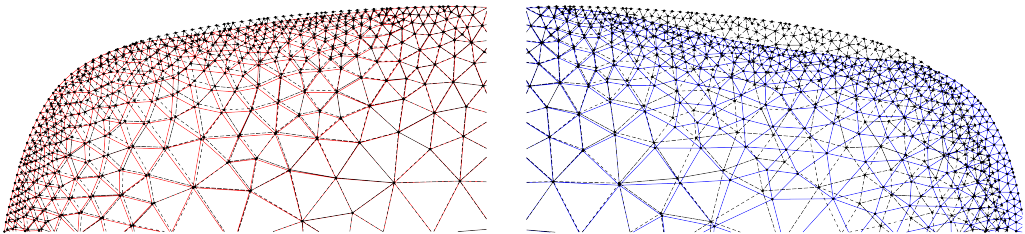




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Towards simulation-based optimisation of materials in railway crossings

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THESIS FOR THE DEGREE OF LICENTIATE IN
SOLID AND STRUCTURAL MECHANICS

Towards simulation-based optimisation of materials
in railway crossings

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CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2018

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Cover:

Simulated plastic deformation of rail profile made of (left) R350HT and (right) rolled Mn13 steel grades.

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ABSTRACT

Railway crossings are subjected to an intense load environment caused by the rail discontinuities needed to accommodate the passage of wheel flanges in intersecting traffic directions. This gives rise to high costs associated with repair and maintenance. For given traffic conditions, several approaches can be undertaken to mitigate the material degradation and hence reduce the life cycle cost. In the present thesis, the option of selecting a more suitable crossing material is explored.

To obtain a guideline for material selection, the in-track performance of different materials during the life of a crossing needs to be predicted. In this work, an existing simulation methodology is extended to improve robustness and computational efficiency. The methodology is able to account for the dynamic vehicle-track interaction, resolve the elasto-plastic wheel-rail contact, and account for the main damage mechanisms related to the running surface of a crossing.

In this thesis, the methodology is updated with a metamodel for plastic wheel-rail normal contact that is introduced to meet the computational challenge of a large number of finite element simulations. The metamodel is inspired by the contact theory of Hertz, and for a given material it computes the size of the contact patch and the maximum contact pressure as a function of the normal force and the local curvatures of the bodies in contact. The model is calibrated based on finite element simulations with an elasto-plastic material model. It is shown that the metamodel can yield accurate results while accounting for the inelastic material behaviour.

Furthermore, the simulation methodology is employed to compare the performance of two rail steel grades that are used in crossings: the fine-pearlitic steel R350HT and the austenitic rolled manganese steel Mn13. A representative load sequence generated by means of Latin hypercube sampling, taking into account variations in worn wheel profile, vehicle speed and wheel-rail friction coefficient, is considered. After 0.8 MGT of traffic, it is predicted that the use of rolled Mn13 will result in approximately two times larger ratchetting strain as compared to the R350HT.

Keywords: Dynamic vehicle-track interaction, switches & crossings, S&C, FEM, metamodel, wheel-rail contact mechanics, plasticity, wear

To Proteus

PREFACE

The work in this thesis has been carried out at the Department of Mechanics and Maritime Sciences at Chalmers University of Technology from May 2015 to May 2018 within the research project TS17 “Optimization of materials in track switches”. This project is part of the research activities within the Centre of Excellence Chalmers Railway Mechanics (CHARMEC). The research has been funded by Chalmers, the Swedish Transport Administration (Trafikverket), partly via the European Horizon 2020 Joint Technology Initiative Shift2Rail through contract no. 730841, and voestalpine VAE GmbH. The simulations were performed on resources at Chalmers Centre for Computational Science and Engineering (C3SE) provided by the Swedish National Infrastructure for Computing (SNIC).

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Second of all, I would like to express my gratitude to my friends and colleagues at the divisions of Dynamics and Material & Computational Mechanics for creating the nurturing environment. Special thanks to those of you who also share your leisure time with me. I truly appreciate your friendship.

Finally, I want to extend my gratitude to my parents Elena and Alexander, and to my katsikaki Panagiota. Thank you for the love and support you surround me with!

Gothenburg, May 2018

Rostyslav Skrypnyk

THESIS

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

Paper A Skrypnyk, R., Nielsen, J. C. O., Ekh, M., Pålsson, B. A. “Metamodelling of wheel–rail normal contact in railway crossings with elasto-plastic material behaviour”. *Engineering with Computers* (2018).

Paper B Skrypnyk, R., Ekh, M., Nielsen, J. C. O., Pålsson, B. A. “Prediction of plastic deformation and wear in railway crossings – comparing the performance of two rail steel grades”. *To be submitted for international publication*.

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, i.e. planning the papers, took part in formulating the theory, developing the numerical implementations and running the simulations, and prepared the manuscript.

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Part I

Extended Summary

1 Introduction

1.1 Background and motivation

The railway turnout (switch and crossing, S&C) is an integral component of any rail network. It provides flexibility to the system by connecting different tracks. The two main parts of a turnout, the switch panel and the crossing panel, give the turnout its alternative name and abbreviation, and are depicted in Figure 1.1 together with its major components. The switch panel is subjected to high lateral loads when traffic passes in the diverging route, i.e. when changing track. Otherwise, the motion is said to be in the through route. In either case, vertical impact loads are induced in the crossing panel. Depending on the direction of motion in each of the routes, either the crossing rail or the wing rail is exposed to the impact. The former is true in the facing move (from switch panel to crossing panel), while the latter holds for traffic in the trailing move (from crossing panel to switch panel).

In Sweden, the estimated cost for maintenance of railway turnouts in 2014 was 400 – 450 million SEK, corresponding to around 12% of the overall railway maintenance costs. These costs are, for example, generated because of the needs for repair and replacement of switch rails and crossings due to damage in the forms of wear (i.e. removal of material from the surface), accumulated permanent deformation, and breaking out of material caused by surface or subsurface initiated rolling contact fatigue (RCF) cracking, see Figure 1.2.

1.2 Aim of research

For a given traffic situation, the design of the S&C could be adapted to reduce the maintenance costs. One aspect of this adaption is to select the most suitable crossing material. The aim of this thesis is to develop a computationally efficient methodology to compare the performance of different rail steel grades in terms of long-term plastic deformation and wear in a robust manner. To this end, the following steps need to be completed:

- Develop an efficient model for the wheel–rail contact accounting for inelastic material response (**Paper A**).
- Design a load collective that mimics the variability in traffic conditions (**Paper B**).
- Calibrate the material model for the investigated rail steel grades (**Paper B**).
- Perform simulations of plasticity and wear for many load cycles (**Paper B**).

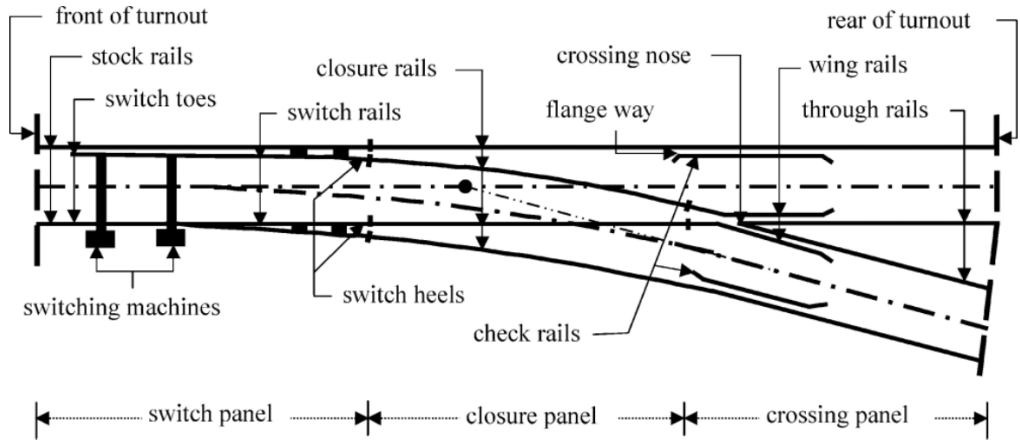


Figure 1.1: Components of a turnout (from Kassa et al. 2006).

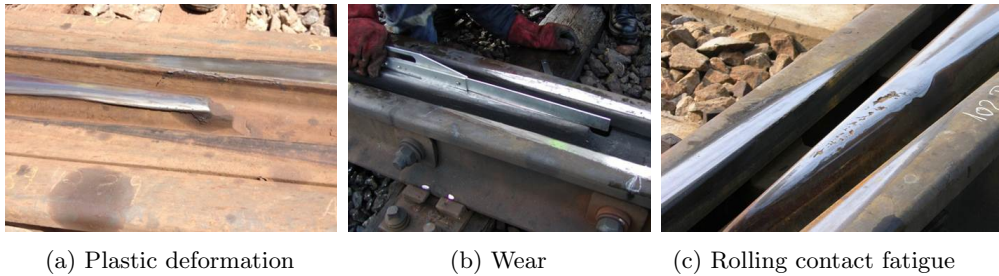


Figure 1.2: Three main damage mechanisms in S&C. Courtesy of voestalpine VAE GmbH.

1.3 Scope and limitations

Since the aim of this research is to carry out simulations of long-term damage in crossings, a large number of load cycles needs to be considered. This comes at a high computational cost. To circumvent this, a number of assumptions and simplifications has been made: 1) the local curvature of wheel and rail around the point of contact is assumed to be constant (also made in the Hertzian theory of contact); 2) the wheel is assumed to deform elastically; 3) the simulation of vehicle-track interaction does not take the geometry change after every wheel passage into account, but after a number of them. That said, as one of the first steps towards simulating the life of a turnout, this should suffice for the material selection, since it will outline the difference in trends of behaviour of the materials. Furthermore, at the time of writing, the available material test data are scarce, especially when it comes to wear, which limits to what extent the damage can be quantified. Lastly, damage attributed to RCF has not yet been considered in this work.

2 Crossing panel design

A wheel travelling over a crossing generally induces an impact load on the crossing rail (in the facing move) or on the wing rail (in the trailing move). The impact load is generated by the downwards-upwards motion experienced by the wheel as it rolls along the wing rail and over to the crossing rail or vice versa, see Figure 2.1. On the wing rail, the vertical motion is caused by the conicity of the wheel and the significant change in lateral wheel–rail contact position that occurs due to the lateral deviation of the wing rail in the running direction. On the crossing rail, the lateral contact position is relatively constant but the crossing rail has a vertical inclination.

Increasing vehicle speeds and axle loads, and wheels with severely worn profiles, induce contact conditions that generate higher magnitudes of wheel–rail contact forces and slip. Accelerated rail profile degradation and damage occur if the rail profiles are not corrected in time since the deteriorated rail profiles induce contact conditions that further magnify the dynamic loads.

For a given traffic situation, at least three different approaches can be identified as means of reducing the wheel–rail contact forces and damage in the crossing panel by design. These are the optimisations of: 1) crossing and wing rail profiles; 2) stiffness of resilient elements in the crossing, such as rail pads, baseplate pads and implementation of under sleeper pads; and 3) material. The shape of profiles along the length of the crossing nose has been optimised in Pålsson 2015 and in Wan et al. 2014. Both studies emphasise that the results of optimisation are only relevant for the traffic conditions considered. The effect of rail pad stiffness on different damage modes was presented in Grossoni et al. 2016. In Li et al. 2017, it is demonstrated that the magnitude of the impact load is more influenced by the wheel–rail contact geometry than by the selection of rail pad stiffness.

In this thesis, the influence of material selection is explored. Common materials used in crossings include austenitic steels (such as the explosively depth hardened manganese steel Mn13), bainitic steels (B360) and high strength pearlitic rail steels (such as the fine-pearlitic rail grade R350HT). Based on field experience, each of the materials has different advantages in terms of resistance to the various types of damage. For example, the manganese steel, which is predominant in the Swedish rail network since the 1990s, has a higher rate of plastic deformation during the initial load cycles but at the same time a better adaptability of rail profile to meet the variation of worn wheel profiles in traffic. A comparison of the performance of crossings made of rolled Mn13 or R350HT in terms of long-term accumulated plastic deformation and wear is presented in **Paper B**.

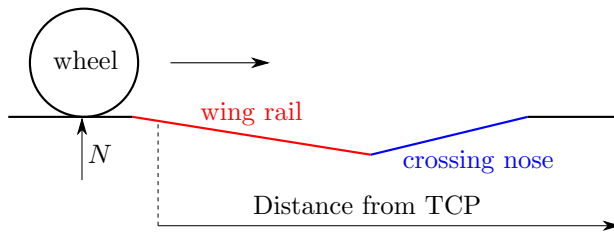


Figure 2.1: Lateral view of the crossing geometry (from **Paper B**).

3 Damage in crossings

A review of common damage (material degradation) mechanisms in S&C is given in Dahlberg et al. 2004. The mechanical damage was divided into three categories:

- 1) Plastic deformation.
- 2) Wear.
- 3) Fatigue.

Plastic (permanent) deformations arise as a result of dislocation movement in grains of the metal due to wheel–rail contact stresses exceeding the yield limit. Plasticity in metals can lead to undesirable residual stresses and make the material more brittle and susceptible to crack propagation.

Wear is the loss of material from a surface in contact. In the context of wheel–rail contact, Lewis and Olofsson 2009 identified two situations that induce wear: sliding and rolling. Sliding is more detrimental in terms of wear rate and it is common for wear models to relate the amount of wear to the sliding distance (see e.g. Archard 1953). Even though the rolling motion is mainly associated with the fatigue driven wear mechanisms, some micro-sliding may occur as well.

Failure of materials due to repeated deformation is called fatigue. If the repeated loading cycle does not involve plasticity, the number of cycles before failure is high and the process is called high cycle fatigue (HCF). On the other hand, if the loading cycle causes plasticity, the failure occurs significantly faster and this type of fatigue is referred to as low cycle fatigue (LCF). In the context of railways, fatigue is caused by the rolling of the wheel, which is therefore often referred to as rolling contact fatigue (RCF). According to Ekberg and Kabo 2005, some of the distinct features of RCF compared to regular fatigue analysis are:

- Multiaxial stress state at a material point, where the principal stress directions rotate during the load cycle, which complicates quantification of the fatigue life.
- Friction between crack faces due to compressive loading has a considerable effect on the rate of crack growth.

The RCF damage mechanism is usually manifested in the form of either surface or subsurface initiated cracks. Surface initiated RCF cracks stem from plastic deformation of the surface material due to frictional contact, which can also result in abrasive wear. The reason for subsurface crack initiation is a high contact stress (that peaks some millimetres under the surface) combined with material imperfections. This type of cracks is less common, but more dangerous as it might lead to breaking out of large pieces of the material. RCF is tightly connected with the other two damage mechanisms described above. Interestingly, under certain conditions, different damage mechanisms can cancel each other out. This is, for example, true for the case referred to as the Magic Wear Rate (see Magel et al. 2014), when the natural wear and grinding prevent RCF cracks from propagating. It defines the tonnage interval for different track curvatures at which the grinding should take place.

4 Wheel–rail contact modelling

One key aspect in the simulation of rail profile degradation is to determine the correct contact pressure distribution in the wheel–rail contact. The wheel–rail contact can be divided into two subproblems: normal and tangential contacts. The shape and size of the contact patch are determined by the geometry of bodies, and the mechanical response of the materials and the normal force. The influence of tangential force on the normal pressure is usually small enough for the interaction to be neglected (see Johnson 1987). The resultant stress in the material is obtained by superimposing the effects of the normal pressure and the tangential traction. Several tools exist for solving the normal contact problem:

- 1) Hertz theory of contact (Hertz 1881).
- 2) Kalker’s variational method (Kalker 1990).
- 3) Finite element (FE) method.

The first two approaches are applicable for elastic material response only. In addition, they rely on the assumption that the bodies in contact are large compared with the dimensions of the contact patch, such that they can be considered as infinite half-spaces. The same holds for most fast methods used in vehicle dynamics simulations (see Piotrowski and Chollet 2005): those that replace the contact zone by a set of ellipses and those that are based on virtual penetration of contacting bodies (or their alternatives that approximate the surface deformation instead of neglecting it, see Sichani et al. 2014a). Furthermore, the theory of Hertz assumes that the geometry of each contact surface can be approximated by an elliptic paraboloid. Kalker’s method imposes no restriction on the wheel–rail contact geometry, while the FE simulation approach allows for both arbitrary geometry and inelastic material response.

The tangential part of the contact problem is typically solved using the FASTSIM algorithm (Kalker 1982), based on Kalker’s simplified theory of rolling contact (Kalker 1973). The simplification is based on the assumption that the surface displacement at a point depends on the traction at that point only, disregarding the contribution of the surrounding points. It was developed to treat elliptic contacts, but can be adapted to non-elliptic problems as well (see e.g. Sichani et al. 2014b for a summary of possible approaches).

Typically, the size of the contact patch is in the order of 1 cm^2 , which is small in comparison with the dimensions of the wheel and rail (see Lewis and Olofsson 2009). Furthermore, the curvatures of wheel and rail contact surfaces are constant over multiple regions of the profiles, see Figure 4.1. However, there are cases where at least one of the assumptions in Hertzian theory is violated. In particular, such situations may occur (especially with worn profiles) when the contact is at the gauge corner of the rail or at the flange of the wheel. For such situations, it has been reported by Lewis and Olofsson 2009 that the results of the Hertzian solution are in vast disagreement with FE simulations. In the presence of plastic deformation, the FE method is the only solution that is available, although at a high computational cost.

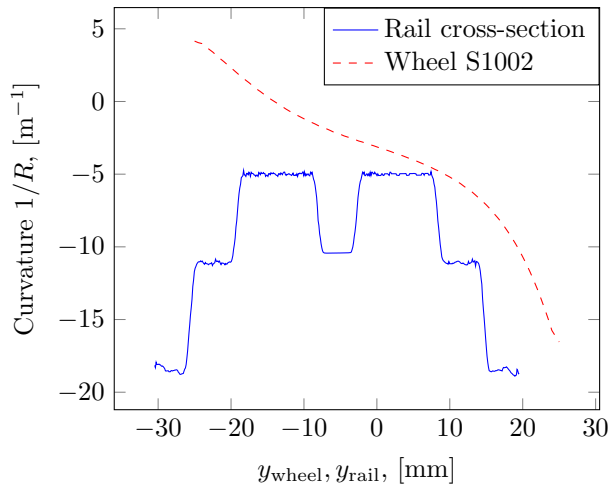


Figure 4.1: Calculated curvatures within the potential contact area (from **Paper A**).

5 Material modelling

As was stated before, the aim of this thesis is the prediction and comparison of long-term damage for selected rail steel grades. It is therefore necessary to understand the cyclic behaviour of the materials and be able to model their mechanical response.

One characteristic feature of metals subjected to cyclic loading that involves plastic deformation is ratchetting. Ratchetting is when a material accumulates a net strain during every cycle in the direction of a non-zero mean stress. Test data from uniaxial cyclic stress-controlled ratchetting experiments (see Schilke 2013) are used in this study, see **Paper B**. For rolled Mn13 and R350HT, the stress-strain curves for 525 load cycles are shown in Figure 5.1. It is evident that rolled Mn13 is much softer than R350HT. For example, at 1% strain it experiences half the stress. Also, the Mn13 undergoes considerable plastic deformation during the initial cycle. During subsequent cycles the rolled Mn13 approaches elastic shakedown, as the width of the hysteresis loops shrinks and the ratchetting rate slows down. Conversely, R350HT has pronounced ratchetting with nearly constant hysteresis loop in each cycle.

A cyclic plasticity model suitable to address ratchetting has been presented in Ohno and Wang 1993. The model assumes linear isotropic elasticity and von Mises plasticity with kinematic hardening. It is formulated in the small strain framework and the strain is assumed to be additively decomposed into an elastic and a plastic part. This model was calibrated against the experiments and is summarised in **Paper B**.

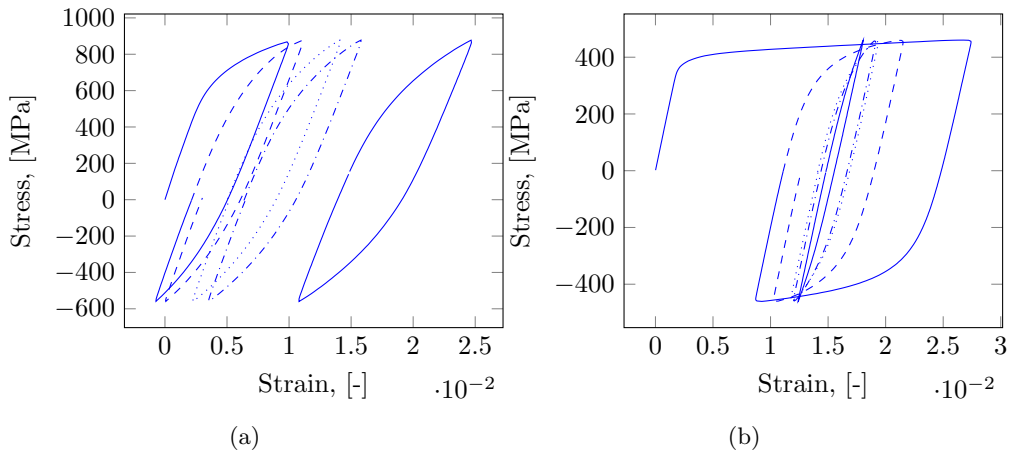


Figure 5.1: Experiments for 525 load cycles for rail grades (a) R350HT and (b) rolled Mn13 (from **Paper B**). Cycles 1 and 525 are denoted by —, cycle 2 by ---, cycle 10 by ·····, and cycle 20 by -·-·-.

6 Simulation of plastic deformation

Laboratory testing of plastic deformation in rails can be traced back to the early 1980s when a two-roller test rig was used to simulate wheel–rail contact on tangent and curved tracks (Kumar et al. 1982). For a standard stock rail material, it was observed that the plastic deformation stabilised at a constant rate. An attempt to quantify plastic deformation in a numerical simulation followed almost a decade later, see Bower and Johnson 1991. Cyclic strain accumulation was predicted over 100 load cycles showing reasonable agreement with experimental data from tension-torsion tests, where specimens were subjected to a load cycle designed to reproduce the stress cycle under sliding contact. A non-linear purely kinematic hardening law for the material was utilised.

Nowadays, non-linear finite element (FE) analysis is the standard tool for the simulation of plasticity in general (no restrictions on geometry) structures, which enables applications of sophisticated material models capable of accurately capturing cyclic plasticity (see e.g. Meyer et al. 2018). An example of application of the FE method to predict cyclic plasticity in turnouts is given in Wiest et al. 2008. There, the authors investigate how the material choice for the crossing nose influences the deformation due to repeated wheel passages, although only one wheel profile was used to roll over the same region. The study suggests that the contact force can be reduced for the manganese crossing compared to a tool steel crossing, which is explained by higher adaptability of the manganese steel.

Long-term prediction of damage implies that many load cycles need to be simulated. Clearly, this comes at a high computational cost. It is thus desirable to carry out the simulations as numerically efficient as possible. In the procedure described in Johansson and Ekh 2007, an extrapolation technique is proposed that is based on a Taylor series expansion ε of the material response \mathcal{S} . The notion *representative time sequence*, illustrated in Figure 6.1, was introduced. The Taylor series of how \mathcal{S} changes from sequence i to sequence $i + \Delta N$ can be written as

$$\varepsilon_{i+\Delta N} \approx \sum_{n=0}^m \frac{\Delta N^n}{n!} D_N^n \mathcal{S}(\tau_i), \quad (6.1)$$

where D_N^n denotes the n th derivative with respect to the sequence number N , and τ_i is the time at the beginning of the i th sequence (see Figure 6.1). In practice, a truncation after the second term in the series is applied, see **Paper B**.

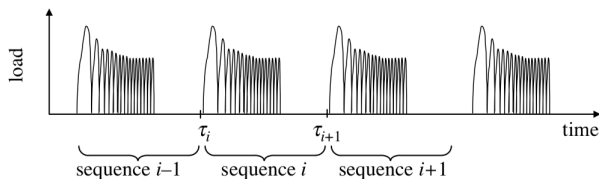


Figure 6.1: Illustration of representative time sequence exemplified by cyclic loading history (from Johansson and Ekh 2007).

7 Wear prediction

Two different types of wear models were identified in Enblom 2009. These are (a) models that relate wear to the friction energy dissipated in the wheel–rail contact area, and (b) Archard-based models that attribute wear to the sliding distance, normal force and hardness of the softer material (see Archard 1953). The latter type has attracted a broad field of applications (e.g. used for the prediction of wear in roller bearings). The wear rate in these types of models depends on the wear regime that can be specified using a wear map, see e.g. Lim and Ashby 1987. However, the generation of a wear map requires extensive testing at different loading conditions and is usually only valid for a given material pair. Due to different wear regimes, wear maps are often discontinuous and a small variation in the contact conditions may lead to an order of magnitude variation in the wear coefficient. Recently, it was shown in Cremona et al. 2016 how a metamodelling technique can be used to construct a continuous wear map.

A comparison of the two types of wear models was performed in De Arizon et al. 2007. The authors compared the Archard-based models used by Jendel 2002, and by Enblom and Berg 2005, with the energy dissipation-based models by Zobory 1997, and Pearce and Sherratt 1991. The models were selected because of their capability of predicting wear in the mild and severe wear regimes and were compared on a theoretical basis. Even though all the models are dependent on experimental coefficients that may not have been estimated in similar test conditions, a reasonable agreement was found. Still, the application of the models to a case of an urban transport vehicle travelling on a network with a distribution of curve radii showed that the model of Pearce and Sherratt predicted wear rates one order of magnitude higher in the severe wear regime than the other models.

Railway turnouts have been identified to be the main driver of wheel wear, see Casanueva et al. 2014. The predicted wheel wear, generated in a turnout without track irregularities, was found to be one order of magnitude higher than the wear on tangent track and curves with irregularities.

8 Methodology

In Enblom 2009, it is concluded that most studies of wheel/rail damage focus on one of several damage modes and that models where wear and plastic deformation are integrated are needed. Such a multidisciplinary methodology allowing to simulate long-term damage in S&C accounting for variability in traffic conditions was proposed in Johansson et al. 2011. This methodology is further extended and improved in this thesis. In each iteration step, the methodology consists of four parts:

- I Simulation of dynamic vehicle–track interaction by means of a commercial code (e.g. GENSYS or SIMPACK) in order to predict wheel–rail contact forces, creepages and contact positions. In this thesis, the simulations are carried out in SIMPACK, taking into account stochastic variations of several input parameters, such as vehicle speed, wheel–rail friction, as well as wheel profiles.
- II Simulation of wheel–rail normal contact using the commercial FE software Abaqus, including a user subroutine UMAT with an elasto-plastic material model to determine realistic contact patches and stresses in the material. Only the rail material is assumed to deform inelastically. To reduce the computational time, local 3D models of the wheel–rail contact are created based on the assumption that the radii of curvature of both wheel and rail are constant in the vicinity of the contact point. In this thesis, to reduce the computational effort, this part of the methodology has been updated with a metamodel of wheel–rail normal contact (see **Paper A**).
- III Simulation of damage evolution. Every load realisation from the simulation of vehicle–track dynamics (part I) and the corresponding contact simulation (part II) constitutes a load cycle. One load sequence is defined by N load cycles, corresponding to N wheel passes. This sequence is repeated M times to obtain the total load history. This part includes the following damage modes (see **Paper B**):
 - a) Plastic deformation. To reduce the computational effort, a plane strain model of the cross-section is used where the load is adjusted such that the maximum von Mises stress is identical to the 3D contact simulation in part II.
 - b) Wear is calculated using FASTSIM and Archard’s wear equation.
- IV Smoothing of total profile change. Since the rail profile is not updated after every load cycle, an artifact occurs in the form of an unrealistically deformed cross-section of the rail. In order to alleviate this problem, a smoothing procedure is applied to the deformed geometry of the rail profile before it is used as input in the next iteration of the methodology.

The methodology has previously been successfully applied to predict the rail profile degradation in a switch panel at Hårad in Sweden (see Johansson et al. 2011) and a crossing panel at Haste in Germany (see Nicklisch et al. 2009).

Another procedure to predict the life of a turnout based on an explicit FE model has been presented in Xin et al. 2016. It also predicts the elasto-plastic material response assuming non-linear kinematic hardening. Both plastic deformation and wear are simulated in Wei et al. 2017 using the FE method. The wheel and rail are modelled assuming

bilinear elasto-plastic material behaviour. Wear is accounted for via frictional work model. However, unlike in Johansson et al. 2011, neither of these studies takes into account the variability in traffic conditions. Also, the cyclic loading is neglected, which may result in an overestimation of rail life.

9 Summary of appended papers

Paper A: Metamodelling of wheel–rail normal contact in railway crossings with elasto-plastic material behaviour

Two types of metamodels for the wheel–rail normal contact with elasto-plastic material behaviour are presented. The first one is a linear regression model inspired by the Response Surface Methodology (see e.g. Myers et al. 2016), while the other one is based on the contact theory of Hertz. Both models approximate the maximum contact pressure and the size of the elliptic contact patch. The inelastic material response is accounted for by calibration against FE simulations with an appropriate material model. An analysis of the performance of the models shows that the Hertzian-based model is more accurate. The error stemming from the assumption of constant local curvature is quantified. The assumption is concluded to be inadequate for cases with small differences in curvature between the two bodies in contact. However, such cases do not lead to high von Mises stresses and are less detrimental from the material degradation point of view.

Paper B: Prediction of plastic deformation and wear in railway crossings – comparing the performance of two rail steel grades

The Hertzian-based metamodel from **Paper A** is incorporated in the simulation methodology that is deployed to compare the performance of two rail steel grades: the fine-pearlitic rail grade R350HT and the austenitic rolled manganese steel Mn13. Plastic deformation and wear are calculated. To account for the spread in traffic conditions, a representative load sequence is generated by means of Latin hypercube sampling. It takes into account variations in worn wheel profile, vehicle speed and wheel–rail friction coefficient. In total, 41400 load cycles, corresponding to 0.8 MGT of traffic, were simulated for a selected rail cross-section in one iteration of the methodology. The overall change of profile and the amount of ratchetting strain were predicted to be smaller for the crossing made of R350HT, while less accumulated plastic strain was predicted for the rolled Mn13. An adaptive extrapolation algorithm is applied to the plasticity calculations. The wear model is calibrated versus field measurements performed on an explosively depth hardened Mn13 crossing. The contribution of wear after 0.8 MGT of traffic to the total shape change of the virgin crossing was found to be small, around 2% of the maximum plastic deformation.

10 Future work

In **Paper B**, the damage due to a load collective equivalent to 0.8 MGT of traffic was simulated for the rolled Mn13 and R350HT materials. The observed trends in the plastic deformation suggest that the fact that the manganese crossing experiences a much larger shape change might alter if more load cycles are considered. This is because the ratchetting stabilised to a lower rate for rolled Mn13 as compared to R350HT. Further, for rolled Mn13 and the considered load environment, it was concluded that the contribution of wear to the total change of rail profile was negligible. This is expected to change if more load cycles are accounted for. An effect that is not yet accounted for is that as the materials harden wear becomes relatively more important.

In future work, the long-term degradation of the crossing will be predicted by performing several iterations of the simulation methodology, and guidelines for selection of crossing material will be provided. Also, rolling contact fatigue needs to be accounted for in the third part of the simulation methodology. The procedure for smoothing of the profiles between iterations will be studied. The influence of the iteration step length and the number of load cases in the load sequence on the accuracy of the predicted rail profiles will be investigated. The simulation methodology will be validated versus field measurements if such data can be made available.

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