University of Pardubice

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Methodology of Thermal Stress Determination in Continuous Welded Rail

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Abstract

Continuous welded rail (CWR) became an integral part of railway tracks over the past decades. Focus on search for a non-destructive methodology of rail thermal stress determination has been one of the leading engineering tasks in the field. Studies summarizing the efforts are presented in papers and works [1, 2, 3, 4, 5, 6].

Investigation into some aspects of rail heating and rail temperature records are presented in the third chapter. The rail temperature investigation is crucial for the CWR stress determination and various research aim can be followed. In the first part of this thesis, results of field investigation into the rail temperature are discussed. Information on the instant rail temperature in the railway network is important for a reliable determination of the rail stress or the rail neutral temperature change.

The third chapter comprises of research into CWR strain. The CWR strain knowledge is essential for the determination of the rail neutral temperature change. In the first part of the chapter, design of an experimental setup is analysed. A quarter bridge configuration was evaluated as the most effective one, providing sufficient precision of measurement, high resiliency in the railway track and quick installation. An extensive investigation into the CWR strain measurement and further analysis conclude the chapter.

The fourth chapter introduces the *Methodology of Non-Destructive Determination of Mechanical Stress in CWR* and analyses the CWR strain data presented and discussed in the preceding chapter. A proposition of the thermal stress determination in CWR and the rail neutral temperature change is given in this chapter. Upon resolving the questions raised by this dissertation and analysing more data, the presented approach can serve for a better and economically feasible determination of thermal stress in CWR and rail neutral temperature change over time.

Chapter 1

Introduction

Continuous welded rail (further referred to as *CWR*) is nowadays an integral part of railway superstructure [7, 8]. It substitutes the original concept of jointed rail and is being installed into more and more railway lines all over the world every year. It offers many advantages in contrary to the jointed rail. The ride is calmer, more comfortable for passengers, wear and deterioration is reduced both at the rolling stock and the infrastructure, and safety level is increased. With these advantages, it contributes to an efficient and sustainable development of the railway network in the world and provides substantial financial savings [9, 10].

Many advantages provided by the CWR carry one problem, however. The change of rail temperature cannot be settled by rail dilation, as it is in the case of jointed track, but a thermal stress of positive or negative value occurs in the rail. In order to safely manage and control the rail stress, a way of reliable determination of the thermal stress shall be found. Many attempts to determine the instant value of the thermal stress were made over the last decades, but none of them was able to provide a satisfactory solution that would get widespread all over the world [1]. Various other attempts were done in order to simulate the problem numerically, which is a great asset to better understanding of the problem [11, 12].

The presented thesis summarizes new options to determine the CWR thermal stress by determination of the CWR neutral temperature change in a non-destructive way. Research into the aspects of rail temperature and CWR strain development is presented in the thesis. A methodology of CWR neutral temperature development determination, derivation of which builds upon the presented investigation, is introduced in Chapter 4. A brief conclusion closes the thesis.

Chapter 2

Rail Temperature Monitoring

Operated railway lines are never built in laboratory conditions. Except for the impact of particular atmospheric effects, as those studied in the previous section of this chapter, the full combination of factors that create the particular ecotope of a spot can be investigated, too. An extensive research into the thermal conditions of selected localities in the Czech railway network was done. This research is summarized in this chapter. This research was a part of investigation of the research project No. TJ04000301 *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail.*

2.1 Experimental Setup

Rail temperature measurements were performed by card thermometers with adjustable interval of recording and built-in data-logger. The thermometers were purchased in more orders, therefore two types were used in total (the older type was substituted by the newer one in the market and not available any more). The older type of the thermometer which was used for the measurements was the type of Elitech ETAG-1 and the newer type Elitech TI-2S. The thermometers are shown in Figures 2.1 and 2.2.

Both types of thermometers store data into a built-in memory with the capacity of 4000, respectively 3840 values. The data can be downloaded into a cell phone via an NFC chip and exported in a *.csv* file. The principle of work of both thermometers is very similar, therefore, no specification on which type was used at which measuring spot is provided further in this section.

The thermometers were attached from bottom to the rail foot between two sleepers (except for the Borovnice locality, see below). A plastic holder with a magnetic system to hold the temperature probe adjoining to the rail surface was developed by undergraduate students Karel Suchý and Tadeáš Šustr collaborating on the research project. The holder is presented in Figures 2.3 and 2.4.

Figure 2.1 – Card Thermometer with Built-in Data-Logger – Type Elitech ETAG-1

Figure 2.2 – Card Thermometer with Built-in Data-Logger – Type Elitech TI-2S

Figure 2.3 – Card Thermometer Holder – Top View

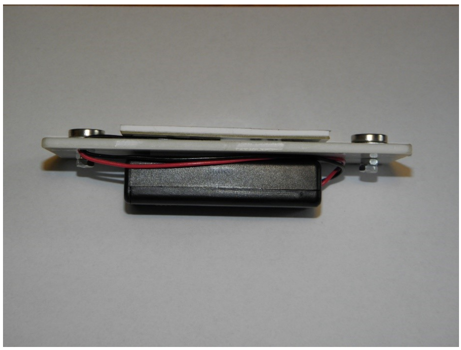

Figure 2.4 – Card Thermometer Holder – Side View

2.2 Monitored Localities

The selection of monitoring localities was done in collaboration with representatives of Správa železnic, s. o., the Czech national railway infrastructure manager. Five localities were selected in total:

- Borovnice,
- Ostružná,
- Hradec Králové,
- Karviná, and
- Harrachov.

2.3 Data Analysis

The data collected from the data loggers were processed in Microsoft Excel and graphs of the temperature records were produced. The following table summarizes the periods of data collection in each locality.

Locality	**Start of Measurement**	**End of Measurement**
A. Borovnice	5th June 2021	26th October 2021
B. Ostružná	5th August 2021	24th October 2021
C. Hradec Králové	16th August 2021	27th October 2021
D. Karviná	25th December 2021	1st April 2022
E. Harrachov	14th July 2021	5th July 2022

Table 2.1 – Temperature Data Collection Periods per Locality

As a presentation example of the data collected, data from the Harrachov locality are presented in this thesis, as they cover the longest period of monitoring: 14th July 2021 – 5th July 2022. The first thermometer is placed in a tunnel, but only 50 m from its portal. The record high temperature of 14.8 °C was measured on 1st July 2022 and the record low of −4.8 °C on 25th December 2021. The second one, placed on the Jizera bridge, shows the record high value of 38.1 °C on 27th June 2022 and the record low of −19.5 °C on 26th December 2021. The third one, placed on embankment next to the bridge, shows the record high value of 46.5 °C on 27th June 2022 and the record low of −12.4 °C on 26th December 2021. The fourth one, placed in the rock cutting, stopped recording on 23rd February 2022. It shows the record high temperature of 38.3 °C on 26th July 2021 and the record low of −9.4 °C on 26th December 2021. The fifth one, placed at the Harrachov station, shows the record high value of 45.8 °C on 27th June 2022 and the record low of -10.1 °C on 26th December 2021. All the records are presented in Figure 2.5. All data are presented in the dissertation.

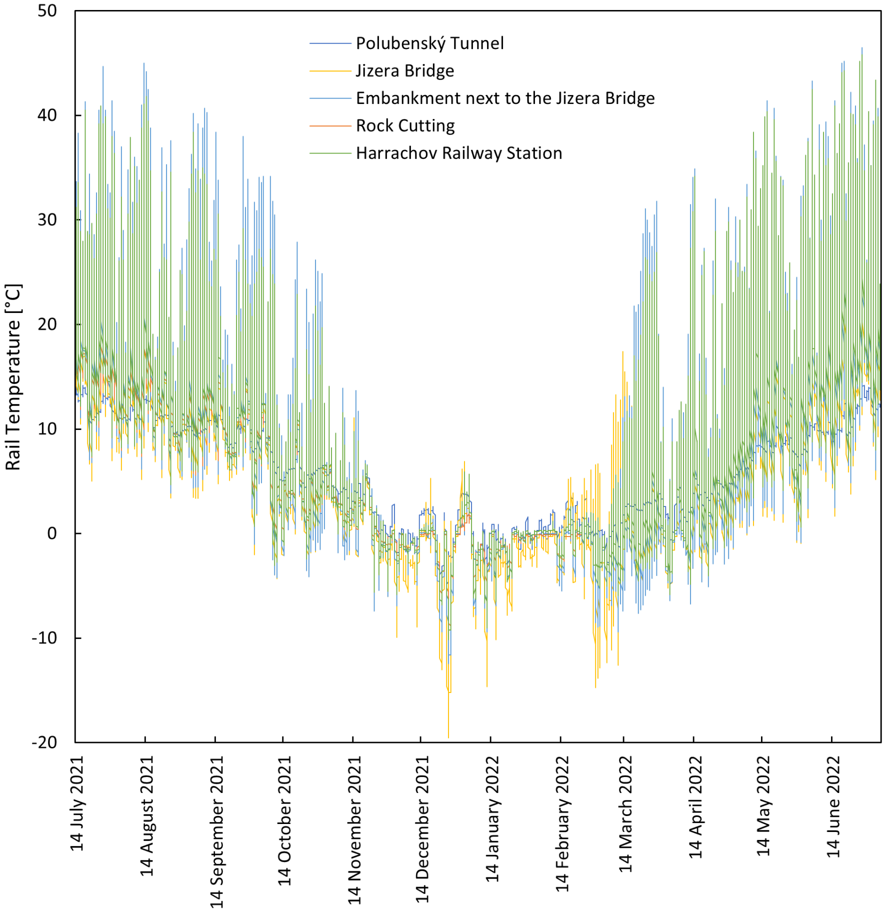

Figure 2.5 – Rail Temperature Recordings in Locality Harrachov

2.4 Discussion

The data from Borovnice confirm the expectations as the left side of the rail web warms up more than the other parts while being exposed to the sunshine over the majority of a sunny day. More importantly, minimum difference is found when the thermometer is attached to the shady side of the rail web and the rail foot. This supports the idea to attach the rail thermometers at the rail foot from the bottom. Such attachment provides constant shade, minimum chance of collision with track maintenance technology and a very good protection from a theft. The measured values can be recalculated across the rail profile using the existing studies (e. g. [13, 14]).

The record high temperature of 56.9 °C recorded on the left web in Borovnice is important not by its absolute value, which is at the top, yet within the expected range for the Czech Republic, but by the locality where it was measured. The railway track in Borovnice is in a hilly terrain at the altitude of 500 m AMSL. The air temperatures do not reach the maximum values in such places within the Czech Republic. Lowlands in southern Moravia or wide low valleys near to Prague are the places of the typical record high temperatures in the country. Rail sections with ballast bed covered by bituminous coal powder in the Ostrava region were known for reaching the topmost rail temperatures in the past. This is not the case of Borovnice either – the ballast bed is new and clean (it was cleaned during the track reconstruction in autumn 2020). Comparing the Borovnice recordings with the Hradec Králové, not so distant locality, recordings, the Borovnice locality shows slightly higher values even if the different recording period is taken into account. One possible part of the impact can be the slightly south-west orientation of the track in Borovnice, which results in receiving more solar radiation in the early afternoon, when the air temperature culminates.

The data from Ostružná show that the mass of soil in the embankment provides a more stable environment for a day/night temperature change than a relatively tinier bridge structure, which can be cooled from below, too. No extreme temperature values were recorded in this locality.

The data from Hradec Králové were expected to show a difference between a temperature record on a rail aligned in the north-south orientation and in the east-west orientation. Such a difference has not been proved. However, it is important to note that only two thermometers were placed into this locality and both were attached to places relatively far from each other. Moreover, the situation may vary here in the case of the rail web, as the south face of the rail web in the Slezské předměstí district is significantly more exposed to sunshine than the north face, while the web sites in the Pražské předměstí district share the exposition to sunshine evenly.

The values recorded in Karviná show the influence of vegetation in the railway track vicinity on the rail temperature. The forest, which surrounds the railway tracks in the former Karviná-Darkov station significantly decreases the record high temperatures in comparison to the ones measures in the relatively open space area of the railway crossing next to the former ČSM Sever coal mine. The ballast bed in both sections is relatively clear. For this reason, no impact of a ballast bed covered by bituminous coal powder fouling could be recorded.

The data from Polubenský Tunnel in the Harrachov locality show the minimum difference between the record high and the record low temperature – less than 20 °C. This is expected and, if the thermometer was placed further in the tunnel tube, even more equal course could be expected. However, no more thermometers were attached further in the tunnel and therefore no more data is available from there.

The thermometer attached on the Jizera bridge recorded significantly lower recorded temperatures than others, reaching the record low as of −19.5 °C. These values are in a clear support of what can be observed in the case of the bridge over the II/369 road near Ostružná. The circulating air cools down the structure and the rail and enables reaching significantly lower extremes than in the case of embankments. In the case of the Jizera bridge, the effect might be even underpinned by the geography of a mountain valley and the fact that the bridge spans across a river as a water body instead of only a road.

The temperatures recorded on the embankment next to the Jizera bridge show significantly higher values than those ones recorded on the next-standing bridge. This is a difference from what was recorded in Ostružná, where the thermometer on the bridge recorded more extreme values on both sides of the spectrum. Here the low amplitudes are on the same level as on the bridge or higher, and the high amplitudes are higher than the ones on the bridge. This leads to an assumption that the bridge acts as a local cool spot in the railway track and this may result in various implications, like a possibility of decrease of the rail neutral temperature in this position.

One more interesting fact can be observed from the data obtained at the embankment next to the Jizera bridge: After a period of freezing the measured temperature does not rise over 0 °C. The reason of this behaviour seems to reside in freezing the thermometer (possibly with a layer of snow) to the rail and therefore keeping the snow melting temperature. The warmer periods in this time was probably so short that the warmth was unable to deliver the necessary latent heat of fusion and the snow and ice packed to the track superstructure did not melt and prevented the thermometer (and the rail!) from increasing its temperature over 0 °C. After a sufficient period of warm weather, the snow and ice melted and the rail could experience higher temperatures again.

The thermometer in the rock cutting stopped logging the temperature on 23rd February 2022, the provided data is, therefore, limited. Yet, the same effect of freezing up in snow and ice can be observed. The record high temperatures are higher than in the case of the Jizera bridge, but lower than in the case of the embankment next to the bridge and the Harrachov railway station. This is assumed to be caused by the specific geographic location of the rock cutting which keeps a relatively cooler climate and sunshine is limited in this environment.

Finally, the records from the Harrachov railway station show a similar progress as the records from the embankment next to the bridge. An interesting comparison can be seen in the months of September/October and March. The temperature recorded in the Harrachov railway station is significantly lower than the temperature on the embankment next to the Jizera bridge. No investigation on this difference was made as of yet, but a local influence on the specific sun rays angle in this time of year is assumed to be the cause.

In comparison of the values from different localities mutually, the clear influence of bridges on the record low temperatures is apparent. It is not unequivocal in the record high temperatures, however. A more closed environment, like a tunnel and a rock cutting helps to reduce the range of recorded temperatures. An interesting role is played by the packed ice and snow, as their ability to prevent the rail temperature rise over 0 °C even if the air temperature rises may be an influencing factor on the yearly average rail temperature, especially if the heat waves are short (i. e. the positive and negative temperatures are changing frequently). A vegetation surrounding helps reduce the record high rail temperatures significantly, too.

Chapter 3

Strain of Continuous Welded Rail

Under optimum conditions, no permanent strain is expected in CWR after stress-controlled welding, according to the theory of CWR. Under such assumption, the neutral temperature shall correspond to the tensioning temperature and shall remain constant over time [9]. In reality however, various reasons can cause an occurrence of permanent strain in CWR [8]. Among such reasons, the lateral displacement of track in a curve, the longitudinal displacement of rail in a fastening node, or the deterioration of track geometry can be considered. If such a displacement occurs, strain is to be detected in the rail.

In this chapter, an investigation into the strain detection in CWR is described. The analysis of an experimental setup under laboratory conditions is presented in the first section. A description of experimentally developed measuring set follows. Finally, an extensive CWR Stain Monitoring, which has been realised within the scope of investigation of the TAČR Zéta Project TJ04000301 *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail* is presented.

3.1 Wheatstone Bridge Setup Analysis

Two types of the Wheatstone bridge arrangements were considered for the purpose of the track installation: the half bridge and the quarter bridge configuration, the latter bringing advantages in the laboriousness of the installation [15]. A comparison laboratory measurement was performed to find out possible drawbacks and constraints of the quarter bridge arrangement. The measurement was repeated at an interval of one week with virtually the same results reached. Without loss of generality, only one of the measurements are presented in this section.

3.1.1 Experimental Setup

A half bridge with one active and one dummy strain gauge, and a quarter bridge arrangement of the Wheatstone bridge were installed on a steel sample 200 mm long, 25 mm wide and 10 mm thick. At both ends, the steel sample was widened to hold better in the clamp jaws of the dynamic stand. All strain gauges were of the same type – HBM K-CLY4-0060-1-350-4-050-Y, i. e. with the nominal resistance of 350 Ω, temperature compensation for ferritic steel, 4-wire cable and RJ11 connector. The sample is shown in Figure 3.1. Please note that the quarter bridge strain gauge and the active strain gauge of the half bridge arrangement are placed next to each other into the same cross-section of the sample, whereas the strain gauge placed closer to the end of the sample is the dummy one of the half bridge arrangement.

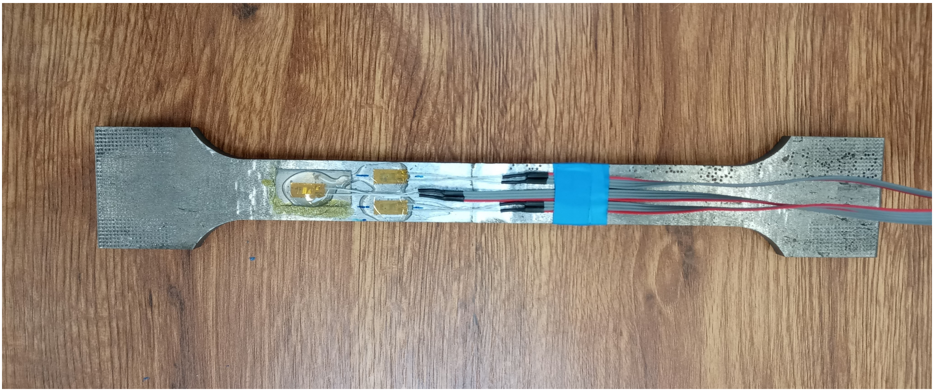

Figure 3.1 – Steel Sample with the Half and Quarter Bridge Arrangements

The sample was placed into the clamp jaws of a dynamic stand with the strain gauges facing down for the heating purposes described further in the paragraph. The strain gauges were connected into the HBM QuantumX MX840A data acquisition system and the data were recorded into the Catman Easy software. The dynamic stand enabled both position-controlled and force-controlled displacement of clamp jaws. The heating of the sample was performed manually using a hairdryer. The hairdryer was moved over the length of the steel sample aiming at the top side at a constant speed there and back to ensure as unilateral thermal loading as possible. Positioning of the steel sample in the clamp jaws of the dynamic stand is visible in Figure 3.2.

Figure 3.2 – Steel Sample Positioned in the Dynamic Stand

3.1.2 Data Analysis

Four tests were performed in the laboratory in order to compare the performance of the quarter and half bridge arrangements. In the first test, the steel sample was loaded by an axial force under constant temperature. This test was performed to calibrate the strain gauges based on the analytical calculations of stress and strain applied by the axial force. In the second and third test, the sample was fixed at both ends and uniformly heated, while strain was monitored at both strain gauge arrangements. The difference of those test resided in the stress state of the sample: in the second test, the sample was free of normal stress (except for the stress emerging from the thermal loading during the test); in the third test, a pre-tension by the axial force of 30 kN was applied to the test before the thermal loading commenced and released after the cool off of the sample. Finally, in the fourth test, the sample was fixed at one side and thermally loaded, while not only strain was monitored by the strain gauges, but the displacement of the free end of the sample was monitored by the dynamic stand control unit.

Loading by Normal Force at Constant Temperature

The first test was performed without a change of temperature of the sample. The sample was loaded with a gradually increasing force from 1 to 30 kN and released back to 0 kN. The value of force was controlled by the dynamic stand control unit. The measured values of strain in relation to the axial force is presented in Figure 3.3 and the values of normal stress in relation to the axial force is presented in Figure 3.4.

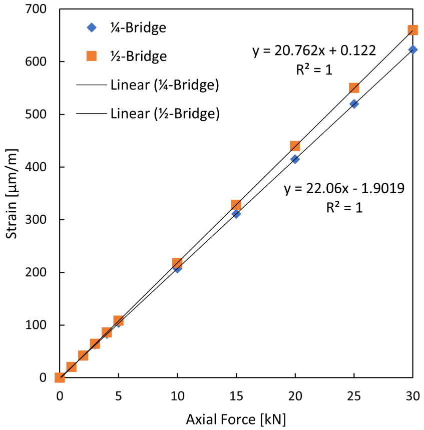

Figure 3.3 – Relation of Measured Strain and Axial Force

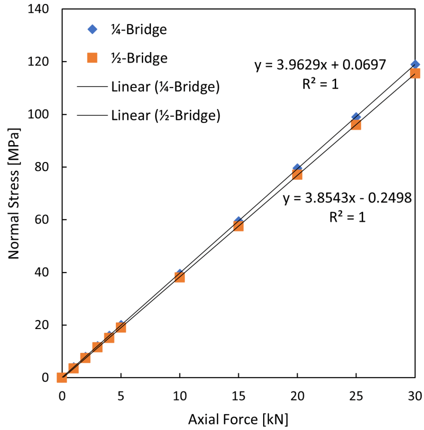

Figure 3.4 – Relation of Normal Stress (Calculated from Measured Strain) and Axial Force

The normal stress values were calculated according to Equations 3.1 and 3.2 to match the expected stress in the sample analytically calculated using Equation 3.3.

$$\sigma_{quarter} = \frac{\varepsilon \cdot E}{1.1} \tag{3.1}$$

$$\sigma_{half} = \frac{\varepsilon \cdot E}{1.2} \tag{3.2}$$

$$\sigma_{analytical} = \varepsilon \cdot E. \tag{3.3}$$

Thermal Loading of Sample Fixed at Both Ends

The steel sample was fixed at both ends by jaw clamps. This position was controlled by the dynamic stand control unit. The sample was subsequently uniformly heated by a hairdryer. Initial temperature of the sample was 23.8 °C. The sample was heated up to 62.1 °C and then naturally cooled off to 25.9 °C. Temperature of the sample was periodically measured by a contact thermometer. At each temperature measurement, the axial force was recorded by the dynamic stand control unit and the strain by strain gauges. The strain was then recalculated into the normal stress according to Equations 3.1 and 3.2. The relation of strain and temperature is presented in Figure 3.5 and the relation of normal stress and temperature is presented in Figure 3.6.

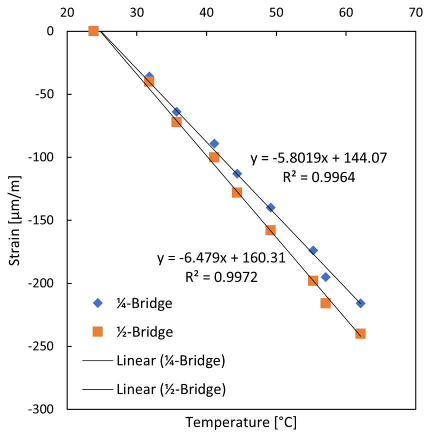

Figure 3.5 – Relation of Measured Strain and Temperature

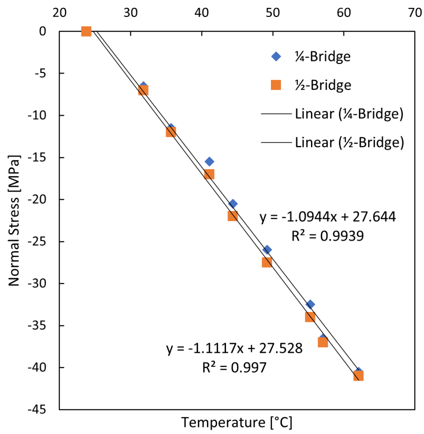

Figure 3.6 – Relation of Normal Stress (Calculated from Measured Strain) and Temperature

After cool off to 25.9 ˚C, the axial force dropped to −1.97 kN, the strain measured at quarter bridge to −43 μm/m, at half bridge to −24 μm/m, the calculated normal stress in both strain gauge arrangements to −8.5 MPa.

Thermal Loading of Sample Fixed at Both Ends and Pre-Tensioned by Axial Force of 30 kN

This test ran in a similar way like the previous one except for the sample being prestressed by the axial force of 30 kN. The position (strain) of the sample was controlled by the dynamic stand control unit and the sample was uniformly heated by a hairdryer. The initial temperature of the sample was 22.7 ˚C. The sample was heated up to 61.5 ˚C and then naturally cooled off to 26.7 ˚C. The relation of strain and temperature is presented in Figure 3.7 and the relation of normal stress and temperature is presented in Figure 3.8.

Please note that the marks at the horizontal axis depict the values measured before prestressing and after releasing of the axial force.

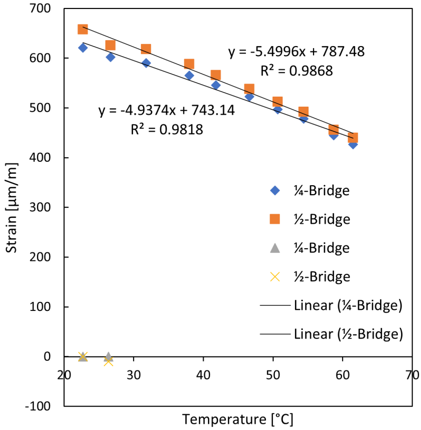

Figure 3.7 – Relation of Measured Strain and Temperature

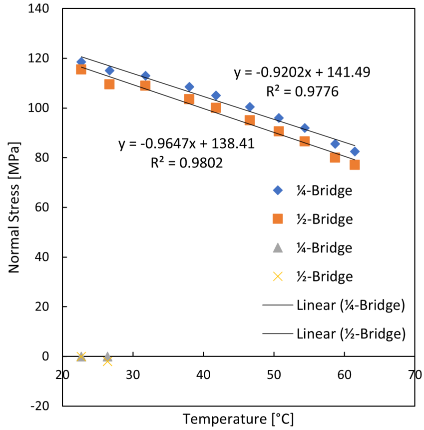

Figure 3.8 – Relation of Normal Stress (Calculated from Measured Strain) and Temperature

Thermal Loading of Sample Fixed at One End Only

The sample was fixed into the dynamic stand clamp jaws at both ends, but the control unit was set to keep the axial force at zero kN, therefore the sample was free to expand under thermal loading and the dilation of the sample was monitored by recording of the clamp jaw position. The initial temperature of the sample was 25.6 ˚C. The sample was heated up to 57.3 ˚C. The relation of displacement of the sample and temperature is presented in Figure 3.9, the relation of strain and temperature is presented in Figure 3.10, and relation of normal stress and temperature is presented in Figure 3.11.

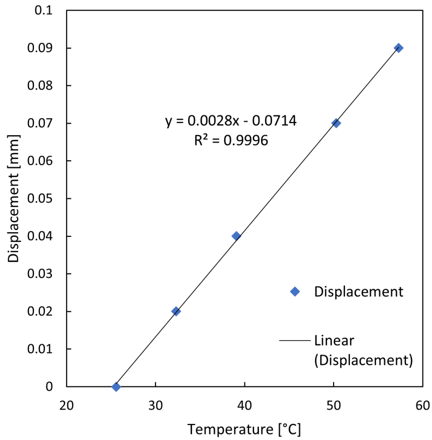

Figure 3.9 – Relation of Displacement and Temperature

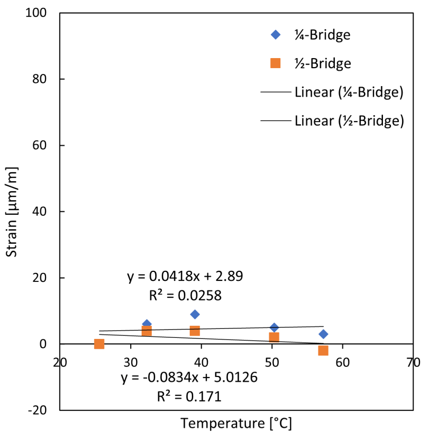

Figure 3.10 – Relation of Measured Strain and Temperature

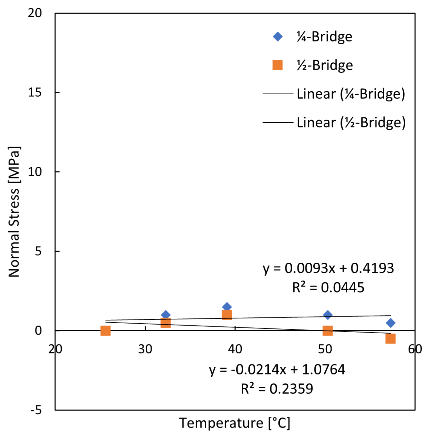

Figure 3.11 – Relation of Normal Stress (Calculated from Measured Strain) and Temperature

3.1.3 Discussion

The tests performed in the laboratory have shown that the use of the quarter bridge arrangement of the Wheatstone bridge provides sufficient precision of measurement and is applicable to the field measurement of strain in track. The application of the quarter bridge arrangement can be used regardless of the prestressing of the sample. The thermal load test with one end of the sample fixed only shows that the thermal compensation of the strain gauge compensates for the vast majority of the thermal-induced strain in the tested sample. The not compensated part, which is the non-linear part according to the instructions of manufacturer, causes a very low impact and can be negligible, at least in the early stages of the field investigation.

The record of strain measured under loading by the axial force and constant temperature presented in Figure 3.3 shows in the case of the quarter bridge arrangement the slope coefficient of 20.762. This value very well corresponds to the mathematical parameter of the relation among strain and the axial loading force, which can be written as

$$\varepsilon = \frac{1}{E \cdot A} \cdot N, \tag{3.4}$$

where ε is the strain, E is the Young's modulus, A is the cross-sectional area and N is the axial loading force.

If E is considered 200 GPa, the parameter, which is the first multiplier in Equation 3.4, equals 20. Considering the strain measured by the half bridge is multiplied by two, since the measured value was lower due to incorrect settings of the data processing programme, the slope coefficient would reach approximately 22. These results lead to the necessity to divide the measured strain by 1.1 in the case of the quarter bridge or 1.2 in the case of the half bridge arrangement to reach the perfect fit to the analytical value. Among the reasons that cause this discrepancy, imperfections of the tested sample or displacement in the hydraulic clamp jaws could be considered, but this question remains unresolved until the date of submission of this thesis.

Very important results come out of the thermal loading test, as this type of loading is crucial in the field measurements. The slope coefficients presented in Figure 3.5 reach values -5.8 for the quarter bridge and -6.5 for the half bridge arrangements and in the test after prestressing, i. e. in Figure 3.7 -4.9 for the quarter bridge and -5.5 for the half bridge. This results into two questions: 1. Why is the slope coefficient negative? 2. Why does it reach such a value? And a subsequent question: 2.1 What is the actual value of the slope coefficient?

The test of thermal loading of the sample fixed at one end gives the solution to the Question 1. If there was no thermal compensation in the strain gauge, the expansion of the sample would have to be recorded by the strain of the strain gauge. Since virtually no strain was recorded, the thermal compensation successfully compensated for the vast majority of the strain. If the sample is heated with both sides fixed, the strain gauge expects the sample, and the strain gauge itself, would expand, but it does not, therefore it experiences the same behaviour as if the sample had expanded by thermal loading and then was pushed back to its original length, thus experiencing negative strain.

This explanation leads to the idea that the slope coefficient shall equal $-\alpha$, i. e. approximately $-11.5 \cdot 10^{-6}$ K^{-1} for the rail steel. However, as mentioned before, the measured value equals approximately -5 or -6 at the measurement in laboratory conditions and sample fixed at both ends. If the coefficients 1.1 and 1.2 from Equations 3.1 and 3.2 are applied, which can be performed without loss of generality, the values for the quarter bridge and half bridge are the same at both tests and they are approximately -5.35 in the case of the test without pre-stressing and -4.5 in the case of the test with prestressing of 30 kN. Since the laboratory conditions allowed for a very high level of support fixing, investigation into the Questions 2 and 2.1 are yet to be done and these questions remain unresolved at the time of submission of this thesis.

3.2 Measuring Set for Diagnostics of Time-Based Development of Stress States in CWR

A measuring set was developed for practical measurements of the CWR strain in railway tracks under operation. The measuring set had to meet the following criteria:

- not limit the railway track operation in any way,
- not interfere with the railway track circuits,
- enable quick measurement, so that it is realisable even in a track section with high intensity of operations,
- enable easy installation,
- provide high precision of measured data,
- withstand all natural and operation effects in the railway track,
- enable track maintenance.

A measuring set meeting the above listed criteria and comprising of a track and mobile unit was developed. The track unit is relatively simple for installation and relatively cheap, which is important because every track unit can be used only for one measuring spot. The mobile unit, on the contrary, contains a relatively expensive data acquisition system, but it isn't fixed to the rail, is easily transferable, and can be used for measurement at unlimited number of measuring spots.

Instructions to install and use the measuring set are closely described in the *Methodology of Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail* and in the *Measuring Set for Diagnostics of Time-Based Development of Stress States in Continuous Welded Rail* documentation, both of which were created as a direct outcome of the research project No. TJ04000301 *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail.*

The measuring set uses the quarter bridge strain gauge arrangement, which is sufficient for field investigation as follows from Section 3.1, easy to install and less prone to damage than the half bridge installation.

3.3 CWR Strain Monitoring

An extensive CWR Stain Monitoring was performed within the scope of investigation of the TAČR Zéta Project TJ04000301 *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail.* The *Measuring Set for Diagnostics of Time-Based Development of Stress States in Continuous Welded Rail*, which was an outcome of the mentioned research project, was used for the purpose of this monitoring.

The CWR Strain Monitoring took place at tracks of the Czech railway network. The localities involved in the monitoring were selected upon discussions with representatives of *Správa železnic*, the Czech national railway infrastructure manager, and based on the plans of track superstructure maintenance which involved CWR welding.

The data of strain, including the apparent strain described in Section 3.1 under laboratory measurements with sample fixed at both ends, were recorded using the introduced measuring set. At each measurement, the rail temperature in the vicinity of the involved strain gauge was recorded, too.

Methodology of Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail was composed out of the measurements. This methodology was another outcome of the above-mentioned research project.

3.3.1 Monitored Localities

There were four localities where the field monitoring of CWR strain took or has been taking place:

- A. Borovnice,
- B. Ostopovice,
- C. Chotěvice, and
- D. Bezpráví.

3.3.2 Data Collection

The strain gauge installation in all localities was performed closely before the stress-controlled rail welding was scheduled. The rails were in their position on sleepers in all the cases. At least one measurement was performed just before the welding, when the rails were in a stress-free state (released from fastenings and on rollers) and at least one measurement was performed just after the tensioning temperature was reached (either by rail pre-tensioning with the use of hydraulic device, or by rail heating). The tensioning temperature, rail strain, and other important data related to rail welding were noted. With this information, the measured values at the time of welding serve as a reference to other measurements of the CWR strain.

Apart from other purposes, the rail strain data of the state prior pre-tensioning and after pre-tensioning serve well to investigate the potential unevenness of the rail pre-tensioning.

The CWR strain measurements using the *Measuring Set for Diagnostics of Time-Based Development of Stress States in CWR* are quick, but not autonomous, and only one measuring spot can be monitored at a time. Therefore, a schedule of measurements was prepared for all the monitored localities. The typical schedule was set as a series of measurements with the daily frequency lasting for approximately one week. This was followed by the weekly frequency lasting for the first month after the CWR welding and the monthly frequency lasting for the first year after the CWR welding. This schedule was set to cover the hypothetical development of a neutral temperature change in the CWR over the time and not overload the research group members.

The detailed records of the measured strain at each measuring spot in Chotěvice and Bezpráví localities are presented in the dissertation. An aggregated record of all measuring spots within Bezpráví locality is presented in Figures 3.12 to 3.13.

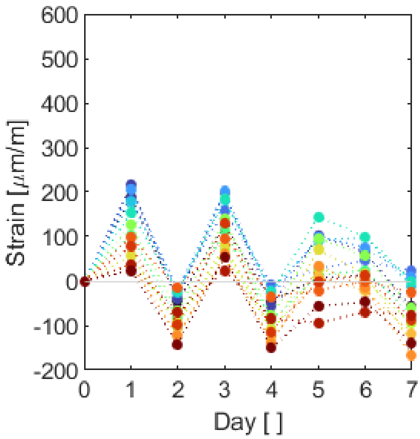

Figure 3.12 – Aggregated CWR Strain Record in the Bezpráví Locality in the Period of Daily Monitoring

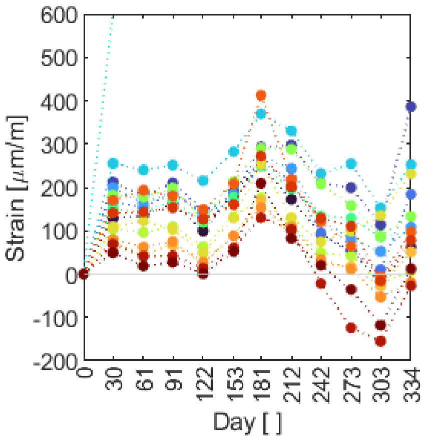

Figure 3.13 – Aggregated CWR Strain Record in the Bezpráví Locality in the Period of Monthly Monitoring

Chapter 4

Neutral Temperature Development of Continuous Welded Rail

Considering the elastic behaviour of rail under thermal loading, it can be assumed that in order to change the rail neutral temperature, a rail strain shall occur. If the rail strain is measured, it shall be proportional to the change of the neutral temperature. In this chapter, an approach to the determination of this change is presented.

4.1 Methodology of Non-Destructive Determination of Mechanical Stress in CWR

The Methodology of Non-Destructive Determination of Mechanical Stress in CWR was developed as an outcome of the research project No. TJ04000301 *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail* and is attached as an annex to this dissertation. A procedure of determination of the stress from thermal loading (the neutral temperature change) is described in the methodology. Since the methodology was released before the release of this dissertation, it does not contain all the ideas written in the dissertation. The data analysis continues as new data are being obtained from the ongoing monitoring and the methodology will be updated as further conclusions will be made.

4.2 Data Analysis

The measured CWR strain data contain both the rail strain and the apparent strain as described in the previous chapters. In order to get the real strain data, the impact of the apparent strain proportional to the rail temperature shall be removed from the measured strain data. According to the user instructions of the strain gauge manufacturer, the self-compensation of strain gauges compensates for the linear part of the thermal impact, leaving the non-linear part uncompensated. However, in Figures 3.5 to 3.8, it can be seen that the non-linear part can be neglected without loss of generality at this moment of analysis.

The relations of strain and temperature for each measuring spot are plotted in the dissertation. These relations can be plotted for various datasets. Datasets of the daily measurement period database, i. e. the data from typically the first week of measurements, when the measurements were performed on a daily basis, and datasets of the complete measurement period are applied in this case. The question on the database selection is discussed further in the discussion to this chapter. A linear trend line is attached to each graph. This trend line is calculated in the shape of a linear polynomial:

$$y = a \cdot x + b, \tag{4.1}$$

where a is the slope coefficient.

The slope coefficient is always negative, the absolute value, however, varies.

The slope coefficient a represents the linear impact of the apparent strain proportional to the rail temperature (further referred to as *linear thermal coefficient of the apparent strain*, or *LTCAS*) and is always negative. The absolute value, however, varies. The LTCAS of the temperature-strain relation per particular measuring spots can be calculated from both datasets – the data from the daily frequency measurements from the first week after installation (further referred to as *LTCAS week*), and the data from all measurements performed within one year after the installation (further referred to as *LTCAS all*). Except for the LTCAS values, the *LTCAS difference* calculated as

$$LTCAS_{difference} = LTCAS_{all} - LTCAS_{week} \tag{4.2}$$

can be obtained.

The experiments presented in Section 3.1 proved that the LTCAS of a sample fixed at both ends remains constant under a changing temperature of the sample if the non-linearity is neglected, and an assumption can be made that only the absolute member of the Polynomial 4.1 changes if a pre-stress (e. g. by a change of the relative distance of fixed supports) is applied. Additionally, an assumption that the LTCAS of a freely expandable member is zero can be made from the experiments presented in Section 3.1. These ideas are interpreted in Figures 4.1 and 4.2.

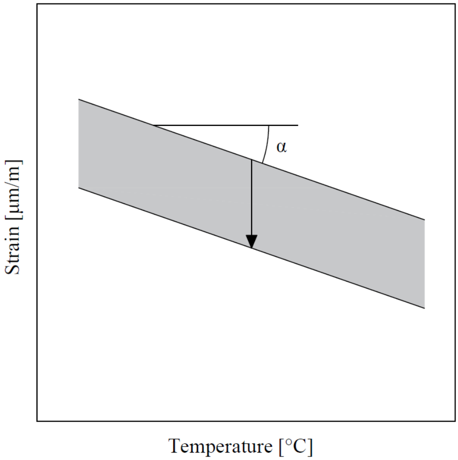

Figure 4.1 – Scheme of a Change in the Absolute Coefficient of the Strain-Temperature Polynomial upon a Sample Pre-Stress Change

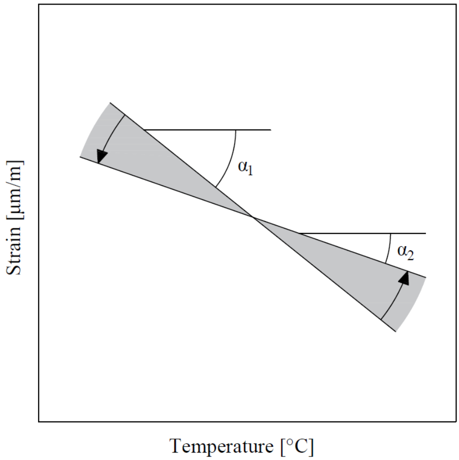

Figure 4.2 – Scheme of a Change in the Linear Coefficient of the Strain-Temperature Polynomial upon a Support Fixation Rigidity Change

The index at LTCAS indicates the coefficient value before (1) and after (2) change. Please note that the change can occur in both directions and the arrows are used for an illustrative purpose only. Both changes presented in Figures 4.1 and 4.2 can occur contemporaneously.

As a result of these assumptions, an extrapolated rail temperature can be determined. If Polynomial 4.1 is written with quantities as

$$\varepsilon = a \cdot T + b, \tag{4.3}$$

where ε is the strain, a is the LTCAS, and T is the temperature, the extrapolated rail temperature is given by equation

$$T = \frac{\varepsilon - b}{a}. \tag{4.4}$$

Please note that this Equation applies the different LTCAS of the particular measuring spots as the denominator, therefore effectively removes its impact from the volume of the calculated rail temperature.

In the daily measurement graphs, the measured and extrapolated temperature, and the difference of these values are presented for each particular measuring spot. The day zero is the day of stress-controlled rail welding.

It can be further assumed that the measured values of strain contain the real strain, the apparent strain, other impacting factors and noise. If the values of the extrapolated temperature express the impact of the apparent strain, the values of difference of the measured and extrapolated temperature contain only the change of the rail neutral temperature, other impacting factors and noise. The impact of the other factors is unknown by the date of submission of this dissertation, however, no evidence is found that it is significant.

Since the day zero represents the data obtained on the day of rail welding after the welding, it can be postulated that **the values of the measured and extrapolated temperature difference represent the determination of the neutral temperature development in continuous welded rail over time, with zero being the tensioning (installation) temperature**. Yet, it has to be taken into account that some outlying values may be caused by a failure of the probes or other reasons, and other factors influencing the neutral temperature may lurk in the curve of the temperature difference.

Out of the data analysed in the above-described way, the development of the neutral temperature can be determined and the actual thermal stress in CWR can be calculated. Partial calculation results are presented in the dissertation. An example of the results for D.I measuring spots is in Tables 4.1 – 4.2.

Day	**Instant Rail Temperature [°C]**	**Instant Neutral Temperature [°C]**	**Instant Thermal Stress [MPa]**
0	30.8	21.3	−23.0
30	9.7	17.8	19.5
61	8.1	15.0	16.7
91	2.5	12.4	24.0
122	11.5	14.7	7.7
153	0.2	10.5	24.8
181	−7.7	11.3	45.9
212	1.3	15.9	35.3
242	15.5	21.3	13.9
273	20.5	23.3	6.9
303	26.1	20.6	−13.2
334	16.9	28.9	29.0

Table 4.1 – Measuring Spot D.I – Left Rail: Instant Rail Temperature, Neutral Temperature and Thermal Stress

Day	Instant Rail Temperature [°C]	Instant Neutral Temperature [°C]	Instant Thermal Stress [MPa]
0	31.1	19.7	−27.5
30	9.7	19.4	23.5
61	7.8	15.0	17.3
91	2.4	13.1	25.7
122	11.6	16.5	11.9
153	0.0	8.9	21.6
181	−7.6	11.8	46.8
212	1.4	16.7	37.0
242	15.3	16.6	3.2
273	20.5	16.3	−10.3
303	26.0	18.0	−19.4
334	16.7	23.0	15.1

Table 4.2 – Measuring Spot D.I – Right Rail: Instant Rail Temperature, Neutral Temperature and Thermal Stress

4.3 Discussion

The crucial point of the neutral temperature development determination is the setting of the LTCAS for the calculation of the extrapolated temperature. Experimentally, the LTCAS can be obtained from a test on a sample under a known fixation of the supports. This is, however, impossible to simulate in the track. If the rail fastenings or the track alignment deteriorates over time and change the magnitude of fixation of the supports, it may cause the change of the LTCAS (as presented in Figures 4.1 and 4.2) and thus improperly omit a change of the rail neutral temperature. It can be assumed that the accuracy of the LTCAS determination increases with shortening of the time needed to obtain the coefficient. This is, because a lower deterioration of the rail fastenings and the track alignment can be expected just after welding than if the data collection is spread over a longer period, where the construction site transport and other impacts can play a role. On the other hand, the more measurements are performed, the more values are obtained and the higher accuracy of the measured data can be determined.

The statistical analysis of the LTCAS values can indicate why the CWR strain measurements in a short period after rail welding is desired. It can be illustrated in Figures 4.3 and 4.4.

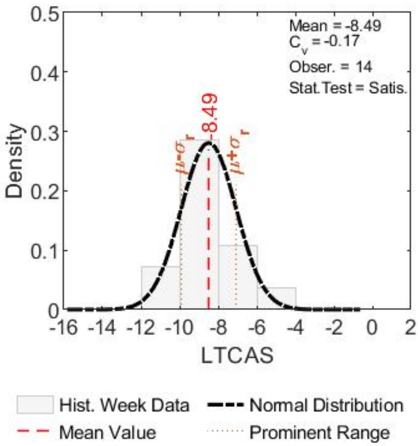

Figure 4.3 – Probability Density of Normal Distribution of LTCAS from the First Week of Measurements in Bezpráví Locality

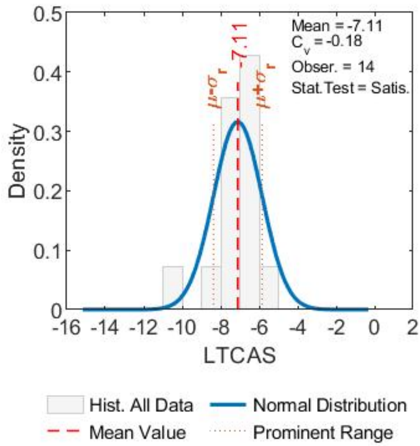

Figure 4.4 – Probability Density of Normal Distribution of LTCAS from All Measurements in Bezpráví Locality

The change of the LTCAS mean value towards zero corresponds to the hypothesis of the CWR fixation deterioration over time [16, 17]. In Chapter 3.1, it was shown that the LTCAS (slope coefficient) is zero in the case of a freely expandable sample and reaches some constant value if the sample is fixed at both sides. An area of a semi-rigid fixation lies between these two values. The same principle can be considered for a railway track. It can be assumed that the fixation of rails slightly deteriorate over time and this corresponds to the slight increase (as the values are presented in the negative scale) of the LTCAS towards zero.

The measurements performed on a daily basis are used as a dataset for the estimation of the LTCAS in this dissertation. This database was selected because the volume of the dataset seems sufficient for the intention of the LTCAS determination on one hand and seem acceptable in the terms of the data collection period length on the other hand. Based on the ideas formulated in the previous paragraphs, it is recommended to obtain as many as possible, but at least ten, values of strain in a shortest possible period, but with a maximum reachable rail temperature change (to be able to construct a reasonable trend line and obtain a reliable LTCAS). An automated data collection system would make the most comfortable way, but a measurement according to the methodology [18] can be used, too. In the latter, it is recommended to perform the measurement at least over the evening and morning within the first 24 hours after the stress-controlled rail welding and collect at least ten values of strain.

Another point which requires elaboration is the initial value of the measured and extrapolated temperature difference, which is different from zero in many cases. This is not an error. This is a result of a relatively long period of data collection for the LTCAS determination dataset. In the case of the presented experiments, the period was typically one week, some deterioration might have occurred and the coefficient of determination was somewhat different from one. If the data collection was performed in a shorter period, the deterioration might be lower and the coefficient of determination higher. In a thought experiment, if the data collection was performed in such a short period that no deterioration occurred and the supports could be considered as fully fixed, the coefficient of determination would reach one (leave apart the non-linear part) and the values of the measured and extrapolated temperature difference would start at zero on the day zero.

The clustered data presented in the dissertation are more illustrative to discuss the particular results of the rail monitoring. Notable effects can be seen in the comparison of the general behaviour of the development of the curve clusters. The curve clusters of the Bezpráví locality (D), except for the cluster D.IV, seem evolving in a very similar shape. Moreover, they show lower amplitudes that the ones at the Chotěvice locality (C), which can be caused by a stronger track elements: 60E2 rail in Bezpráví to 49E1 rails in Chotěvice, fastening system Vossloh W 30 HH in Bezpráví to W 14 in Chotěvice, etc.

Another way of the neutral temperature development results presentation is the visualisation of the thermal stress in rails. The example analysis for the D.I measuring spot can be visualized by Figures 4.5 and 4.6.

In Figures 4.5 and 4.6, the red line corresponds to the instant rail temperature in Tables 4.1 and 4.2 and represents the thermal stress if neutral temperature was considered constant in the level of the tensioning temperature (23 °C in the case of the Bezpráví locality). The green line corresponds the instant neutral temperature in Tables 4.1 and 4.2 and represents the neutral temperature change over time (in this graphs, however, expressed in the equivalent stress). The difference coloured as the grey area represents the actual level of the thermal stress in the particular measuring spot of the CWR if the new approach to the determination of the neutral temperature change over time according to the dissertation is adopted.

Presentation of the results in the form of graphs shown in Figures 4.5 and 4.6 can be done under several constraints, which must be kept in mind for interpretation. First of all, the values corresponding to the instant rail temperature (marked by the red line) and the values corresponding to the neutral temperature change (marked by the green line) were not measured continuously, therefore only the discrete values in the particular days of measurement are calculated. The discrete points were connected for a better visualisation of the discussed effect. The instant rail temperature (marked by the red line) changes cyclically every day and a correct visualisation would include the cycles, but the measurements were performed on a monthly basis in the discussed period. Therefore, the intraday change of the instant rail temperature cannot be shown.

Figures of more measuring spots are presented in the dissertation. Several important effects can be seen in Figures 4.5, 4.6 separately, in their mutual comparison, and if compared to the other figures presented in the dissertation:

- **The neutral temperature change in the left and right rail of the same measuring spot show a similar trend.**
- **The neutral temperature change is different in different measuring spots.**
- **The neutral temperature seems to adjust itself to the yearly temperature cycles into a certain extent.**

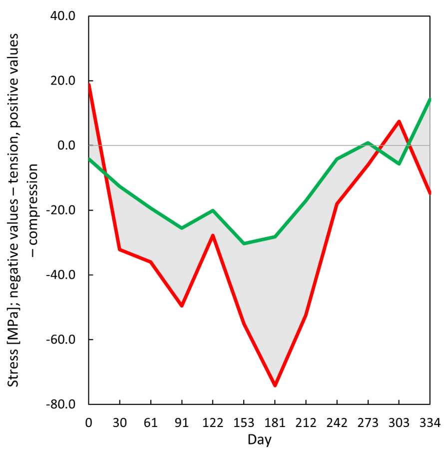

Figure 4.5 – D.I – Left Rail: Comparison of Standard and New Approach to the Thermal Stress Determination in CWR

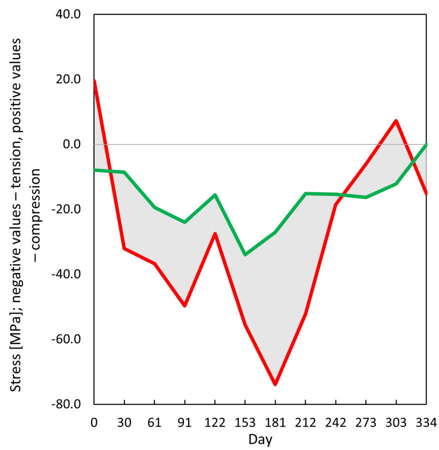

Figure 4.6 – D.I – Right Rail: Comparison of Standard and New Approach to the Thermal Stress Determination in CWR

Chapter 5

Conclusions

The problem of determination of the instant value of the neutral temperature in the CWR is an up-to-date topic all over the world. Many attempts have been made to develop a non-destructive direct methodology of the normal rail stress measurement, so far without an appreciable success. The proposed dissertation deals with this problem searching for a development of a methodology using the state-of-the-art technology that is affordable and easy to deploy, and presents research results that provide an insight into the CWR behaviour, propose a methodology for the determination of the neutral temperature change and the calculation of the thermal stress in the CWR, and charts a way of investigation to gain a better knowledge on the development of the neutral temperature in the CWR.

Chapter 2 presents the research results in the area of the rail temperature measurement, which is important for the further work on the neutral temperature determination. A short analysis of two critical parameters that have an impact on the rail temperature, i. e. the air temperature and cloudiness, is given. Further, an extensive investigation into the rail temperature development in selected localities in the Czech Republic is presented. Various parameters connected to the railway track position are identified as factors influencing the rail temperature. A railway track location on a bridge across a river is identified as the most prone one to the extreme cold temperatures, whereas the south-west orientation of rail on a sunny plain is identified as the most prone to the extreme hot temperatures. A specific impact of snow cover of a railway track is discussed in this section, too.

Chapter 3 focuses on an investigation into the strain monitoring of the CWR. The laboratory measurement setup in analysed in the first section. In this section, a self-compensation attribute of the strain gauges used in the tests is proven and further questions regarding the slope coefficient are raised. A comparison of the half bridge and quarter bridge configurations of strain gauges is performed and the quarter bridge configuration is recommended for the field measurements. A functioning sample *Measuring Set for Diagnostics of Time-Based Development of Stress States in CWR*, which follows the first section is briefly introduced in the second section. The third section presents a large-scale extensive CWR strain monitoring that was performed in several localities across the Czech Republic in the past years. The CWR strain data of the investigated sections are the outcomes of this monitoring.

Chapter 4 follows the CWR strain monitoring with research ideas that were elaborated from the obtained data, presents the *Methodology of Non-Destructive Determination of Mechanical Stress in CWR* (with the full text available in the annexes), and embraces the ideas into the methodology to form a proposal of determination of the neutral temperature change in CWR and a new approach to the thermal stress calculation. A hypothesis of an important role of the LTCAS is presented and applied in the example of one measuring spot monitored within the scope of the extensive CWR strain measurement presented in Chapter 3. A change of neutral temperature within the interval of $\langle 8.9; 28.9 \rangle$ °C in the case of the measuring spot D.I rails with the tensioning temperature of 23 °C is calculated. Figures visualising the results of the new approach to the CWR neutral temperature determination and thermal stress calculation are introduced in the discussion.

Chapter 6

Summary of Ph.D. Candidate's Publications Related to the Dissertation

[1] VNENK, Petr and CULEK, Bohumil. Long-Term Measurements in the Neutral Temperature Identification Problems in Continuous Welded Rail. In: *Advanced Manufacturing and Repairing Technologies in Vehicle Industry*. Budapest: Budapest University of Technology and Economics, 2017. p. 173-178. ISBN 978-963-313-258-6.

[2] VNENK, Petr and CULEK, Bohumil. Measurement Methods of Internal Stress in Continuous Welded Rail. In: *Acta Polytechnica CTU Proceedings*. Prague: České vysoké učení technické v Praze, 2017. p. 91-96. ISBN 978-80-01-06297-5. ISSN 2336-5382.

[3] PĚTIOKÝ, Marek, CULEK, Bohumil and VNENK, Petr. Měření napjatosti pružných svěrek v provozu. In: *Juniorstav 2018 Proceedings*. Brno: Vysoké učení technické v Brně, 2018. p. 357-365. ISBN 978-80-86433-69-1.

[4] MIRKOVIĆ, Nikola, BRAJOVIĆ, Ljiljana, MALOVIĆ, Miodrag and VNENK, Petr. Measurement Methods for Residual Stresses in CWR. In: *Advances in Intelligent Systems and Computing*. Vol. 982. Berlin: Springer, 2019. p. 346-355. ISBN 978-3-030-19755-1. ISSN 2194-5357.

[5] ŠMEJDA, Aleš, VNENK, Petr, BORKOVCOVÁ, Anna, BORECKÝ, Vladislav, LOPOUR, Pavel and ŠEVČÍK, Filip. Diagnostika a průzkum drážního tělesa. In: *Konference Dopravní infrastruktura 2020: sborník*. Prague: Agentura VIACO, 2020. p. 27-30.

[6] CULEK, Bohumil, PĚTIOKÝ, Marek, SCHMIDOVÁ, Eva, TOMEK, Petr and VNENK, Petr. Fatigue behaviour of Vossloh SKL14 tension clamps. In: *Structural Engineering for Future Societal Needs: Congress Proceedings.* Zürich: IABSE, 2021. p. 1555-1563. ISBN 978-3-85748-176-5.

[7] UNIVERSITY OF PARDUBICE. Measuring set for diagnostics of time-based development of stress states in continuous welded rail. Authors: Petr VNENK, Özgür YURDAKUL, Jiří ŠLAPÁK, Vladimír SUCHÁNEK, Bohumil CULEK, Ladislav ŘOUTIL, Ondřej SADÍLEK, Filip KLEJCH, Zdeněk SHÁNĚL, Karel SUCHÝ, Tadeáš ŠUSTR and Miloš ŠULA. Czech Republic. Functioning sample TJ04000301-V2. 8th November 2021.

[8] UNIVERSITY OF PARDUBICE. Methodology of Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail. Petr VNENK, Özgür YURDAKUL, Jiří ŠLAPÁK, Vladimír SUCHÁNEK, Ondřej SADÍLEK, Filip KLEJCH, Bohumil CULEK and Ladislav ŘOUTIL. Czech Republic. Certified methodology TJ04000301-V1. 7th March 2022.

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