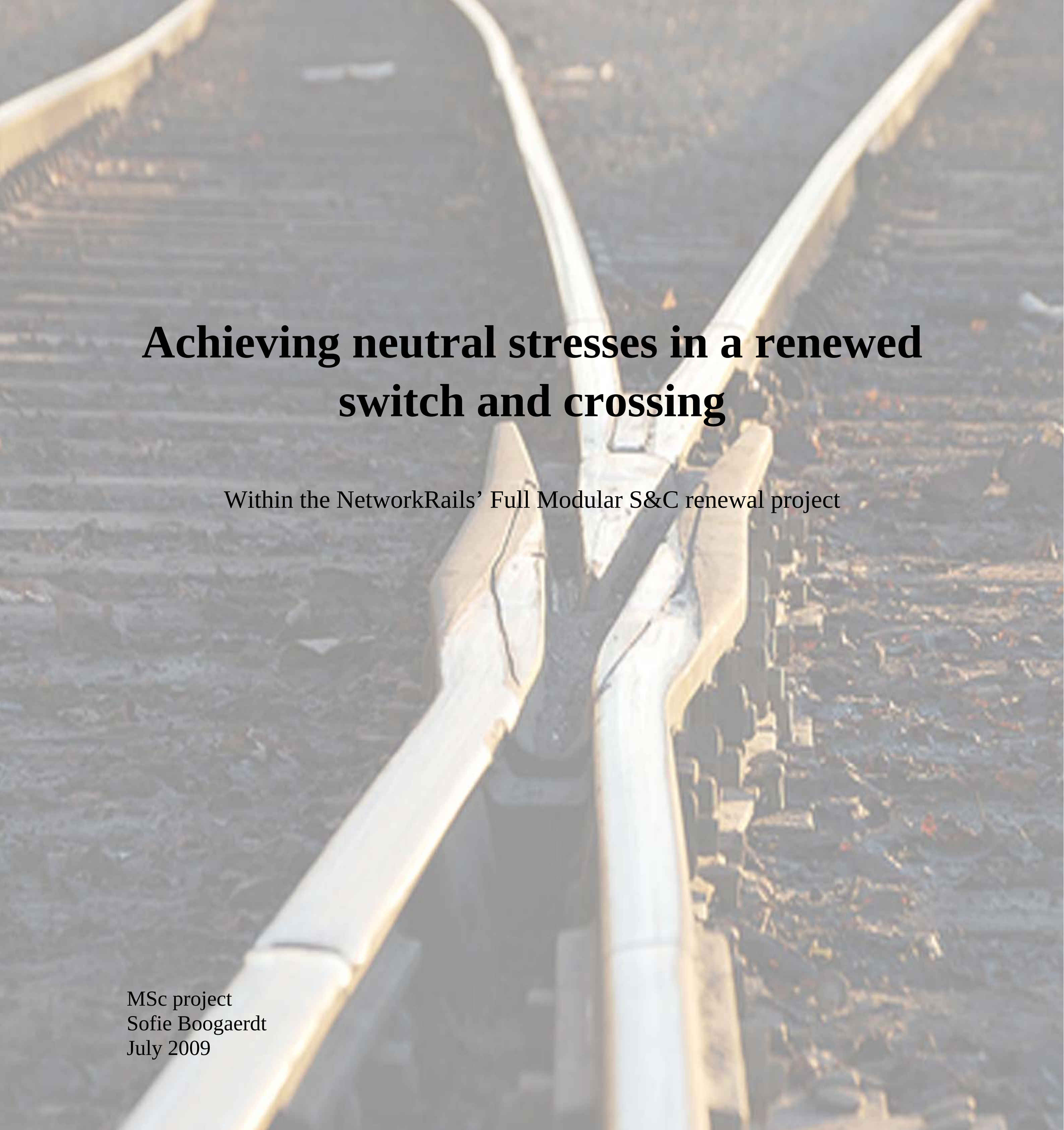

Achieving neutral stresses in a renewed switch and crossing

Within the NetworkRails' Full Modular S&C renewal project

MSc project
Sofie Boogaerdt
July 2009

Master thesis

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Preface

This report is the result of the graduation project at the Faculty of Civil Engineering of the Delft University of Technology. For the last eight months the author performed research at the section Road and Railway of this faculty. In this project a working sequence to achieve neutral stresses in a renewed switch and crossing is investigated.

I would like to thank my committee, prof. dr. ir. A.A.A. Molenaar, dr. ir. V.L. Markine, dr. ir. P.C.J. Hoogenboom and J.P.T. van Eck, for their supervision and their advice. I enjoyed working with them and could always ask for advice.

As a part of this project were some tests done on a track. I would like to thank Petra Oude Groote Beverborg, Karlo van der Wetering and Rinus van Oort for making it possible to do the tests in Houten. For the good test results I would like to thank Leo Heester (Peekel Instuments BV).

Also I would like to thank all the employees of VolkerRail who contributed to the making of this report, especially the people of the O&I department. I also would like to thank David Philpott for the correction work.

Finally I would like to thank my family and friends for their support and compassion and all the help they offered to make this report possible.

Vianen, 9 juli 2009

Sofie Boogaerdt

Summary

The increased demand on the capacity of railway tracks has the consequence that less time is available to do maintenance. With more efficient methods for renewal and maintenance, installation time can be reduced and this will improve availability of the track.

VolkerRail in combination with Corus and Vossloh (VCV) has developed a full modular working method to reduce the time needed to renew a switch and crossing (S&C) unit from the current standard of 48 hours to a maximum period of 8 hours. Also this method improves the quality of the new unit. This new installation method requires a different approach to stress the S&C unit and the adjacent plain line to obtain no stress at the Stress Free Temperature (SFT). The SFT is aimed at reducing either tensile or compressive stresses in the rail due to respectively a decrease or an increase in the temperature compared to the temperature at which the rail has been fastened. This is achieved by either heating or stressing the rails to introduce the equivalent forces in the rail corresponding to the forces to a stress level in the rail equal to 0 N/mm^2 at a rail temperature of 27°C.

The full modular method is aimed at including the stressing in an 8 hours possession in which the whole S&C unit is renewed and thus stressed. As the S&C unit is pre-built to the exact geometry in a factory, the aim is not to introduce any changes in the geometry of the unit during installation. This results in the requirement that the rail displacements due to stressing should be less than 4 mm and the displacement difference between the rails at the location of the clamplock are limited to 2 mm.

During this Master Thesis project a working sequence has been developed to achieve a stress free temperature in a renewed S&C unit and the plain line, satisfying these requirements in a worst case scenario (ΔT = 30°C, S&C unit type C11, rail type UIC54, sleeper spacing 0.6 m).

Tests were performed to determine the longitudinal resistance between the sleepers and the ballast. This is done for the situation with top ballast and without top ballast. The results of these tests have been used to validate a model of the S&C unit made in the finite element program Longstab.

With the model different situations were tested to determine the best working sequence for stressing of the plain line. Within the requirements set by the full modular working method the test results from the model show it to be impossible to stress the plain line by pulling, as the longitudinal ballast resistance is not sufficient.

Based on the results of the numerical simulations the following working sequence for stressing is proposed:

- The S&C Unit is to be installed at its final location before any other track is welded to the S&C unit.
- The S&C unit has to be installed at the SFT of 27°C and kept at this temperature using heating blankets until the closure welds have been made.
- The existing track needs to be un-clipped over a length of 90m from the location of the closure weld.
- The new plain line that needs to be installed on either end of the S&C unit is installed in panels of 18-19 m.
- The new panels need to be unclipped prior to the welding to the S&C unit.

- After welding the panels to the S&C unit they need to be heated using a heating wagon. Behind the heating wagon the rails have to be clipped.
- The plain line has to be heated extra to compensate for the extra length needed to stress the unclipped 90 m of existing track.
- All welds to be made with a Flash Butt Welder to reduce the time required for the welding.
- Top ballast needs to be installed in the S&C unit after welding the panels to the S&C unit and making the closure weld.

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Definitions

Anchor length	The length of CWR track that is clipped down with the fasteners during the stressing operation to check that no movement occurs at the fixed ends of the length being stressed.
Ball and Claw	A device for monitoring creep of the heel of the switch blades. Also called creep monitor.
Ballast	Rock or other non rounded granular material placed on a subgrade to support sleepers and rails and to aid in holding the desired track geometry.
Bottom ballast	The bottom ballast is installed in two layers, thickness dependent on track category, usually totalling 25 cm, on which the sleepers are installed. The two bottom ballast layers are compacted and levelled to the required profile.
Clamplock	A clamplock is a hydraulic ram arrangement that operates, clamps and detects the closed switch blade to the stock rail, at the same time holding open the other blade to give the required flangeway gap. It is located adjacent to the switch toe.
Continuous welded rail (CWR)	CWR consists of rails which are welded together to produce a long string of rails. CWR is stress free from temperature stresses when the rails have reached a temperature equal to the neutral temperature
Sleeper	The timber, concrete or steel tie that holds the rails together and supports them to transmit the train loads down to the ballast. In S&C, these are called bearers and are to a different profile.
Spoil	Old and dirty ballast which may be polluted and require treating as hazardous waste.
Stress free temperature (SFT)	Also called neutral temperature, is the temperature at which the stressed track is free from thermal stress. (Stress free temperature in GREAT BRITAIN is 27^{o}C)
Switches and Crossings (S&C)	A turnout is a single unit. A Crossover between two tracks would be two units.
Top ballast	The ballast that is installed between the sleepers and at the ends of the sleepers to form a ballast shoulder.
Tell-tales	Marks made on each rail in line with a suitable fixed reference mark on an adjacent unclipped sleeper, in order to monitor the effectiveness of the anchor length. A tell tale is required at each end of each anchor length: the one adjoining the free rail is the inner tell-tale, the other one is the outer tell-tale.

1 Introduction

In the last few years the usage of the rail infrastructure has increased. It is the job of the railway operator to have the track available as much as possible and at the same time to maintain the track at a safe level. The time needed for maintenance and renewal is in conflict with the availability. With more efficient methods for renewal and maintenance, installation time can be reduced and will improve availability of the track.

VolkerRail in combination with Corus and Vossloh (VCV) has investigated the challenging requirement of Network Rail (the British railway operator) to renew a switch or crossing (S&C) with an improved quality in a maximum period of 8 hours.

During the consultancy period of this study it has been proven, that the requirements can be met with a combination of improved existing methodologies combined with the development and the introduction of new equipment, resulting in a World Class installation method.

The new installation method requires a different approach to stress the S&C unit compared to the existing process. When optimized, S&C units will be delivered on site at a Stress Free Temperature (SFT), meaning that the S&C unit is at the correct length when installed on the compacted ballast. The top ballast layer is installed at the end, so it can be installed all at once and no temporary connections are needed during installation. This will make it more difficult to stress the track that will have to be connected to the S&C unit to the SFT length because without ballast there is hardly any resistance.

Stresses in the rail occur when the temperature changes. The SFT is aimed to reducing these stresses to improve the quality of the S&C unit. The stressing of the S&C unit to the SFT is a time consuming part of this full modular method. In order to reduce this time a different approach is needed.

The goal of this report is to present a working sequence to achieve a stress free temperature in a renewed S&C unit and the plain line, satisfying the requirements as set within the world class full modular installation method.

Therefore it is important to prove that the longitudinal ballast resistance is sufficient to stress the plain track to the required length, within the allowable displacements of the requirements. Experiments were needed to determine the resistance for different ballast situations. Also the sequence to weld and stress the S&C unit and the plain line to the stress free temperature length is determined. This is done with a final element model of the track structure.

The working sequence for welding and stressing the S&C unit and the plain line is found to be suitable for the stressing of a S&C unit and plain line in a straight track.

Report structure

The report is divided in four parts:

Part 1 describes the activities during the renewal of the S&C unit for the current and the new working method and insight is given in the problems around the new working method. From the working method the requirements for stressing of the S&C unit is deducted.

The theory about the ballast behaviour and the test performed to determine the longitudinal ballast resistance is described in part 2.

Part 3 describes the model that is made to analyze the behaviour of a S&C unit when stressed. Using the result of this model a recommended working sequence for the stressing of the rail is given.

In part 4 the answers on the research question stated in part 1 is given in a couple of conclusions. In the recommendations a few proposals are made to do additional research on the friction resistance between the sleepers and the ballast and the parameters related to this resistance.

Part 1 Problem analyses

In the first part of this report, the different parts of a track construction and the activities for renewing a S&C unit are expressed. The current and new working methods and the challenges of the new method are explained. After which the problem definition and the goal of this report is defined.

2 Track construction

In this chapter the basics of a track construction are described. First the construction of the ballasted tack is explained. Further a description of a switch and crossing unit and its most important parts are given.

2.1 Ballasted Track

In the study of VCV the renewal of a S&C unit in ballast is investigated. A ballasted track is the most commonly used principle. Ballasted track consists of a framework of sleepers and rails supported on a ballast bed. The ballast rests on the subgrade. Figure 2.1 shows the construction of a ballasted track.

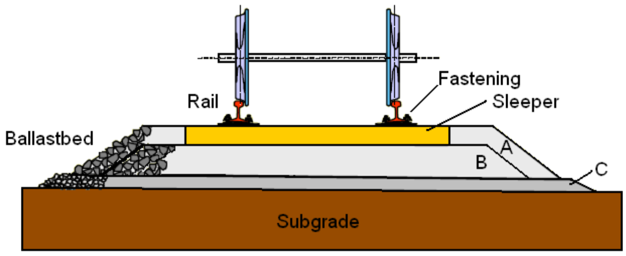


Figure 2.1 Cross section ballasted track

Ballast is made from crushed stones and divided in three layers. Top ballast is layer A, which provides part of the lateral and longitudinal resistance on the ends and sides of the sleepers. The remainder of the resistance of the track to distortion comes from the weight of the sleepers and the friction between the ballast bed and the sleepers. The layers B and C are the bottom ballast which carries the vertical load. The membrane layer between the subgrade and the ballast bed, layer C, prevents the mixture of the ballast with the subgrade and levels the unevenness of the subgrade.

2.2 Switches and crossings (S&C) units

Switches and crossings (S&C) units are turnouts, crossovers and other more complex arrangements not covered in this paper. A turnout is used to divide a track in two tracks and allows the train to move in a straight direction on the through track or in a divergent direction. The purpose of a crossover is to allow trains to cross between two adjacent tracks to intersect at the same level. In figure 2.2 and figure 2.3 a single turnout is shown.

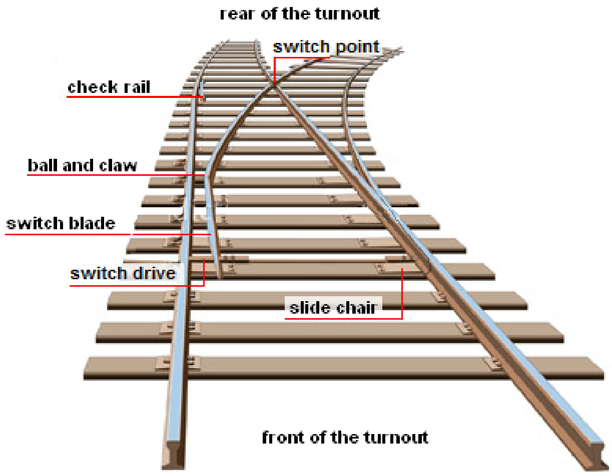


Figure 2.2 Standard right hand turnout

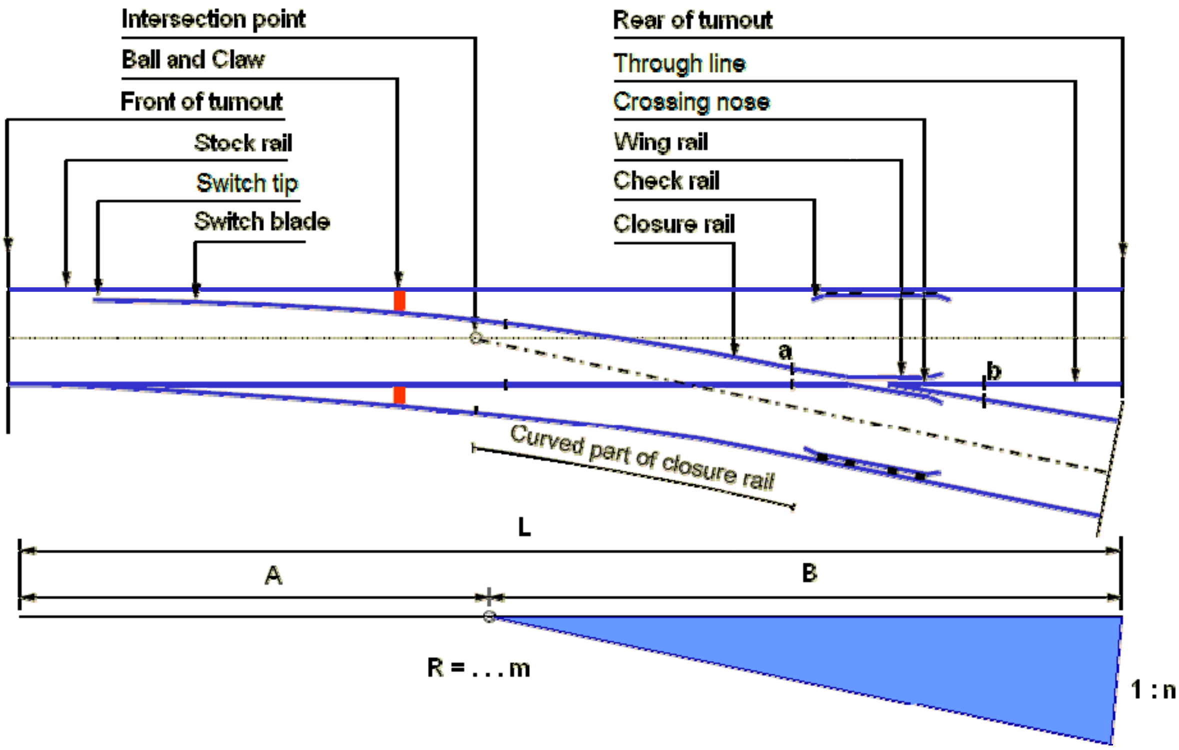


Figure 2.3 Top view right hand turnout

The most important parts of a S&C unit are:

The front/rear of the turnout

The front of the turnout is the centre of the rail joint/weld outside the switch to the tip of the switch blades. The rear of the turnout lies at the beyond the crossing on the divided tracks.

Stock rail

The rails in the switch area that are not interrupted are the stock rails.

Switch blades

The switch blades are the parts of the switch that can be moved and which determine the direction of the traffic. In picture in figure 2.4 this is the through track. The switch blades are tapered in such a way that when they are placed against the stock rail, the traffic moves onto the blade. The switch blades are operated by a point machine.

Figure 2.4 Pair of switch blades

Switch tip
The switch tip is the very end of the switch blades. The switch blades are connected to move simultaneously by the Operating Mechanism (e.g. clamplock). This causes one of the rails to be forced hard against the stock rail whilst holding the other switch rail clear of the stock rail to maintain the appropriate geometry and clearance through the switch.

Clamplock
A clamplock is a hydraulic ram arrangement that operates and clamps the closed switch blade to the stock rail, giving a positive indication of closure and supporting the open switch blade. It is located adjacent to the switch toe. In figure 2.5 a clamplock is shown.

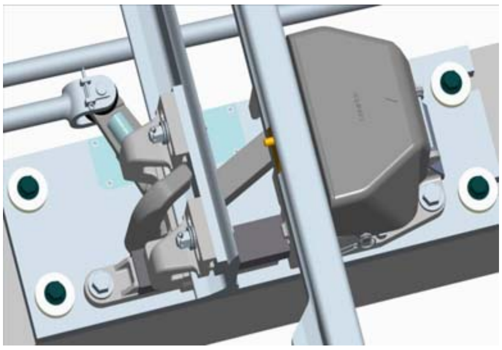


Figure 2.5 Clamplock

Creep monitor "Ball and Claw"
The ball and claw is a device for monitoring creep at the heel of the switch blades. A picture is of a 'Ball and Claw' is shown in figure 2.6.

Figure 2.6 Ball and Claw

Closure rail
A closure rail is a rail between the parts of any special track work layout, as the rails between the crossing and the switch blades; also the rails connecting the crossings of a crossover or between back to back switches in multiple layout S&C or of adjacent crossings, but not forming parts hereof.

Check rail
To guide the train through the chosen direction where there is a discontinuity in the rail (e.g. at a crossing), a check rail is installed at the rail on the other side of the fourfoot. The check rail forces the wheel against the running rail to ensure that the other wheel is forced in a certain direction (on the right side of the crossing). In figure 2.7 a check rail is shown.

Crossing
The crossing is the part of the turnout shown in figure 2.3 between point a and b. The crossing is constructed in such a way that the wheels are supported and it provides passageways for the flanges. The crossing consists of two main parts, the wing rails and the crossing nose.

Wing rail
The wing rails are formed from extensions to the running rail in front of crossing and flare out to non running rails in the body of the crossing.

Crossing nose
The point where the crossing rails meet is also called the crossing nose. In figure 2.7 a crossing nose is shown.

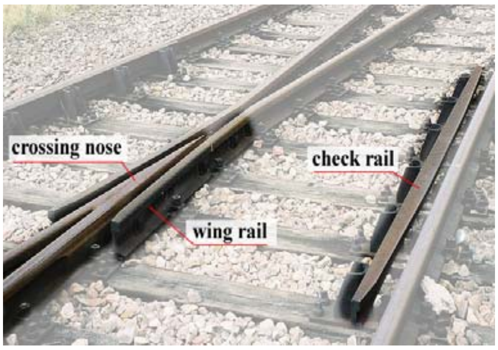


Figure 2.7 Wing rails, frog and check rail

The angle between the centre line of the straight track and the tangent to the centre line at the crossing nose of the diverging track is the crossing angle of the turnout. The layout geometry of a turnout defines the speed that is possible on the diverging route of the turnout and determines what forces are created between the rail and the wheel. Common crossings in Great Britain have angles of 1 in 7 to 1 in 44.5. In Great Britain standard types of switch points and crossings are used. The switch points are categorized with the letters A until H and the crossing is categorized with the crossing angle. The closure rail between the switch point and the crossing is specifically designed for the location. A crossing is for example numbered as a size C11 turnout; this is a crossing with a switch point C and an crossing with an angle of 1:11.

3 Activities during renewal

In this chapter the different activities during the renewal of a S&C unit are described. In parts 3.1, 3.2 and 3.3 the activities for the preparations works, the core works and the follow-up works are mentioned. Part 3.4 and part 3.5 go into more detail about the welding and stressing of the track.

3.1 Preparation works

During the nights before the core works the preparation works are done. During these nights the site is prepared for the work that needs to be done during the core possession. No major track items such as Ballast, Rail, Sleepers or S&C unit are replaced.

3.2 Core works

The core work Possession is the possession in which one or more major track items are replaced. The activities during the core works for renewing a S&C unit are explained below, only the activity of stressing and welding of the rail is described more extensively in part 3.4 and part 3.5.

Taking possession

When taking possession of a track, the track is blocked for trains and the current is isolated and earthed to permit work to be carried out safely. At the same time the workers are instructed on their tasks and safe method of work; and all the necessary paperwork is filled out.

Removal of the existing construction

For the removal of the existing construction of the S&C unit, the rails have to be cut in parts, the sleepers/bearers and rails have to be taken out, suitable for transporting away.

Excavate spoil

Spoil is the old and polluted ballast that has to be removed. All old ballast has to be excavated down to the subgrade, with appropriate crossfall.

Install and compact bottom ballast

The new bottom ballast is unloaded in two layers with a total depth of 25 centimetres (dependent on line category. Each layer is compacted and aligned flat.

Installation of new track

The new sleepers/ bearers and rails are installed on top of the new bottom ballast.

Place top ballast

The top ballast is placed around the sleepers/ bearers. This layer has the same height as the sleeper/ bearer tops.

Tamp top ballast and align track

The top ballast is tamped and aligned with a tamping machine. This machine lifts the track up to the required level and then squeezes the ballast under the sleeper with so called tamping tines. In figure 3.1 the tamping principle is shown. [2]

Welding and stressing of the track

The welding and stressing of the track are complex activities and the main subject of this thesis. Therefore these are explained more thoroughly in part 3.4 and part 3.5.

Testing signalling works and commissioning

Before giving the track back to the traffic the signalling has to be reconnected and tested. The side has to be cleared. When the new track has been approved the track is commissioned to allow the traffic to run.

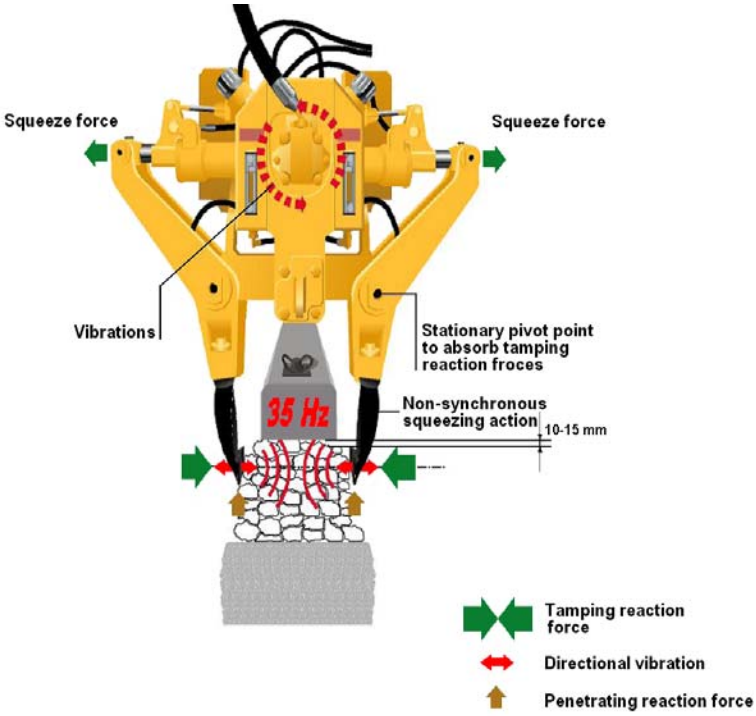


Figure 3.1 Tamping unit

3.3 Follow-up works

After the core possession the track can be used but there may still some activities that need to be finished. These activities will be completed during the follow-up works in the nights after the core possession. As the track consolidates, it is re tamped and levelled, usually up to 3 times, gradually achieving stability and the necessary quality to run at high speed.

3.4 Welding

The joints between the rails can be welded in two ways, by thermic welding or flash butt welding. In this part these techniques are explained.

3.4.1 Thermic welding

The internal joint in the turnout will be alumino thermic welded. Thermic welding is a process which joins metals by heating them with super hot liquid metal from a chemical reaction between a metal oxide and aluminum or other reducing agent, with or without the application of pressure. Filler metal is obtained from the liquid metal.

The parts that need to be welded together are aligned and enclosed in a mould with a gap between the rails. The crucible for the molten metal is preheated with a compressed-gas torch and the rail ends may become heated by this process. A thermic reaction in a crucible above the mould produces molten steel. This reaction is an exothermic reaction or chemical change between iron oxide and aluminum. The most common reactions are shown by equations 3.1 and 3.2.

$$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3 + 181.5kcal \quad (3.1)$$

$$3Fe_3O_4 + 8Al \rightarrow 9Fe + 4Al_2O_3 + 719.3kcal \quad (3.2)$$

In the exothermic reaction, about 20 to 25 seconds is required for separation of the slag from the molten steel. After the slag has floated to the top of the crucible, molten steel is released from the bottom of the crucible. Liquid steel pours down into the mould. The rail ends, which have been preheated, are partially melted by the liquid steel as the mould fills. When the weld is solid the moulds are removed and the excess weld metal is ground off to the proper contour of the rail. [3] In figure 3.2 a drawing of a thermic welding material is shown.

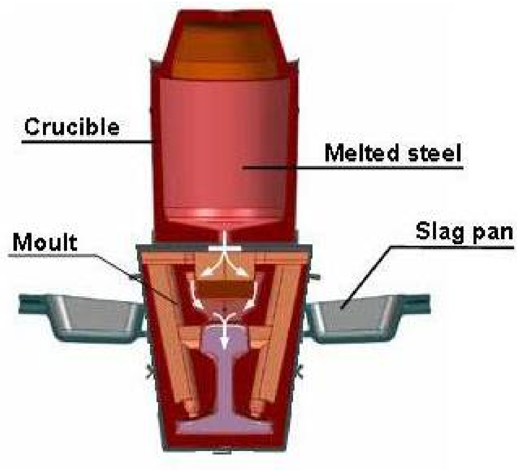


Figure 3.2 Thermite welding

Making a thermic weld is a time consuming process. Making one weld including cooling and grinding, will take approximately 1.5 – 2 hours.

The different steps of the process are divided in parts; preparation, welding and finishing.

Preparation

1. Cutting rail ends to tolerance using a disc cutter (or flame cutter)
2. Positioning of the rail including cutting the rail gap to the correct size
3. Shimming the rail with wedges or alignment beam to correctly align the rails.

Welding

1. Placing and sealing the mould
2. Install crucible
3. Preheating the crucible
4. Ignite the alumino thermic mixture
5. Allow the molten steel to flow into the mould
6. Remove crucible
7. Remove mould
8. Shear weld
9. Check weld

Finishing

1. Cool down period
2. Grinding of the rail head
3. Weld inspection

The advantages and disadvantages of thermite welding are pointed out below:

Advantages:

- Flexibility of the process to weld, particularly in small areas.
- Portability of the materials.
- Cheaper (for small numbers of welds) because there is no expensive machine necessary.

Disadvantages:

- Speed of the welding process.
- Lower quality than with flash butt welding
- Weld material is different from rail material
- Time required for cooling the weld prior to loading (minimum 45 minutes).
- Many process steps that can be affected by the welders performance and/or the environmental conditions; e.g. the rail end gap, quality of the mould packing job, duration of preheat, moisture in the air, time duration until moulds are removed, rail interference during weld solidification.

3.4.2 Flash butt welding

The joints in the plain line and the closure welds will be flash butt welded. Flash butt welding is a form of resistance welding that involves pressing two ends together, while simultaneously running a current between them.

Flash butt welding uses a flash to provide enough heat to soften the ends of the rails to be welded, to near-molten temperatures. As the rails are moved together, small areas come in contact, and through resistance heating, become overheated. These high-temperature areas burst out as tiny bits of molten steel. Once the rail ends are hot enough, the joints are forced together to form a weld. This has the effect of forming a joint between the two metals that is free of oxides as the surfaces of the two joining rails are forced out the sides of the joint. The welding head automatically shears this upset metal to within 3 mm of the rail profile. The whole process is computer-controlled.

As a final step the head of the rail is ground to the profile of the parent rail. For each weld the flash butt welding process consume 30 mm off the track. This overlength is consumed at the side with the least resistance. A flash butt welding machine is shown in figure 3.3.

Figure 3.3 Flash butt welding machine

SuperWeld (part of VolkerRail) combines electric flash welding with securing (or restoring) neutral temperature by means of super pulling technology. This technique is used to make the closure welds at stress free temperature length. This is a proven technique in the Netherlands, but the stressing technique has yet to achieve client approval in Great Britain.

The complete welding process is defined in three steps: preparation, welding and finishing. Below the different steps are described.

Preparation

1. Cleaning the rail ends
2. Cleaning and grinding the web of the rail
3. Loosen the fastenings

Welding

1. Adjust welding head and rail positions within rail head
2. Weld
3. Remove superfluous melted material (shear upset)
4. Remove welding head
5. Check weld

Finishing

1. Cool down period
2. Grinding of the rail head
3. Reinserting the fastenings

The advantages and disadvantages of flash butt welding are pointed out below:

Advantages:

- High weld quality because there is no material addition.
- Automated remote control system, so manual welding skills are not necessary.
- Cycle time to make the weld is three to six minutes.
- Pre- and post heating are not necessary, so productivity and quality are not affected by weather, temperature, or delays caused by other factors.
- The time to cool the weld prior to loading is considerably shorter than the thermic welding (15 minutes)

Disadvantages:

- Heavy equipment, thus a crane is needed.
- It is not possible to weld in small areas, like a turnout.
- More expensive, unless large numbers of welds (20+) are done in one shift.

3.5 Stressing

In conventional track, the rail ends are joined together mechanically, leaving a gap between the rails to allow for thermal expansion. However, these joins weaken the track structurally, and increase the track maintenance cost and loads on the running trains.

In continuously welded rails (CWR) the rail ends are welded together. The CWR has many advantages compared to the jointed track. The use of CWR prevents high impact loads at the joints on the track and the train. Therefore the passenger comfort improves, the required maintenance decreases and higher speed traffic is possible.

However due to temperature differences high compressive stress (at high temperatures) or tensile stress (at low temperatures) may occur. At low temperature this can cause failure of welds with small imperfections, leaving a gap of several centimetres, potentially causing a train to de-rail. At high temperature the compressive stress can cause the track to buckle.

The normal force in the rail due to the temperature differences can be described with equation 3.3 [2].

$$N_{temp} = -E \cdot A \cdot \alpha \cdot \Delta T \tag{3.3}$$

With:

N_{temp} =	Force in one rail due to the temperature differences [N]
E =	Young's Modulus of the rail [N/mm^2]
A =	Rail cross section area [mm^2]
α =	Linear expansions coefficient of the rail [1/˚C]
ΔT =	Temperature difference between the SFT and occurring rail temperature [˚C]

To achieve the best balance between the high tensile stresses causing possible rail break and the high compressive stresses, the rail is stressed to 27^{o}C (Stress free temperature). The rails are fastened to the sleepers at the Stress Free Temperature. This is the temperature at which the track is free from thermal stresses. According to the Network Rail specifications for continuous welded rail, the SFT has to be 27˚C [14].

The stress free temperature of the rail can be achieved by heating the rails causing them to expand or by stretching the rails to the length that corresponds to the length at the SFT. The heating of the rail is a not approved working method in Great Britain.

Currently the most commonly used method to achieve the SFT is the stretching of the rails with tensors to the equivalent SFT length. The tensor clams the rails that have to be stressed and pulls them with hydraulic force towards each other. Thermal Stressing of the rail is not yet an approved working method in Great Britain.

The following specifications apply for tensor stressing according to the guidelines for continuous welded rail (CWR) track from Network rail [14]:

- Stressing is not possible at a rail temperature higher than the SFT.
- The bottom and top ballast has to be installed and be of good quality and depth.
- The overall track condition has to be acceptable.
- The minimum length of CWR to be fastened down to form an anchor shall be as in table 3.1.

Table 3.1 Anchor lengths

Track conditions	**Minimum anchor length**
High resistance – where all fastenings are new, all present, installed with the correct tools and in good condition with all pads and insulators in place and good consolidated ballast conditions	30 m or three sleepers per degree Celsius temperature difference from the proposed SFT, whichever is greater
Standard resistance – other sleepers with integral housings and good consolidated ballast conditions	90 m
Low resistance – base plated sleepers and early designs with screw fastenings, or where ballast conditions is poor or where adjustment switches exist	135 m

- The outer and inner tell-tales have to be marked. Tell-tales are marks made on each rail in line with a suitable reference mark on an adjacent unclipped sleeper, in order to monitor the effectiveness of the anchor length. A tall tale is required at each end of each anchor length; the one adjoining the free rail is the inner tell-tale (ITT), the other is the outer tell-tale (OTT).
- The unclipped rails have to be lifted clear of all obstructions and placed on solid rollers positioned at intervals not exceeding 12 sleepers. The rail pads on the sleepers where the rollers are located must be temporarily removed to reduce the resistance to rolling. In figure 3.4 two examples of stressing rollers are given.

Figure 3.4 Stressing rollers

- The rail extension required, to produce a stress free condition at the SFT, shall be calculated by equation 3.4.

$$e = 1000 \cdot L \cdot \alpha \cdot \Delta T \tag{3.4}$$

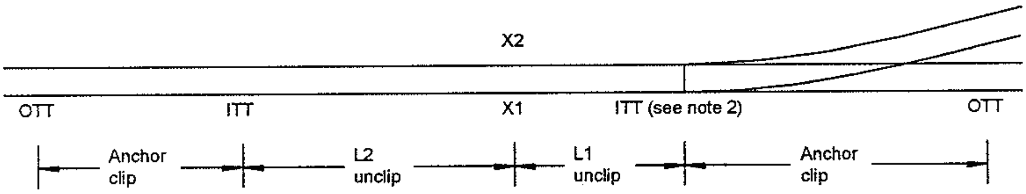
With:
e = Extension [mm]
L = Length of free rails [m]
α = Expansions coefficient of the rail (0,0000115 per ˚C for normal grade rail) [1/˚C]
ΔT = Temperature difference between the SFT and occurring rail temperature [˚C]

- The pull force appropriate to the rail temperature can be calculated with equation 3.5.

$$F = W \cdot \Delta T \cdot 0.01543 \tag{3.5}$$

With:
F = Tensor pull force [tonnes]
W = Rail weight per yard [lbs/yd]
ΔT = Temperature difference between the SFT and occurring rail temperature [˚C]

- To stress the new track or S&C unit, a part of the adjacent track has to be unclipped. In figure 3.5 and figure 3.6 the length that has to be unclipped for stressing at the front and the rear of the crossing, is given. To calculate the required extension and force, the length $L = L_1 + L_2$ is used. Stressing of the switch is mandatory for switches with a length larger than 20 meter. Figure 3.7 shows how this has to be done.

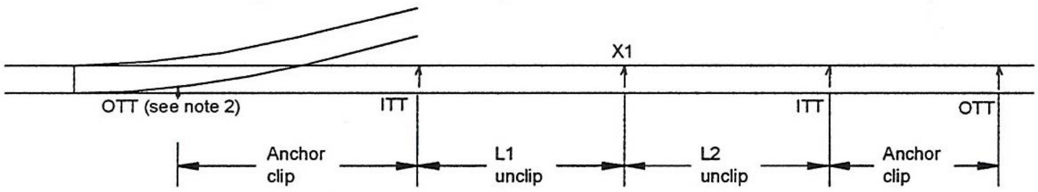


X1 and X2 are pulling points
OTT = Outer tell tale
ITT = Inner tell tale

L1 = 18m approx
L2 = 90m

Notes
(1) The ITT next to the switch toe shall be on the first plain sleeper, which shall be unclipped
(2) Switch toes must be maintained square, it may therefore be necessary to stress both half sets

Figure 3.5 Stressing at the front of the turnout

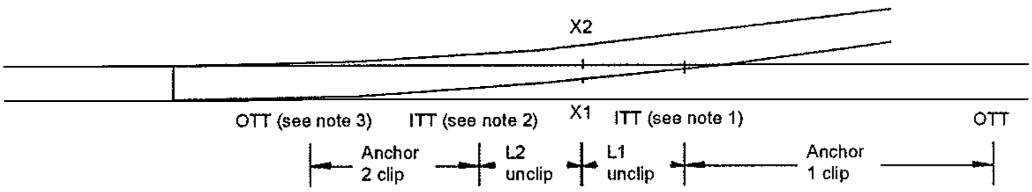


X1 pulling point
OTT = Outer tell tale
ITT = Inner tell tale

L1 = 18m min, but ideally equal to L2
L2 = 90m min

Notes
(1) Reference points required in L1 or L2 if the length excedes 90m
(2) OTT nearest the switches to be on the switch heel bearer, bearer unclipped from all rails
(3) For anchor lengths see table 2
(4) If the crossing has been installed/replaced then both rails on both roads shall be stressed

Figure 3.6 Stressing at the rear of the turnout



X1 and X2 are pulling points L1 = L2 ideally
OTT = Outer tell tale
ITT = Inner tell tale

Notes
(1) ITT on bearer next to wing rail joints/welds, bearer unclipped from all rails
(2) ITT at an anchor length of 3 bearers per degree or 30m from OTT
(3) OTT on the first fastening at the switch heel
(3) For anchor lengths see table 2
(4) Through road shown, turnout road is the same method

Figure 3.7 Stressing between switch heel and crossing

- A turnout and a cross-over have to be stressed in the sequence shown in figure 3.8.

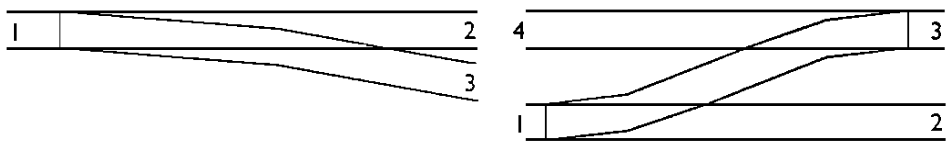


Figure 3.8 Sequence for stressing common S&C layout

The steps for making a closure are given below:

1. Identify the position and lengths of the anchors, lengths to be pulled, and pulling points
2. Mark the outer and inner tell-tales, any reference points and the pulling point.
3. Cut the CWR at the pulling point
4. Unclip the rails from the pulling point towards the inner tell-tales.
5. Place unclipped rails on rollers.
6. Check tell tales
7. Measure rail temperature.
8. Calculate the extension of the rails
9. Mark the calculated extensions at the pulling point and at any other reference points.
10. Cut the rails at the pulling point to allow for the calculated extension and the welding gap.
11. Fit tensors and apply tension to both rails until the required extension is achieved.
12. Check for any further movement of the inner tell-tale to ensure that the anchors have held.
13. Cut the rails again if necessary to produce the correct welding gap and complete the welding at the pulling point, with the tensors in position.
14. Remove all rollers. Replace all pads, insulators and clips.
15. Remove tensors. Remove welding debris. Fill cribs with ballast.
16. Clip all the fasteners.

To calculate the pulling force at a certain temperature difference is in Great Britain done with equation 3.5 and in the Netherlands done with equation 3.6. The difference between the equations is that in the English equation the weight is a rail type dependent variable and in the Dutch equation the cross section of the rail is the rail type dependent variable. The relation between these two variables is dependent on the density. This is a constant value for steel. In the constant of 0.01543 these different constant values are combined. In the force is calculated for a few rail types at a temperature difference of 20 ˚C. The difference between the two forces is smaller than 1.1 % of the force calculated with equation 3.5.

$$F_{GB} = W \cdot \Delta T \cdot 0.01543 \tag{3.6}$$

$$F_{NL} = \alpha \cdot \Delta T \cdot E \cdot A \tag{3.7}$$

With:
F_{GB} = Tensor pull force [tonnes]
F_{NL} = Tensor pull force [N]
W = Rail weight per yard [lbs/yd]
ΔT = Temperature difference between the SFT and occurring rail temperature [˚C]
α = Expansions coefficient of the rail (0,0000115 per ˚C for normal grade rail) [1/˚C]
E = Stiffness of the rail (210000 N/mm^2 for steel) [N/mm^2]
A = Cross section of the rail [mm^2]

Table 3.2 Calculated pulling force with different equations

	UIC 54	**BS 113 A**	**UIC 60**
A [mm^2]	6934	7183	7687
W [lbs/yd]	109,73	113,68	121,64
F_{GB} [kN]	338,6	350,8	375,4
F_{NL} [kN]	334,9	346,9	371,3

For track construction, ballasting and tamping following track laying will smooth out irregularities in track line and level but this may tend to lower Stress Free Temperature, if the slues and lifts are greater than the permissible limits (variable but circa 25+mm)

4 Renewal of a S&C unit

For the renewal of a S&C unit the old turnout has to be removed and a new one has to be installed. According to the regulations also 36 meters (two panels of 18 meters) of plain line at the front and the rear of the turnout have to be renewed to achieve a good run in and out of the S&C. Next to the 18m panels, the so-called ramp is build using old sleepers and rail, gradually increasing the amount of new ballast from the existing level to the full depth of the dig to create a transition effect. The length of the ramp is determined from the line speed.

At the maintenance and renewal of the plain line the 36 meter in front of the turnout is tamped but because tamper has to run out before the S&C and the S&C tamper does not tamp sufficient plain line therefore neither does a very good job. Therefore it is put in the regulations that this has to be done while renewing the S&C unit. The diagram in figure 4.1 shows the S&C Unit and a couple of track panels that have to be renewed during the S&C renewal.

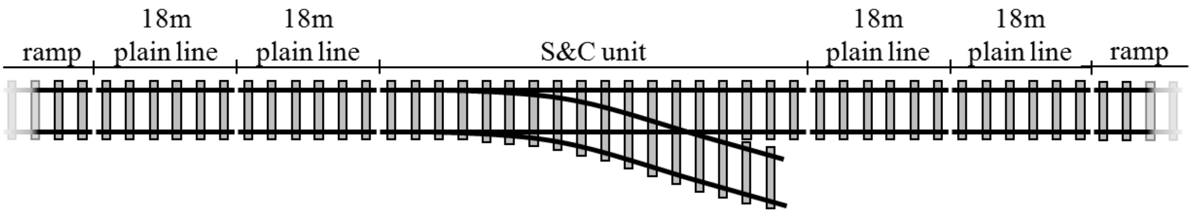


Figure 4.1 Panels that have to be renewed

Currently this renewal takes place in a weekend because with the current working method it takes 56 hours to renew the ballast, a S&C unit and the plain line and ramp before and after the turnout. Network Rail wants to do this renewal within a period of 8 hour, to reduce the possession time and weekend traffic disruption as well as creating opportunity for more work to be done on weekday nights. VolkerRail in combination with Corus and Vossloh (VCV) has investigated this and developed a new working method with a modular S&C system. In sections 4.1 and 4.2 the current and the new working methods are described.

4.1 Current working method

The working method to renew a S&C unit, that is described here is the method currently used in Great Britain. The working method can differ a little bit depending on the contractor and the machines used . The most important steps in the renewal process are described.

The preparation work of the existing working method consists of inspection of the site and if necessary the pre assembly of the new S&C unit close by.

The shift for the renewal starts with taking possession of the track and isolation of the overhead wires (where present) and the preparation of the site. All the materials arrive at the site and the machines are prepared for the work. The first task is cutting the long wooden bearers of the turnout with a chainsaw and cutting of the rails in sections suitable for removal from site by the chosen means.

The rails and sleepers are lifted in panels of approximately 20 meter and placed next to the working area, where they can be demolished to be transported in parts or they are directly lifted onto a lorry or a train for transportation. After removal of the panels, the ballast is removed with excavators. During this work the cables and pipes are diverted, disconnected or protected.

New bottom ballast is unloaded in two layers (not exceeding 150 mm each) and aligned flat with a remote controlled triple whacker. A triple whacker is a vibrating plate compactor. On top of the bottom ballast the S&C unit and the plain line are installed. In the plain line, the sleepers are installed first and afterwards the rails. In Great Britain the S&C unit is assembled and tested in the factory. After approval by the client the S&C unit is match marked, dismantled into loose elements and brought to the site. For installing the turnout on site two different methods are used in Great Britain:

- The turnout arrives in loose elements and is assembled at the location. To assemble one S&C unit takes about 48 hour. Therefore this method is only used in a renewal periods of one weekend.
- The turnout arrives in loose elements and is assembled close to the location during preparation works while the track is still in use. When the track is out of service the assembled turnout is moved into place by special cranes or portable gantries (PEMs and LEMs). Large Kirow Cranes are now the most commonly used method In Great Britain.

Figure 4.2 Kirow crane

The joints in the plain line and the S&C unit are temporally connected with fishplates and clamps so the ballast wagons can unload the top ballast. The ballast layer is tamped and aligned.

When the tamping is finished the S&C unit can be adjusted and the signalling systems can be reconnected and tested. The track and other functional checks are undertaken before the site can be cleared and the track is handed back to the traffic.

The welding and stressing of the track is done in the follow-up works after the installation and tamping of the top ballast and achieving the final alignment. All the joints are thermic welded and the S&C unit and the plain line are stressed to the stress free temperature. The track is checked again and lifted/realigned if necessary over the days and weeks following to ensure the correct quality has been achieved

The work is currently executed as a sequence of events.

4.2 New working method

The new working method developed by VCV is a working method to renew a turnout within a period of 8 hours to reduce the possession time and increases infrastructure availability for the client. The new method shall allow for better track quality and a reduction in the life cycle costs.

With a combination of improvement of existing methodologies combined with the development and the introduction of new equipment, VCV developed a modular S&C method to renew a S&C unit. The main principles of the new working method will first be described and afterwards the differences with the existing working method are explained.

In the nights before the renewal preparation work is done. These works include the realigning, temporarily removal of obstruction and if necessary, renewing or relocating the cables and pipes. The signalling systems to be installed are “plug and play” systems to reduce the time on site. The S&C layout will have been set up previously at the manufacturer and tested for functionality with all the plug and play components.

At the beginning of the 8 hour period, all the material and machines arrive in two trains at the working area. There the trains are split and the bearer (switch and crossing sleeper) cutting machine and the Kirow cranes starts preparing to work. The bearer cutting machine is a specially engineered track, mounted machine, produced to incorporate the use of tried and tested (existing) cutting techniques. In figure 4.3 an animation of the machine is shown.

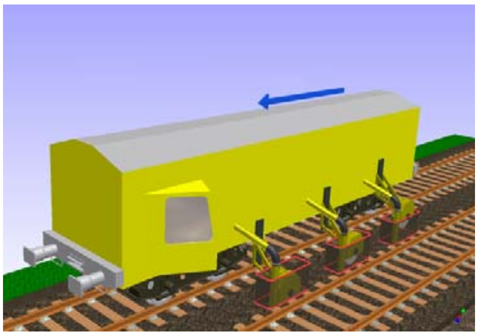


Figure 4.3 Bearer cutting machine

The tilting wagons with the S&C panels are unloaded next to the site to start with the first thermic welds because these take a lot of time. Also heating blankets are installed on the S&C panels. The heating blankets warm the panels to the stress free temperature so they do not have to be stressed.

Meanwhile the rails of the plain line are cut and the track is lifted out in panels of 20 metres. With specially engineered, rail mounted, excavators the ballast is removed and the subgrade is levelled to profile. Behind the excavation of the old ballast, geotextile and a new ballast layer must be laid and compacted in at least two layers. This is done with a Ballast Laying and Compaction Machine (BLCM). In figure 4.4 a, b and c functional options for the BLCM are shown. From left to right a geotextile and ballast support laying system, a first ballast layer system with compactor and a second or further ballast layer system with whacker compaction can be seen.

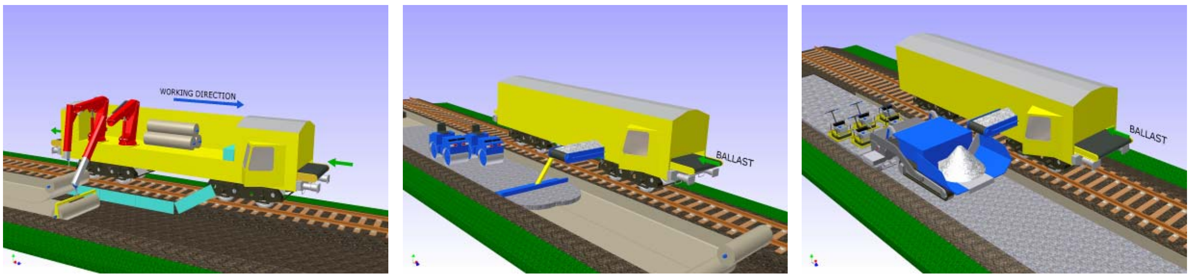


Figure 4.4 a, b, c Ballast laying and compaction machines

The panels of the S&C unit, which come to site on special wagons or have been pre assembled on site, are lifted into place with a tandem lift of two Kirow cranes. The rails are wrapped in heating blankets when they arrive to ensure they can be welded at SFT without stressing pulls. The last panels of the S&C unit are installed with one crane. While the plain line panels are being installed, the last thermite welds in the turnout are made.

During and after the installation and before the top ballast, all the joints in the plain line are welded and stressed to the stress free temperature with the Flash Butt Welding Machine and the puller. When the plain line is stressed the heating blankets which have kept the S&C temperature at SFT are removed and the top ballast can be installed and tamped.

The “plug and play” system of the signalling equipment is connected. Before clearing the site and handing it back to the traffic, the track is tested and commissioned.

When a cross-over has to be renewed, in the first 8 hours one turnout will be replaced. The track will only be usable in the through direction (see figure 4.5). In the second 8 hours the other turnout will be renewed and connected so the cross-over can be used in all directions.

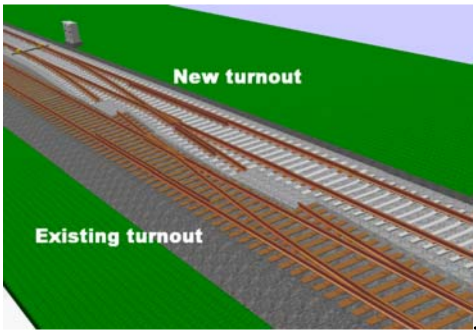


Figure 4.5 Situation after first 8 hours

This working method is unsuitable for a single line, because a service track next to the working area is needed. So a single turnout without an adjacent line is not suitable for this new working method. Single line working is not possible during core works.

The new working method is much quicker than the existing working method. The biggest saving in time is parallel working instead of working in a sequence of events. For example the welding of the first thermite welds in the S&C unit is done next to the track while the ballast is being renewed. The preassembled modular panels should make the installation of the new track much faster and the quality much better. In figure 4.6 the difference in time per activity for a crossing is shown.

Furthermore the switch operation equipment is tested at the assembly area reducing the required signalling working times from 2 hours to 45 minutes.

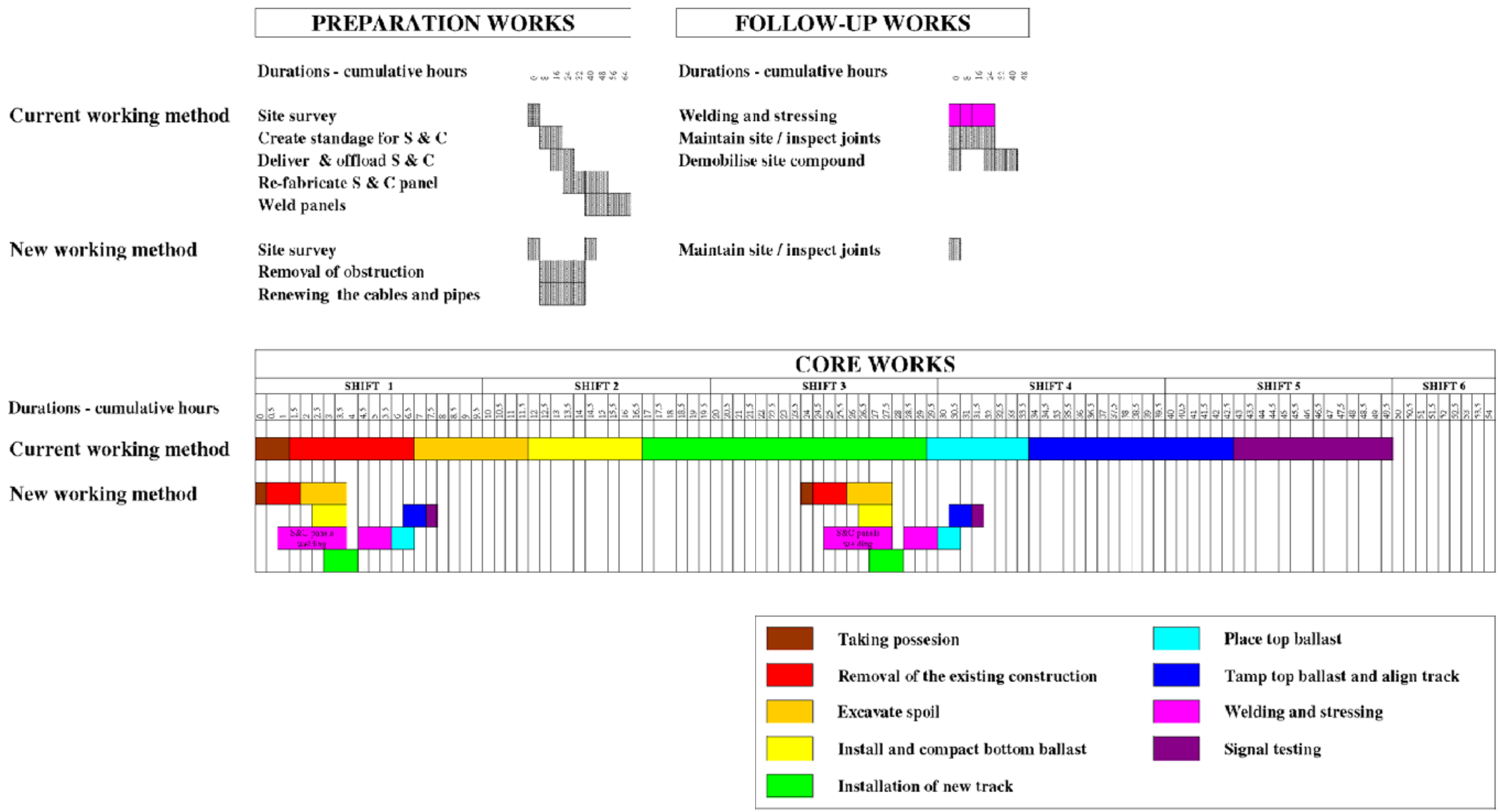


Figure 4.6 Time per activity for renewing of a crossing for the working methods

4.3 Challenges

The new working method still has a lot of challenges. In this part the challenges will be described. Fist the suggestions for the equipment design will be discussed and afterward the challenges around the stressing are explained. In the last part the problems for installing the plain line and the ramp are described.

New equipment

Next to the equipment that has to be developed there are also some client standards that will need modification to implement this new equipment. First of all, all the new equipment including: bearer cutting machine, ballast laying and compaction machine and the heating blankets, have to be approved by Network Rail. Also the working methods of these machines have to be approved. For instance the use of the Flash Butt welding machine in combination with the puller is a proven technique in the Netherlands, in Great Britain this type of welding is not yet approved for making closure welds.

The heating of the rail to bring the rail to the SFT is a technique that is not yet proven and hence not yet an approved working method in Great Britain. Therefore the process surrounding the stressing of S&C track using heating blankets has to be approved before they can be used for stressing S&C

Plain line and ramp

When replacing the S&C unit, 36 metres of plain line has to be renewed and the so-called ballast ramp have to be renewed at each end of the turnout. The ramp is gradually increasing the amount of new ballast from the existing level to the full depth of the dig. At the ramp the old rails have to be loosened and placed next to the ballast bed without cutting the rails. The sleepers are removed and after installing the new ballast ramp placed back on the compacted ballast bed.

The loosening of the rails and removing of the sleepers a few a time is a time consuming job. Within the 8 hours time period this is not possible. Therefore a solution has to be found which will be acceptable to Network Rail as the whole reason for the sleeper panels and ramp is to provide a run in to the new S&C. The objective may not be achieved by renewing these separately.

Stressing

In the new working method the top ballast is installed after making the closure weld. This is in conflict with the requirements of the client’s standards and therefore acceptable alternatives have to be developed and agreed with the client. Also the S&C unit is already adjusted and not allowed to move more than 4 mm at the switch point. The goal of this report is to find a solution for these challenges.

5 Problem definition

The stressing and welding of the S&C units are a time consuming processes. There are still some parts of the process of which are not validated as possible. This results in the following problem definition:

Is it possible to stress the S&C unit and the plain line to the stress free temperature length within the time limits of the new modular S&C method? The following aspects are important:

- Is the ballast resistance sufficiently small to stress the plain track to the required length, within the allowable displacements?
- What is the best sequence to weld and stress the S&C unit and the plain line to the stress free temperature length staying as close as possible to the NetworkRail best Practice guide?

5.1 Goal

The objective of this thesis is to find a working sequence to achieve a stress free temperature in a renewed S&C unit and the adjacent plain line, satisfying the requirements as set within the world class installation method.

5.2 Program of requirements

The requirement of the world class installation method is given below. The solution for the stressing problem has to satisfy these requirements.

- The stress free temperature is 27˚C
- 36 meter plain line and a ramp at the front and at the rear of the turnout have to be renewed with the S&C.
- The maximum allowable temperature difference between the SFT en the temperature at which the S&C unit is being stressed is 30˚C.
- The closure weld in the plain line needs to be stressed with pullers (stressing equipment).
- All the welds in the plain line will be flash butt welds, due to time constrains.
- The working method has to be usable for all weather circumstances

5.3 Assumptions

Because of the wide variety of working methods and regulations and a lack of theoretical background of some processes, the following assumptions are made:

- The allowable displacement at the switch point has to be less than 4 mm
- The allowable displacement difference between the switch point and the through rail has to be less than 2 mm
- The transportation of the adjusted and tested S&C unit shall not damage the set up so that any rework is required.
- The S&C unit and the plain line are not on a curve.
- The length of the ramp is 20 metres.
- The pulling force introduced by the pulling equipment is equal both rails pulled by the equipment.

Part 2 Ballast behaviour

In this part the ballast behaviour and the parameters that cause the variation are explained. And a description of the longitudinal ballast resistance tests and the results of the test are given.

6 Ballast resistance

The ballast supports the track in the longitudinal, lateral and vertical directions. In this section on ballast behaviour, the support is described for the behaviour of the sleeper in the ballast. The forces in all three directions working on the sleeper are transferred to the ballast via friction at the bottom, side and end of the sleeper as well as the resistance horizontally and laterally from the ballast between the sleepers and at the sleeper ends (see figure 6.1).

The following sections deal with the ballast behaviour in the three directions.

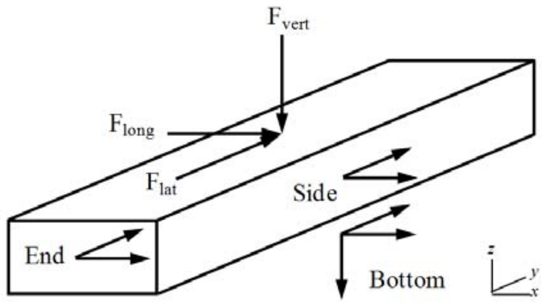


Figure 6.1 Sleeper with its loads and reactions

6.1 Longitudinal ballast resistance

In a well designed and maintained track mechanical and thermal loads are resisted without excessive deformation of the track structure. The longitudinal force of the train on the track and the thermal loads by temperature differences are resisted by friction on the foot of the sleepers, longitudinal resistance from the ballast in the beds and tension in the rail below the SFT.

The longitudinal ballast resistance is a combination of the resistance of the ballast at the sleeper side and bottom.

The longitudinal displacement of the track is a combination of the longitudinal movement of the rail with respect to the sleeper and the longitudinal displacement of the rail-sleeper system through the ballast. Normally slip will arise in the ballast because it is common to have a larger longitudinal fastening strength (so that there is no creep between rail and sleeper), than the longitudinal resistance of the ballast to sleeper movement.

There is a large variation in longitudinal resistance from ballast strengths due to: sleeper type, ballast type, sleeper spacing, ballast compaction and vertical load, will be discussed.

Sleeper type

In CWR-track concrete, wooden and to a limited extend steel sleepers are used.

A wooden sleeper is made of different types of wood. Its mass is about 100 kg. The sleeper is prismatic in shape with a cross section of 125 mm high and 250 mm wide and the length is 2.60 – 2.70 m. At switches and crossings the timber bearers would be typically 150 mm high, 300 mm wide with lengths up to 5.50 m.

There are two basic types of concrete sleepers: monoblock sleepers with an almost constant cross section and twin-block sleepers, which consists of two blocks of reinforced concrete connected by a steel coupling rod or pipe. The mass of the concrete sleeper is between 200 and 300 kg. Its dimensions are similar to wooden sleepers but generally narrower and deeper.

Concrete sleepers are heavier than wooden sleepers, which is an advantage with regard to the longitudinal resistance of the track because the friction force at the bottom of the sleeper is higher and the physical mass of the sleeper resisting the movement is much higher.

With track renewal wooden sleepers are usually replaced with concrete sleepers. Timbers, however still have high usage in S&C due to the flexibility offered for difficult layouts and their ability to be configured in any pattern.

Ballast type

Different types of ballast have different particle sizes, particle shape and different loading strength. These influence the longitudinal resistance. For instance broken ballast particles interlock better into each other than rounded ballast particles and therefore the longitudinal resistance is larger.

Sleeper spacing

Sleeper spacing is the centre to centre distance between sleepers. A sleeper spacing of 0.60 m is common. Historically, in some lightly loaded CWR track this distance may be increased to 0.75 m, but is unlikely in renewals.

According to research done by the Indian Railway Institute of Civil Engineering [3] the ballast resistance per sleeper decreases as the sleeper spacing reduces, but the ballast resistance per unit length of track remains more or less constant for sleeper spacings larger than 0.65 m. For smaller sleeper spacing the value of the longitudinal ballast resistance will increases due to heavier track structure. GREAT BRITAIN view is that more weight and more friction provide much better resistance to movement and lightweight CWR is only created in low category lines.

Ballast compaction

When the track is laid without compaction, the longitudinal ballast strength is small. This can be increased by compaction of the bottom ballast. Due to further compaction, including that from trains traversing the site, the longitudinal strength increases over time. The longitudinal resistance when only the bottom ballast is installed is low because the ballast is compacted to a level surface.

Tamping of the track improves track geometry but dramatically reduces the longitudinal ballast strength. After a couple of passages of trains the strength improves again. If it is necessary to speed up this process track stabilizers can be used. This is a machine that simulates the passing of a certain amount of trains.

Vertical load

Vertical stresses between sleeper and ballast as a result of vertical load affect the longitudinal resistance to movement at the bottom of the sleeper. Results of measurements performed by van ‘t Zand and Moraal are presented in figure 6.2. These tests were performed with a test track that consists of two UIC54 rails of 3 m length, 5 prestressed concrete NS 90 sleepers with Vossloh fastenings and a layer of crushed stone ballast (30/63) with a thickness of 30 cm under the sleepers.

The friction coefficient found in the tests performed by ‘t Zand and Moraal is 0.75.

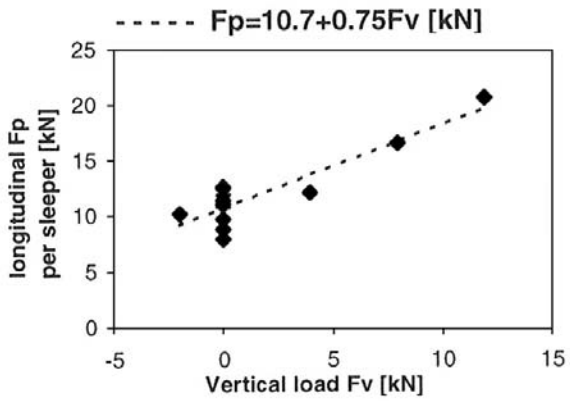


Figure 6.2 Longitudinal peak strength F_p versus vertical load F_v

6.2 Lateral ballast resistance

The lateral ballast resistance is similar to the longitudinal ballast resistance dependent on the same parameters: sleeper type, ballast type, ballast compaction and vertical load. Also the ballast profile with the shoulder width and height are of influence on the lateral resistance (see figure 6.3). Raising the height of the ballast profile considerably increases the lateral ballast strength.

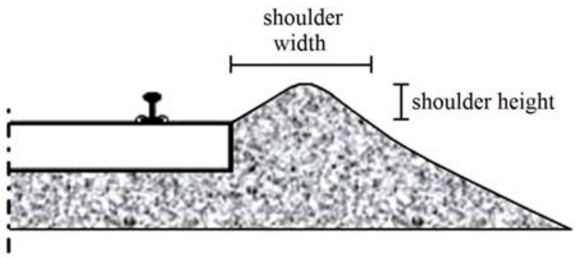


Figure 6.3 Shoulder width and height

6.3 Vertical ballast resistance

The ballast is loaded vertically by the load of the track structure and the vertical axle load of the trains. Due to these loads the sleeper will move vertically at the interface with the ballast before it is fully compacted and after some time running under traffic when the ballast has begun to settle following tamping and voids are developing. The vertical ballast resistance limits this deformation. To avoid fatigue problems minimum vertical design stiffness is required.

A generally accepted model for the vertical ballast behaviour is a beam supported by vertical, linear-elastic springs, known as a *Winkler foundation*. A typical value for the vertical spring stiffness is 100 kN/mm per meter of track.

7 Ballast resistance tests

To determine the ballast resistance behaviour some experiments were done. This thesis examined the behaviour of the track during stressing operations in the longitudinal direction. In this thesis there is only looked at a switch in a straight track, therefore the lateral and vertical resistance are not part of the experiments. The tests were done on two test panels of one of 9 meter and one of 40 meter of plain line track. The track consist of two UIC54 rails, prestressed concrete NS90 sleepers with Vossloh fastenings and a prepared layer of compacted crushed stone ballast (31,5/50). The measurement report is added in appendix A. Ballast type is important. For a meaningful test for NWR it has to be done on granite ballast to their specification, flakiness and shape.

The plan view of the tests are shown in figure 7.1 and figure 7.2.

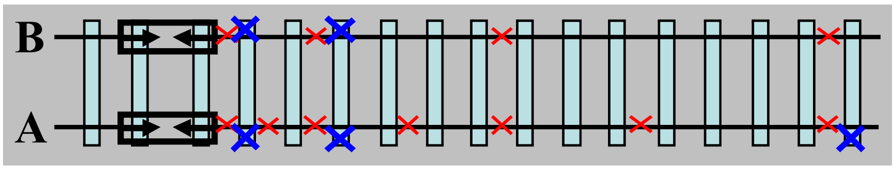


Figure 7.1 Top view 9 meter test panel

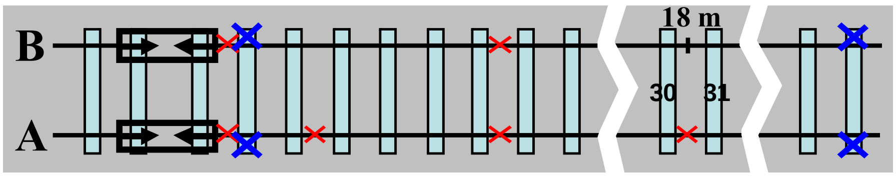


Figure 7.2 Top view 40 meter test panel

The loading in the longitudinal direction was done with the pulling equipment normally used for stressing the rail. The strain in the rails and the displacement in longitudinal direction were measured at several places. These locations are marked in figure 7.1 and figure 7.2 with a red cross for the strain and a blue cross for the displacement.

The tests were done in three series.

1. the test on the 9 meter test panel **without the top ballast layer** (tests 1 to 6).
2. also on the 9 meter test panel but **with the top ballast layer** (tests 8 to 12).
3. the test on the **40 meter** test panel (tests 18 to 21).

In the first series an additional vertical load of 6 sleepers was added in the third and fourth tests and a load of 13 sleepers at the fifth and sixth tests.

The results from these tests give a good indication about the maximum longitudinal resistance force, but for a good scientific proof more tests will need to be done.

The result from the tests *without* the top ballast layer and without extra weight show an average maximum longitudinal resistance force of 2.23 ±0.60 kN per sleeper. This can be seen in figure 7.3.

In figure 7.4 the results of the tests *with* the top ballast layer are shown. An average maximum longitudinal resistance force of 7.20 ±0.85 kN per sleeper can be seen in this graph.

The influence of the vertical force on the longitudinal ballast resistance peak force measured without the top ballast layer is shown in figure 7.5. Extra weight on top of the rail increases the resistance between the ballast and the rail. With extra weight equal to the own weight of the sleeper, the resistance almost doubles. From these test the friction coefficient found is 0.3796.

Because of the noise on the measured data, the data from the extra strain-gauges were not analyzed. Only the data from the strain-gauges directly behind the pulling equipment were used for the analysis.

The use of the test result for the validation of the model is described in chapter 10.

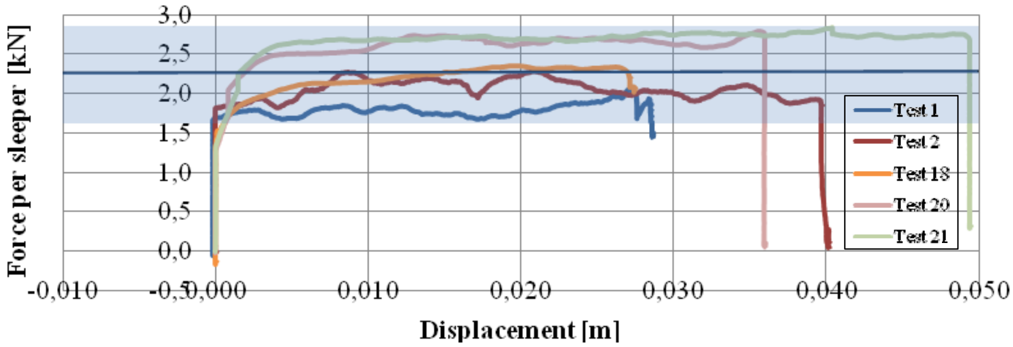


Figure 7.3 Longitudinal resistance force per sleeper without top ballast

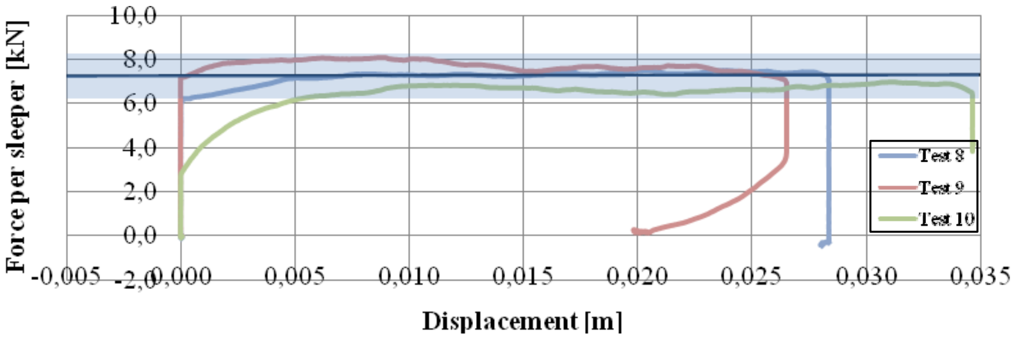


Figure 7.4 Longitudinal resistance force per sleeper with top ballast

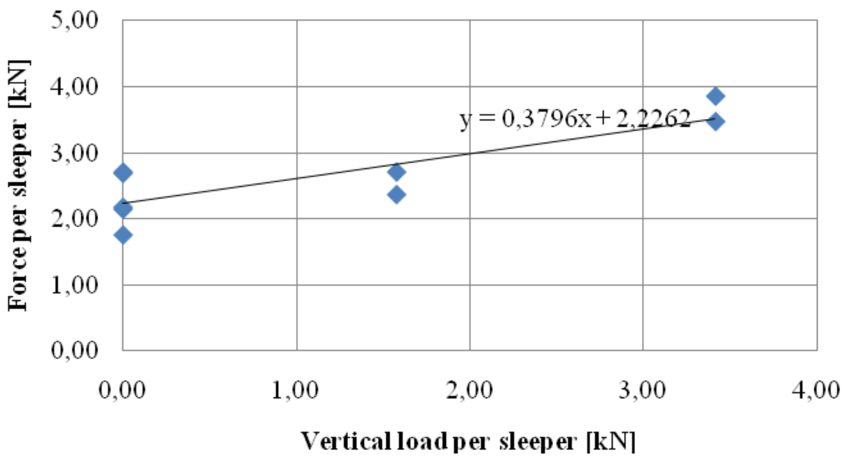


Figure 7.5 Influence of the vertical force on the longitudinal resistance

Part 3 Model Longstab

To analyze the behaviour of a S&C unit a model S&C unit was made. With the result from the tests described in part 2 this model is validated by using a model of a plain line. To model the S&C unit and the plain line the program Longstab is used. The program is a finite element program developed by M.A. Van for the PhD thesis called ‘Stability of continuous welded rail track’ [6]. In this part the models of the plain line and the S&C unit are explained. Afterwards the validation of the model and the analysis done with the model are described. And at the end the conclusions of the model are given. In Appendix B a document that describes the numbering of the nodes in both the models is added.

8 Plain line model

The track structure of the plain line is modelled as shown in figure 8.1. The model consists of beam elements and springs. The rails and the sleepers are modelled as beams and the fasteners and the ballast are modelled with the springs. A description of the type of elements, their properties and the way of supporting the nodes is described in the paragraphs below.

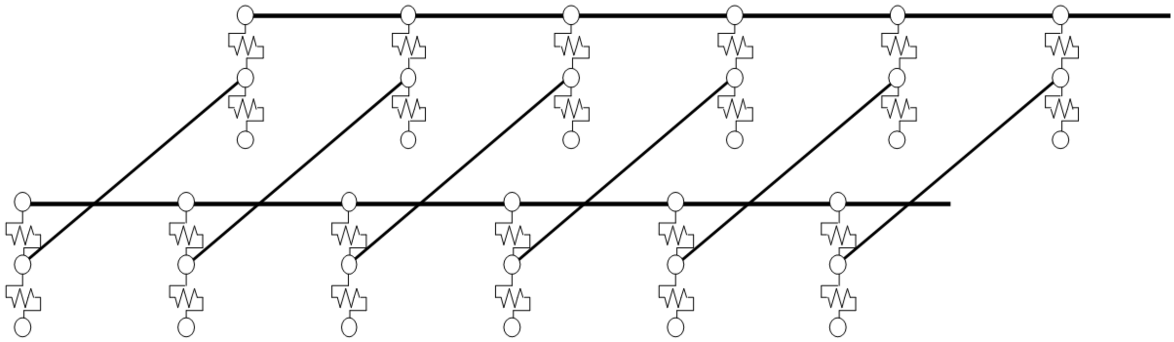
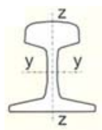
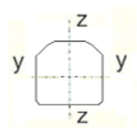


Figure 8.1 Model track structure

8.1 Beam elements

The beam elements represent the rails and the sleepers. The beam elements are a geometrically non-linear beam element. They have a bending and a shear stiffness in two perpendicular directions and an axial and a torsional stiffness. The properties of the beam elements are given in table 8.1.

Table 8.1 Properties of the beam elements

	Rail UIC54 	**Sleeper NS90** 
Stiffness E [N/m]	$210 \cdot 10^{9}$	$38.45 \cdot 10^{9}$
Area A [m²]	$69.34 \cdot 10^{-4}$	$600 \cdot 10^{-4}$
Poissons ratio υ [-]	0.3	0.2
Linear expansion coefficient α [1/°C]	$1.2 \cdot 10^{-5}$	$1.2 \cdot 10^{-5}$
Moment of inertia I_x [m⁴]	$1000 \cdot 10^{-8}$	$3906 \cdot 10^{-4}$
Moment of inertia I_y [m⁴]	$2337.9 \cdot 10^{-8}$	$1667 \cdot 10^{-6}$
Moment of inertia I_z [m⁴]	$419.2 \cdot 10^{-8}$	$4000 \cdot 10^{-8}$

8.2 Spring elements

The fastenings and the ballast are modelled with springs in different directions. Two different types of springs are used; a linear-elastic spring and an elasto-plastic spring. Underneath the springs used for the fastenings and the ballast are described.

Fasteners

The fastenings are described by linear-elastic springs in the longitudinal, lateral and vertical direction and a rotation spring in phi z direction. The springs have a constant stiffness DS [N/m] defined by equation 8.1.

$$DS = \frac{F_p}{W_p} \tag{8.1}$$

The stiffness of the spring in the longitudinal direction is considered to be $1741 \cdot 10^4$ N/m, as M.A. Van [6] describes that the yielding force directly fastened on a bridge to be 48 kN per meter of track with a relative displacement of 2.8 mm. The stiffness is the yield force divided by the displacement, see equation 8.1.

For the vertical and lateral stiffness of the fasteners, the stiffness of the rail pad is used. These are $250 \cdot 10^6$ N/m for the lateral stiffness and $350 \cdot 10^6$ N/m for the vertical stiffness (see appendix A). The rotational stiffness is considered to be $100 \cdot 10^3$ Nm/rad per fastener, as used in the buckling model of M.A. Van [6].

The ballast behaviour is modelled with springs in the longitudinal, lateral and vertical direction. The lateral and vertical springs are linear-elastic and the longitudinal spring is modelled elasto-plastic. The stiffness of the vertical ballast springs is 100 kN/mm as mentioned in part 6.3. Without the top ballast layer the lateral ballast stiffness is the same as the longitudinal ballast stiffness. This is because the area of friction, the bottom of the sleeper and the load on this area is the same as for the longitudinal direction. With the top ballast layer the lateral ballast stiffness is smaller than the longitudinal direction. This is because the amount of ballast in between the sleepers that cause extra friction in longitudinal direction is much larger than the amount of ballast in front of the sleeper end in the lateral direction. The assumption is that for the situation with the top layer of ballast, the ballast resistance in the lateral direction is ¾ of the ballast resistance in the longitudinal direction [9].

According to van ‘t Zand and Moraal [7] and Van [6] the longitudinal ballast behaviour can be modelled as elasto-plastic. The ballast behaviour is modelled as linear-elastic until the maximum longitudinal force F_p is reached, after which the ballast starts yielding and the plastic deformation starts to increase. This is shown in figure 8.2.

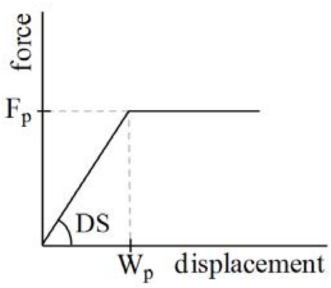


Figure 8.2 Elasto-plastic behaviour

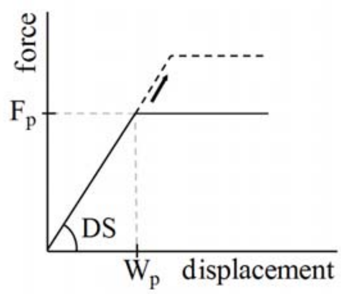


Figure 8.3 Elasto-plastic behaviour dependent on vertical force

The stiffness of the elastic part can be described with the same equation as for the linear-elastic spring, equation 8.1.

The results from the measurements in figure 7.5 show that the longitudinal ballast strength F_p is linearly dependent on the vertical force. To incorporate this in the model described above, the Mohr-Coulomb criterion is used. The criterion is a failure model in which the maximum shear stress τ is linearly dependent on the normal stress σ_{vert}. This dependency is described by equation 8.2.

$$\tau_{\max} = c^* - \sigma_{vert} \tan \phi \qquad (8.2)$$

With:
c^* = cohesion, the shear stress at zero normal stress
φ = friction angle

With the Mohr-Coulomb criterion the ballast behaviour model results in the behaviour shown in figure 8.3. If τ, σ_{vert}, c^* of equation 8.2 are multiplied by the horizontal area of a unit track length, the dependency between the maximum longitudinal force F_{long} per unit track length and the vertical force F_{vert} per unit track length can described with equation 8.3.

$$F_{long} = c - F_{vert} \tan \phi \qquad (8.3)$$

With:
c = cohesion per unit track length; maximum longitudinal resistance force at zero vertical force
tan φ = the friction coefficient between the bottom of the sleeper and the ballast

8.3 Supports

The degrees of freedom in a node can be either free or supported. If a degree of freedom is supported the displacement or rotation is restricted. The nodes of the rails are only restricted in the rotation around the x-axis (phi *x*). Displacements of the rail in the x, y and z-axis and bending of the rail in the vertical and horizontal direction are permitted.

The nodes of the sleepers are restricted in the rotation around the x-axis and the y-axis. Displacements of the rail in the x, y and z-axis and bending of the rail in the vertical direction are possible.

The bottom nodes of the ballast springs are restricted in all the decrease of freedom. The decreases of freedom of the nodes are shown in figure 8.4.

Two springs with a low stiffness are added at the end of both rails to prevent uncontrolled displacements when the longitudinal ballast springs deformation becomes plastic.

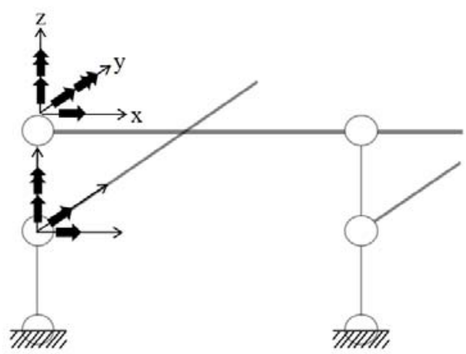


Figure 8.4 Decrease of freedom of the nodes

8.4 Solution

A static non linear analysis is preformed on the model. The total external load on the model is applied in two load steps. At the first load step the vertical force is applied and at the second step the pulling force is added. Each load step consists of a number of load increments. For each load increment a number of iterations are required to find the correct displacement vector for which an equilibrium is found. For the first load step the increment is fixed in one load increment. For the second load step the arc-length increment is controlled, the load increment is determined by a so-called arc-length that depends on the loads and the computed displacements of the degrees of freedom in the model.

The analysis will stop when the last load step has been reached or when the maximum amount of steps has been reached.

9 S&C model

A C11 switch is used for the S&C model. This is a switch with a switch angle of 1:11. The S&C is modelled in the same way the plain line is modelled. With three different layers of nodes for the rail, the sleepers and the ballast. In front of the S&C unit a part of the plain line is modelled. This plain line can vary from length by the variable of the amount of sleepers and the sleeper spacing. Hereby the length of the plain line panels and the ramp can be simulated. In figure 9.1 the model of the S&C units is shown.

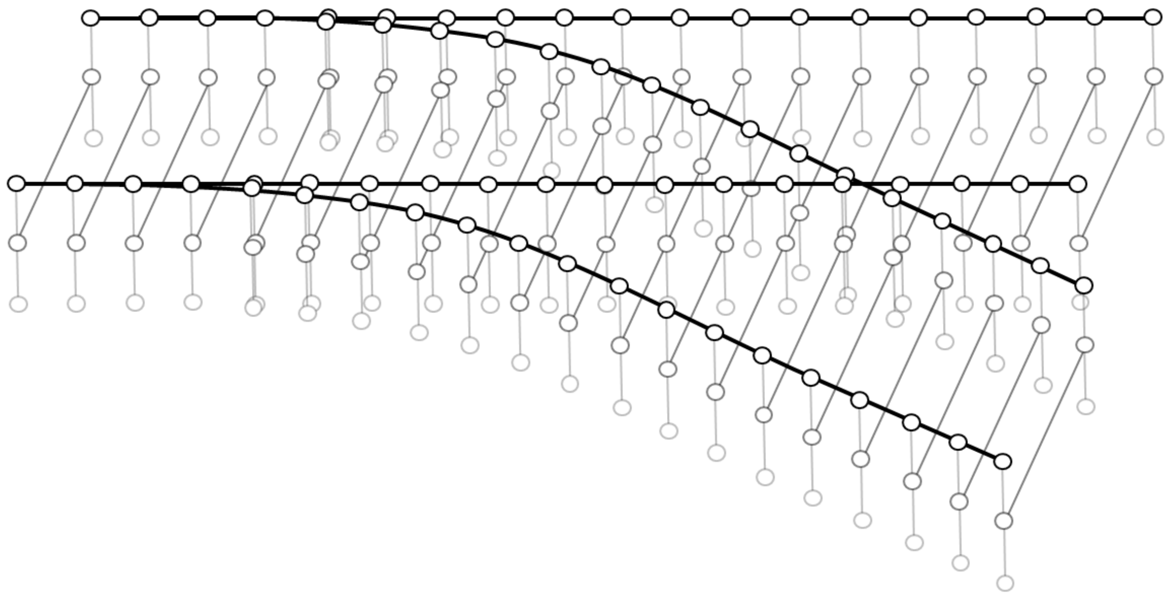


Figure 9.1 Model of the S&C unit

The beam elements representing the rails and the sleepers are assumed to have the same properties as the plain line model. Also the supports of the nodes are the same as the plain line.

The coordinates of the nodes are determined with the radius of the curve. From a CAD drawing of the S&C unit the different radiuses of the curve and the transition curve are determined. The x-coordinate is given by the sleeper spacing and the y-coordinate is calculated with equation 9.1.

$$y = \sqrt{r^2 - x^2} \qquad (9.1)$$

With:
y = y-coordinate
x = x-coordinate
r = radius

9.1 Fastenings

The springs of the fastenings are the same as in the plain line. Only at the switch blade the connection is different because the switch blade is only connected to the sleeper and the detection mechanism and through rail by the clamplock. Also the ongoing rail is connected with only one fastening the tip of the switch blade until the ball and claw. Therefore in the longitudinal, lateral and torsional direction the stiffness of the springs at the nodes of the ongoing rails are divided by two.

At the switch blade the springs in longitudinal, lateral and torsional directions are left out. Only at the location of the clamplocks is a spring in these directions added. These are springs with a small stiffness representing the nut connecting the clamplock to the rail. This nut is the weak point that cannot withstand displacement differences between the two rails larger than 2 mm.

9.2 Ballast

In the plain line the friction between the sleeper and the ballast is divided evenly over the two springs underneath the rails. In the S&C unit the friction has to be divided over four springs under the sleeper. The stiffness of the spring is dependent on the contact area between the sleeper and the ballast and the vertical force. The assumption is that each spring represents the friction of the area under the sleeper until halfway distance to the next spring.

Underneath the derivation of the relation between the longitudinal resistance force (shear force) in the plain line and the resistance force in the switch is given.

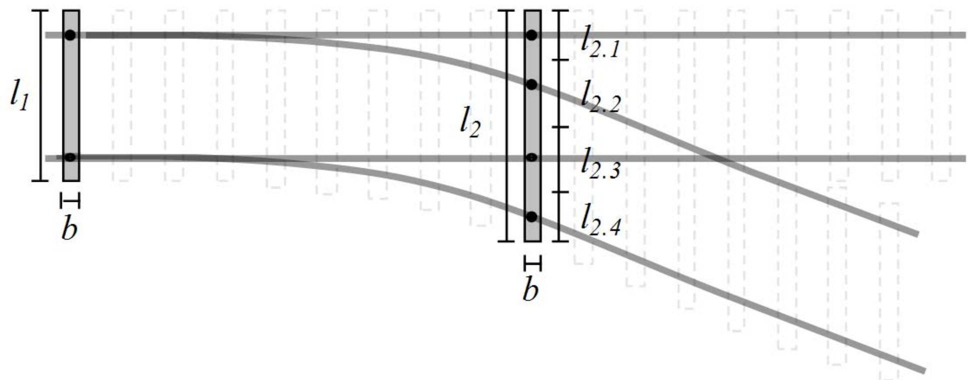


Figure 9.2 Relation between the resistance in the plain line and in S&C unit

The stress on the bottom of the sleeper is the weight of the rail and the sleeper divided by the contact area:

$$\sigma_1 = \frac{\left(W_{r_1} + W_{s_1}\right)}{l_1 \cdot b} \qquad \sigma_2 = \frac{\left(W_{r_2} + W_{s_2}\right)}{l_2 \cdot b} \tag{9.2}$$

With:
$W_r =$ the weight of the rail
$W_s =$ the weight of the sleeper
l_1, $l_2 =$ see figure 9.2

In the switch the weight of the rail is twice the weight of the rails in the plain line because of there are four rails in the switch instead of two. The weight of the rail and the concrete sleeper in the switch can be described with equation 9.3 and 9.4.

$$W_{r_2} = 2 \cdot W_{r_1} \tag{9.3}$$

$$W_{s_2} = \frac{l_2}{l_1} \cdot W_{s_1} \tag{9.4}$$

With substituting equation 9.3 and 9.4 in 9.2, the normal stress (σ) becomes:

$$\sigma_1 = \frac{W_{r_1}}{l_1 \cdot b} + \frac{W_{s_1}}{l_1 \cdot b} \qquad \sigma_2 = \frac{2 \cdot W_{r_1}}{l_2 \cdot b} + \frac{\frac{l_2}{l_1} \cdot W_{s_1}}{l_2 \cdot b} \tag{9.5}$$

$$b \cdot \sigma_1 = \frac{W_{r_1}}{l_1} + \frac{W_{s_1}}{l_1} \qquad b \cdot \sigma_2 = \frac{2 \cdot W_{r_1}}{l_2} + \frac{W_{s_1}}{l_1} \tag{9.6}$$

The shear stress τ_2 in the switch can be described as:

$$\tau_2 = \tau_1 \frac{b \cdot \sigma_2}{b \cdot \sigma_1} \tag{9.7}$$

After substitution of equation 9.5 and 9.6 in 9.7 the shear stress becomes:

$$\tau_2 = \tau_1 \frac{\frac{2 \cdot W_{r_1}}{l_2} + \frac{W_{s_1}}{l_1}}{\frac{W_{r_1}}{l_1} + \frac{W_{s_1}}{l_1}} \tag{9.8}$$

$$\tau_2 = \tau_1 \frac{2 \cdot W_{r_1} \frac{l_1}{l_2} + W_{s_1}}{W_{r_1} + W_{s_1}} \tag{9.9}$$

$$\tau_2 = \tau_1 \left(\frac{2 \cdot W_{r_1}}{W_{r_1} + W_{s_1}} \frac{l_1}{l_2} + \frac{W_{s_1}}{W_{r_1} + W_{s_1}} \right) \tag{9.10}$$

The shear force and shear stress relation is:

$$F_1 = \tau_1 \cdot l_1 \cdot b \quad \Rightarrow \quad \tau_1 = \frac{F_1}{l_1 \cdot b} \tag{9.11}$$

$$F_2 = \tau_2 \cdot l_2 \cdot b \tag{9.12}$$

The substitution of equations 9.10 and 9.11 in 9.12 gives the equation for the shear force on the sleeper in the S&C unit.

$$F_2 = \tau_1 \left(\frac{2 \cdot W_{r_1}}{W_{r_1} + W_{s_1}} \frac{l_1}{l_2} + \frac{W_{s_1}}{W_{r_1} + W_{s_1}} \right) \cdot l_2 \cdot b \tag{9.13}$$

$$F_2 = \frac{F_1}{l_1 \cdot b} \left(\frac{2 \cdot W_{r_1}}{W_{r_1} + W_{s_1}} \frac{l_1}{l_2} + \frac{W_{s_1}}{W_{r_1} + W_{s_1}} \right) \cdot l_2 \cdot b \tag{9.14}$$

$$F_2 = F_1 \frac{l_2}{l_1} \left(\frac{2 \cdot W_{r_1}}{W_{r_1} + W_{s_1}} \frac{l_1}{l_2} + \frac{W_{s_1}}{W_{r_1} + W_{s_1}} \right) \tag{9.15}$$

The assumption is that each spring represents the shear force of the area under the sleeper until halfway distance to the next spring. Therefore the maximum yield force of the spring is given by equation 9.16.

$$F_{2.1} = F_2 \frac{l_{2.1}}{l_2} \tag{9.16}$$

In the longitudinal peak yield force over the length of the switch is shown. At the distance of 37.2 m the peak force is constant because there the sleepers consist of two normal sleepers instead of one long bearer.

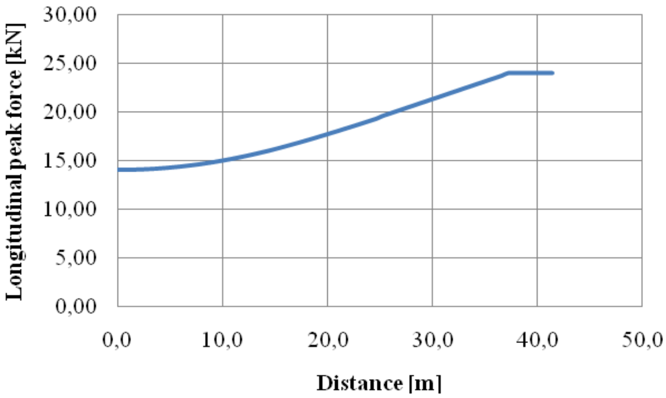


Figure 9.3 Longitudinal peak force in the switch

The loading on the model is done with a pulling force and a vertical load. The pulling force is applied at the front of the plain line on both rails. The vertical load is divided over a length of 6 meters (10 sleepers) at the front of the plain line. This load represents a wagon or different kind of load that can be placed on the rail with a small crane. Figure 9.4 gives an indication of the location of the loads.

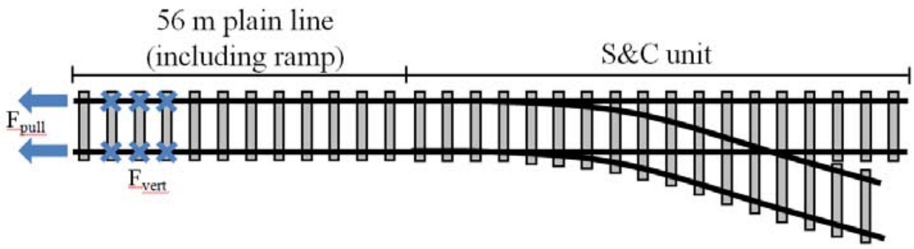


Figure 9.4 Location of the loading of the S&C model

10 Validation and sensitivity analysis

In this chapter the validation of the models made in Longstab is described. Also the sensitivity analysis of some parameters of the model is explained.

10.1 Validation

The result form the test on the 9 meter and 40 meter test panel are used to validate the model. The average maximum longitudinal resistance force per meter is used. This is the longitudinal resistance force per sleeper given in chapter 7 times the sleeper spacing of 0.6 m.

To describe the transition in the elastic and plastic part of the ballast springs the displacement at which the maximum longitudinal resistance occurs has to be used. In the test results this displacement is almost zero. Therefore the results from the test from J. van ‘t Zand and J. Moraal [7] is used. This is a displacement of 5 mm.

In figure 10.1 and figure 10.2 the longitudinal resistance force without the top ballast layer is shown. In Longstab 3710 N/m (2.226 kN per sleeper) is used for the longitudinal peak force of the ballast. The results from Longstab are similar to the results from the tests.

In figure 10.3 the results from the tests with top ballast are compared with the results form Longstab. In Longstab 12000 N/m (7.20 kN per sleeper) is used for the longitudinal peak force of the ballast.

To validate the influence of the vertical load the results of Longstab are compared with the trendline determined in the measurements, see figure 7.5. As a vetical load the weight of 6 and 13 sleepers is used. This weight is divided over the last 5 sleepers of the model, the same as done in during the test. To get the same results with Longstab, the friction coefficient 0.25 is used instead of 0.3793 found in the tests. The results from the tests and from Longstab are shown in figure 10.4.

The parameters that describe the behaviour of the springs of the model after validation are mentioned in table 10.1. These parameters are used in the analysis with the S&C model.

Table 10.1 Parameters with the initial values

Parameters	Values
Longitudinal stiffness of the fastener [N/m]	$17140 \cdot 10^3$
Lateral stiffness of the fastener [N/m]	$250 \cdot 10^6$
Vertical stiffness of the fastener [N/m]	$350 \cdot 10^6$
Torsional stiffness of the fastener [Nm/rad per fastener]	$100 \cdot 10^3$
Lateral stiffness of the ballast [N/m] (without top ballast)	$742 \cdot 10^3$
Lateral stiffness of the ballast [N/m] (with top ballast)	$1800 \cdot 10^3$
Vertical stiffness of the ballast [N/m]	$100 \cdot 10^6$
Longitudinal peak yield force of the ballast [N/m] (without top ballast)	$3.71 \cdot 10^3$
Longitudinal peak yield force of the ballast [N/m] (with top ballast)	$12.0 \cdot 10^3$
Displacement at the peak yield force [m]	0.005
Displacement at the limited yield force [m]	0.050
Friction coefficient between sleeper and ballast [-]	0.25

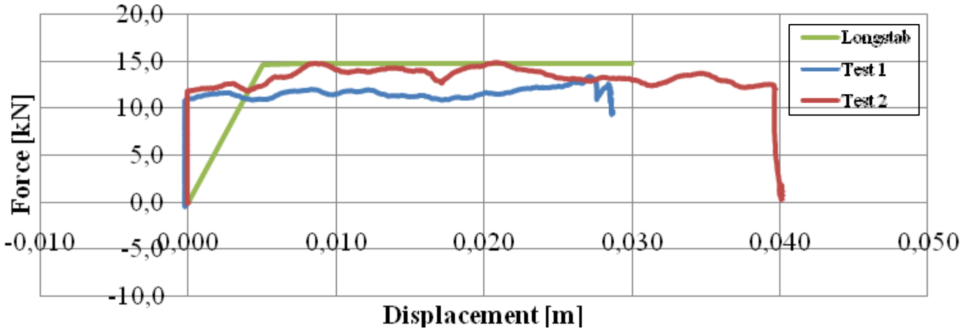


Figure 10.1 Longitudinal resistance force without top ballast tests 1 and 2

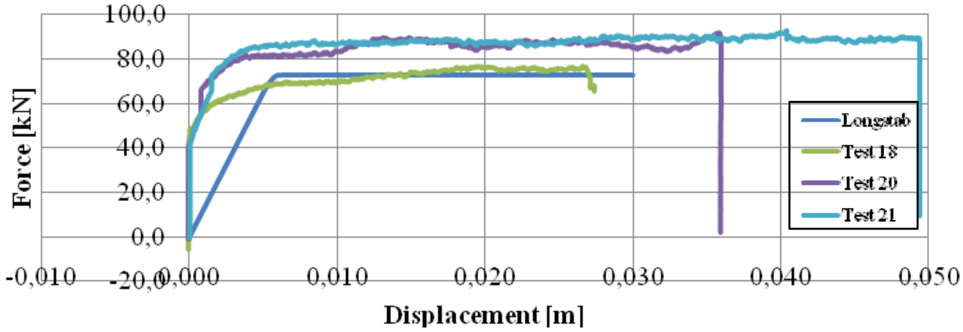


Figure 10.2 Longitudinal resistance force without top ballast tests 18, 20 and 21

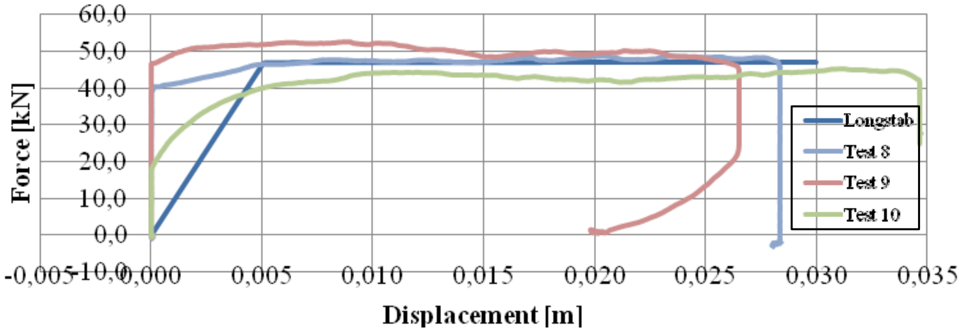


Figure 10.3 Longitudinal resistance force with top ballast tests 8-10

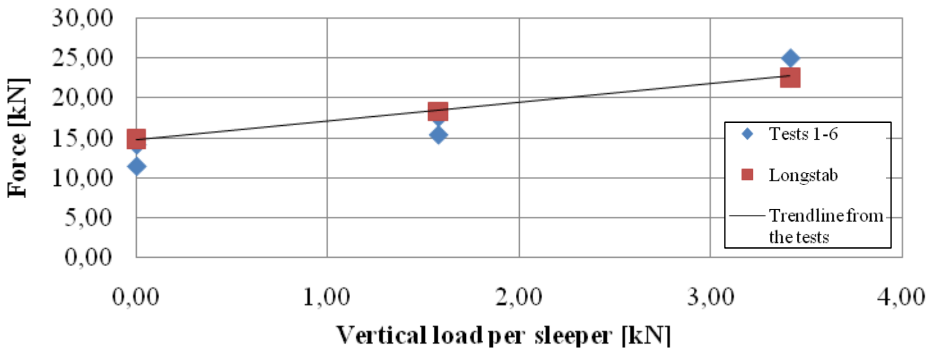


Figure 10.4 Influence of the vertical force

10.2 Sensitivity analysis

The sensitivity of the difference in displacement (Δx) at the clamplock with regard of the parameters as listed in table 10.2 will be investigated for the S&C model. Also the sensitivity of the displacement of the sleepers (W) at the front and the back of the switch is investigated. Each parameter will be varied in a practical range while the other parameters will be fixed. The reference values for the parameters are those used in the validation in chapter 8. The analysis is preformed for the situation with ballast, except for the sensitivity analysis with regard of the parameter of the longitudinal peak yield force of the ballast. The pulling force used in the analysis is 544 kN for the situations with top ballast and 160 kN for the situation without top ballast.

Firts the sensitivity analysis of the displacement difference (Δx) at the clamplock is described. Afterwards the sensitivity analysis of the displacement of the sleepers (W) at the front and the back of the switch is given.

Table 10.2 Parameters of S&C model in sensitivity analysis

Parameter	Reference value	Range
Longitudinal stiffness of fasteners [N/m]	$1714\cdot10^4$	$171.4\cdot10^4$ - $3428\cdot10^4$
Torsional stiffness of the fastener [Nm/rad per fastener]	$100\cdot10^3$	0.0 - $300\cdot10^3$
Longitudinal peak yield force of the ballast, F_p [N/m] (with top ballast)	$12.0\cdot10^3$	$10.6\cdot10^3$ - $13.4\cdot10^3$
Longitudinal peak yield force of the ballast , F_p [N/m] (without top ballast)	$3.71\cdot10^3$	$2.72\cdot10^3$ - $4.72\cdot10^3$
Displacement at the peak yield force, W_p [m]	0.005	0.001 - 0.006
Longitudinal stiffness of the spring at the clamplock [N/m]	$1714\cdot10^3$	$171.4\cdot10^3$ - $3428\cdot10^3$
Friction coefficient between sleeper and ballast [-]	0.25	0.15 – 1.0

10.2.1 Displacement difference

For displacement difference at the clamplock a sensitivity analysis is preformed. At both moving points a displacement difference occurs by pulling on the stock rails. These displacements are almost similar on both sides. Therefore only the displacement difference between the moving point and the through curved rail is analyzed.

Figure 10.5 shows the variation of Δx with a varying longitudinal stiffness of the fasteners. The reference value for the stiffness is $1714 \cdot 10^4$ N/m per m track. With a smaller stiffness the difference in displacement starts to increase exponentially.

When the switch starts to move the rotation of the panel is very small. Therefore variation of the torsional stiffness of the fasteners hardly influences Δx, see figure 10.6. The variations that occur are smaller than 0.01 mm.

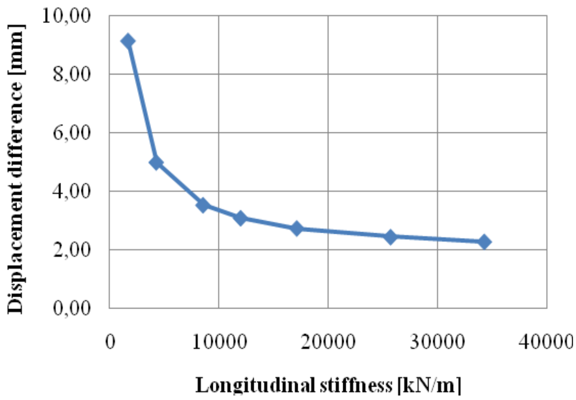


Figure 10.5 Δx versus longitudinal stiffness of fastener

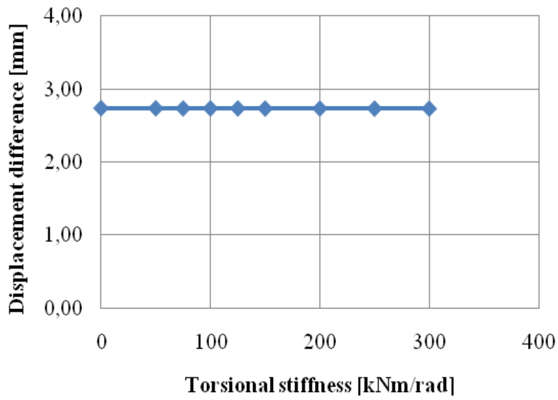


Figure 10.6 Δx versus torsional stiffness of fastener

The influence of the longitudinal peak force for the situation with top ballast and without top ballast is shown in figure 10.7 and figure 10.8. The peak force is varied within the range found during the tests, see part 7. For the situation with the top ballast this is ±0.85 kN and for the situation without the top ballast layer this is ±0.60 kN. In the situation with the top ballast the displacement difference increases with 0.54 mm and decreases with 0.42 mm. Without the ballast Δx increases with 0.22 mm and decreases with 0.11 mm with ±0.60 kN.

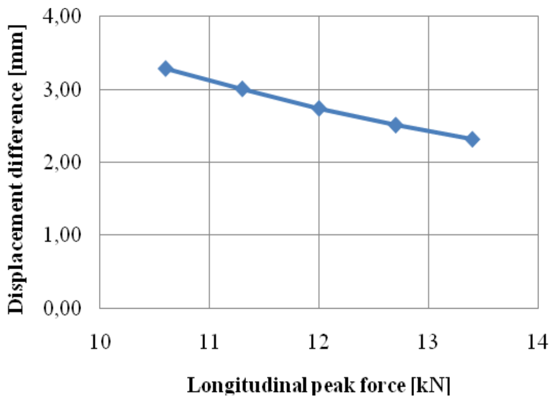


Figure 10.7 Δx versus Fp (with top ballast)

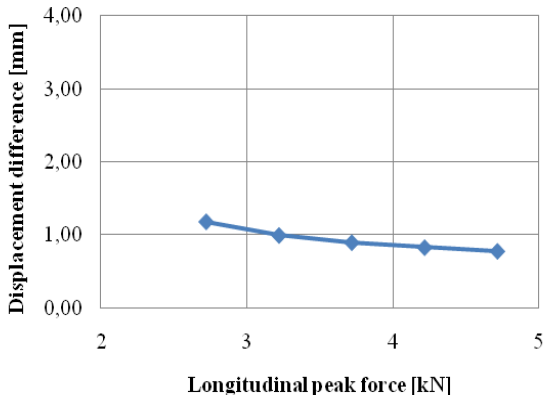


Figure 10.8 Δx versus Fp (without top ballast)

The influence of the deformations at peak force is shown in figure 10.9. For small values of W_p, implying a large initial stiffness, the displacement difference is very sensitive.

The longitudinal stiffness of the spring at the clamplock is varied from 1% to 20% of the longitudinal sitffness of the fasteners. This variation is of hardly any influence on the displacement difference, as can be seen in figure 10.10.

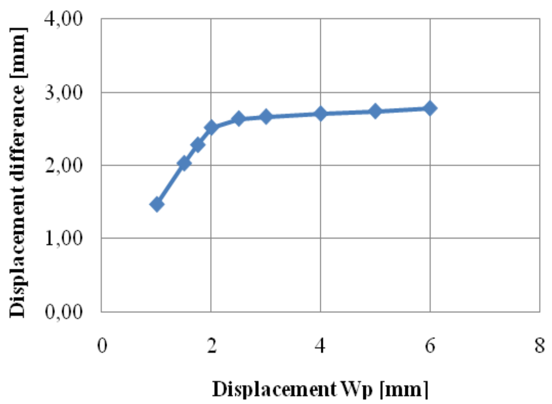


Figure 10.9 Δx versus Wp

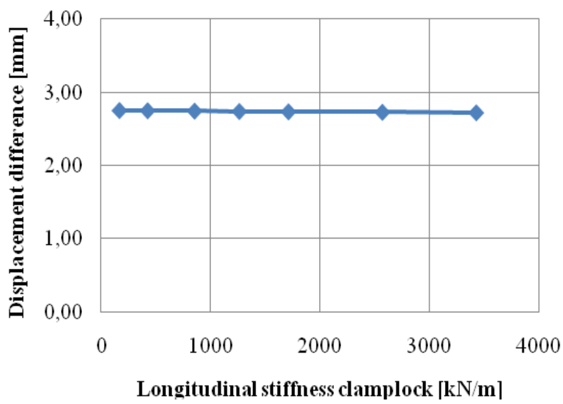


Figure 10.10 Δx versus longitudinal stiffness clamplock

In figure 10.11 the influence of friction coefficient of the longitudinal ballast springs on Δx is shown for different vertical loads, 200 kN and 1000 kN. The load is applied at the beginning of the plain line in front of the S&C unit, divided over ten sleepers. The variation of the friction coefficient barely influences Δx with a vertical load of 1000 kN, whereas the sensitivity of Δx with a vertical load of 200 kN shows to be stronger.

The variation of the friction coefficient barely influences Δx with a vertical load of 1000 kN, whereas the sensitivity of Δx with a vertical load of 200 kN shows to be stronger.

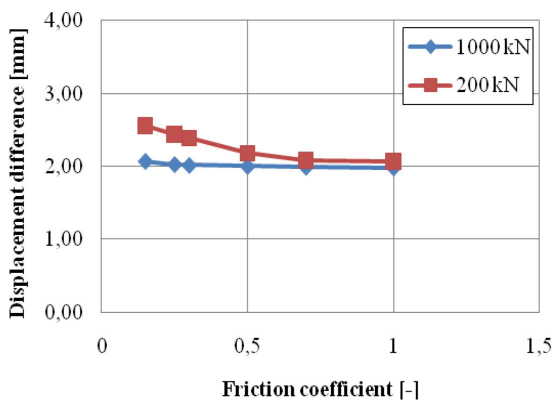


Figure 10.11 Δx versus friction coefficient

10.2.2 Displacement of the sleepers

The sensitivity of the displacement at the front and the back of the switch (W_{front} and W_{back}) with regards to the parameters is investegated. The front of the switch is at the first sleepers under the switch point, at the clamplock. The back of the switch is at the last sleeper after the crossing. In the front and the back of the switch are shown.

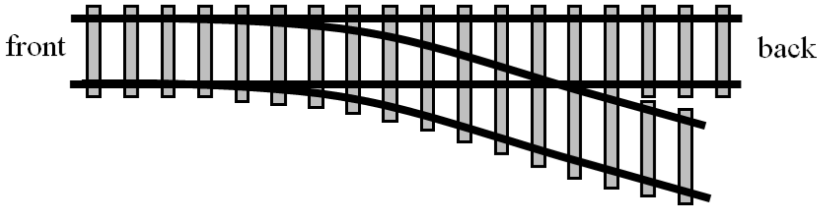


Figure 10.12 Front and back of the switch

The influence of the longitudinal stiffness and the torsional stiffness of the fasteners are shown in figure 10.7 and figure 10.8. The torsional stiffness of the fasteners has no influence on the displacement. Only small values of the longitudinal stiffness affects W, but at a values lower than 50% of the reference value the model can not calculate the realistic displacements any more.

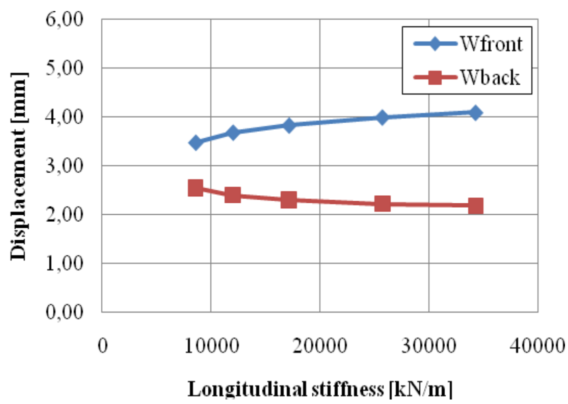


Figure 10.13 W versus longitudinal stiffness of fastener

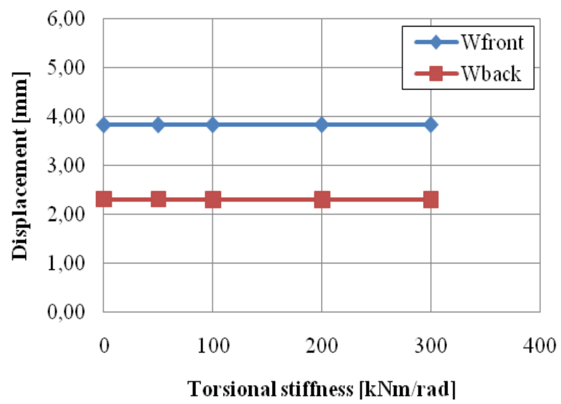


Figure 10.14 W versus torsional stiffness of fastener

Figure 10.15 and figure 10.16 shows the variation of W with a varying longitudinal peak yield force for the situation with and without the top ballast layer. For the situation without the ballast the variation of the longitudinal peak force has a significant influence on the displacement. With the top ballast, the displacement is less sensitive.

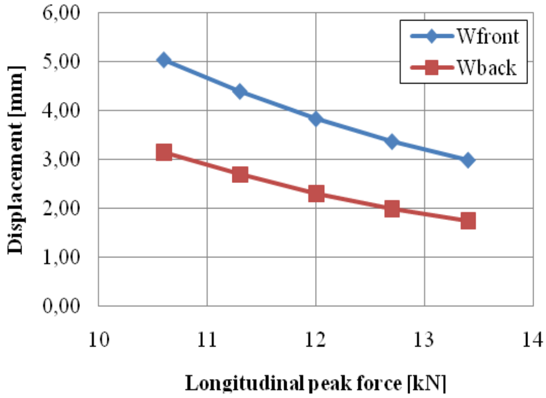


Figure 10.15 W versus Fp (with top ballast)

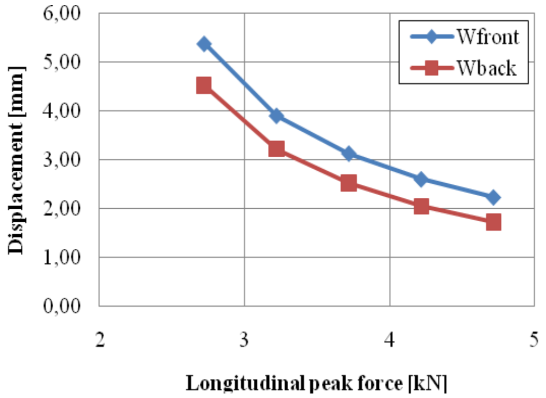


Figure 10.16 W versus Fp (without top ballast)

The deformations at peak force is shown in figure 10.17. W varies al most linear with this parameter, whereas the sensitivity of W_{front} shows to be a little bit stonger than that of W_{back}.

The sensitivity of W with regard to the friction coefficient is shown in figure 10.18. The vertical load used for this anlysis is 200 kN, placed on the first ten sleepers of the plain line infront of the switch. The influence on W is very small. The same as with the sensitivity anlysis of the displacement difference at the clamplock the sensitivity of W decreases with a larger vertical load.

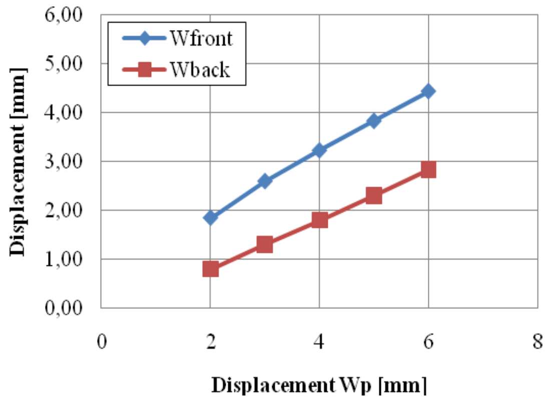


Figure 10.17 W versus Wp

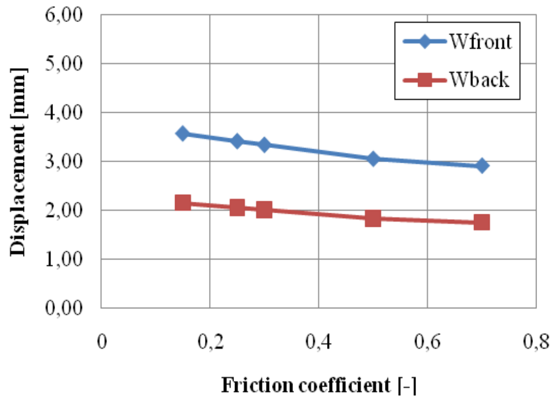


Figure 10.18 W versus friction coefficient

11 Analysis

The analysis is preformed to find a working sequence to achieve a stress free temperature in a renewed S&C unit and the adjacent plain line, satisfying the requirements as set within the world class installation method. With the model eight cases are tested. In the first four cases the pulling force is applied at the end of the plain line in front of the switch. In the other four cases the pulling force is applied at back of the switch. Between the cases the ballast situation, the vertical load and the length of plain line in front of the switch is varied. In table 11.1 the situations for the cases are described. For the cases the maximum allowable pulling force per rail is determined.

Table 11.1 Cases for the analysis

Case number	Location of pulling force	Top ballast situation	Length of the plain line in front	Vertical load
1	Front	Without	56 m	0
2	Front	Without	56 m	Yes
3	Front	With	56 m	0
4	Front	With	56 m	yes
5	Back	Without	0 m	0
6	Back	Without	56 m	0
7	Back	With	0 m	0
8	Back	With	56 m	0

There are two restrictions for determining the maximum allowable temperature difference.

1. The switch panel is not allowed to move more than 4 mm at the side the panel is pulled. For the cases 1-4 this is in the front and for the cases 5-8 this is at the back of the switch panel.
2. The displacement difference (Δx) at the clamplock has to be smaller than 2 mm. For the cases 1-4, where the pulling force is applied at the plain line in front of the switch, this restriction count for the clamplock at the point of the movable switch blade. The “ball and claw” is the critical point for the cases 5-8, because the pulling force is placed at the back of the switch.

As the switch is already installed to the correct SFT, the fasteners remain in all cases clipped over the total length of the renewed track. This is in contradiction with the guidelines decribed in part 3.5, shows the clipped and the unclipped parts.

To make sure that the stress is evenly divided through the rails,the fasteners are unclipped after making the closure welds. This is done from the end of the renewed plain line towards the switch.

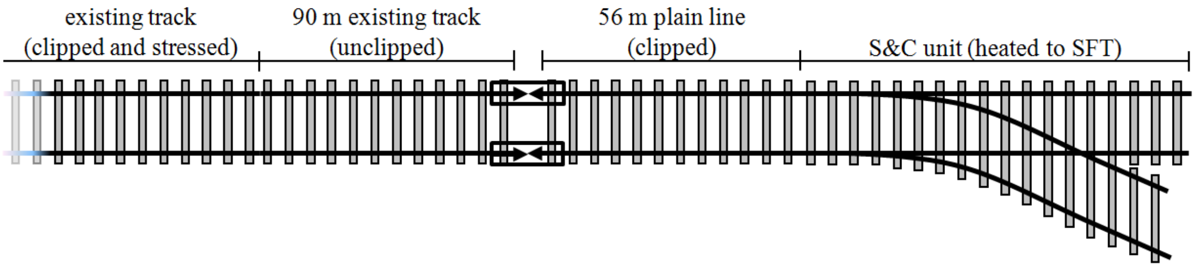


Figure 11.1 Clipped and unclipped rails that need to be stressed

The force on the rails is applied with the pulling equipment. This equipment clamps on the rails on both sides of the weld and the rails are pulled towards each other with jacks. Therefore the force on both rails can be made to be the same.

When stressing the rail the unclipped rail on the existing track is extended to a specified length depending on the temperature difference. With the maximum allowable pulling force the maximum allowable temperature difference (ΔT) between the SFT and the temperature at which the panels are being stressed is determined. Also the length of rail that has to be unclipped ($L_{unclipped}$ to stress the rail at the maximum temperature difference of 30°C is calculated. Underneath the derivations of the relations with the maximum allowable pulling force is given.

Maximum allowable temperature difference

The relation between the maximum allowable pulling force and the extension of the unclipped rail is described with equation 11.1.

$$F_{\max} = EA \frac{\Delta L_{unclipped}}{L_{unclipped}} \tag{11.1}$$

$$\Delta L_{unclipped} = \frac{F_{\max}}{EA} L_{unclipped} \tag{11.2}$$

The rail that has to be stressed is the plain line in front of the switch, this rail is clipped, and the rail of the exiting track that is unclipped. To stress the rail to the required level the extension has to be:

$$\Delta L = \Delta L_{unclipped} + \Delta L_{clipped} \tag{11.3}$$

The extension of the unclipped rail can be calculated with equation 11.2 and the extension of the clipped rail is determined with the S&C model in Longstab.

The relation between the extension and the temperature difference (ΔT) between the SFT and the temperature at which the panels are being stressed is:

$$\Delta L_{unclipped} = \alpha \cdot \Delta T \cdot L_{unclipped} \tag{11.4}$$

$$\Delta L_{clipped} = \alpha \cdot \Delta T \cdot L_{clipped} \tag{11.5}$$

$$\Delta L = \alpha \cdot \Delta T \cdot \left(L_{unclipped} + L_{clipped} \right) \tag{11.6}$$

$$\Delta T = \frac{\Delta L}{\alpha \cdot \left(L_{unclipped} + L_{clipped} \right)} \tag{11.7}$$

Substituting equation 11.2 in 11.7 gives equation 11.8 for the allowable temperature difference (ΔT) between the SFT and the temperature at which the panels are being stressed.

$$\Delta T = \frac{\frac{F_{\max}}{EA} L_{unclipped} + \Delta L_{clipped}}{\alpha \cdot \left(L_{unclipped} + L_{clipped} \right)} \tag{11.8}$$

Length of the unclipped rail

To determine the relation between the maximum allowable pulling force and the length of the unclipped rail with a given temperature difference equation 11.8 is rewritten into equation 11.11.

$$\alpha \cdot \Delta T \cdot \left(L_{unclipped} + L_{clipped} \right) = \frac{F_{\max}}{EA} L_{unclipped} + \Delta L_{clipped} \tag{11.9}$$

$$\alpha \cdot \Delta T \cdot L_{unclipped} - \frac{F_{\max}}{EA} L_{unclipped} = \Delta L_{clipped} - \alpha \cdot \Delta T \cdot L_{clipped} \tag{11.10}$$

$$L_{unclipped} = \frac{\Delta L_{clipped} - \alpha \cdot \Delta T \cdot L_{clipped}}{\left(\alpha \cdot \Delta T - \frac{F_{\max}}{EA} \right)} \tag{11.11}$$

In the first part of this chapter the result of the test will be described. In the second part the conclusions of the analysis and the recommendation for the working sequence are given.

11.1 Result

In the first case the situation is similar as suggested in the new working method described in part 4.2. This is the situation without the top ballast layer and without a vertical load on the rails. For this case the displacement of the panel is normative. The maximum allowable pulling force per rail for this case is 185 kN. Hereby the displacement difference at the clamplock is 1.14 mm. The displacement of the switch panel is at the front 3.98 mm and at the back 3.20 mm. The extension of the clipped rail determined with the model is 5,1 mm. The allowable temperature difference determined is 9.8°C. With a temperature difference of 30°C it is not possible to stress the rails to the SFT, because the length of the unclipped rail to be unclipped is more as 1000 m. Figure 11.2 and figure 11.3 show the results from the iterations for case 1.

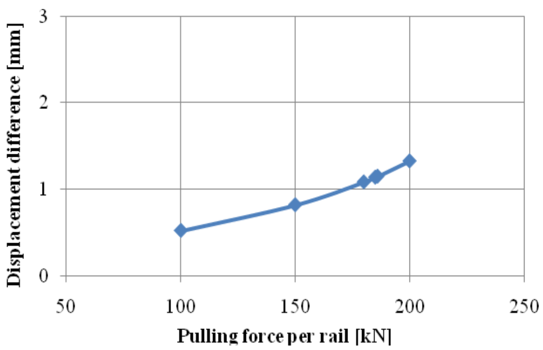


Figure 11.2 Case 1 Δx versus F_{max}

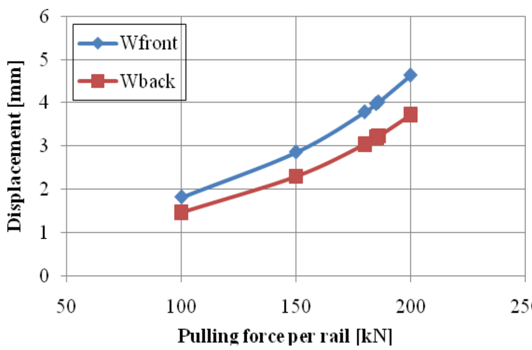


Figure 11.3 Case 1 W versus F_{max}

The displacement in the longitudinal and lateral direction over the length of the plain line and the switch are shown in figure 11.4 and figure 11.5. This is the displacement of the straight on going rail in the switch and is marginal larger (< 1mm) than the displacement shown in figure 11.3 because this is the displacement of the rail and the displacement shown in figure 11.3, because this is the displacement of the rail where figure 11.3 shows the displacement of the sleeper.

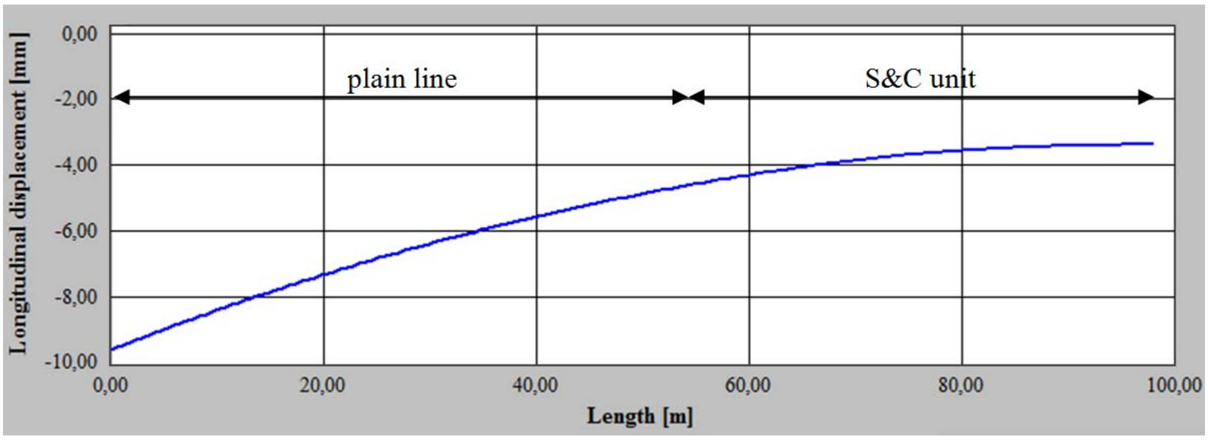


Figure 11.4 Longitudinal displacement of the rail

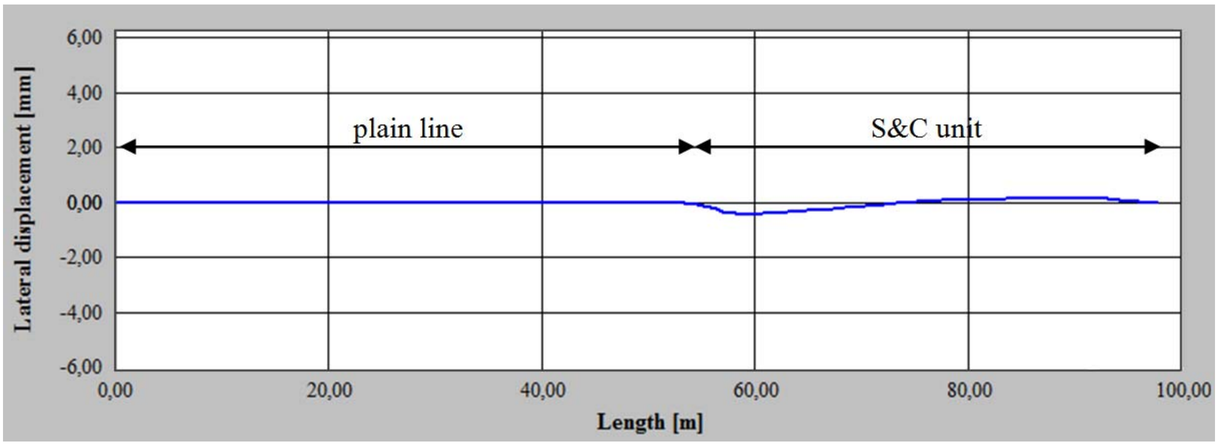


Figure 11.5 Lateral displacement of the rail

The goal for case 2 is to determine the amount of vertical load needed to make it possible to stress the panels at the maximum allowable temperature difference of 30°C. The vertical load is applied on 10 sleepers at the end of the plain line. The load is restricted by the amount of load a crane can place on the panels in a short period of time. Therefore the limit of the vertical load is set on 1000 kN.

A vertical load of 1000 kN is not enough to stress the rails at the maximum allowable temperature difference of 30°C. To stay within the limits set by the two restrictions, F_{max} is 195 kN with the vertical load of 1000 kN. With a extension of the rail of 5.1 mm this means that it is allowed to stress the rail at a ΔT of 10.2°C. In figure 11.6 and figure 11.7 the result from case 2 are shown. The displacements of the rails in the longitudinal and lateral direction show a similar image as shown in figure 11.4 and figure 11.5.

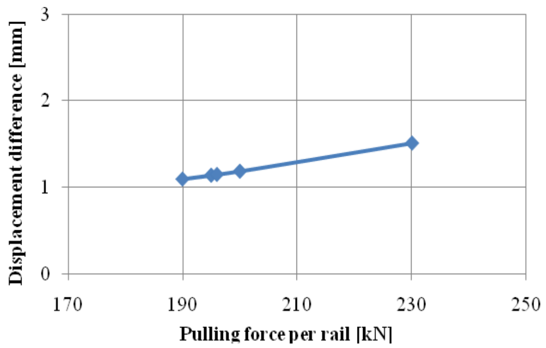


Figure 11.6 Case 2 Δx versus F_{max}

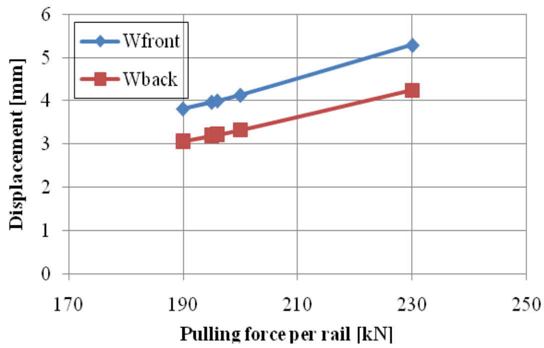


Figure 11.7 Case 2 W versus F_{max}

Case 3 and 4 investigate the situation with the top ballast layer. These cases have the restriction of the displacement difference at the clamplock. Without the vertical load the maximum allowable pulling force is 474 kN. This pulling force gives an extension of the rails of 11.6 mm, which complies with a ΔT of 24.4°C. Figure 11.8 and figure 11.9 show the result of the iteration for case 3; the situation with the top ballast layer and without a vertical load.

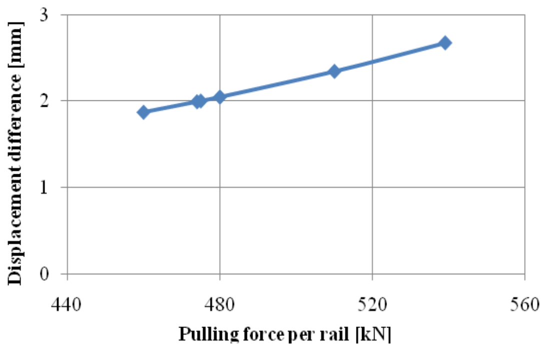


Figure 11.8 Case 3 Δx versus F_{max}

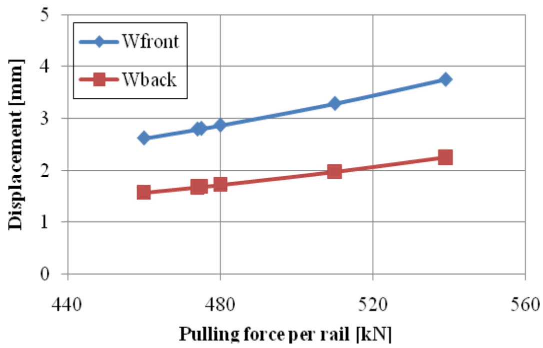


Figure 11.9 Case 3 W versus F_{max}

Simmulair as with case 2 a vertical load of 1000 kN is not enough to stress the rail to the maximum allowable temperature difference of 30°C for case 4. As can be seen figure 11.10 and figure 11.11 a pulling force of 539 kN is still within the limits for the situation with a vertical load of 1000 kN. Therefore it is allowed to stress the rails at a temperature difference of 26.9°C. To stress the rails at the at the maximum allowable temperature difference of 30°C the exiting track has to be unclipped over a length of 295 m.

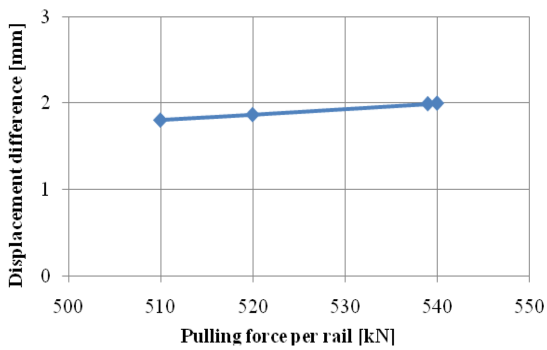


Figure 11.10 Case 4 Δx versus F_{max}

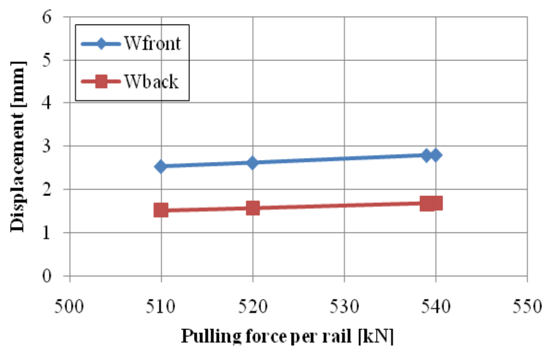


Figure 11.11 Case 4 W versus F_{max}

In the next four cases (5-8) the pulling force is applied at the back of the switch panel, as shown in figure 11.12. In case 5 and 6 the simulation is done for the situation without the top ballast layer. Between these cases there is looked at the influence of 56 m plain line behind the switch. In case 5 there is no plain line behind the switch and in case 6 there is 56 m plain line behind the switch. The results of these analyses are shown in figure 11.13 and figure 11.14. For the situation of case 5 F_{max} is 61 kN.

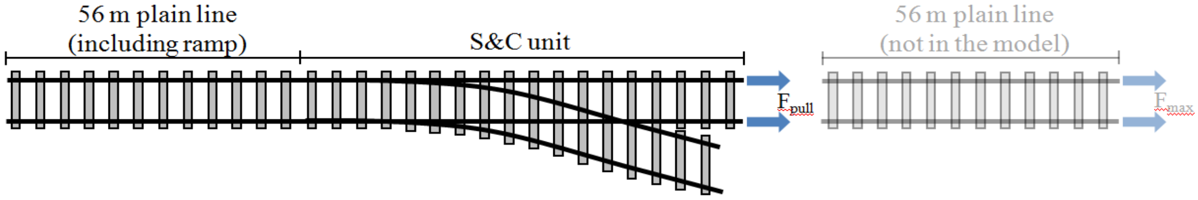


Figure 11.12 Loading for cases 5-8

From the results of case 1 the amount of force taken on by the plain line is determined by taking the normal force in the rail in front of the switch and distracting this from the total allowable pulling force. For case 1 this is 102.2 kN. When adding this to the calculated allowable pulling force of case 5 the total pulling force at the end of the newly installed plain line (F_{max}) is 163.2 kN. This is slightly less than the F_{max} of case 1 (185 kN). This can be explained as the friction at the front of the switch directly increases by the extra weight of the movable rails where the back the switch panel consists of 4 sleepers which have the same friction as the plain line. Therefore the restriction that the panel is not allowed to move more than 4 mm is reached earlier when pulling at the back of the switch panel than when pulling at the front of the switch panel.

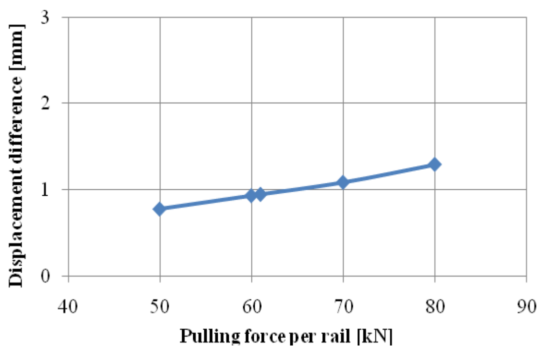


Figure 11.13 Case 5 Δx versus F_{max}

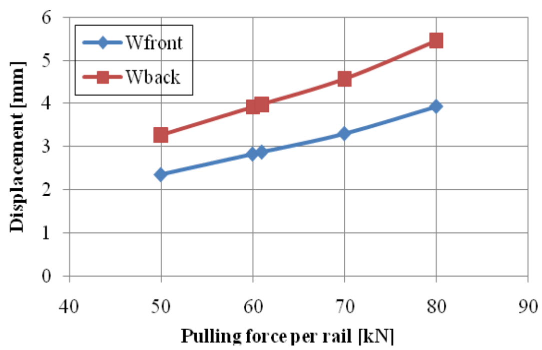


Figure 11.14 Case 5 W versus F_{max}

The allowable temperature difference at which it is allowed to stress the plain line can not be determined because it is not known what the extension of the plain line at the back of the S&C unit is. An estimate can be given using the extension of the plain line from case 1. The estimate of the allowable temperature difference is 9.0°C.

By pulling at the back of the panel the sleepers are rotating. The displacement of the sleeper under the straight outer rail and under the curved outer rail is shown in figure 11.15. The difference between these two rails is almost 2.5 mm at the longest sleeper in the switch. When pulling at the front of the switch this difference is less than 0.1 mm. This difference can be explained, as , the pulling force on the last long sleeper at the back of the switch panel is eccentrically, at the front of the switch the pulling force of the sleeper is the eccentricity is build up gradually.

The influence of the 56 m of plain line behind the panel is looked at in case 6. The results are shown in figure 11.16 and figure 11.17. The maximum allowable pulling force is 83 kN so the extra pulling force cause by the plain line behind the switch is 22 kN.

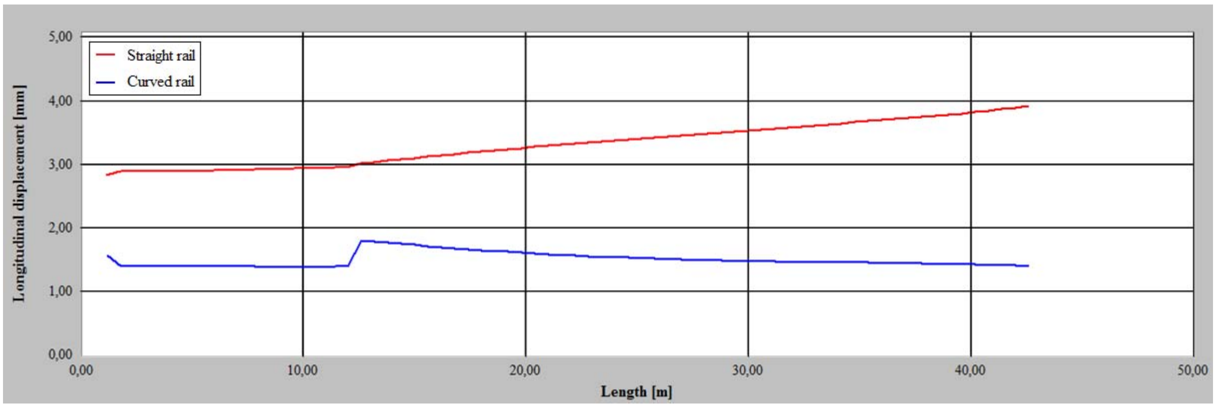


Figure 11.15 Case 5 displacement of the sleeper over the length of the switch

Case 7 there investigates the same situation as in case 5 only now with the top ballast layer. In figure 11.18 and figure 11.19 can be seen that the restriction of W is determining for the F_{max}. The allowable F_{max} is 143 kN. When adding the force taken on by the plain line, determined with the results from case 3, the maximum allowable pulling force becomes 465 kN.

The estimate of the allowable temperature difference using the extension of the plain line from case 3 is 24.0°C

The displacement of the sleeper under the straight outer rail and under the curved outer rail is almost 3 mm. This is larger than the rotation found in case 5 because the force on the rails is also larger. Therefore the sleepers rotate more than in case 5.

When adding the plain line behind the panel (case 8) the additional pulling force is 23 kN. The maximum pulling force becomes 166 kN. The results are shown in figure 11.20 and figure 11.21.

An overview of the result of the cases is given in table 11.2.

Table 11.2 Results of the cases

Case number	F_{max} [kN]	W_{front} [mm]	W_{back} [mm]	Δx [mm]	Extension of the rail [mm]	ΔT [°C]
1	185	3.98	3.20	1.14	5.1	9.8
2	195	3.97	3.19	1.14	5.1	10.2
3	474	2.79	1.68	1.99	11.6	24.4
4	539	2.84	1.71	2.03	11.9	26.9
5	61	2.88	3.98	0.95	-	9.0
6	83	2.35	3.97	1.09	-	-
7	143	1.94	3.97	1.27	-	24.0
8	166	1.26	3.98	1.37	-	-

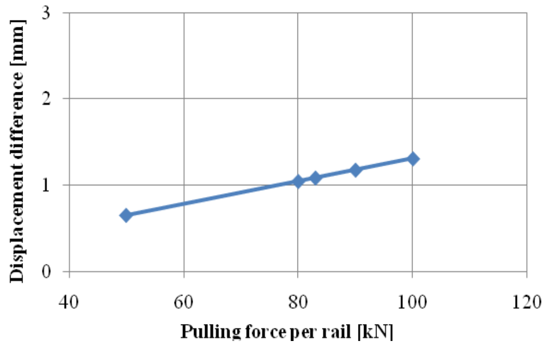


Figure 11.16 Case 6 Δx versus F_{max}

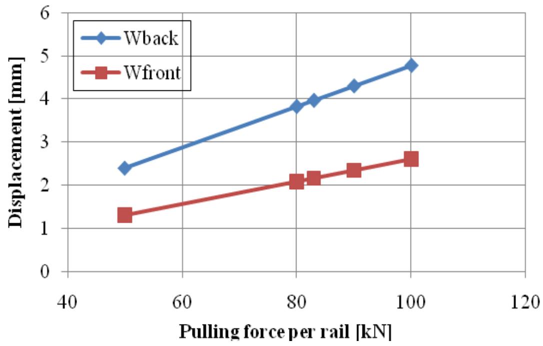


Figure 11.17 Case 6 W versus F_{max}

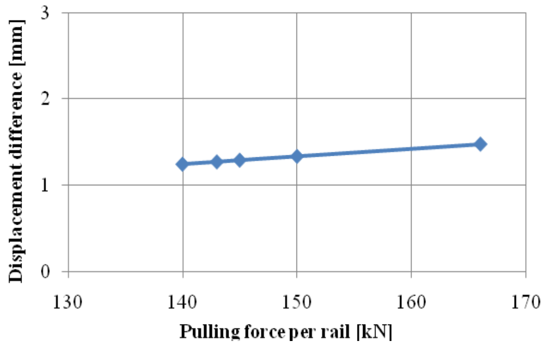


Figure 11.18 Case 7 Δx versus F_{max}

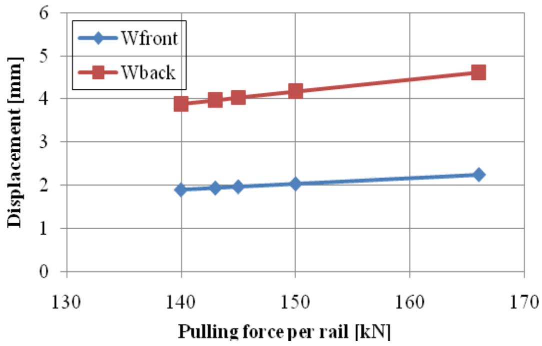


Figure 11.19 Case 7 W versus F_{max}

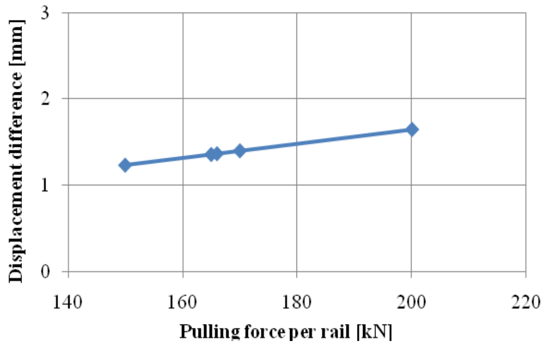


Figure 11.20 Case 8 Δx versus F_{max}

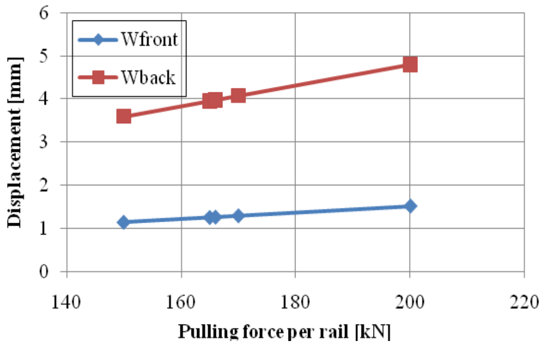


Figure 11.21 Case 8 W versus F_{max}

11.2 Stressing sequence

During the development of this working methodology, the displacements of a number of different stressing scenarios have been calculated. These scenarios are combinations of the following parameters that can be influenced during the stressing:

- S&C Unit and adjacent rails heated or not heated
- Rail Clipped or Unclipped
- Top Ballast installed or not

All analysis investigated a method for achieving the SFT by applying pulling forces on the rails instead of heating. As can be seen from the results of the analysis it is not possible to stress the rail at the maximum allowable temperature difference of 30°C within the restrictions for the displacement and the displacement difference.

Pulling at the back of the switch panel is determining for the maximum allowable pulling force to stress the rails. For the situation without the top ballast layer this is 163.2 kN and with the top ballast layer this is 465 kN.

Placing a vertical load on the rails hardly influences the allowable pulling force. It is also time consuming and it is therefore not advised to use.

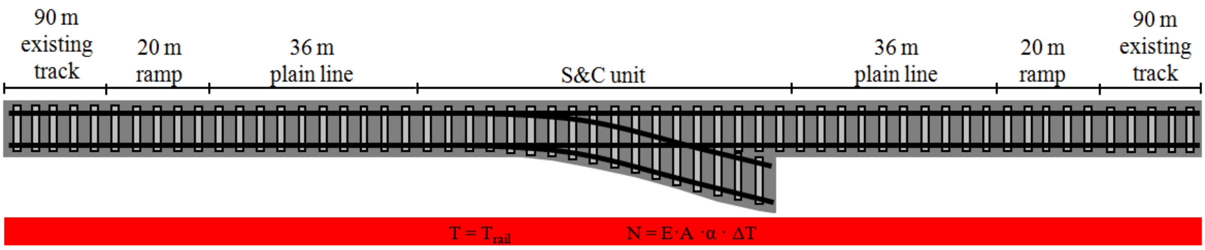
The solution to prevent any displacements of the S&C unit is to heat the plain line to the SFT. This can be done with heating blankets or with heating wagons. When using heating blankets it is still needed to pull the existing track that is unclipped to the SFT length. If the 18 m panels of the plain line are heated with the heating blankets, then it is possible to stress the unclipped existing track and the 20 m ramp when the top ballast is installed. Without top ballast this can only be done until a temperature difference of 13.1°C.

When the heating wagon is used the plain line near the end can be heated a bit further than the SFT to create the extra length needed to stress the 90 m existing track. Therefore pulling is not necessary.

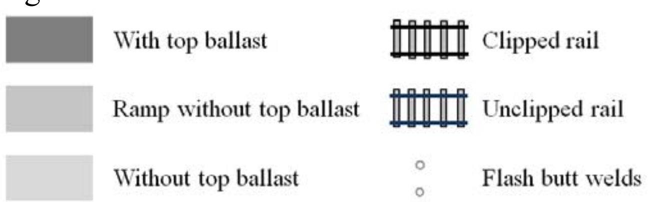
To prevent displacements of the S&C unit larger than 4mm and displacement difference between the rails at the clamplock larger than 2 mm, the S&C Unit and the adjacent 18m panels and 20m ramp need to be heated to the SFT according to the stressing sequence described below.

Step 1

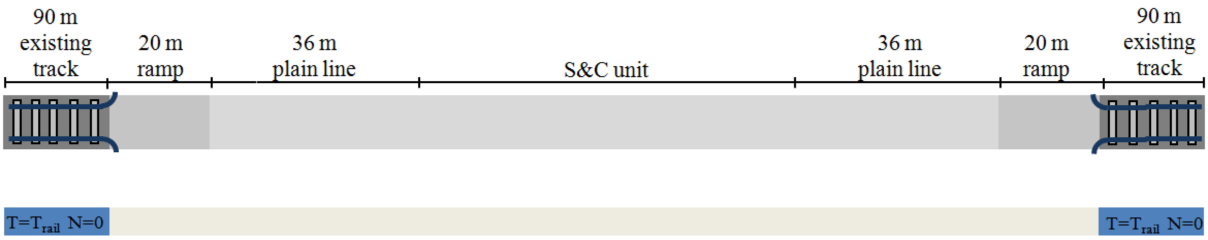
Step 1 describes the situation before renewal.



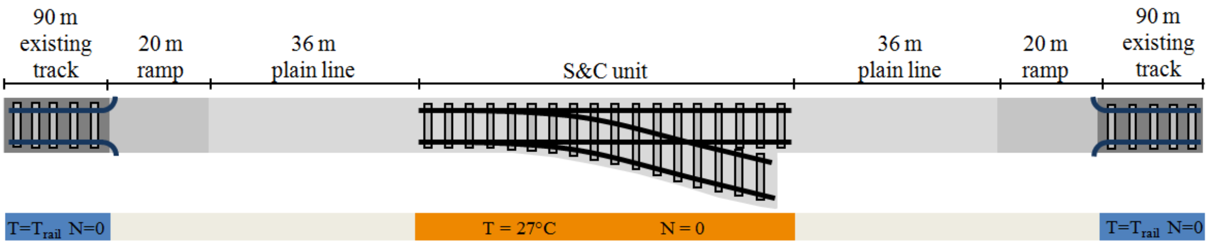
Legend



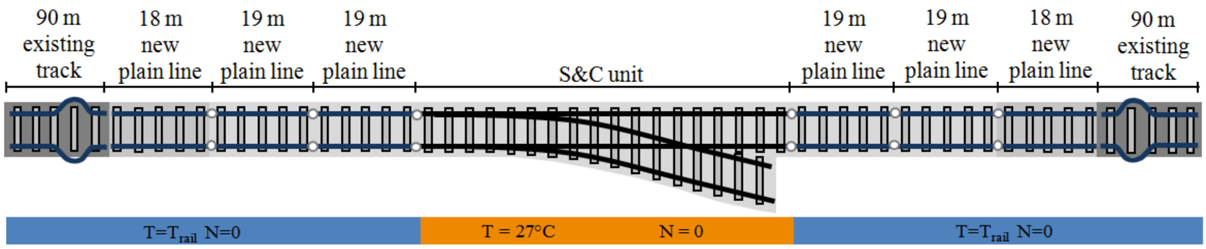
Step 2
During step 2 the S&C unit, 56 m of plain line track on both sides of the switch and the old ballast are removed. They are removed in panels of 18 – 19 m so they can be loaded on a wagon to be transported to a site where they will be demolished. The new bottom ballast layer is installed and the ballast ramp is made. The existing track is unclipped over a length of 90 m.



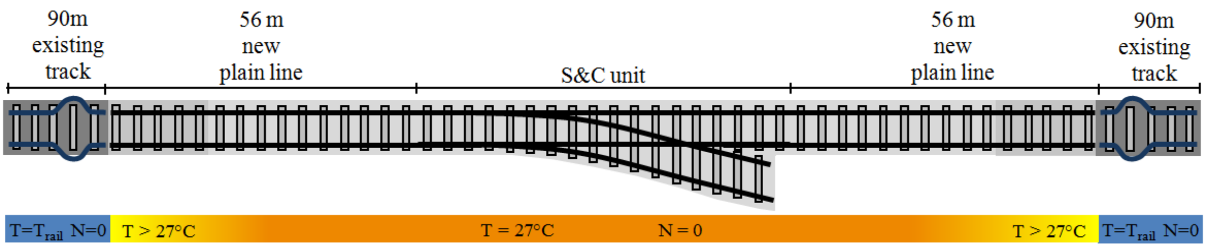
Step 3
In step 3 the S&C unit is placed with heating blankets connected to the rails. The panels of the S&C unit are welded together using aluminum thermite welds.



Step 4
The new plain line is installed in panels of 19 m length. The panels are welded to the S&C unit using flash butt welding. During this process the plain line panels have to be unclipped, so that displacements caused by the consumption of the flash butt weld will take place in plain line and not in the S&C unit.

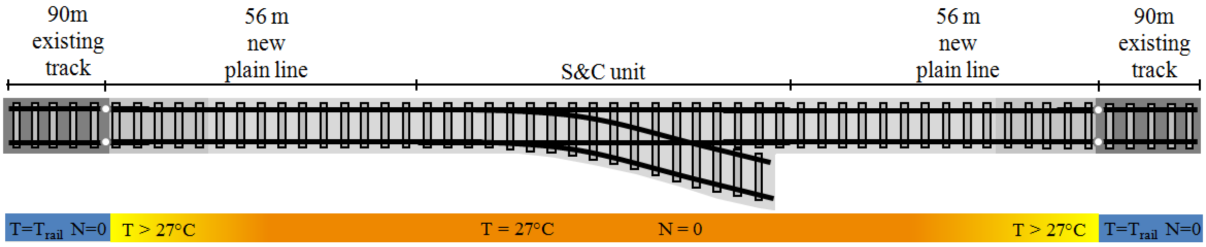


Step 5
The plain line is heated with a heating wagon. The wagon commences at the S&C unit and works towards the end of the ramp. The plain line is heated to the SFT and a bit warmer to give it the extra length that is needed to stress the 90 m of existing track that is unclipped. Behind the heating wagon the plain line is clipped.



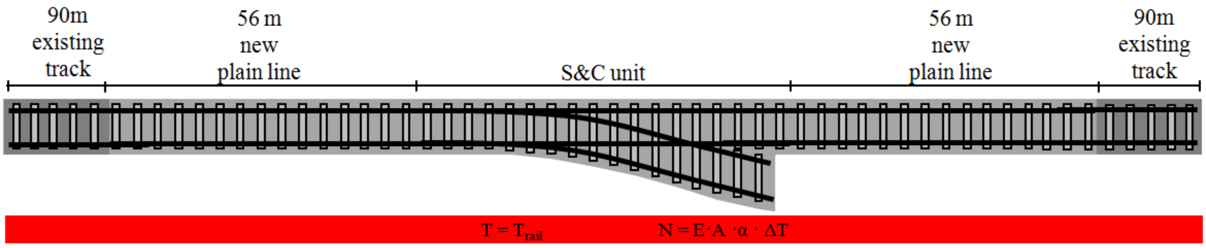
Step 6

The closure welds are made with the flash butt welding machine.



Step 7

The top ballast layer is installed.



Part 4 Conclusions and recommendations

In this part the answers on the research questions are given in a few conclusions. Also other conclusions that can be made from the results of the study are described. In the recommendations a few proposals for additional research are given.

12 Conclusions

There is less time available to do maintenance because of the increasing demand of the capacity on the railway track. More efficient methods are needed for renewal and maintenance, to improve availability of the track. The project of VCV with the full modular working method to renew a S&C unit within 8 hours is a more efficient method. However due to the innovative nature of this full modular method its implementation led to the following research questions:

Is it possible to stress the S&C unit and the plain line to the stress free temperature length within the limits of the new full modular S&C method?

- *Is the ballast resistance sufficient to stress the plain track to the required length, within the allowable displacements?*
- *What is the best sequence to weld and stress the S&C unit and the plain line to the stress free temperature length?*

To find the answers to these questions was the goal of this project. Firstly, to determine the longitudinal resistance between the ballast and the sleepers field tests with a straight track have been performed. During these tests the track has been pulled with a certain force and the resulting deformations and displacements of the track have been measured. From the results of these tests the following conclusions have been made:

- The results give a good indication of the longitudinal resistance for the different ballast situations. The maximum longitudinal resistance force for the plain line without the top ballast layer is 2.20 ±0.60 kN per sleeper and with the top ballast layer it is 7.20 ±0.85 kN per sleeper.
- Extra weight on top of the rail increases the resistance between the ballast and the rail.

In order to analyse the switch behaviour during the stressing process the Finite Element model of the S&C unit has been developed. Additionally a numerical model of the straight track used the field tests has been developed as well. This model has been used to identify the mechanical properties of the track model which later have been used in the FE model of the whole S&C unit. The numerical models have been developed using the LONGSTAB software (TU Delft).

Using the FE model of the switch a series of numerical simulations have been performed. Based on the results of the simulations the following conclusions have been made:

- The results of the numerical simulation have shown that it is not possible to stress the plain track to achieve the required equivalent temperature by pulling the 56 m of the track in front of the S&C unit. The longitudinal resistance of the track with or without top ballast was not sufficient to prevent the displacements of the S&C and the displacements of between the rails at the clamplock from exceeding the prescribed limit of 4 mm and 2 mm.
- For the situation without the top ballast layer the calculated maximum allowable pulling force is 163.2 kN per rail and with the top ballast layer this force is 465 kN per rail. The corresponding temperature differences that can be achieved with these pulling forces are 9.0°C without top ballast and 24.0°C with top ballast. That is below the desirable temperature difference of 30°C.

- The best sequence to weld and stress the S&C unit and the plain line is to heat the S&C unit with heating blankets and to heat the plain line with the heating wagon. In the plain line an extra length should be created to compensate for the stressing of the unclipped existing track.
- First the S&C unit has to be welded with thermic welding. Then after installation of the new plain line panel the panels are welded to the S&C unit using flash butt welding. The closure weld is made between the renewed plain line and the existing track.

The main conclusion of this research is that with the usage of pulling equipment it is impossible to achieve the required stress free temperature in the S&C unit and the adjacent plain line within the limits of the proposed full modular S&C method, as the longitudinal ballast resistance is not sufficient. The plain line needs to be heated using either heating blankets or a heating wagon and therefore an extra activity in the process needs to be added to get the plain line at the SFT.

Next to the answers on the research questions the following conflict with the regulations and guidelines has been found.

- In the regulations a standard anchor length of 90 m should be sufficient. The definition of the anchor length given in the regulations is the length of CWR track that is clipped down with the fasteners during the stressing operation to ensure that no movement occurs at the fixed ends of the length being stressed. In the results of the numerical analysis it can be seen that the movements still occurs even after the 90 m of clipped rail.

In this report a few assumptions are made. The main assumptions and the influence of changes of these assumptions on the end result is described.

When the allowable displacement at the switch point and the allowable displacement difference between the switch point and the stock rail could be enlarged, then larger pulling forces can be used. With these adjusted tolerances it might be possible to pull the rails instead of heating to the SFT length at the maximum allowable temperature of 30°C after the top ballast is installed.

When stressing the rail by pulling, the top ballast needs to be installed. It has to be installed from the adjacent track or it should be installed from the renewed track. When it is installed from the renewed track temporary joints need to be made at the location of the closure welds. Also the heating blankets on the S&C need to be removed to allow the ballast wagon to discharge the ballast on the renewed track.

When the S&C unit and the plain line are in a curve the lateral ballast behaviour becomes more important. When pulling in the longitudinal direction the rail starts to displace in the longitudinal and lateral direction, making the radius of the curve larger.

13 Recommendations

Based on the conclusions and the gained experience some recommendations are done. The recommendations are done for the stressing sequence, the restrictions and regulations and the material properties.

Stressing sequence

For the stressing of the rails there is looked at pulling of the rails to the SFT length. In the results it appeared not to be possible to use this within the new full modular S&C method. To stress the rail it is recommended to use heating of the rail. The S&C unit will be heated with heating blankets according to the working method in the full modular program. It is advised to stress the plain line by heating it with a heating wagon to the SFT and to investigate how this fits within the new full modular S&C method.

In the full modular S&C method the top ballast is installed after making the closure weld. When the rail is heated the rail starts to cool immediately after the heating wagon has passed. Because the top ballast is not yet installed the rail is able to move. It is recommended to investigate which displacements occur due to the cooling of the rail before the top ballast is installed.

It is recommended to investigate how the model can be used to determine the anchor length and stressing sequence for different situations. With a few adjustments the model can be used to determine the displacements in plain line track of lengths larger than 60 m. In the model there is only one type of S&C unit (C11) used. When adding the geometry of different S&C units the stressing sequence can be adjusted per type of S&C unit.

Restrictions and regulations

The requirements about the displacement of the S&C units are not very clear. Therefore, for this research, an assumption is made about the allowable displacement of the S&C unit. To determine what the restrictions of the displacement of a S&C unit are, more research is necessary. In this research there should be looked at the limits of rotation of the switch panel, the limits of displacement in the longitudinal and lateral direction and the allowable displacement difference between the rails at the location of the clamplock.

The reason for a certain guideline around the S&C has to be investigated to determine the limitations.

The assumption is made that the S&C unit and the plain line are not in a curve. It is recommended to investigate the influence of pulling on the rail in the longitudinal direction when the S&C unit and the plain line are in a curve.

Material properties

Ballast is a very inhomogeneous material. Therefore a lot of test will have to be performed to give a good overview of the friction between the ballast bed and the sleeper. The test described in appendix A are not enough to give good scientific proof. More tests have to be done to make this possible.

The displacement of the rails is sensitive for the displacement at the peak limit force (W_p). In the test it was very difficult to determine this displacement because it was almost 0, compared to the results from the earlier tests done by van ‘t Zand and Moraal, whom found a displacement of 5 mm. Therefore it is recommended to do more tests to determine this displacement.

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Appendixes

Appendix A Report Ballast resistance testing

Ballast Resistance Testing

S. Boogaerdt

May 2009

Contents

1 Introduction

This document contains the test results from tests to determine the longitudinal ballast resistance for different ballast situations and load cases. These tests were done as a part of a thesis about a new working method to achieve neutral stress in a renewed S&C unit. The result will be used to validate a theoretical final element model.

The stress free temperature (SFT) can be achieved by heating the rails causing them to expand or by stretching the rails to the length that corresponds to the length at the SFT. To use the last option the anchor length has to be sufficient to prevent displacements at the end. The anchor length is the length of the rail that is clipped down with the fasteners during the stressing operation to ensure that no movement occurs at the fixed ends of the length being stressed. This length is dependent on the longitudinal resistance between the ballast and the sleeper. Tests were done to determine this resistance.

Two tests were done, one test on 9 m of plain track and a large scale test on 40 m of plain track. The 9 m test will be used to calibrate the computer model in the final element program Longstab and the large scale test will be used to determine the accuracy of the computer model.

The tests were done in the Netherlands at a renewal project in Houten.

2 Description of the test condition

In this chapter the test conditions are described. First the site set up is explained and then the loading system. Also the test procedure is described.

2.1 Site set up

The tests were done at a renewal project in Houten, the Netherlands. A part of a plain line track was used for the tests. This part of track consisted of prestressed concrete sleepers (NS90) and UIC54 rails. The specifications of the sleepers, rails, fasteners, rail pads and ballast are given in appendix I.

The track was used as a tram line. To prepare the track for the test a 9 meter section was cut and the top ballast was removed between the sleepers in the 9 meter section and between the 40 meter plain line adjacent to it (second test panel). Furthermore the ballast bed between the sleepers was leveled.

Strain-gauges and LVDT's were installed on the track during two days prior to the test day. The LVDT's were mounted on a box with ballast inside to prevent displacement. They were connected to the sleeper with a piece of wood connected to the sleeper.

The locations and the numbering of the strain-gauges and the LVDT's are shown in figure 2.1 and figure 2.2.

On the test day the strain-gauges and the LVDT's were connected and the pulling equipment was installed. The jacks of the pulling equipment were connected to one generator, to make sure that the pressure in the jacks is the same.

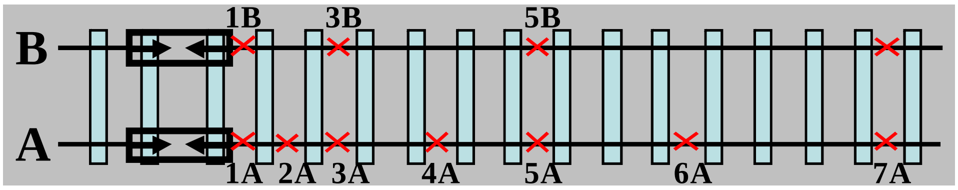


Figure 2.1 Location and numbering of the strain-gauges on 9 meter test

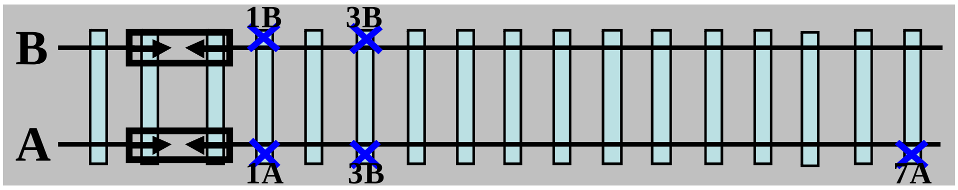


Figure 2.2 Location and numbering of the LVDT's on 9 meter test

The tests on the 40 meter plain line were done at the same location as the 9 meter plain line. The preparation of the test panel was also done the same way.

The locations and the numbering of the strain-gauges and the LVDT's are shown in figure 2.3 and figure 2.4.

At the beginning of the test on the 40 meter plain line, strain-gauges 3B and 4A were not working properly. Therefore no data were collected from these strain-gauges.

In appendix II some photographs of the test site are added.

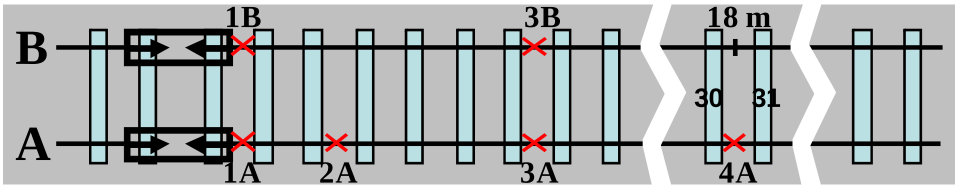


Figure 2.3 Location and numbering of the strain-gauges on 40 meter test

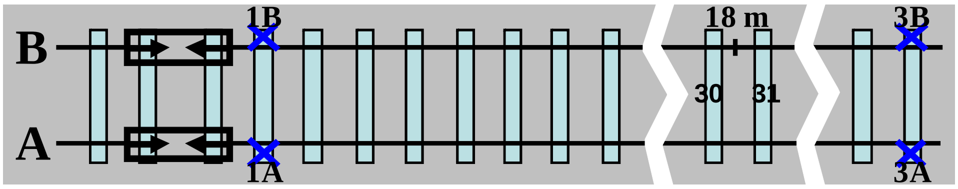


Figure 2.4 Location and numbering of the LVDT's on 40 meter test

The weather condition during the tests was sunny with a few clouds. At the beginning of the tests the test panels were partly in the shade and at the end of the test the whole test panel was in the sun. The rail temperature at the beginning of the tests was 5°C in the shade and 7.5°C in the sun. At the end the rail temperature was 21°C.

2.2 Loading system

The loading in the longitudinal direction is done with the pulling equipment normally used for stressing the rail. In figure 2.5 a picture of the equipment is shown.

This device closes a gap between two rails by pulling them towards each other. The clams (3) of the device grab the rails at the flange. At one end of the steel rods, which go through the clams, jacks (1) are placed. These jacks pull the clams towards each other and close the gap between the rails. If the length of the gap is larger than the distance the jack can pull a bolt (2) can be screwed towards the clams to keep the tension on the rails while the jacks are placed back.

During the test the bolts (2) were screwed by hand to keep them in the middle of the opening. This was done to prevent the jack to be blocked.

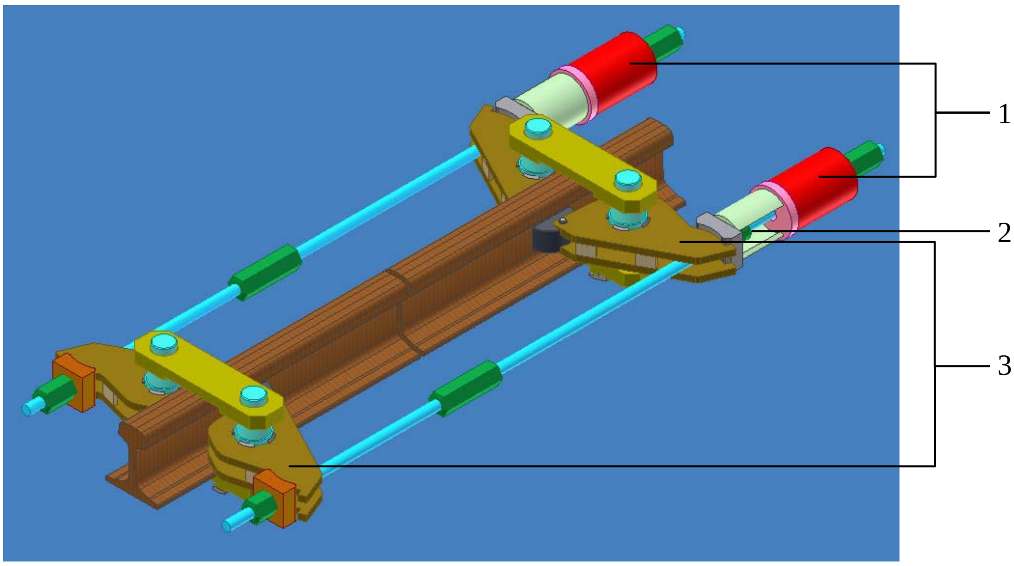


Figure 2.5 Pulling equipment used for stressing for the rail

2.3 Test procedure

During each test the recording of the data from the stain-gauges and the LVDT’s was started and then the pressure in the jacks was raised until the panel started to move. The recording of the data stopped after relaxing of the pulling equipment.

Test on the 9 meter was repeated with different loads on the rail and with different ballast situations. The tests with the different loads were done without top ballast. For the extra load sleepers were placed on top of the rail at the end of the test panel. The different ballast situations were with or without the top ballast layer.

Test on the 40 meter long test panel was only repeated without the top ballast layer and without additional weight. In table 2.1 an overview of the test is given.

The tests were done in three series.

1. the test on the 9 meter test panel **without the top ballast layer** (tests 1 to 6).
2. also on the 9 meter test panel but **with the top ballast layer** (tests 8 to 12).
3. the test on the **40 meter** test panel (tests 18 to 21).

In between these series all the strain-gauges were put back to zero.

Table 2.1 Overview of the tests

Test number	Ballast situation	Load	Remarks
1	without top ballast	-	
2	without top ballast	-	
3	without top ballast	6 sleepers	
4	without top ballast	6 sleepers	
5	without top ballast	13 sleepers	
6	without top ballast	13 sleepers	
8	with top ballast	-	
9	with top ballast	-	
10	with top ballast	-	
11	with top ballast	-	Pulled through until a large displacement. Recording stopped before relaxation of the pulling equipment
12	with top ballast	-	Only pulled on rail A
18	without top ballast	-	
19	without top ballast	-	
20	without top ballast	-	
21	without top ballast	-	

3 Results

In this chapter the results from the test will be discussed. First the expected relationships are explained and afterwards some general remarks about the results are given. Finally the results from the different test will be compared.

3.1 Expected relationships

The sketch given in figure 3.1 shows the typical elasto-plastic relationship for the expected longitudinal resistance and the displacement. The maximum force for the tests with the top ballast layer is expected to be in the order of 5 to 10 kN per sleeper.

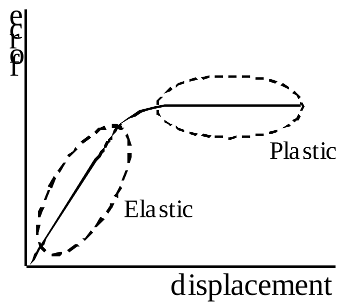


Figure 3.1 Expected relationship

3.2 General remarks

During each test all data were recorded digitally resulting in a data matrix of 23 columns for the 9 meter test panel and a data matrix of 15 columns for the 40 meter test panel. All the data is recorded with a rate of 100 Hz.

After filtering the data, the measured strain is used to calculate the force in the rail with formula 3.1

$$F = \varepsilon \cdot E \cdot A \qquad (3.1)$$

Where F is the force in the rail; □ is the strain; E is the stiffness of the rail ($2.1 \cdot 10^5$ N/mm^2) and A is the area of the rail cross section (69.34 cm^2).

In the figure 3.2, figure 3.3 and figure 3.4 the longitudinal force at both rails directly behind the clams of the pulling equipment is shown for all the three series of tests. In the graphs it can be seen that the force on one of the rails or sometimes on both rails do not always go back to zero completely at the end of each test. This can be explained by the fact that during the test the bolts (2) of the pulling equipment (see part 2.2) were sometimes tightened too far. Therefore it was not possible to relax the pulling equipment completely and a force was left on the rails. However, it can be seen that the maximum force in the rails is not influenced.

In between the test there is a minor change in the force in the rails. This can be explained by the relaxation of the rail and small temperature differences between the tests.

Appendix III contains all graphs from the test results. For every test the graphs comparing the force in rail A and B and the displacement are given. The forces at the beginning of the tests were used as a zero setting. Therefore some results cannot be used because the force on the rail was not removed completely. Only for test 11 and test 19 the results from both rails are not usable.

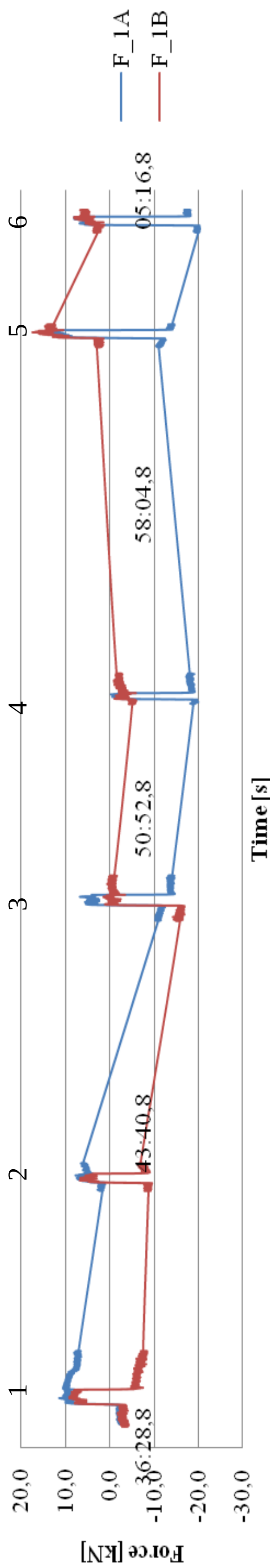


Figure 3.2 Force at 1A and 1B for test 1 – 6

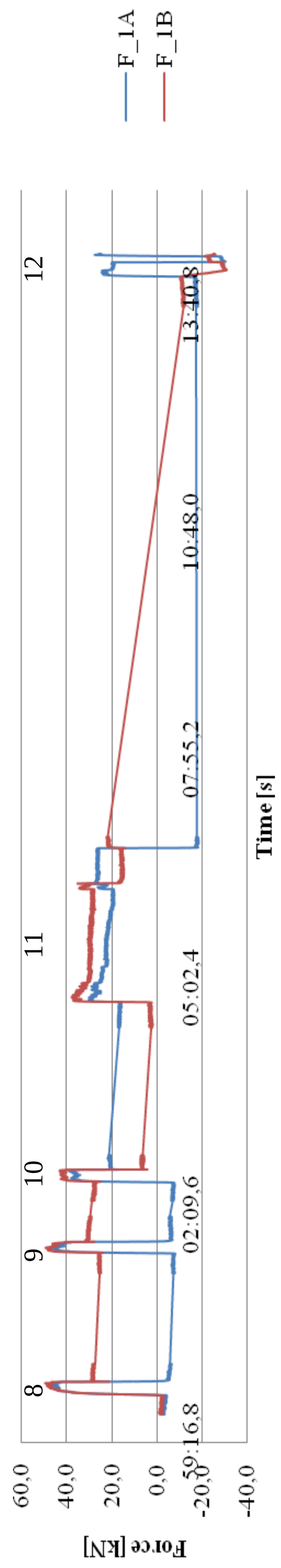


Figure 3.3 Force at 1A and 1B for test 8 - 12

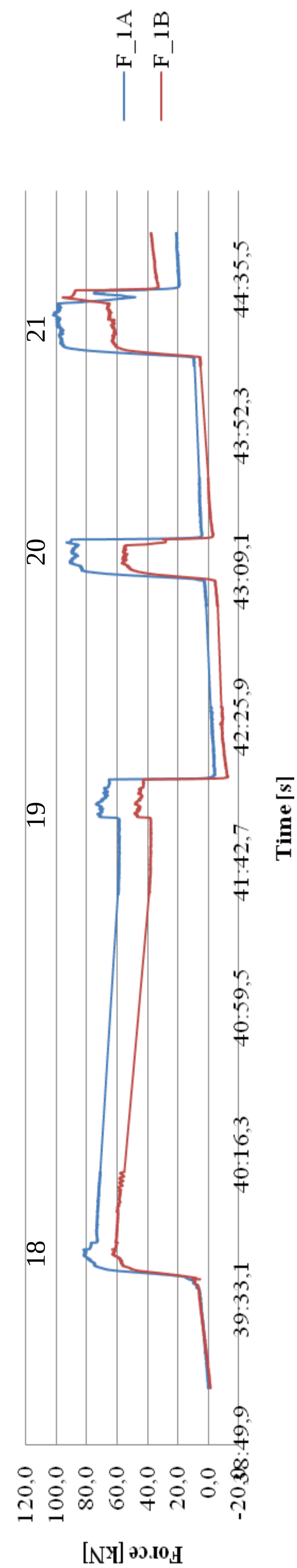


Figure 3.4 Force at 1A and 1B for test 18 -21

3.3 Comparing the test results

To compare the results from the different tests the force is divided per sleeper (14 sleepers for the 9 meter test panel and 65 sleepers for the 40 meter test panel). The force directly behind the pulling equipment at rail A is used, except for test 2. For test 2 the force in rail B is used because the force in rail A was not completely released after test 1. From the results the moving average over 20 points is used to reduce minor measurement errors that create noise.

Figure 3.5 shows the results of the tests which were done *without* the top ballast layer. These are test 1 and 2 on the 9 meter test panel and test 18, 20 and 21 on the 40 meter test panel. The results show an average of the longitudinal resistance force of 2.23 ±0.60 kN per sleeper.

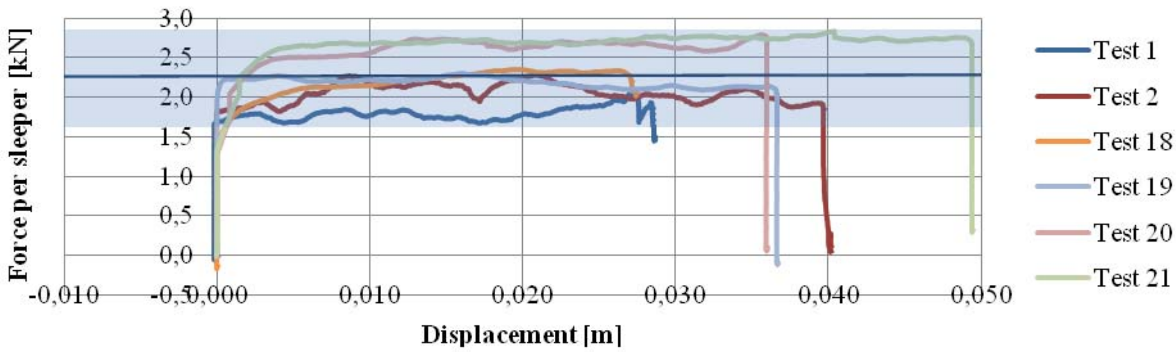


Figure 3.5 Longitudinal resistance force per sleeper without top ballast

The results of the tests *with* the top ballast layer are shown in figure 3.6. This are test 8, 9 and 10 on the 9 meter test panel. The results show an average of the longitudinal resistance force of 7.20 ±0.85 kN per sleeper.

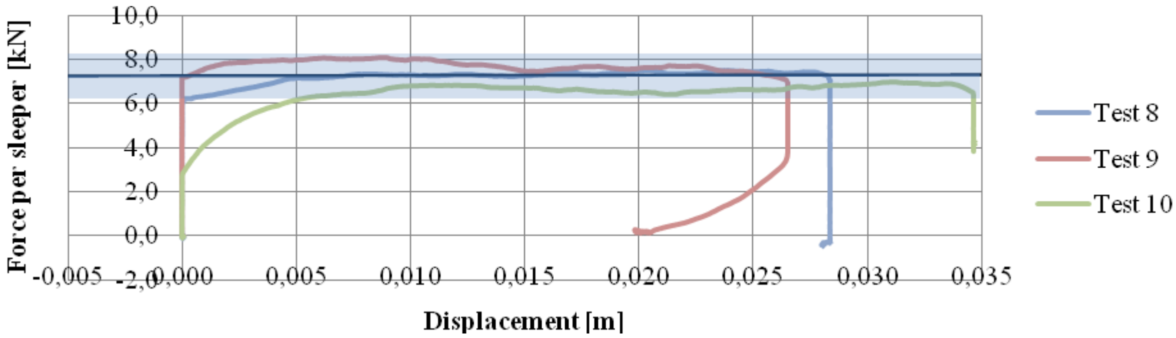


Figure 3.6 Longitudinal resistance force per sleeper with top ballast

The influence of the vertical force on the longitudinal ballast resistance peak force is shown in figure 3.7. The black line can be represented by the function 3.2.

$$y = 0.3796 \cdot x + 2.2262 \qquad (3.2)$$

Where y is the longitudinal resistance force per sleeper and x is the vertical load of the extra sleepers on the rail.

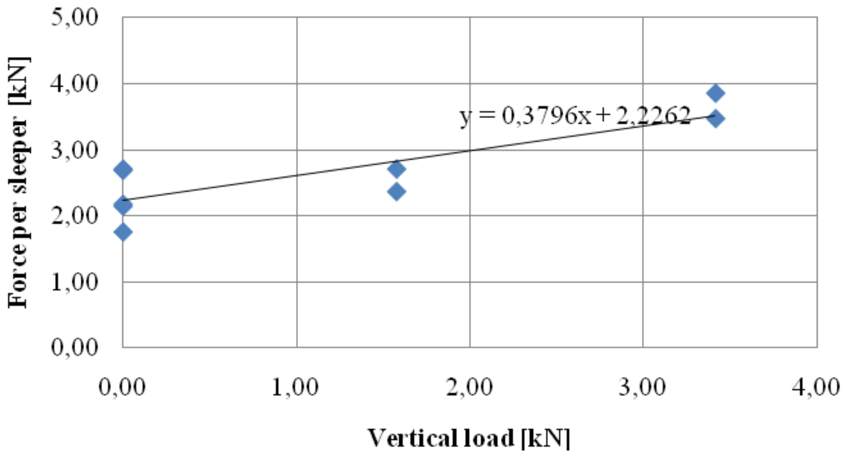


Figure 3.7 Trend line longitudinal resistance force with vertical load

4 Conclusion

The expected relation between the force and the displacement given in figure 3.1 does not completely match with the results. In the results the elastic part of the relationship is missing. A zoomed version of the graph shown in figure 3.6 is given in figure 4.1. In this picture it is clear the graph is going vertically.

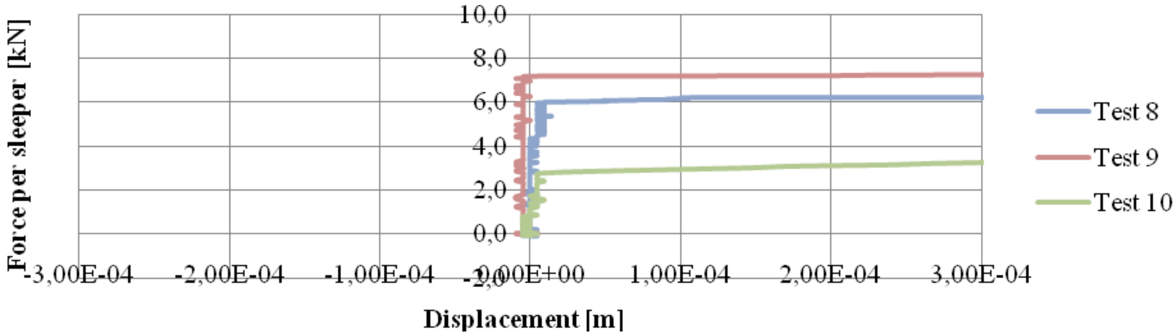


Figure 4.1 Zoomed graph figure 3.6

The results give a good indication of the maximum longitudinal resistance force with the different ballast situation. Without the top ballast layer the resistance is 2.20 ±0.60 kN per sleeper and with the top ballast layer it is 7.20 ±0.85 kN per sleeper.

Extra weight on top of the rail increases the resistance between the ballast and the rail. With extra weight equal to the own weight of the sleeper, the resistance almost doubles.

There is a lot of noise in the signal of the strain-gauges. Therefore lines of the first six tests are very unstable because the strain in the rail is very small.

5 Recommendations

Ballast is a very inhomogeneous material. Therefore a lot of test will have to be preformed to give a good overview of the friction between the ballast bed and the sleeper. The tests described above give a good indication but are not enough to give good scientific proof. More tests will have to be done to make this possible, but it was too expensive en time consuming to do this during this project.

For future tests it is recommended to use other pulling equipment. It should be able to build up the force more gradually. Also it should be easier to release to prevent stress staying on the rails in between the tests.

Also before every test all the measurement equipment has to be set to zero again to prevent unmeasured relaxation and extension or shrinkage due to temperature changes.

To make the data easier to process a lower frequency rate for the recording of the data can be used. When the force is build up much more gradually a frequency between 1 and 10 will be enough.

Appendix I Details materials

Rail UIC 54

Weight	54.4 kg/m
Dimensions	- height: 159 mm - head width: 70 mm - foot width: 140 mm - area: 69.3 cm^2
Moment of inertia	- I_y = 419.2 cm^4 - I_z = 2337.9 cm^4

Fasteners Vossloh SKL 14 (W14)

Stiffness	Approximately 10 kN toe load at a spring deflection of approximately 13 mm per tension clamp
Torque	200^{-20} Nm (according to the Dutch standard ISV00080)

Railpad FC9

Stiffness	- vertical stiffness: $0.35 \cdot 10^9$ N/m - lateral stiffness: $0.250 \cdot 10^8$ N/m

Sleeper NS 90

Weight	+/- 310 kg/piece assembled
Dimensions	See Figure A
Prestressing steel	1670 N/mm^2
Concrete quality	C 50/60

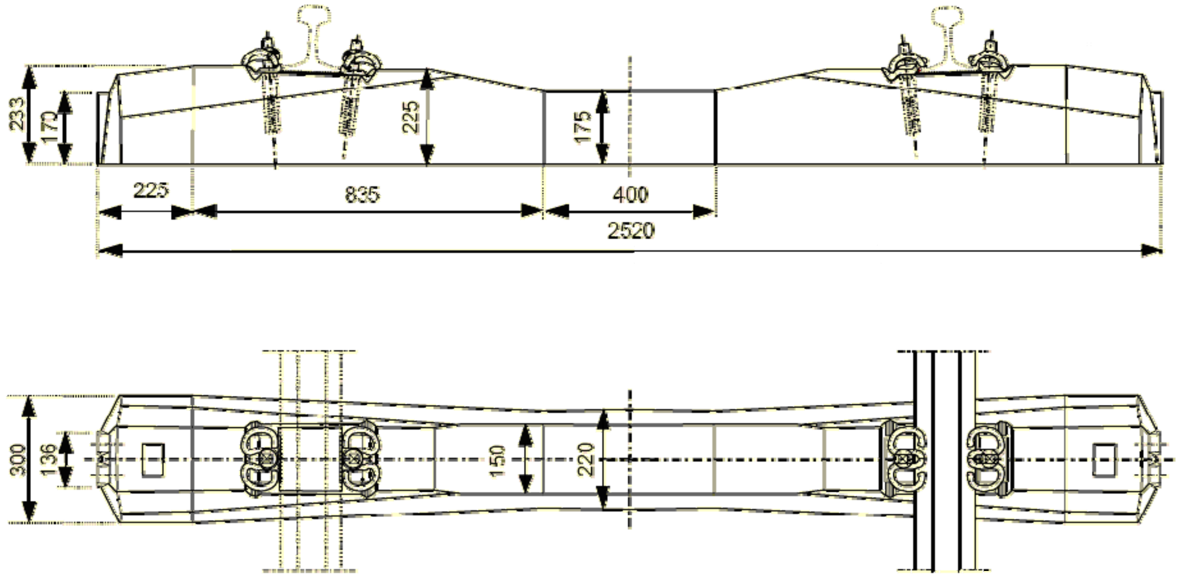


Figure A.1 Dimensions concrete sleeper NS90

Ballast 31.5/50

Type	Bremanger stone from Norway 31.5/50
Density	2725 kg/m^3
Grading	See figure A.2 for the grading curve (Product specification from ProRail; SPC00033-004)

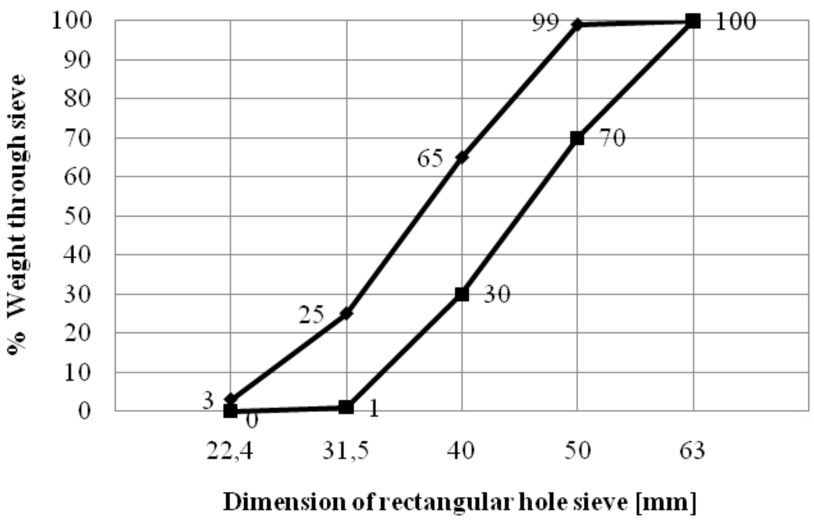


Figure A.2 Grading of Ballast 31.5/50

Appendix II Photographs

Picture 1 Removing the ballast between the sleepers

Picture 2 the 9 meter test panel without ballast

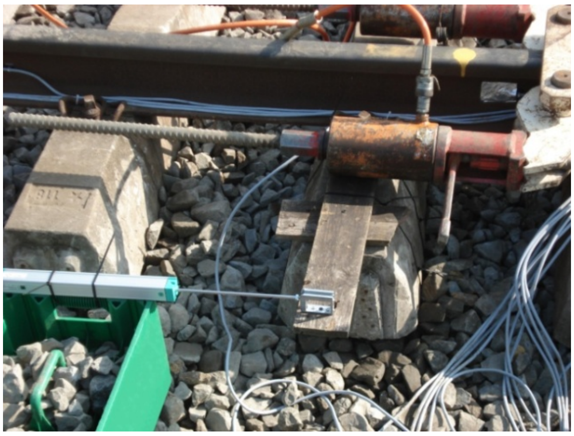
Picture 3 Installing top ballast layer

Picture 4 Test panel with top ballast layer

Picture 5 Strain-gauge

Picture 6 Connected strain-gauge

Picture 7 Installed pulling equipment



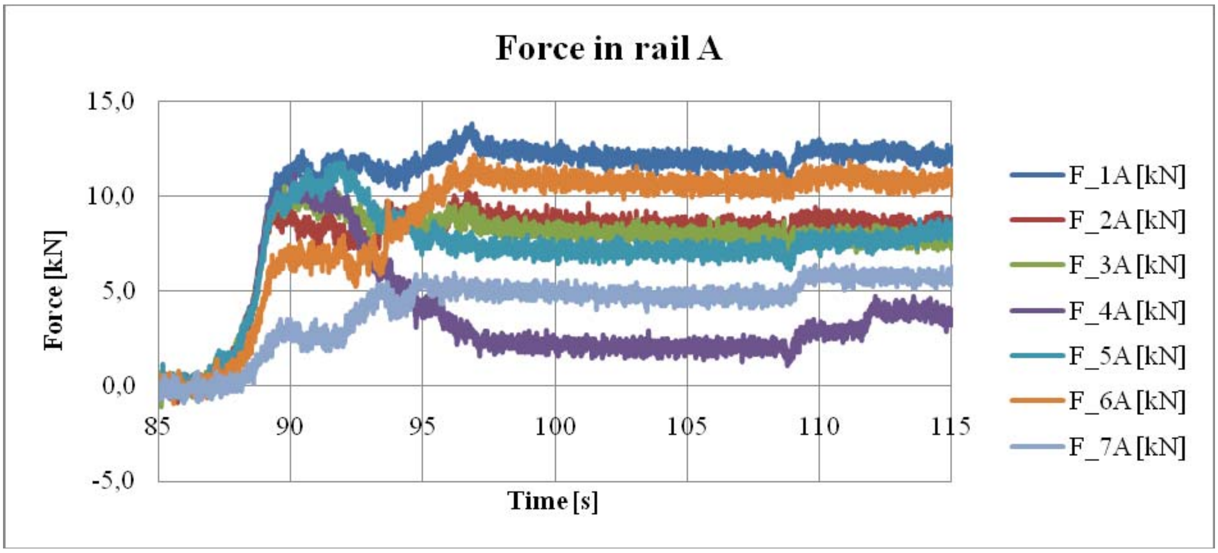
Picture 8 Installed LVDT

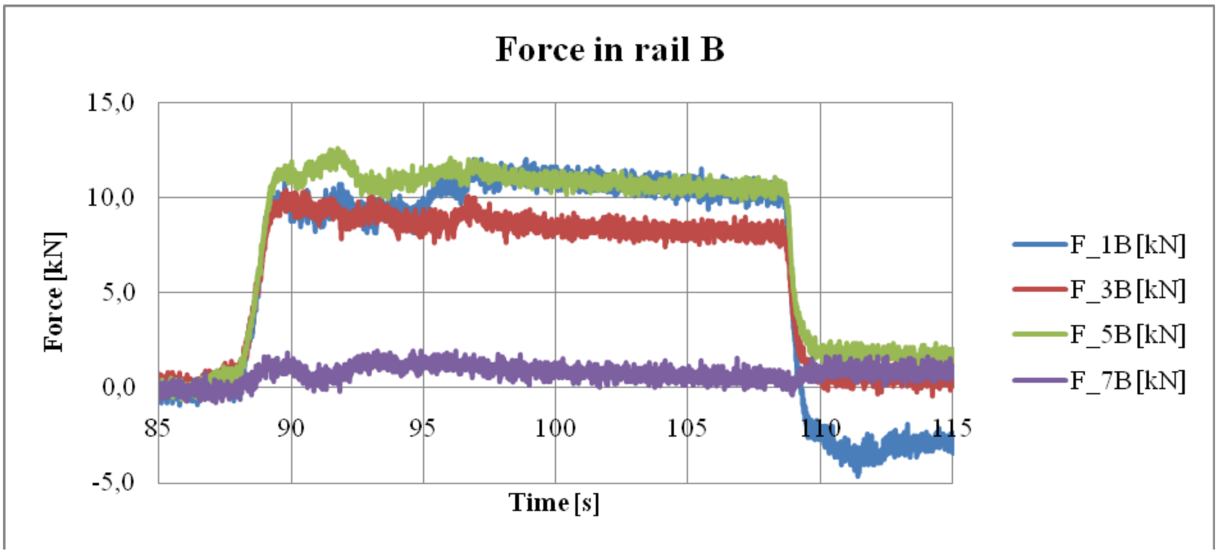
Picture 9 Extra weight on the test panel

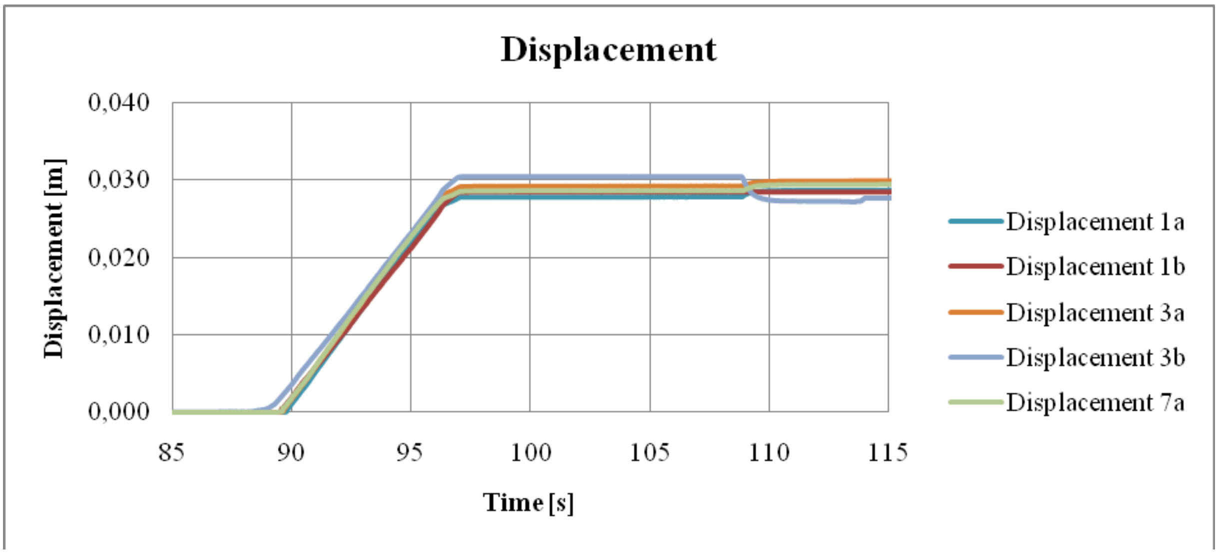
Picture 10 Extra weight on the test panel

Appendix III Test results

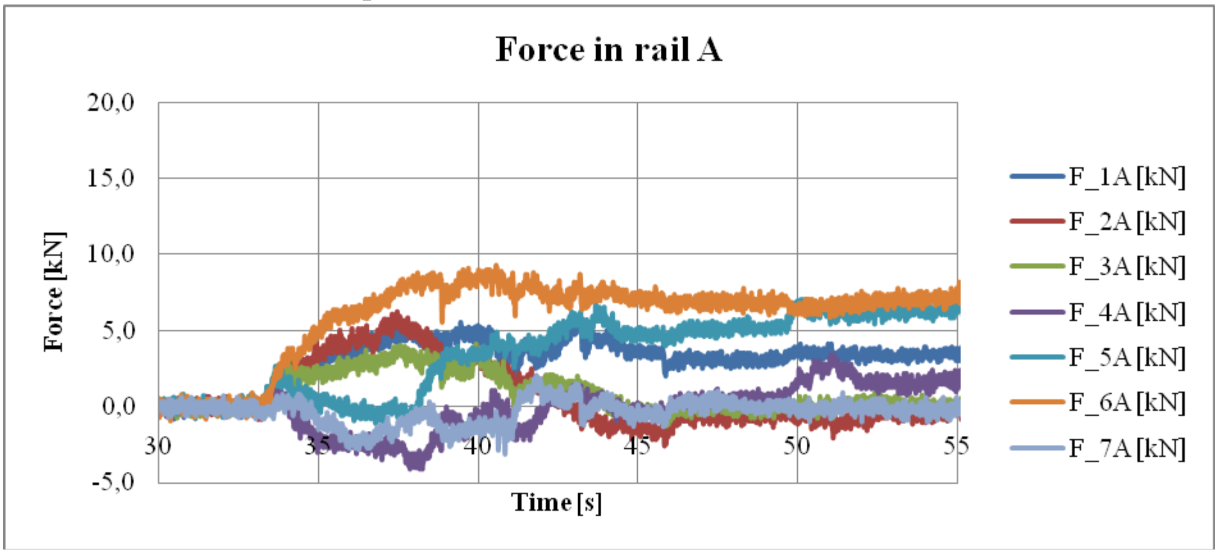
Test 1: 9 meter, without ballast

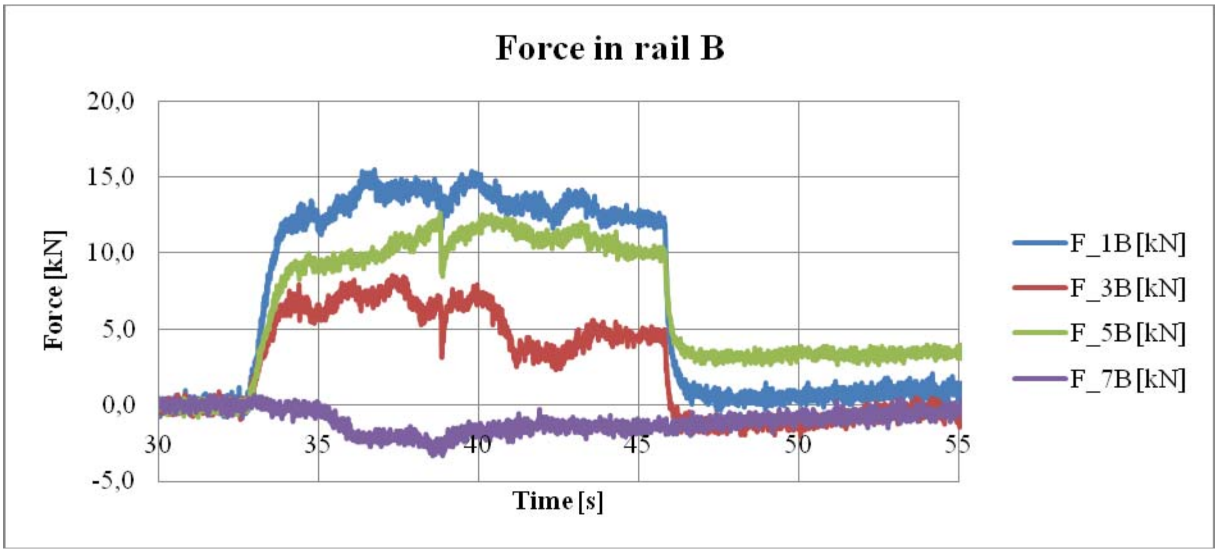


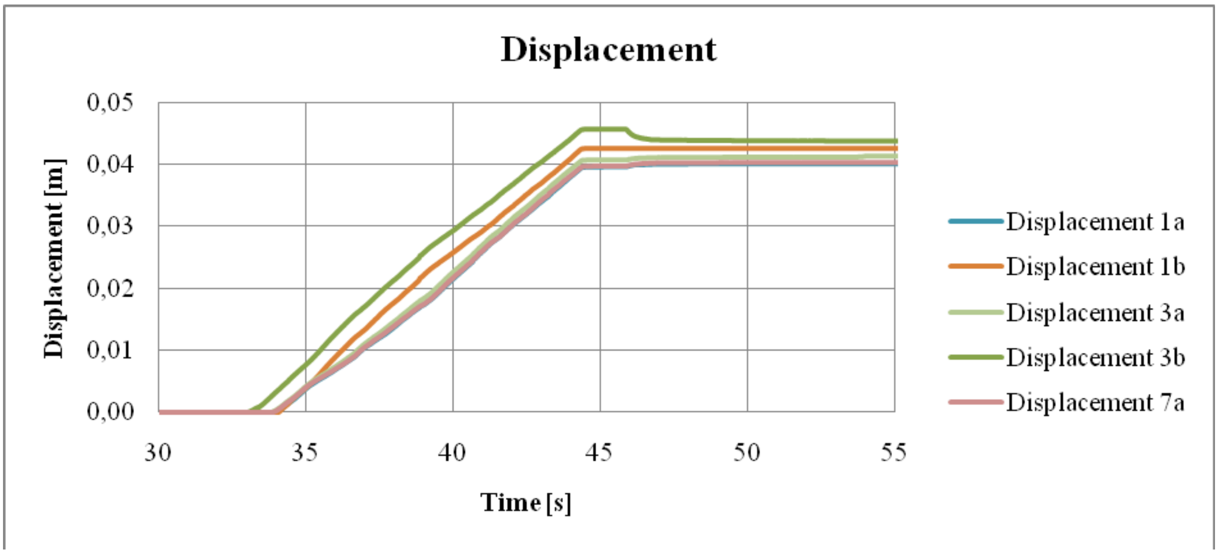




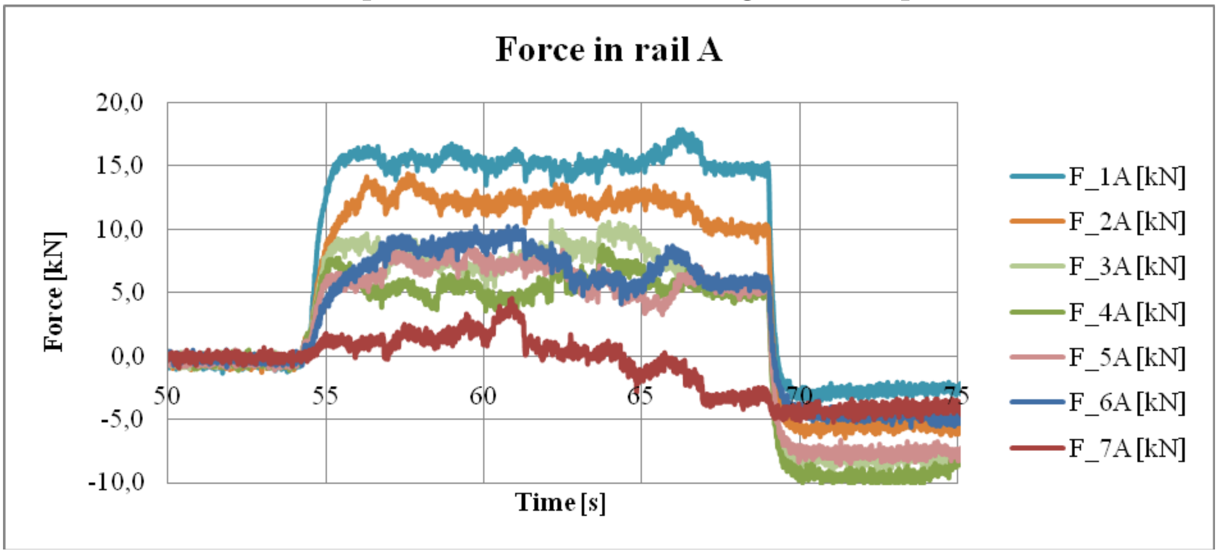
Test 2: 9 meter, without top ballast

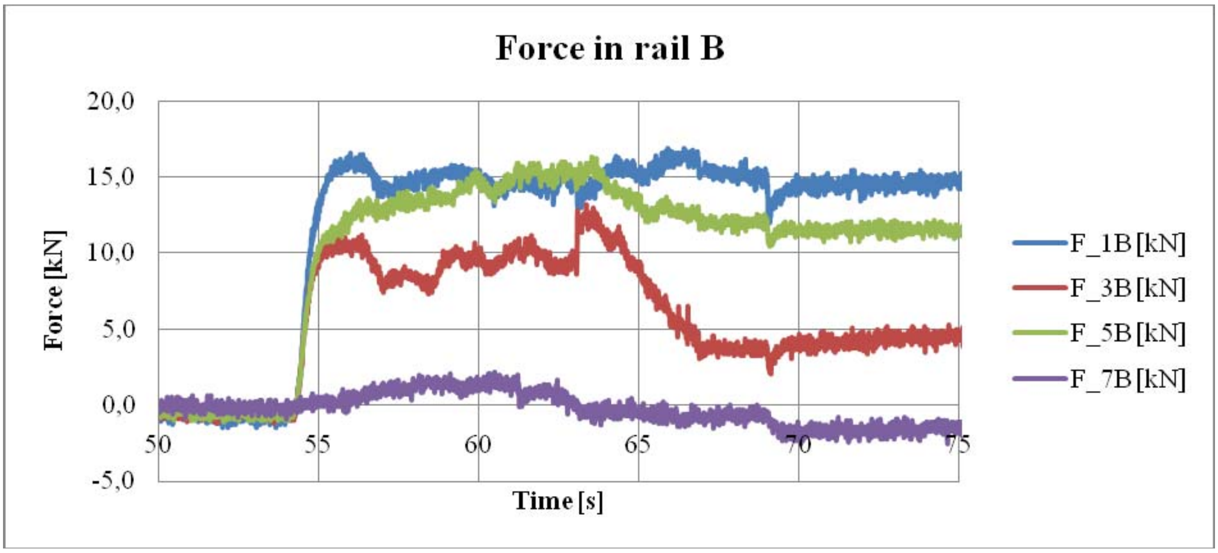


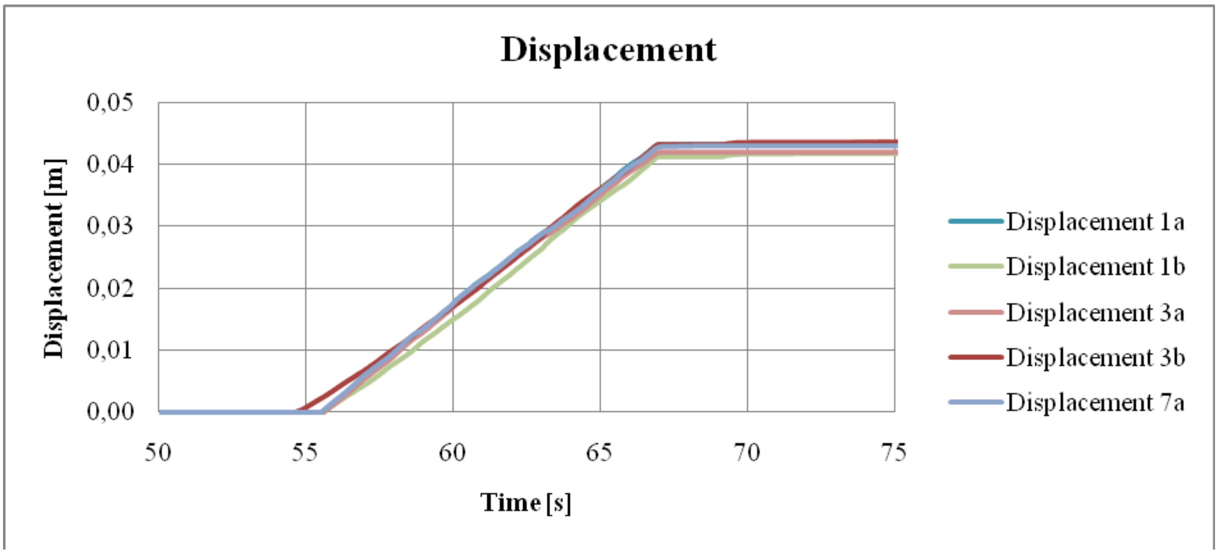




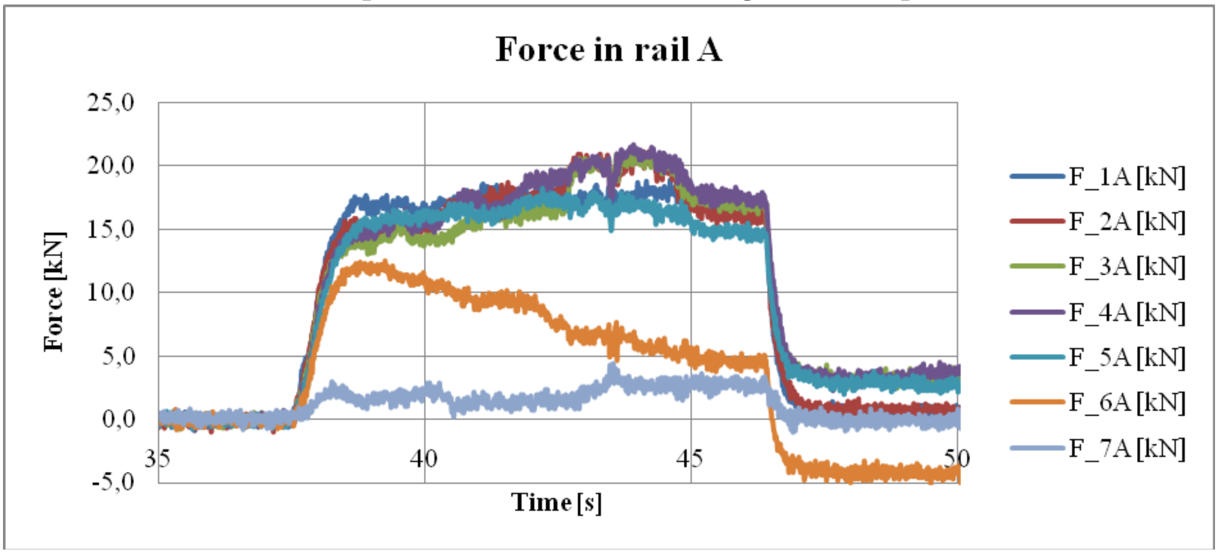
Test 3: 9 meter, without top ballast and with extra weight of 6 sleepers

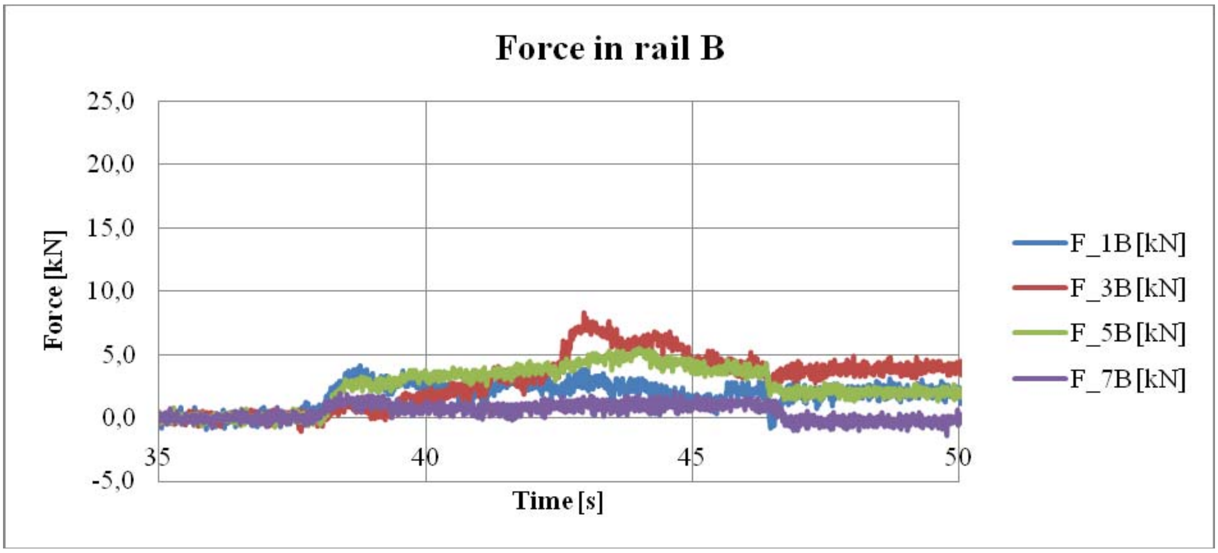


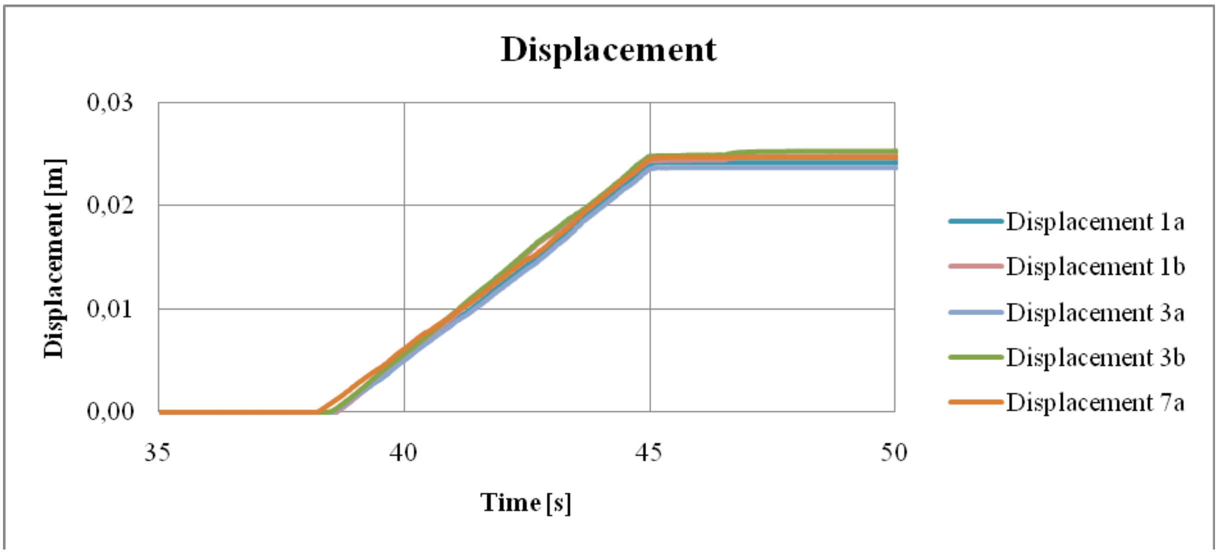




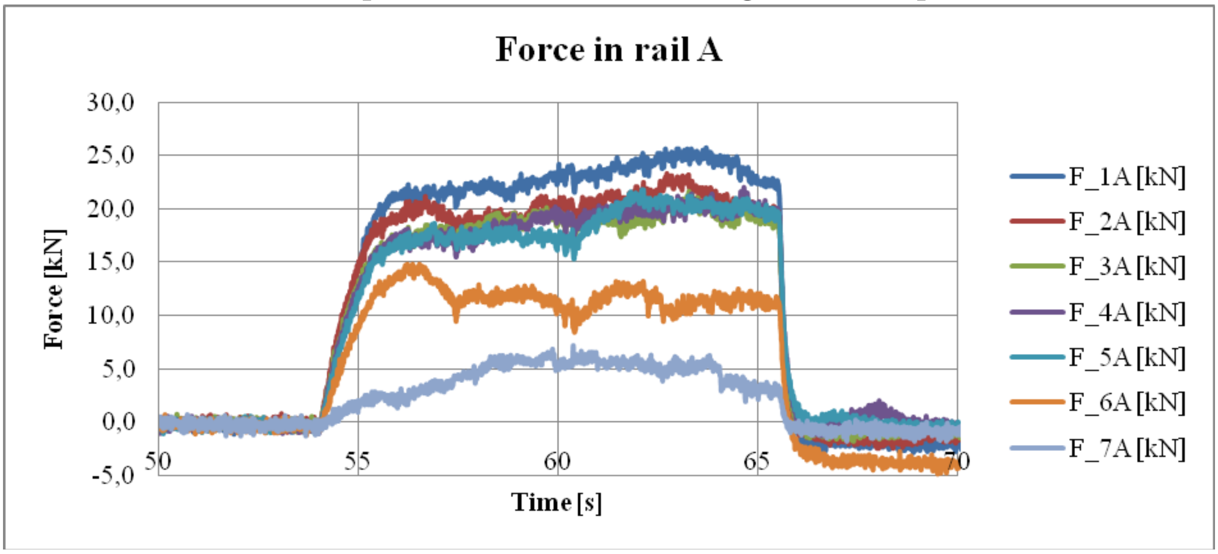
Test 4: 9 meter, without top ballast and with extra weight of 6 sleepers

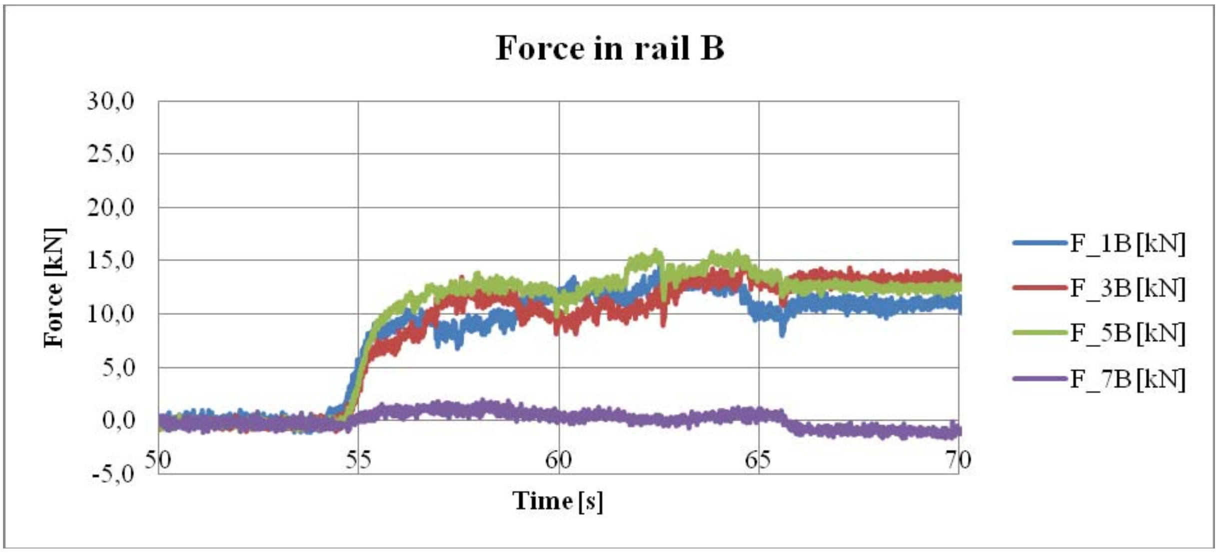


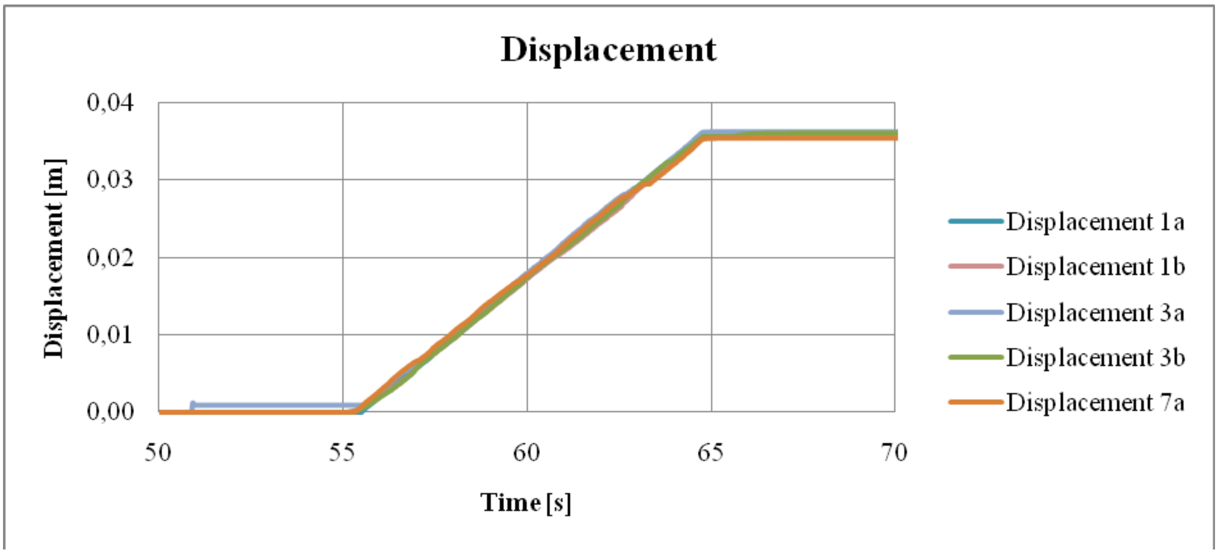




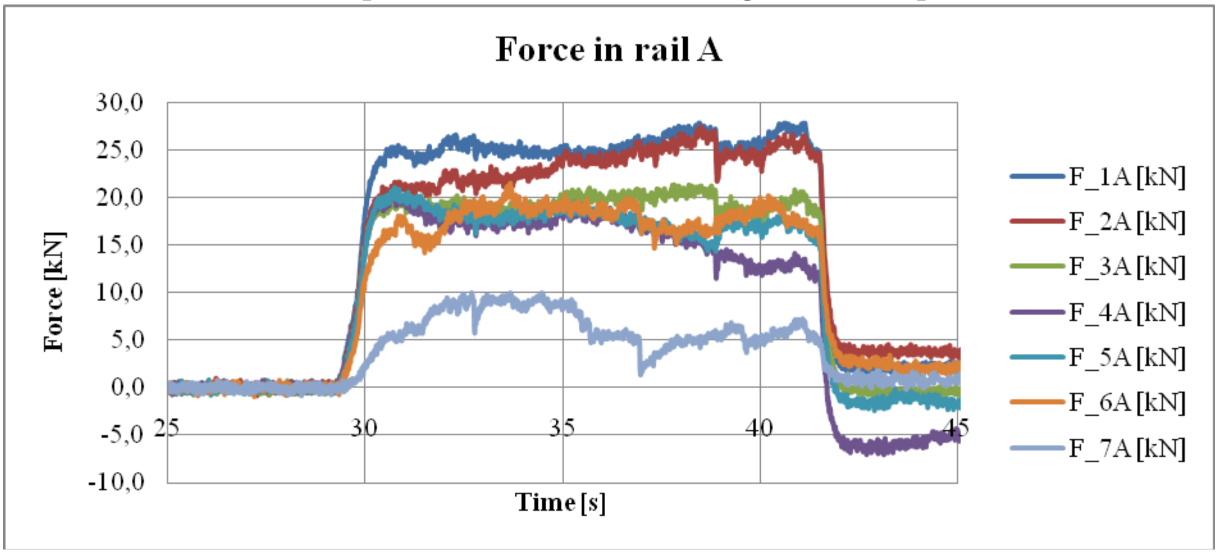
Test 5: 9 meter, without top ballast and with extra weight of 13 sleepers

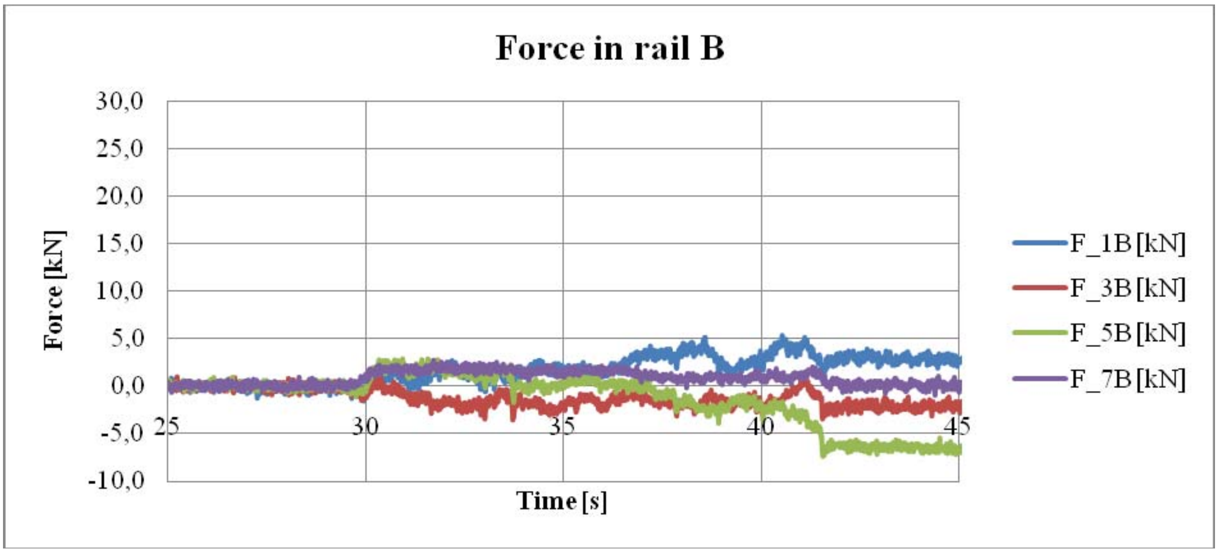


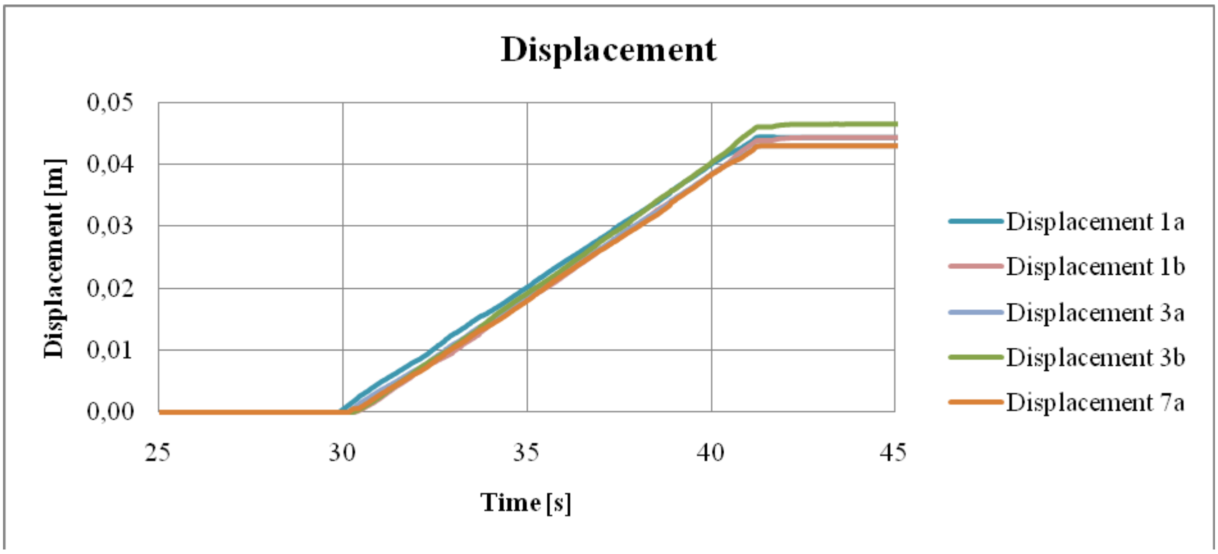




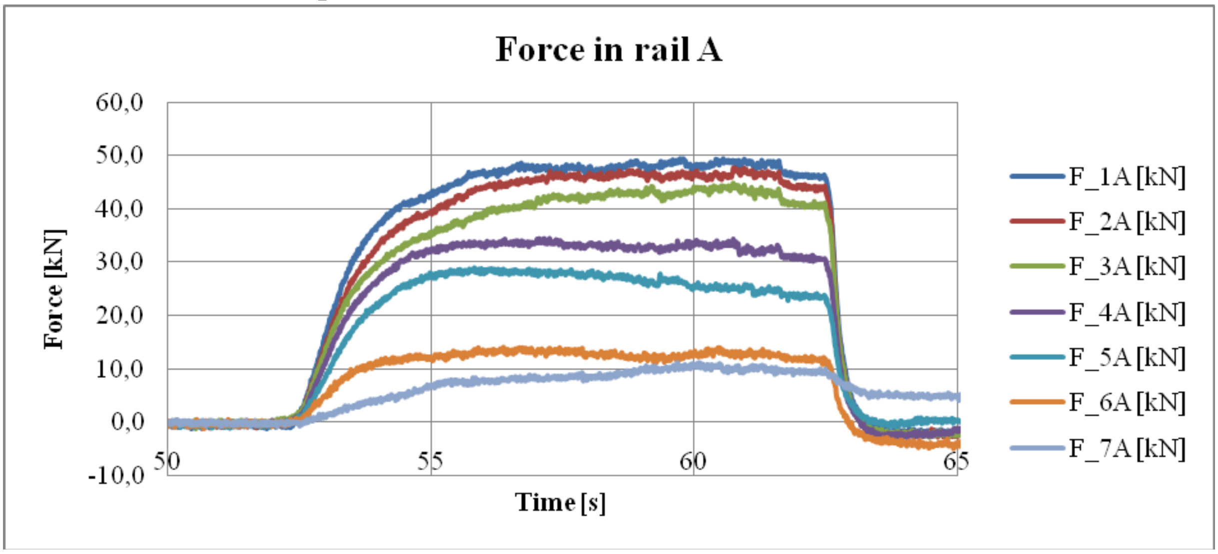
Test 6: 9 meter, without top ballast and with extra weight of 13 sleepers

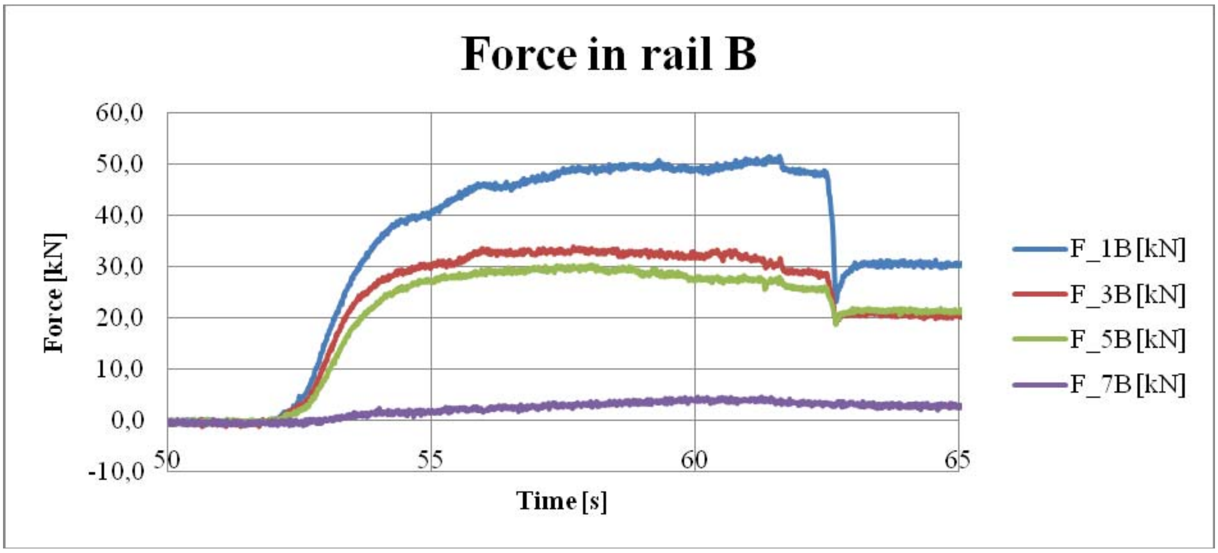


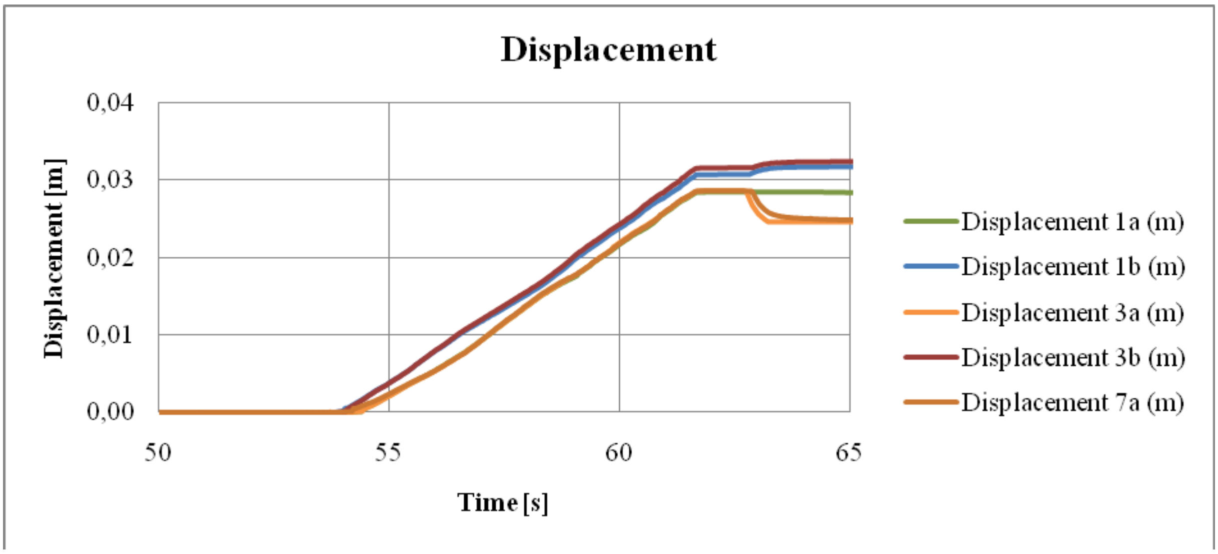




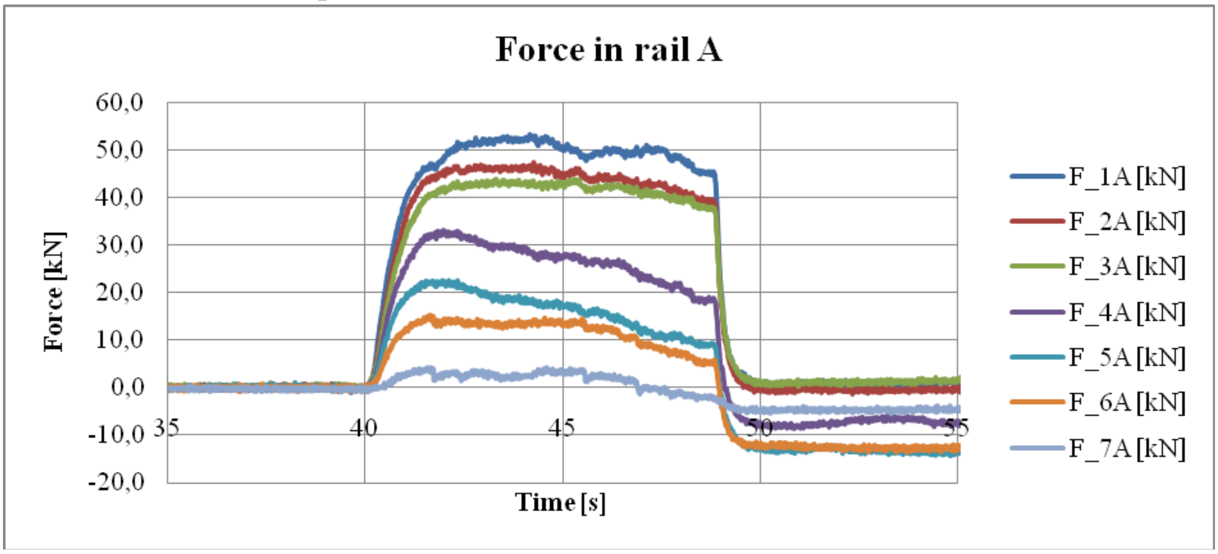
Test 8: 9 meter, with top ballast

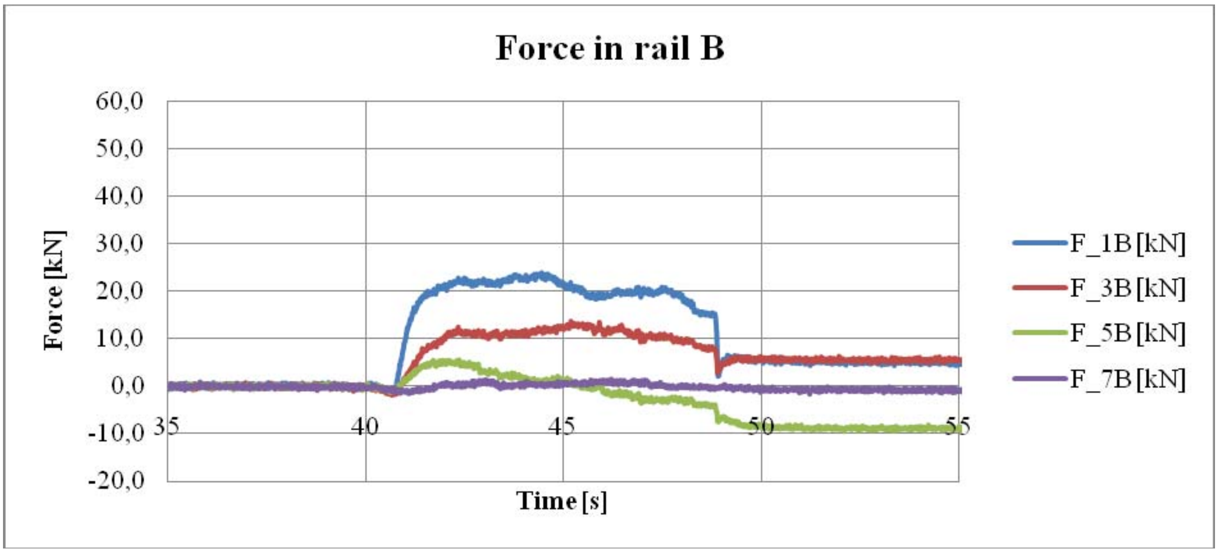


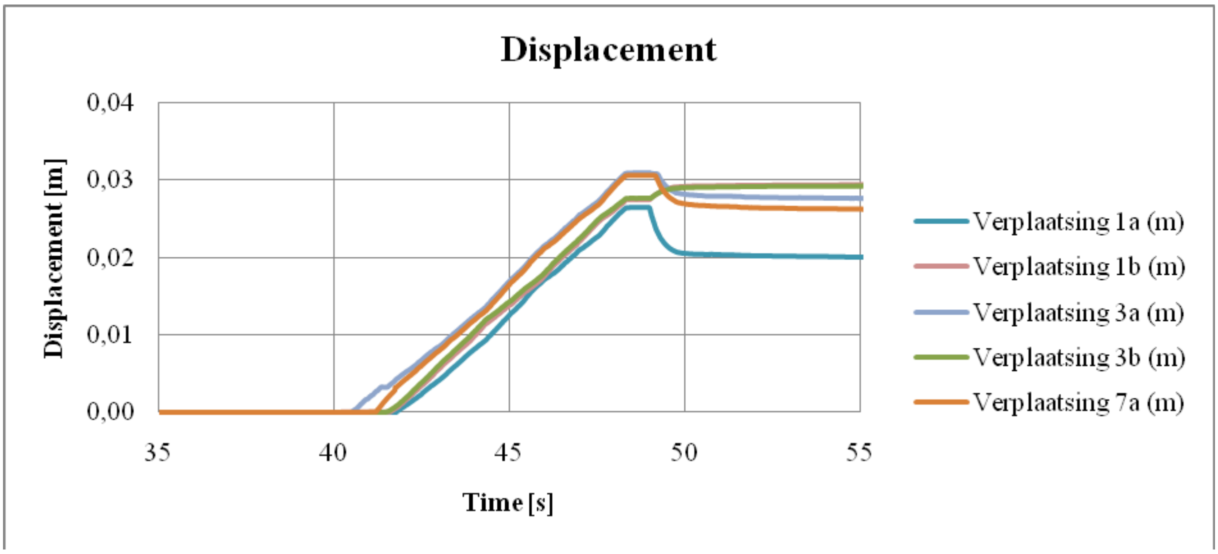




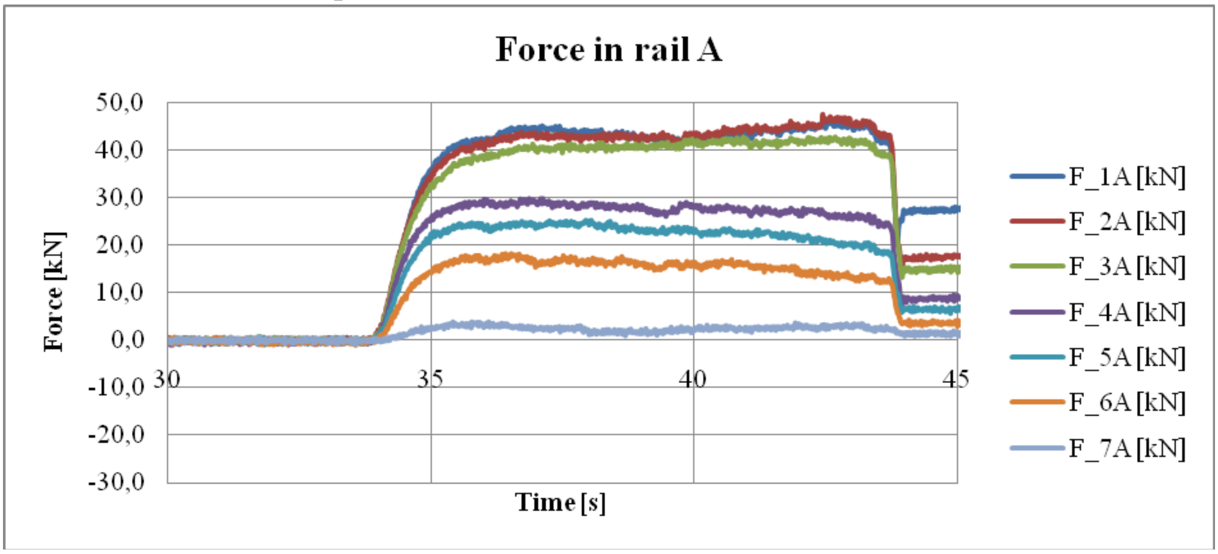
Test 9: 9 meter, with top ballast

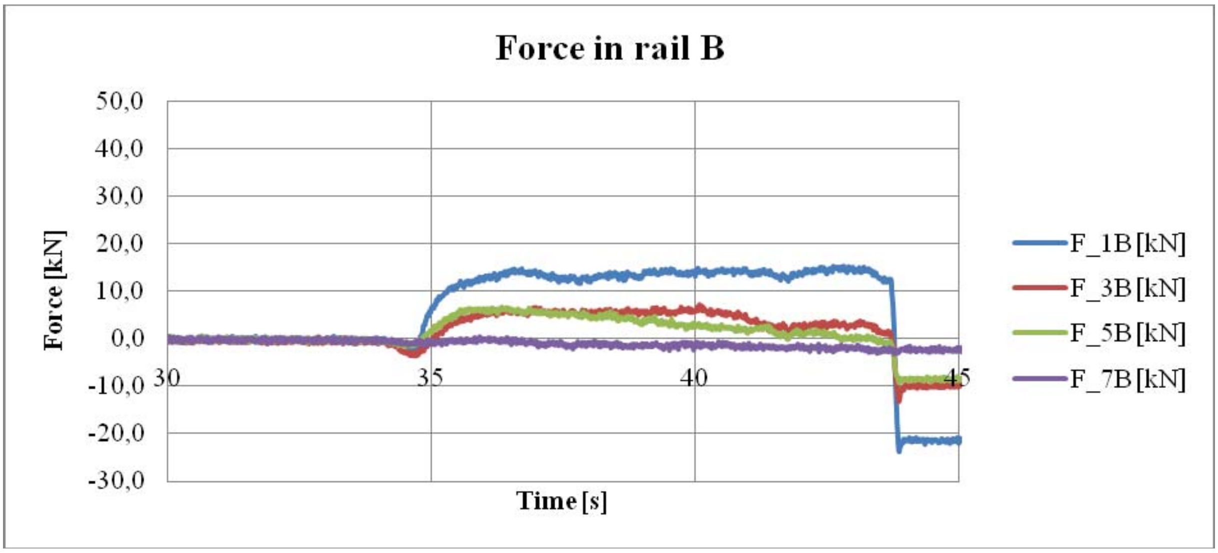


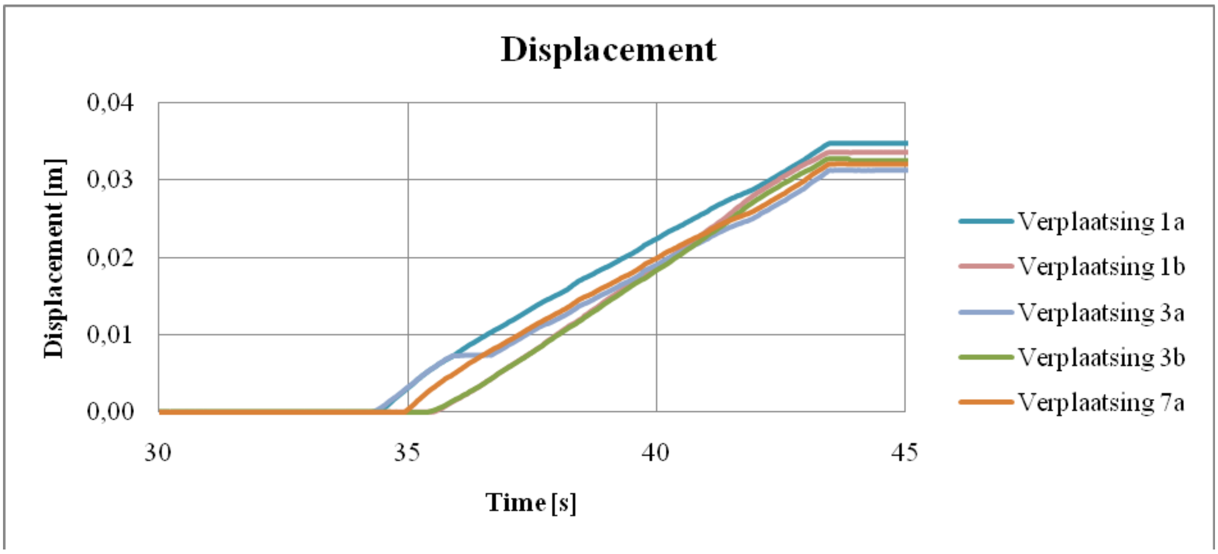




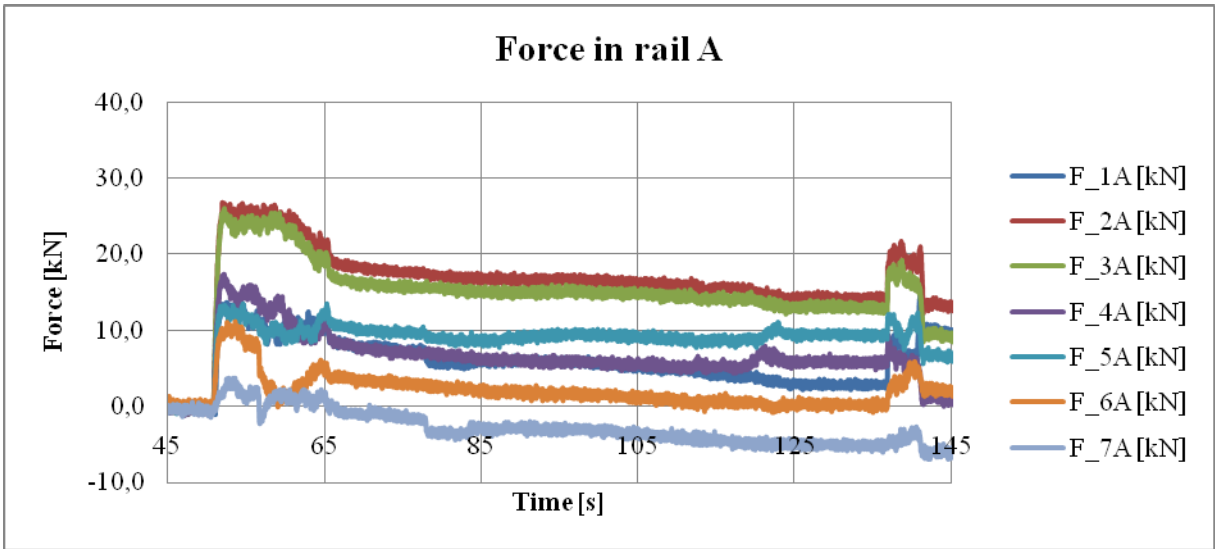
Test 10: 9 meter, with top ballast

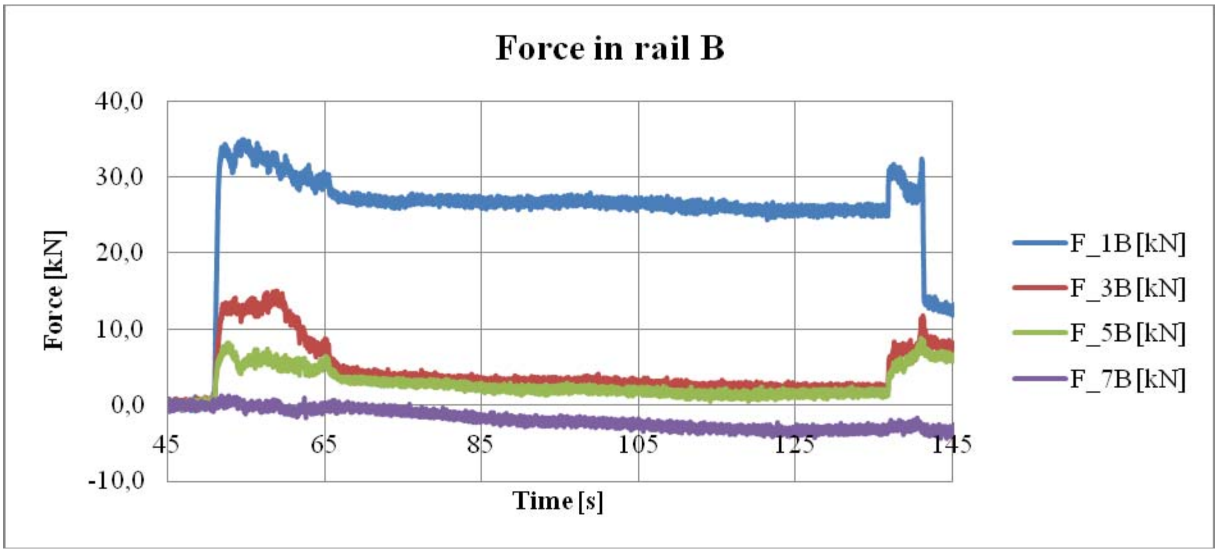


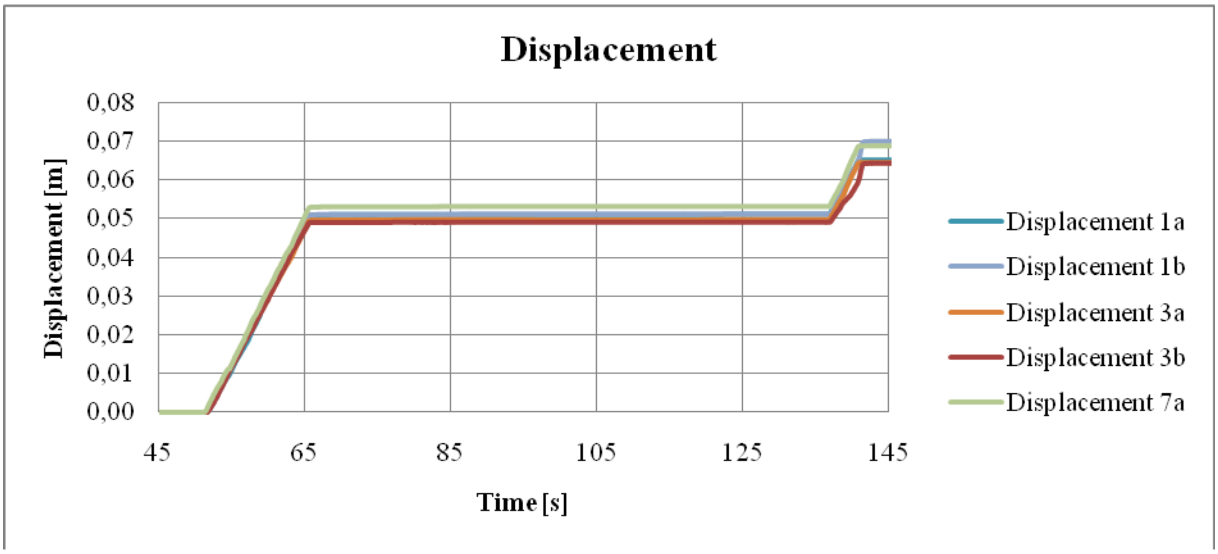




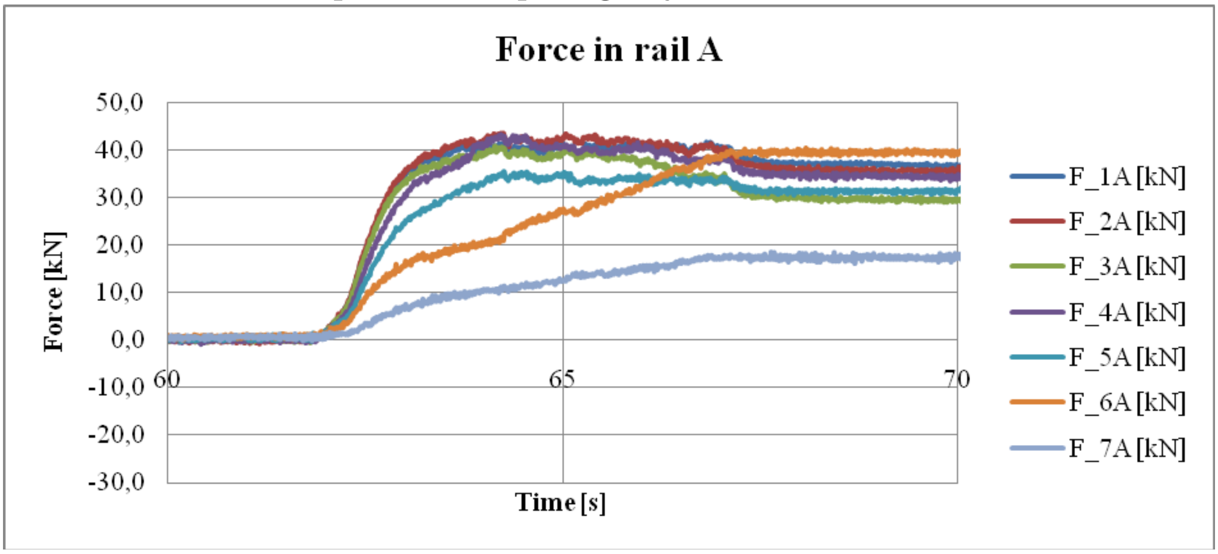
Test 11: 9 meter, with top ballast and pulling until a large displacement

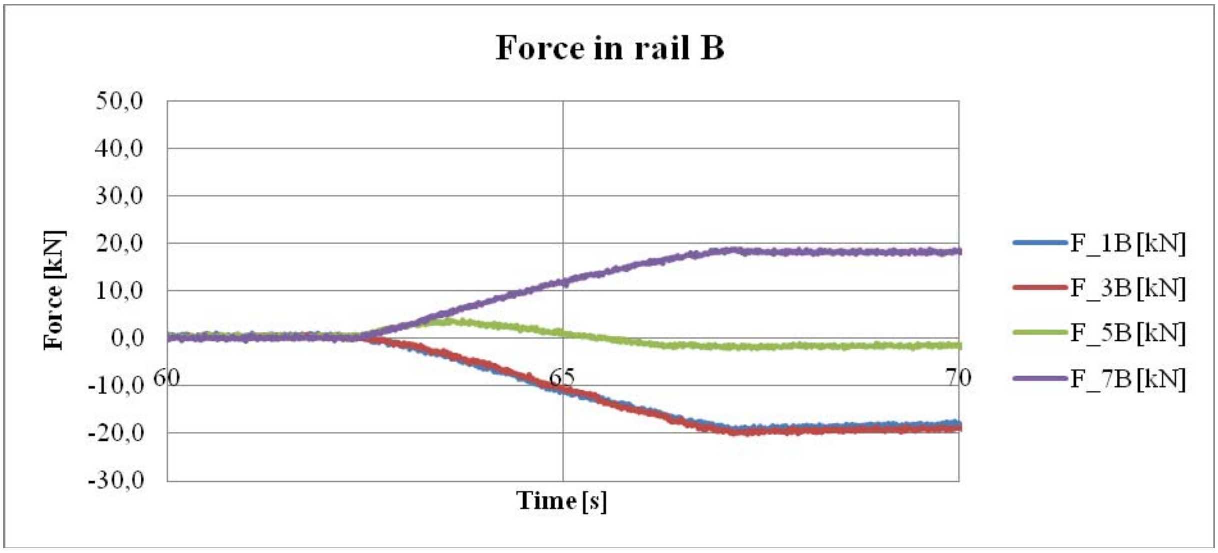


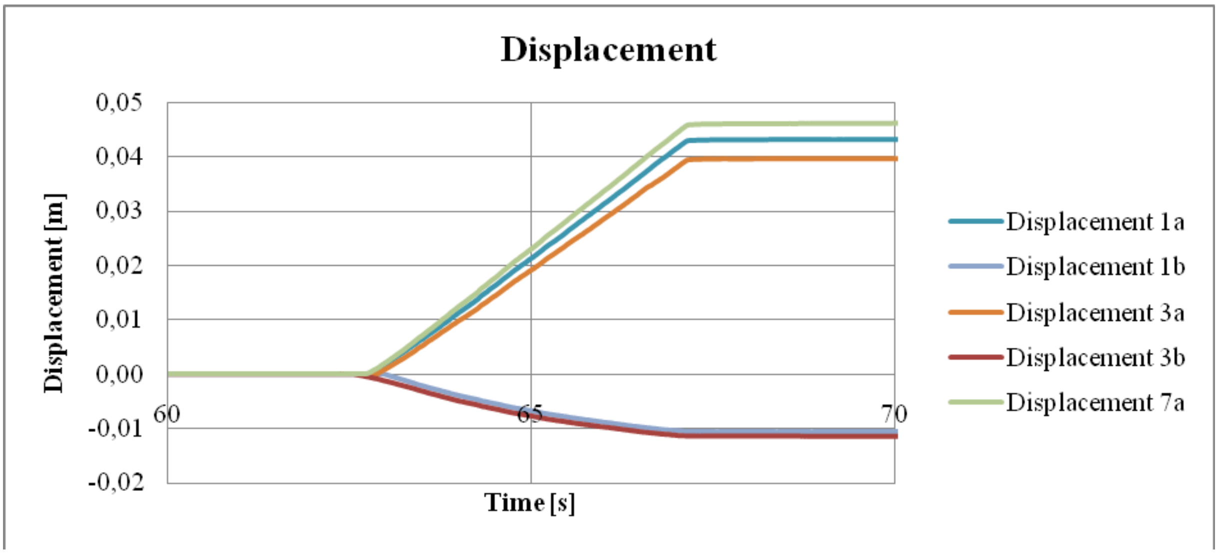




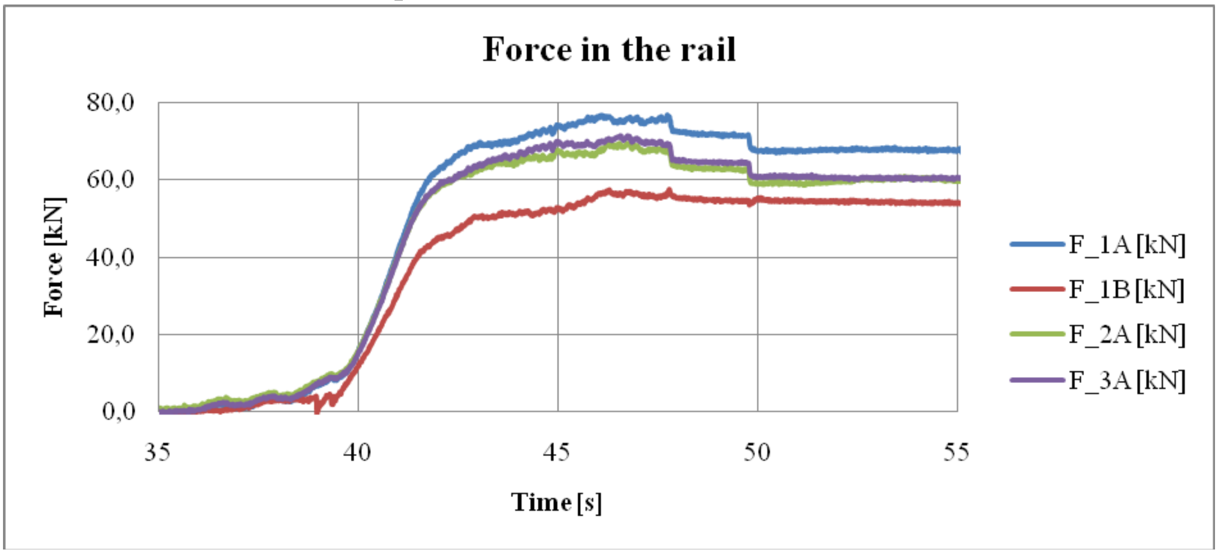
Test 12: 9 meter, with top ballast and pulling only on rail A

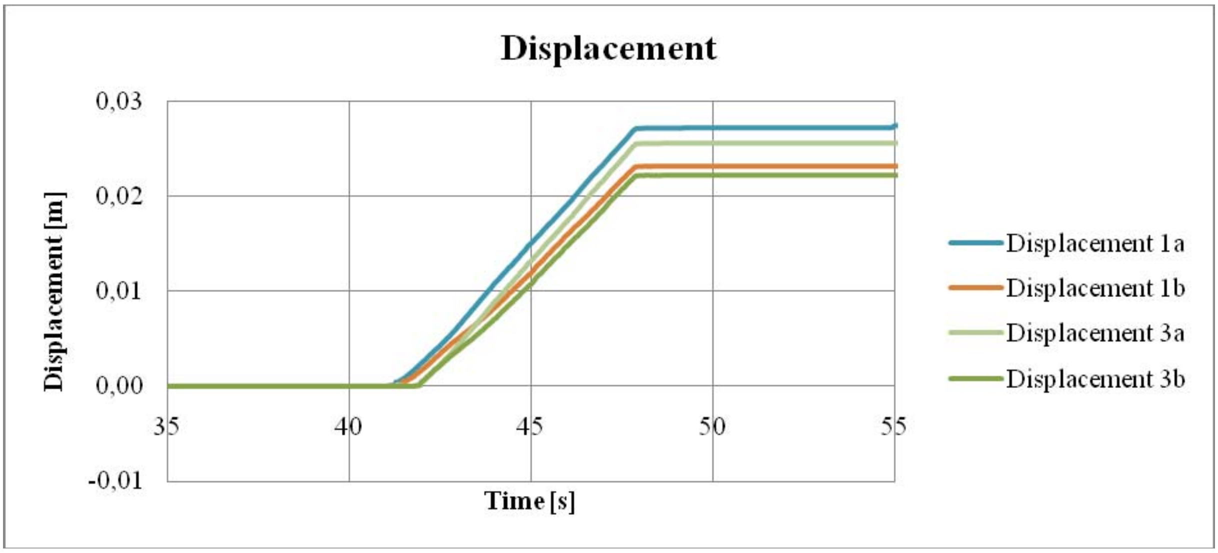




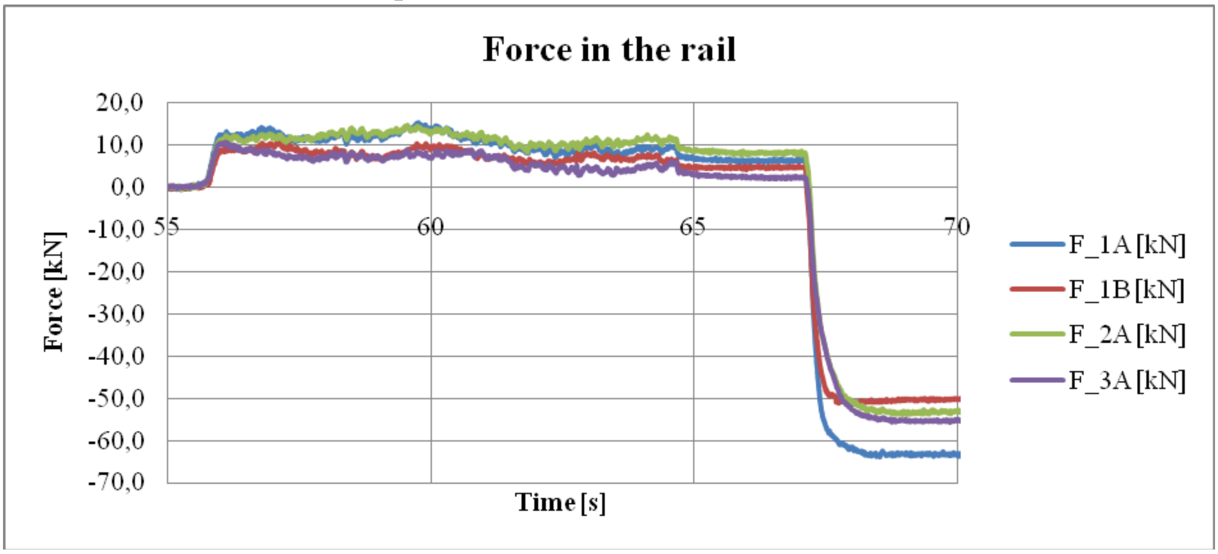


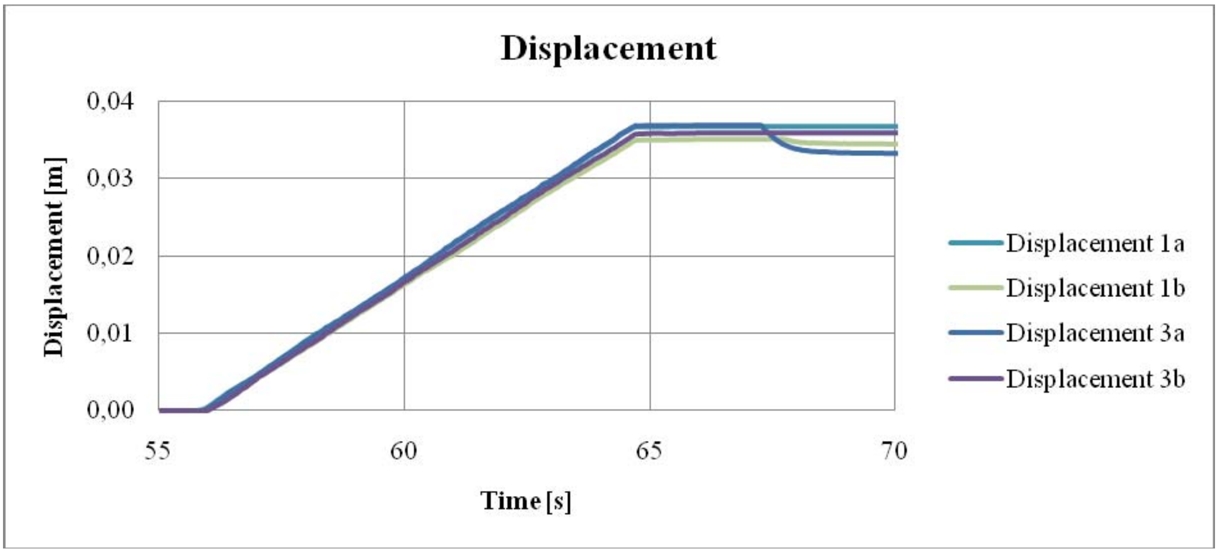
Test 18: 40 meter, without top ballast



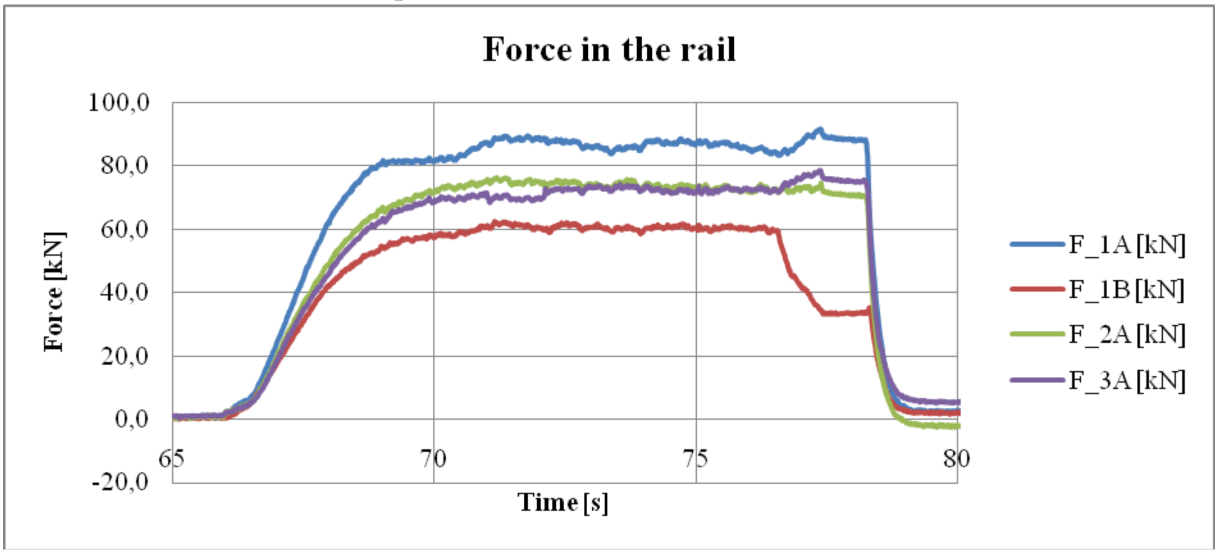


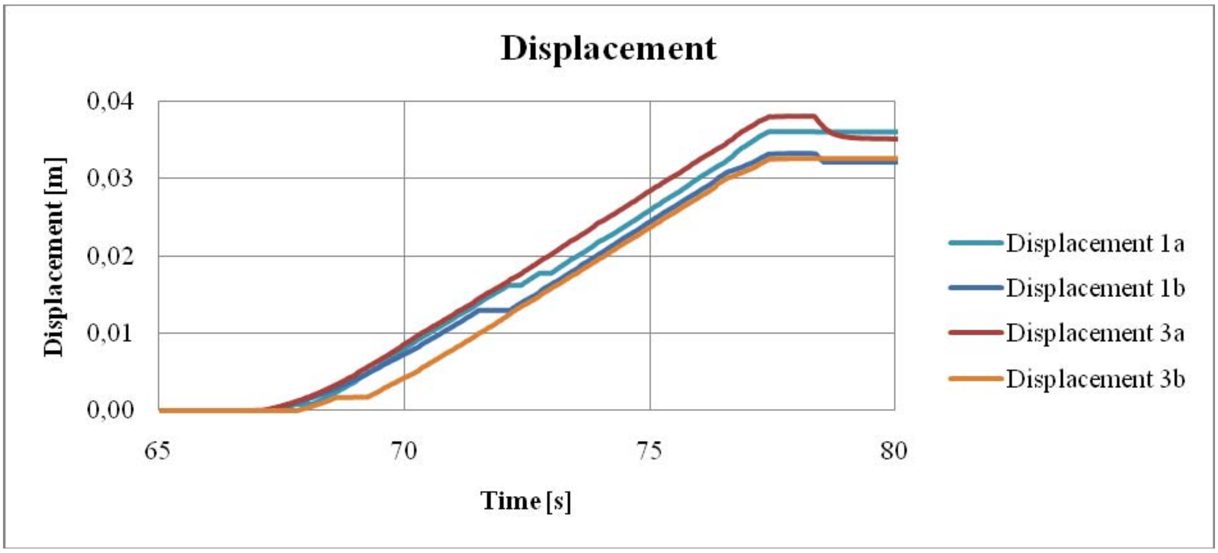
Test 19: 40 meter, without top ballast



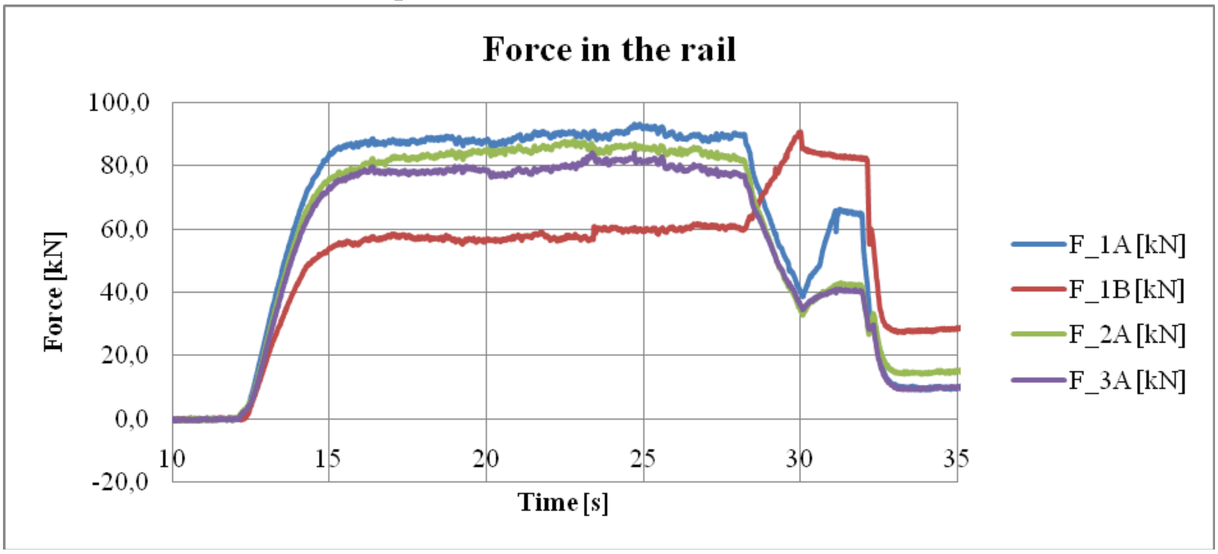


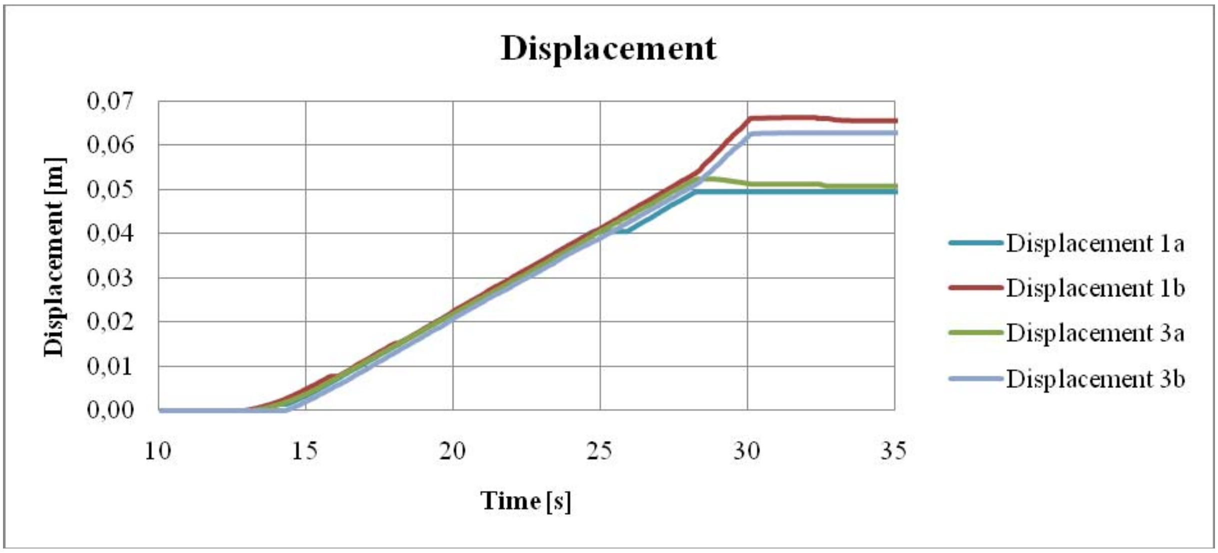
Test 20: 40 meter, without top ballast





Test 21: 40 meter, without top ballast





Appendix B Numbering of the nodes

Numbering of the plain line model

The nodes are numbered per rail. The numbering of the rails can be seen in figure 3. There are three layers of nodes:

1. the layer of the rail,
2. the layer underneath the rails, the nodes of the sleepers
3. the layer beneath the sleepers for the nodes of the ballast springs

The numbering of the nodes is shown in table 1.

Table 1 Numbering of the nodes in the plain line model

	A	**B**
Rails	1 - (_N)	101 - (100 + _N)
Sleepers	201 - (200 + _N)	301 - (300 + _N)
Ballast	401 - (400 + _N)	501 - (500 + _N)

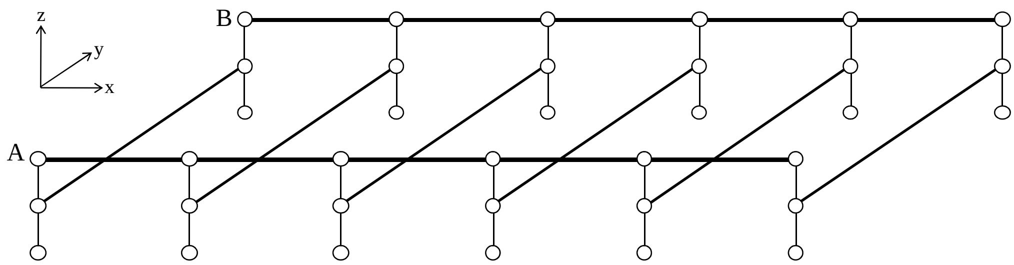


Figure 1 Model of the plain line

The elements are numbered in the same way as the nodes per rail. The elements between the rail layer en the sleeper layer are the springs that describe the behaviour of the fasteners and the elements underneath are the springs that describe the ballast behaviour.

The fasteners are modelled with four springs in the longitudinal, lateral, and vertical direction and a rotation spring in phi z direction.

The ballast is modelled with three springs in the vertical, longitudinal and lateral direction. The numbering of the elements is shown in table 2.

The decrease of freedom of the nodes are shown in figure 2. The nodes of the rails are only restricted in the rotation around the x-axis. The nodes of the sleepers are also restricted in the rotation around the y-axis and the bottom nodes of the ballast springs are restricted in all the decrease of freedom.

In the plain line model two springs are added at the end of both rails to prevent uncontrolled displacements when the longitudinal ballast springs deformation becomes plastic.

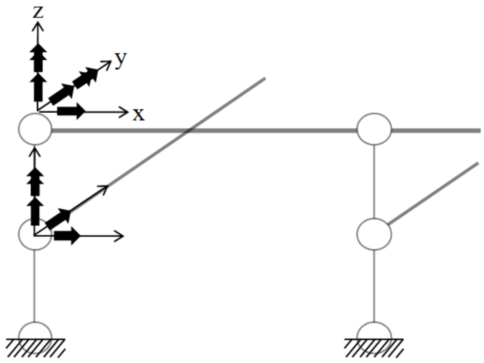


Figure 2 Decrease of freedom of the nodes

Table 2 Numbering of the elements in the plain line model

	A	**B**
Rails	1 - (_N)	101 - (100 + _N)
Sleepers	201 - (200 + _N)	
Fastener		
- Longitudinal (x)	301 - (300 + _N)	401 - (400 + _N)
- Lateral (y)	501 - (500 + _N)	601 - (600 + _N)
- Vertical (z)	701 - (700 + _N)	801 - (800 + _N)
- Phi z	901 - (900 + _N)	1001 - (1000 + _N)
Ballast		
- Longitudinal (x)	1101 - (1100 + _N)	1201 - (1200 + _N)
- Lateral (y)	1301 - (1300 + _N)	1401 - (1400 + _N)
- Vertical (z)	1501 - (1500 + _N)	1601 - (1600 + _N)

Numbering of the S&C model

The same as in the plain line the nodes are numbered per rail. The numbering of the rails can be seen in figure 3. The layers are also build up the same way as in the plain line. In the numbering of the nodes is given table 3.

Table 3 Numbering of the nodes in the S&C model

	A	B	C	D
Rails	2001 - 2070	2101 - 2170	2201 - 2270	2301 - 2370
Sleepers	2401 - 2470	2501 - 2570	2601 - 2670	2701 - 2770
Ballast	2801 - 2870	2801 - 2870	2801 - 2870	2801 - 2870

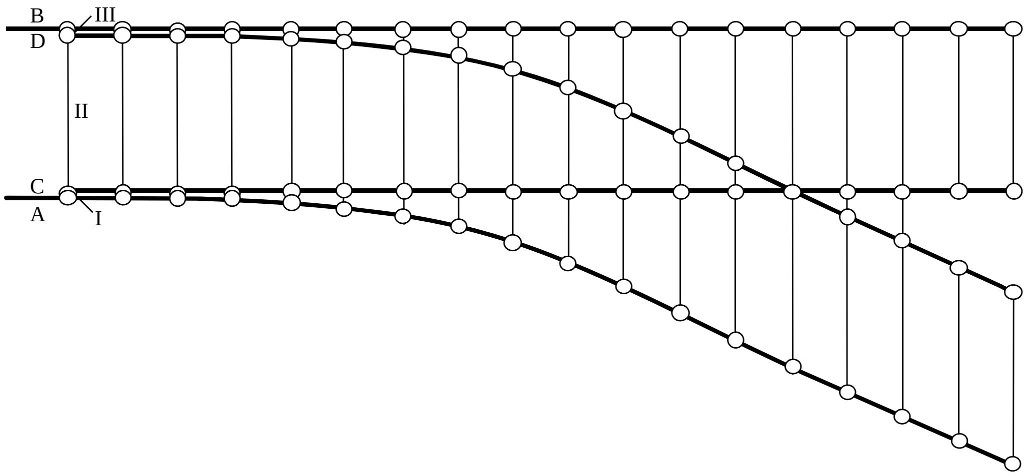


Figure 3 Numbering of the rails and the sleeper part

The elements are numbered in the same way as the nodes per rail. The numbering of the outer rails starts with the first element between the last node of the plain line and the first point of the S&C model. The inner rails start with the element between the first two nodes of the S&C model.

The sleepers are divided in three parts between the nodes under the rails. The numbering of the parts can be seen in figure 3. The numbering of the sleepers elements are given in table 4.

The numbering of the rail elements and the fasteners and ballast springs are given in table 5.

The decrease of freedom of the nodes is the same as in the plain line.

Table 4 Numbering of the sleepers in the S&C model

	I	II	III
Rails	2401 - 2470	2501 - 2562	2601 - 2670

Table 5 Numbering of the elements in the S&C model

	A	**B**	**C**	**D**
Rails	2001 - 2070	2101 - 2170	22021 - 2270	2302 - 2370
Fastener				
- Longitudinal (x)	2701 - 2770	2801 - 2870	2901 - 2970	3001 - 3070
- Lateral (y)	3101 - 3170	3201 - 3270	3301 - 3370	3401 - 3470
- Vertical (z)	3501 - 3570	3601 - 3670	3701 - 3770	3801 - 3870
- Phi z	3901 - 3970	4001 - 4070	4101 - 4170	4201 - 4270
Ballast				
- Vertical (z)	4301 - 4370	4401 - 4470	4501 - 4570	4601 - 4670
- Longitudinal (x)	4701 - 4770	4801 - 4870	4901 - 4970	5001 - 5070
- Lateral (y)	5101 - 5170	5201 - 5270	5301 - 5370	5401 - 5470