the influence of wheel tread condition on the shift of stress amplitude spectra is relatively weak (in the order of 1 MPa). More studies have been performed in **Paper C** to separately quantify the increase in axle stresses due to the change in wheel OOR and the increase in stresses due to the lateral shift of the wheel–rail contact point on the wheel tread e.g. due to curving or to a change in the wheel tread conicity. It was concluded that the lateral shift has a larger influence on predicted stress magnitudes.

5 Towards optimised wheelset maintenance

Many of the studies presented in this thesis are aimed at gaining more knowledge regarding the evolution of stresses in the wheelset for different loading cases. Being able to predict the state of stress and the residual life for different components would allow train operators to optimise maintenance routines and save on overall costs while increasing the availability of their vehicle fleet. In this chapter, some common approaches used in maintenance planning will be described. These will be discussed from a stress monitoring point of view.

5.1 How can stresses be used to optimise maintenance?

Different approaches can be adopted for the maintenance of an asset. One of these is called reactive maintenance and consists of the strategy of not repairing a component before it fails or reaches the end of its life [48]. This approach is not favourable if the failure of the component can lead to high economic or non-material costs, such as in many cases in the railway industry. For example, an axle fracture can lead to a derailment. This would imply high additional costs for the train and track operators and, in the worst case, loss of lives.

Most maintenance plans from the previous century were based on preventive policies or fault-driven action [49]. Preventive maintenance (also referred to as planned maintenance) was performed by taking assets off-service at specific intervals in order to avoid unexpected failures. While this maintenance strategy allows to save on costs and downtimes due to catastrophic failures, it often implies that some assets are replaced while they still have a residual lifespan.

Traditionally, inspections of train wheelsets have been scheduled depending on the mileage covered by the vehicle. This means that the trains are inspected in depots at regular intervals depending on the local regulations and/or the company expertise. Maintenance can also be planned according to the design of the component. If a “safe life” design approach is used, the fatigue strength of the component and the stresses it is subjected to in service are used to estimate its residual fatigue life. Maintenance intervals are derived by applying a safety factor to the residual fatigue life. A “defect tolerant” design, on the other hand, is based on the estimated growth rate of a defect and its critical size. In this case, the inspection intervals are planned by applying a safety factor to the residual life of the detected defect. This means that fatigue cracks may develop, but to prevent failures these have to be detected before they grow to a critical size [50].

Predictive maintenance foresees faults or failures in a deteriorating system in order to optimize maintenance efforts. Predictive maintenance is based on three main steps: data acquisition, data processing and maintenance decision-making [51]. Sensors collect data about the conditions of the system. The right time to intervene is based on the evaluation of such data by means of statistics from the past or simulations. This approach is based on technology which connects sensor data with a remote system of data control. The advantage of a predictive approach is that maintenance works become more proactive, and thus effective and efficient [51].

If a condition-based maintenance approach is adopted, the condition of an asset is monitored continuously and maintenance is scheduled when an indicator shows a decrease in performance or a possible upcoming failure [52]. The axle stress data gathered by the instrumented wheelset described in **Paper C** can be employed, in combination with more data from other monitoring systems, to adopt either a condition-based maintenance approach for the wheelset (in that case maintenance is performed when stresses reach a limit) or a predictive maintenance approach. In the latter case, maintenance would be scheduled based on the evolution of the stresses over time or based on numerical predictions of how the deterioration of the axle increases in subsequent operations. In the same paper, the possibility to recognise wheel tread deterioration from data collected by the instrumented wheelset is tested by means of simulations.

A more flexible planning of maintenance could reduce overall maintenance costs as well as increase the availability of the fleet. Some applications in the railway industry allow for the planning of maintenance intervals according to the observed conditions of the asset. For example, in **Paper A**, information on the status of a wheelset was acquired by measuring the loads generated by the passage of the vehicle over a WILD. In **Paper C**, information was gathered by monitoring bending stresses at a specified section of an axle. Data collected by the instrumented wheelset described in **Paper C** can be used in combination with residual life estimation software, such as the one presented in [53]. Maintenance can thus be postponed as long as the monitored parameters fall within the intervals determined by regulations or company practice.

Integrated simulations of the deterioration of a complex structure can be done by using data from sensors as inputs to a large physical model. This is part of the idea of a digital twin, which consists of a comprehensive physical and functional description of the component, product or system. It includes information and algorithms required to mirror the life of its corresponding physical twin [54]. Based on pre-computed wheel–rail impact forces, the work in **Paper B** includes the development and application of an in-house software for the simulation of wheelset stresses. In the future, such work can be included in a digital twin model of a wheelset.

5.2 Future work

The implementations in the in-house software can be used to establish fatigue-stress spectra for running gear accounting for the influence of wheel tread irregularities. This should be useful for future wheelset design. The established model can be used to predict fatigue damage in the running gear caused by different wheel tread irregularities (wheel flats, RCF clusters and different types of out-of-roundness). The sensitivity to operational parameters can be investigated and critical phenomena can be identified.

The scanned tread damage from **Paper A** can be used as input to the in-house software presented in **Paper B** to investigate the influence of train speed on impact loads generated by a discrete form of tread damage that is not characterised by a smooth surface geometry and/or by a uniform defect distribution over the wheel tread. The measured data can be used for a validation of the simulation model. A better understanding of the influence of train speed on generated impact loads would help in investigating the possibility to apply a speed restriction for damaged wheels in order to allow operations until maintenance can be carried out without causing too severe damage to track and running gear and without jeopardizing safety.

6 Outline of the appended papers

6.1 Paper A

A field test in which a train was run at different speeds over an impact load detector is described. One of the wheelsets in the train had severe wheel tread damage. The defects on the wheel tread have been scanned by means of 3D laser and their characteristics are described. The relation between the speed of the train and the magnitudes of the impact loads registered for the two wheels is presented. According to the guidelines of the standard EN13013 [40], a quasi-static fatigue analysis is performed for the axle using the impact loads measured in the field test.

6.2 Paper B

An extension of the in-house software WERAN, where both wheels in a wheelset and both rails in the track are included, is presented. The software is capable of accounting for generic distributions and shapes of wheel tread damage using a cost-efficient method to simulate the vertical dynamic interaction between wheelset and railway track. The influences of non-symmetric wheelset designs (such as the one for the powered wheelsets of the X40 train) and non-symmetric distributions of tread damage on the two wheels (or irregularities on the two rails) can be studied. Time-variant stresses are computed for the locations in the wheelset axle which are prone to fatigue. An extensive parameter study has been performed where wheel–rail impact loads and axle stresses have been computed for different distributions and sizes of tread damage as well as for different train speeds.

6.3 Paper C

A combination of instrumented wheelset measurements and numerical analyses of axle bending stresses is used to investigate the consequences of evolving RCF damage and wheel out-of-roundness on a passenger train wheelset. In a field test campaign, axle stresses have been monitored using a telemetry system with strain gauges installed on a powered wheelset mounted under an X40 passenger train. The evolution of wheel tread damage on that wheelset has been measured on regular occasions. The instrumented wheelset is described and some of the collected results in terms of stress amplitudes are presented. In a parallel study, the measured wheel out-of-roundness has been used as input to numerical simulations of vertical dynamic wheelset–track interaction and the evaluation of pertinent axle stresses using the approach developed in **Paper B**. Simulated and measured axle stresses are compared for cases involving different levels of rail roughness combined with the measured levels of RCF damage. The study enhances the understanding of how wheel tread damage and track quality influence axle stress magnitudes. In addition, the influence of the angular positions of the mounted strain gauges relative to the positions of the discrete wheel tread damage in terms of measured bending stresses is assessed through simulations.

7 Main results and conclusions

In this thesis, a numerical method to compute wheel–rail contact forces in the time domain based on pre-computed Green's functions has been enhanced by accounting for the dynamic cross-coupling (via the axle and via sleepers and ballast) between the two contact points (one on each wheel) . The simulation of dynamic vehicle–track interaction is carried out in the time domain using a convolution integral approach, while the non-linear wheel–rail normal contact is solved using Kalker's variational method. The Green's functions for the wheelset are obtained by the inverse Fourier transform of frequency response functions computed at the nominal contact points of the wheelset model. The Green's functions for the track account for the relative motion between the wheelset and the rail. These moving Green's functions are obtained by an assembly procedure of functions computed at different locations within each sleeper bay for a longer stretch of the track model.

A routine for the post-processing of time histories of stresses at critical locations of the wheelset has been developed based on a similar convolution integral approach. Pre-calculated time histories of wheel-rail contact forces for the two contact points are convoluted with their respective stress Green's functions. These are the inverse Fourier transforms of the stress frequency response functions that have been obtained by applying a load on each of the wheel contact points while extracting the response in terms of the six stress components at the studied wheelset location. In this study, stresses have only been computed at selected locations of the axle, but the same procedure can be applied for any location in the wheelset.

Calculated time histories of axle stresses have been compared to mean stresses and stress amplitudes measured by an instrumented wheelset on an X40 train. For the studied contribution of vertical loading on axle bending stress spectra, good agreement between simulations and measurements has been observed. Numerical simulations have been used to assess the influence of shapes and distributions of discrete tread damage and different levels rail roughness on wheel–rail contact forces and axle stresses. It was shown that variations in rail roughness level may lead to a significant influence on axle stresses, which may supersede the influence of the degradation of wheel OOR and generation of RCF clusters. The effects of the vehicle speed and of the angular position of the point where stresses are monitored have also been assessed. An increase in train speed leads to a substantial increase in wheel–rail impact loads, while the influence on axle bending stresses is not as pronounced. For the wheel tread damage measured on the instrumented wheelset, both the results from the simulation and the field test show that, from a fatigue point of view, the variation in bending stress amplitudes was not significantly affected by the measurement position

The developed simulation model can be used to predict stresses at critical locations of the wheelset and can be updated with measured data from an instrumented wheelset, WILD or other condition monitoring equipment. This can help the train operator to obtain a better understanding of the health status of their wheelsets. Results from connected simulations and measurements can be used to plan for more flexible maintenance intervals based on the observed condition of the wheelset.

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