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Methodology of Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail

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Development of this methodology is a direct outcome of research performed within the scope of investigation of the TACR TJ04000301 project *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail.*

Contents

Introduction

This methodology describes a procedure for a non-destructive determination of an instant value of normal stress in continuous welded rail (CWR).

In addition, it focuses on determining the development of longitudinal deformation of continuous welded rail in time and on the rail neutral temperature changes. Further significant factors influencing the stress in rail are the residual stress and the stress from railway operations. State-of-art literature provides determination of these stresses [1, 2, 3, 4, 5], but their description exceeds the scope of this methodology.

The methodology brings benefits to science and practice. Although the methodology meets the criteria set for the desired way of the CWR stress determination by Kish and Samavedam [6] in 1987 only partially, it allows scientific and academic institutions' research teams and rail-way infrastructure R&D managers focusing on the continuous welded rail to benefit from the valuable information on the CWR behaviour. [7, 8]

A precise determination of the stress in the CWR is essential for a correct and timely adoption of measures preventing failures of the continuous welded rail, mostly rail breaks and track buckling. The methodology assets lie in its non-destructive character, relatively simple installation of a measuring set track unit, high precision of strain gauges and fast measurement, which may be carried out even on heavy haul railway lines without the need for a track closure.

Implementation of this methodology enables obtaining data on longitudinal rail deformation, which can be observed both in the long and short term.

The long-term observation may reside in the determination of a level or a period of consolidation of a newly constructed permanent way. The short-term observation may serve to control the level of rail stressing or the equality of its elongation at the time of welding.

The rail neutral temperature is a temperature at which there is zero thermal stress in the CWR. [7] It is one of the important factors influencing the current value of the normal stress in the CWR.

The methodology was developed within the scope of investigation of the TACR TJ04000301 project *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail*. The research team consisted of the following departments of the Faculty of Transport Engineering of the University of Pardubice: Educational and Research Centre in Transport, Department of Transport Structures, Department of Transport Means and Diagnostics, and Department of Electrical and Electronic Engineering and Signalling in Transport.

1 Goals

1.1 This methodology contains a procedure to determine the instant value of normal stress in the CWR by a non-destructive way using strain gauges and a measuring set. It focuses mostly on values of strain and neutral temperature in the CWR.

1.2 Functioning sample No. TJ04000301-V2 *Measuring Set for Diagnostics of Time-Based Development of Stress States in Continuous Welded Rail*, which is an outcome of investigation of the TACR TJ04000301 project *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail* is utilised for determination of the instant value of stress in the CWR, CWR strain, and neutral temperature according to this methodology. Documentation of this functioning sample is provided in the annex to this methodology.

2 Terms and Acronyms

2.1 Terms

in alphabetical order:

breathing end	–	section at the beginning and the end of a CWR where rail dilation occurs due to rail temperature changes [8]
continuous welded rail (CWR)	–	rail of length of 150 m and more [8]
corridor line	–	main railway line which concentrates a significant amount of traffic performance in a network
data acquisition system	–	hardware that serves to charge sensors, collect and process recorded signal
measuring set	–	functioning sample with identification code TJ04000301-V2, which is an outcome of investigation of the TACR TJ04000301 project *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail*
measuring spot	–	place on rail where strain monitoring is performed using a measuring set
monitored section	–	railway line section where measurement according to this methodology is performed
rail foot	–	bottom flange of rail, which resides on supports and is tightened by fasteners
rail neutral axis	–	rail axis which defines zero normal stress level under bending load from a vertical force
rail neutral temperature	–	rail temperature at which rails are stress-free from rail temperature change [8]
rail web	–	central, narrow part of rail
sleeper spacing	–	axial distance of two adjacent sleepers in traditional track structure
stationing	–	railway line distance marking from a specified datum
strain gauge quarter bridge	–	electrical circuit for measuring of small changes of resistance using one strain gauge sensor only
strain gauge	–	passive electrotechnical component utilised for strain measurement
stress-controlled rail weld	–	weld with imperative stress management for a CWR construction
stress-free rail weld	–	weld for connection of rails into a longer rail as a preparation for a CWR construction [8]
surface emissivity	–	ratio of the energy radiated from a material's surface to that radiated from a blackbody at the same temperature
tonnes carried	–	total weight of rolling stock and freight that were transported through a particular railway line section

2.2 Acronyms

in alphabetical order:

α	–	coefficient of linear thermal expansion for steel
CZ	–	Czech Republic
CZK	–	Czech koruna
E	–	Young's modulus
ε	–	rail strain
h	–	length of installation of the measuring set track unit in hours
l	–	original length of rail, or its part
Δl	–	change in original length of rail, or its part
LED	–	light-emitting diode
n	–	number of workers installing the measuring set track unit
σ	–	normal stress induced by thermal load on rail
t	–	instant value of rail temperature
t_0	–	initial (tensioning, i.e. neutral at the time of welding) value of rail temperature
t_1	–	instant value of rail neutral temperature
USA	–	United States of America
USD	–	United States dollar
x	–	number of installed measuring set track units

3 Used Instruments and Software

3.1 Following instruments and aids are needed for installation of measuring set track unit (the complete equipment used by the authors is listed in the annex to this methodology):

- strain gauges
- covering foil with kneading compound
- cleaning agent with cleaning pads
- sandcloth of grit size 180
- sandpaper of grit size 400
- gauge of rail neutral axis
- thin permanent markers, oil markers can be applied
- steel ruler
- cable ties
- cable tie holders
- contact adhesive
- polypropylene tubes HTEM DN 40 of 150 mm length
- end caps to polypropylene tubes HTEM DN 40
- polyurethane foam cube of 5 cm length edge
- polyurethane lacquer
- strain gauge adhesive
- connecting cable D-Sub 15 pin male/RJ11 female
- recording sheet for measurement results
- digital data acquisition system
- computer with software for collection of strain gauge measured data
- 12 V maintenance-free battery
- surface thermometer

3.2 Following instruments and aids are needed for performing measurements (the complete equipment used by the authors is listed in the annex to this methodology):

- connecting cable D-Sub 15 pin male/RJ11 female
- recording sheet for measurement results
- digital data acquisition system
- computer with software for collection of strain gauge measured data
- digital radios
- reflective vests
- 12 V maintenance-free battery
- surface thermometer

4 Methodology Description

4.1 Test Fundamentals

4.1.1 Test procedure according to this methodology is combined out of two basic parts:

- installation of measuring set track unit and
- performing measurement at measuring spots.

Procedures of installation and measurement are described separately in the following chapters.

4.1.2 Measuring spots shall be determined within the scope of each monitored section. Selection of number and position of measuring spots is given by an intent where the information of values and development of normal stress in rail shall be gained. It is advisable to select more measuring spots in each monitored section. This helps to eliminate the relative effect of failed strain gauges and is practical for mutual comparison of deformation development of several near rail sections. It is advisable to establish four measuring spots in each monitored track in each selected stationing. One measuring spot shall always be positioned on each side of each rail. Using this procedure, maximum volume of information on rail deformation in the selected track stationing shall be gained.

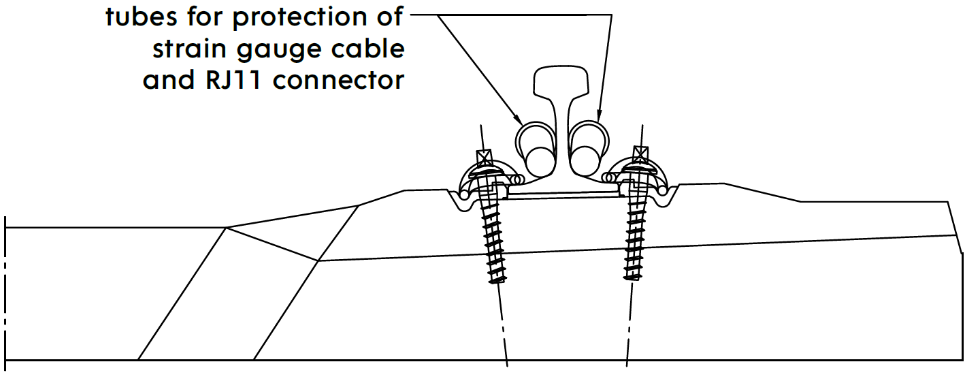

Figure 1 – Cross Section of Rail with Double-Sided Position of Measuring Spots.

4.1.3 Length of monitored section and number of involved measuring spots are parameters, which shall be chosen. Selection of the spots yields to the rule that the higher density of points in a certain length of monitored section is, the more accurately the course of axial deformation of rail in monitored section can be determined.

4.1.4 A new measuring set track unit shall be installed into each measuring spot.

4.1.5 It is necessary to install measuring set track unit on rails before construction of the CWR for non-destructive determination of instant value of normal stress in the CWR and its development in time. Installation on rails can be performed both before and after stress-free rail welding, but always before stress-controlled rail welding. The rail can be fastened to sleepers in the time of installation. State, when the rail is already placed in a track, is desirable as rail web surface for installation of measuring set track unit can be set in a better way.

4.1.6 After the installation, it is necessary to measure the instant value of strain gauge deformation at freely laid rail, i. e. rail which is supported by rollers and not fastened. It is advisable to perform this zero axial stress measurement at least twice. The best time to perform this measurement is just before stress-controlled rail welding, or just before rail stressing (if applied) that precedes the stress-controlled rail welding.

4.1.7 It advisable to measure the instant rail temperature (see Figure 2) and make a cloudiness record at every measurement, including the initial one, described in the preceding point. The best spot for temperature measurement is on the rail web as close to the installed strain gauge as possible. The best way to measure the temperature is to use a surface thermometer, which provides an accurate value regardless the instant state of rail surface emissivity. It is sufficient to determine the cloudiness in meteorological tenths by estimation. The list of necessary and recommended measurements is provided in the Table 1.

Table 1 – List of Necessary and Recommended Measurements.

	Necessary	Recommended
Monitored Section	• Date	• Cloudiness • Air Temperature • Precipitation Intensity • Air Velocity • Track Structure Humidity
Measuring Spot	• Strain [μm/m] • Rail Temperature • Time	• Strain Gauge Technical State

Figure 2 – Temperature Measurement by Surface Thermometer with Parallel Connection of Track and Mobile Unit of Measuring Set (in the Background).

4.1.8 If rail stressing is applied before stress-controlled rail welding, the measured values can be used for verification of applied strain gauges functionality, and, if measuring set track unit is installed in multiple measuring spots along the stressed rails, unevenness of rail stressing can be determined out of the measured data.

4.1.9 Recommended time schedule of measurements is presented in the Table 2. It is advisable to perform a measurement on the day preceding the start of track operation, on the day of the start of track operation and on one day after the start of track operation, especially in the case of heavy haul railway tracks.

Table 2 – Recommended Schedule of Measurements.

Measurement Number	Date
1	on released rails on sliding pads, or rollers, before stress-controlled rail welding
2	on released rails on sliding pads, or rollers, before stress-controlled rail welding (repeating)
3	immediately after stress-controlled rail welding, or after fastening of stressed rail
4	immediately after stress-controlled rail welding, or after fastening of stressed rail (repeating)
5	$D + 1$ (D denotes day of stress-controlled rail welding)
6	$D + 2$
7	$D + 3$
8	$D + 4$
9	$D + 5$
10	$D + 6$
11	$D + 7$
12	$D + 14$
13	$D + 21$
14	$D + 28$
15	$D + 2M$ (M denotes month)
16	$D + 3M$
17	$D + 4M$
18	$D + 5M$
19	$D + 6M$
20	$D + 7M$
21	$D + 8M$
22	$D + 9M$
23	$D + 10M$
24	$D + 11M$
25	$D + 12M$

4.2 Test Procedure – Part I: Installation of Measuring Set Track Unit

4.2.1 Procedure of measuring set track unit installation at one measuring spot is described in this chapter. The procedure shall repeat for installation in more measuring spots.

4.2.2 It is advisable to perform the installation in higher number of persons. For a rough estimation of time required for installation, under good weather conditions, if workers are dexterous, and if installation is not limited by works in the affected section, an experience-based formula can be defined as

$$h = \frac{x}{n}, \tag{1}$$

where h is the number of installation hours, x is number of installed measuring set track units and n is number of workers. The time required for installation of determined number of strain gauges needs to be prolonged under unfavourable weather conditions, especially rain, or if it is the first installation of the group of workers, or if the installation works need to be suspended due to space clearing for other works in the track.

4.2.3 Rail surface shall be cleaned from rust in an area of 3×3 cm at a neutral axis level in a position determined for a measuring spot. At first, coarse rust shall be cleaned by a drilling machine with a coarse steel ending brush. Afterwards, manual cleaning by a sandcloth with grit size of 180 shall be applied. Finally, rail surface shall be cleaned by sandpaper with grit size of 400.

4.2.4 Areas on rail web of 3×3 cm dimensions for attachment of cable tie holders for cable protecting and strain gauge connector tube shall be cleaned in the same way approximately (a) 10 and (b) 20 cm from the measuring point. Upper edge of area (a) is under the rail neutral axis in such a way that its lower edge is on the level of the rail web to rail foot transition rounding. Area (b) is by its centre placed to the rail neutral axis.

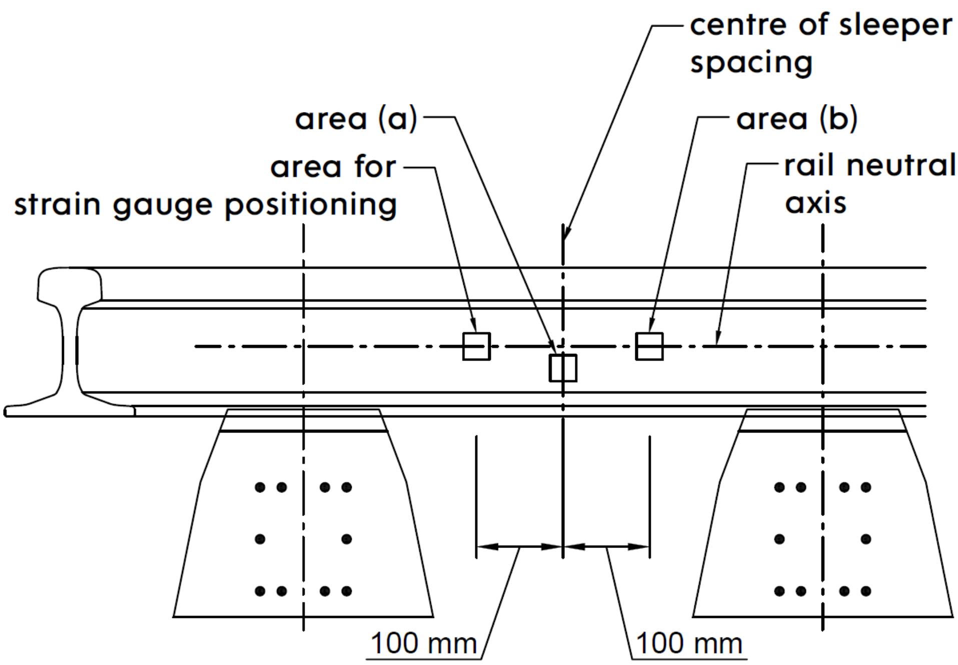

Figure 3 – Scheme of Cleaning Areas Distribution on Rail Web.

4.2.5 The complete removal of rust from rail is necessary. Thicker layer of material than necessary shall not be removed from rail web surface. At the area intended for strain gauge installation, it is necessary to ensure as high measure of evenness as possible after the rust removal. Material level removed due to the rust affection shall be as even as possible and ground surface shall be as smooth as possible, without grooves caused by uneven intensity of grinding.

4.2.6 Smooth and ground surface after rust removal shall be degreased by freon-free cleaning agent with cleaning pads.

4.2.7 Neutral axis level shall be marked by a permanent marker of a thin nib in the area cleaned for strain gauge installation. It shall be marked by two horizontal marks interrupted by a space for a strain gauges.

4.2.8 Strain gauge shall be glued using a strain gauge adhesive into the space between marks of the rail neutral axis. Strain gauge installation shall be done according to the user instruction.

Figure 4 – Glued Strain Gauge (with Teflon Cover) with Marked Horizontal Lines.

4.2.9 Adhesive pad shall be removed from cable tie holders to keep the plastic part of the holder only. Cable tie holder surface after the adhesive pad removal and degreased areas (a) and (b) of the rail web shall be covered by a contact adhesive and after a period set in user instructions, cable tie holders shall be glued by pressure to the areas (a) and (b) of the rail web..

4.2.10 After the cable tie holders safely hold at the rail web, a polypropylene tube HTEM DH 40 of 150 mm length ended by an end cap from one side shall be connected to them using cable ties. The tube shall be attached in such orientation that the fill end is on the side of the (b) area.

4.2.11 Redundant part of the tied cable tie shall be cut off by pincers. The cable tie on the tube shall be covered by a contact adhesive as a precaution.

4.2.12 A layer of polyurethane lacquer shall be painted on the strain gauge with dried adhesive. The lacquer shall get dry according to its user instruction.

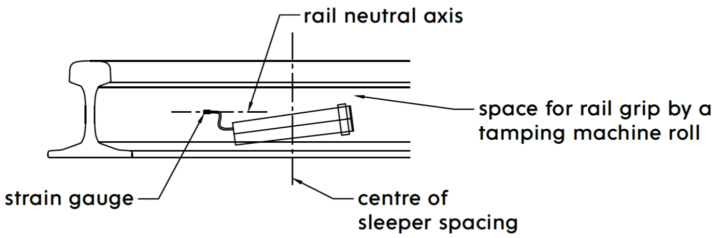

Figure 5 – Scheme of Strain Gauge and Protective Tube Position on a Rail.

4.2.13 The strain gauge shall be covered by a snippet of covering foil with kneading compound. The snippet shall be of 3×3 cm size and shall be pressed to the rail web.

4.2.14 Strain gauge cable with the RJ11 connector shall be inserted into the protective tube.

4.2.15 The free end of the protective tube shall be filled by a polyurethane foam cube of 5 cm length edge.

4.3 Test Procedure – Part II: Measurement

4.3.1 Procedure of longitudinal rail deformation in one measuring spot is described in this chapter. The procedure shall repeat for measurement in more measuring spots.

4.3.2 Before the measurement commencement, it is necessary to connect a data acquisition system to both a 12 V maintenance-free battery and a computer. If the data acquisition system requires warm up period according to the user instruction, it shall be kept. Software for data collection shall be run in the computer. Signal show as a strain gauge quarter bridge deformation in μm/m units shall be set in the particular data channel. Further settings shall be set according to the data collection software user instruction. A connecting cable with the RJ11 female connector shall be connected to the data acquisition system. With the described procedure, mobile unit of the *Measuring set for diagnostics of time-based development of stress states in continuous welded rail* shall be ready.

4.3.3 Following the above described procedure, polyurethane foam cube shall be removed from the protective tube, and male and female RJ11 connectors shall be connected. This shall provide a connection of the track and mobile units of the measuring set.

4.3.4 After reading and recording of the measured value in the data collection software, measuring set mobile and track unit shall be disconnected. Track unit cable shall be inserted back into the protective tube at rail. The tube shall be filled by the polyurethane foam cube again. The measuring set mobile unit can be transferred to the next measuring spot without the need to turn the unit off if there are multiple measuring spots in the locality.

4.3.5 If there are two readings performed at any measurement after the stress-controlled rail welding, the measured values in both readings performed minutes after each other shall be practically the same – acceptable difference is in the order of magnitude of single digits of μm/m.

4.3.6 **Warning:** Measurement must be performed on rails separately to exclude their conductive connection if performed on both rail of a track.

4.4 Test Output

4.4.1 Minimum scope of test output corresponds to the list of necessary measurements presented in the Table 1 and therefore contains:

- date,
- strain gauge deformation [μm/m],
- rail temperature [°C] and
- time.

4.4.2 Gaining the longitudinal rail strain of the CWR is the first goal of the methodology. The instant value of this strain in a measuring spot can be directly read with μm/m units in the software for data collection.

4.4.3 The test output can be recorded in the form of the Table 3. The recommended labels is in the format of *capital letter.Roman numeral.Arabic numeral*, where *capital letter* denotes the monitored section (can be omitted if the measurement is not performed on multiple monitored sections contemporaneously), *Roman numeral* denotes track stationing and *Arabic numeral* denotes measuring spot at given stationing. It is advisable to label measuring spots by increasing Roman numerals in the direction of increasing stationing. If a track in cross section contains four measuring spots (one measuring spot from each side of each rail), there shall be the maximum number of Arabic numeral used for identification of particular measuring spots.

Table 3 – Recommended Recording Table.

Monitored Section:		**Date:**	
Measuring Spot	**Time [hh.mm]**	**Rail Temperature [°C]**	**Strain [μm/m]**
X.I.1	hh.mm	xx,x	xxxx
X.I.2	hh.mm	xx,x	xxxx
X.I.3	hh.mm	xx,x	xxxx
X.I.4	hh.mm	xx,x	xxxx
X.II.1	hh.mm	xx,x	xxxx
X.II.2	hh.mm	xx,x	xxxx
X.II.3	hh.mm	xx,x	xxxx
X.II.4	hh.mm	xx,x	xxxx
X.III.1	hh.mm	xx,x	xxxx
X.III.2	hh.mm	xx,x	xxxx
...	...	...	...
x.x.x	hh.mm	xx,x	xxxx

4.4.4 Recording table according to the sample Table 3 can be complemented by a record of information listed in the column of recommended measurements of the Table 1 at every measurement in the monitored section.

4.5 Test Evaluation

4.5.1 Every installed strain gauge can show a different value of deformation measured in μm/m units upon the installation on rail without axial stress. It is therefore advisable to subtract the value measured in the measurement No. 3 or 4 according to the Table 2 (values from the measurement No. 3 and 4 shall differ in the order of magnitude of single digits at maximum). This procedure ensures gaining a relative value of deformation to the state of the CWR rail stressing. Values from the measurement No. 3 or 4 shall be at the level of zero (or nearly zero).

4.5.2 Time of measurement shall be added to every measured value of deformation to get a pair of data time–deformation.

4.5.3 Measured data pairs shall be pictured in the form of a graph with time being in the independent axis and strain measured by strain gauges and data acquisition system and processed by a data collection software being in the dependent axis. Obtained points shall be connected into a line graph. It is advisable to depict data from more strain gauges into one graph. It is, however, important to keep in mind parameters which may differ for particular stain gauges. Identification and research into the impact of particular parameters are subject of a further research and exceed the scope of this methodology.

4.5.4 Rail axial strain changes after stress-controlled rail welding, as illustratively shown in the Figure 6, can be observed from the course of the graph. Length of the consolidation phase depends on tonnes carried in the track section. In the case of a heavy haul corridor line, the consolidation phase ends shortly after the start of operation after the stress-controlled rail welding. In the case of a more regional character of railway operation, this phase can be observed several months after the start of operation after the stress-controlled rail welding. A closer identification of particular phases and parameter that affect their length are subject of a further research and exceed the scope of this methodology.

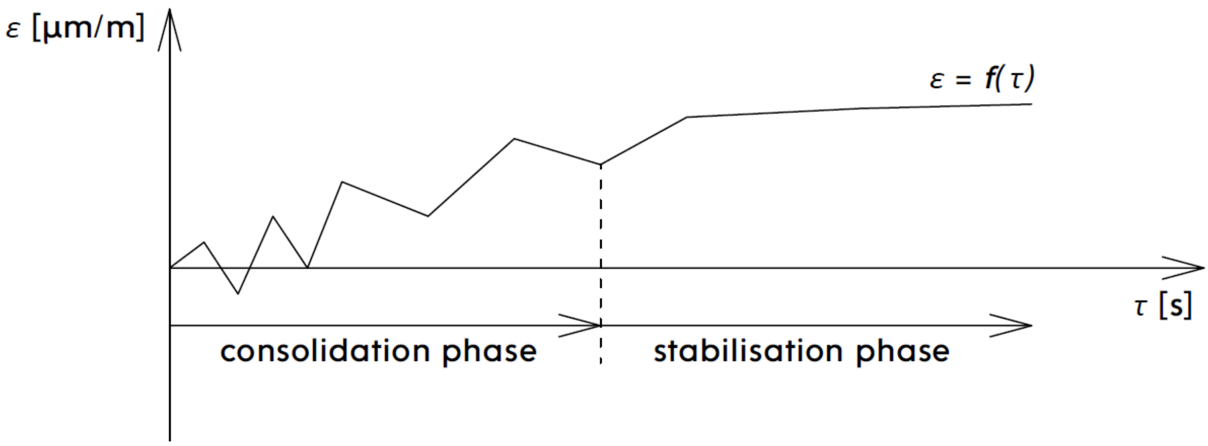

Figure 6 – Scheme of the CWR Deformation Development Gained from Measured Data Pairs Time–Deformation.

4.5.5 Under no deformation (length change) of the CWR, the instant value of normal stress in rail could be derived from (e. g. in [5]):

$$\sigma = -\alpha \cdot (t - t_0) \cdot E, \tag{2}$$

where σ is stress from thermal loading on rail, α is the coefficient of linear thermal expansion of steel, t is the instant value of rail temperature, t_0 is the rail tensioning temperature and E is the Young's modulus of rail.

4.5.6 If a strain occurs in the confined length of the CWR (i. e. out of a breathing length), this deformation appears as a change of neutral temperature in a spot (section) where the deformation occurred. Strain

$$\varepsilon = \frac{\Delta l}{l} \tag{3}$$

is directly proportional to the stress

$$\sigma = E \cdot \varepsilon \tag{4}$$

and this can be substituted to a formula analogical to the Formula 2, and after modifications, it can be obtained in the form

$$\varepsilon = \alpha \cdot (t_1 - t_0), \tag{5}$$

where t_1 is the instant value of rail neutral temperature and t_0 the original rail neutral temperature (if deformation is subtracted from a value measured just after stress-controlled welding, it is the rail tensioning temperature). The theoretical change of rail neutral temperature is schematically depicted in the Figure 7 (The presented shape of neutral temperature function curve t is illustrative only.).

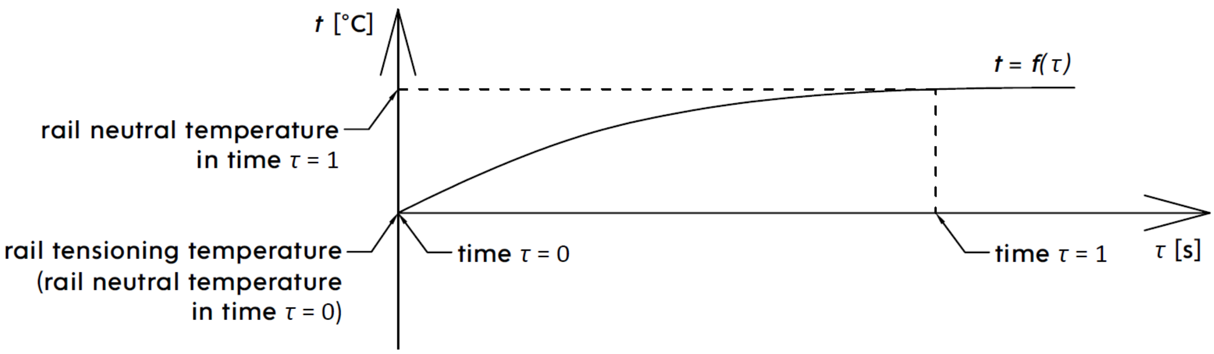

Figure 7 – Scheme of Rail Neutral Temperature Time Development.

4.5.7 The instant value of rail neutral temperature, which is the second goal of the methodology, can be easily derived from the Formula 5

$$t_1 = \frac{\varepsilon}{\alpha} + t_0. \tag{6}$$

4.5.8 If the instant value of rail neutral temperature is substituted for the original t_0 in the Formula 2, a formula for stress calculation in the CWR including the impact of its potential deformation after the stress-controlled rail welding is obtained. This formula can be written in the form of

$$\sigma = -\alpha \cdot (t - \frac{\varepsilon}{\alpha} - t_0) \cdot E. \quad (7)$$

Determination of the neutral value of stress in the CWR is the third goal of this methodology. Please note that α, t_0 and E are constants in this formula, whereas measured quantities t and ε are variables.

4.6 Recommendations

4.6.1 Areas to be cleaned on the rail web shall be selected in such a way that the resultant position of the protective tube is in the centre of the sleeper spacing. Otherwise the protective tube may collide with rail clamp if the rail longitudinally moves. There is no danger of collision of strain gauge with rail clamp.

4.6.2 It is advisable to avoid spots with rail marking at measuring spot selections, as it may be challenging to create a smooth and even surface by rust removal.

4.6.3 3D printed gauges can be used to easily mark rail neutral axis.

Figure 8 – 3D Printed Rail Neutral Axis Gauge.

4.6.4 It is advisable to orient the strain gauge at installation on the rail in such a way that the conductors aim to the opposite side than the protective tube is located. The conductors are then bent by 180° and reach the orientation towards the tube. Complete bending of the conductors can be covered under the snippet of aluminium foil with kneading compound and better protected from mechanical damage.

4.6.5 Cable tie holders can be better connected in the way that their edges are parallel, i. e. both holders have the same tilt as is the longitudinal slope of the protective tube. The protective tube shall then better keep the longitudinal slope required for minimizing of water retention inside the tube.

4.6.6 It is necessary to take into account the need for a sufficient space for rail grip by a tamping machine roll, mostly at vertically positioning the cable tie holder in the (b) area.

4.6.7 It is advisable to keep the directional orientation of the protective tubes in all the measuring spots of a measuring locality. The preferred orientation is with the unplugged end of the protective tube in the direction of decreasing vertical alignment of track. This measure helps water drainage from the protective tubes.

4.6.8 Polyurethane foam cube plugging one end of the protective tube can easily freeze to the tube if measurement is performed under freezing weather conditions. In this case, it is advisable to be equipped with a gas burner and propane-butane cartridge to heat up the end of protective tube to melt the freezing connection between the polyurethane foam cube and the protective tube and gain access to the strain gauge cable with RJ11 connector.

4.6.9 It is advisable to place the measuring set mobile unit and all other equipment into a transport crate, which enables quick transport along the track, for measurement at more measuring spots of one measuring locality.

4.6.10 It is advisable to place the crate on a terrain sack truck and carry it for an access to more remote track sections.

4.6.11 It is better to use a surface thermometer for rail temperature measurement, as the rail web surface emissivity, which affects the contactless thermometer measurements, can change over the time.

4.6.12 Measuring set track unit structure is made in such a way that it enables track tamping by an automatic tamping machine without any restrictions and the measuring set is kept safe. A restriction comes into effect in the case of a ballast profiling machine ride. Its technology to clean rails from ballast may lead to tearing the measuring set track unit off the rail. It is therefore important to agree on a procedure of measuring set track unit protection with railway infrastructure manager and construction site manager. Possible solutions are marking of measuring spot positions by bold red marks on the upper surface of neighbouring sleepers outside the track channel, or by a sign placed nest to the track at the affected stationing.

Figure 9 – Marking of Stationing with Measuring Spots in the Bezpráví Measuring Locality by Red Colour on the Upper Surface of Sleepers Outside the Track Channel and by a Flag Made from an Orange Reflective Vest.

5 Novelty of Procedures

5.1 Many non-destructive approaches to determine stress in the CWR are described in the Czech and world literature (selective overview e. g. in [9]). None of them, despite partial successes in laboratory environment, managed to reach a wider application at railway infrastructure managers.

5.2 This methodology proceeds from the strain gauge technology, which is known for decades [10], but only the long development of this technology enabled using the products available in the market to perform long-term measurements, especially in a significantly larger scope of rail sections and data collection on the CWR behaviour, which is one of the key aspects of this methodology.

5.3 Novelty of procedure described in this methodology resides in the use of *Measuring Set for Diagnostics of Time-Based Development of Stress States in Continuous Welded Rail*, too. This measuring set is an original research result realized within the scope of the TACR TJ04000301 project.

5.4 Novelty of procedure, which is a result of experimental development of mentioned measuring set and applied research, resides in recommendation of using only one strain gauge installed on the rail web for one measuring spot, too. This decreases noise of the measured signal, as it was shown in many performed measurements.

6 Methodology Applicability Description

6.1 Methodology finds a wide applicability in the research of the CWR. Because of time-demanding research of effects connected to the CWR deformations and normal stress development, it can be assumed that research comes to further recommendations over time. These recommendations shall proceed out of this methodology, but shall make the information experimentally gained using this methodology more precise.

6.2 This methodology reacts to a long-term demand for easily performable investigation of normal stress in the CWR. Combination of the use of the established technology that leads to precise measured data by keeping a sufficient simplicity of procedures applicable for practical use is its advantage.

6.3 This methodology is applicable at all CWRs regardless the track gauge, track order, track speed (the methodology is applicable at high speed railways, too), and other parameters. It is applicable in all countries of the world with a railway network.

6.4 Low costs needed for performing measurements are another factor that contributes to the applicability of the methodology. Moreover, the initial investment costs for railway infrastructure managers are relatively low, too, especially upon consideration the scope of the problems connected to the stress in the CWR.

6.5 The development of the CWR all over the world leads to the idea that world extent of the CWR will increase. Therefore, it can be assumed that the applicability of this methodology will increase over time.

7 Economic Aspects

7.1 Measurement Costs

7.1.1 Measurement Costs can be divided into:

- investment costs of measuring set mobile unit acquisition,
- investment costs of measuring set track unit acquisition,
- costs of measuring set installation, and
- costs of performing a measurement.

7.1.2 It is sufficient to expend the investment costs of measuring set mobile unit acquisition only once, as one measuring set mobile unit can be used for measurement of each individual measuring spots. The most expensive item of the measuring set mobile unit is the data acquisition system. The price of the system depends on the type and producer selection. Another expensive item is the computer and software for data collection. Costs of other items of the measuring set mobile unit are negligible. The total investment costs of measuring set mobile unit can vary based on the instant price of data acquisition system, but it can be estimated as several hundred thousand Czech korunas.

7.1.3 Investment costs of measuring set track unit acquisition are very low and can be estimated as one thousand Czech korunas. It shall be noted that investigation of a longer track section requires several dozens (e. g. in the case of a hundreds meter long track section) or hundreds (e. g. in the case of a track section of several kilometres) of measuring set track units.

7.1.4 Costs of measuring set installation comprise of relatively negligible costs of used energy, costs of transport of workers to the installation locality and back, and costs of work of installation workers. For an estimation total number of working hours that can significantly differ based on the planned extent of installation, the Formula 1 can be applied.

7.1.5 Costs of performing one measurement are, except for costs of workers performing the measurement, negligible, too. In the case of experienced workers who work in a pair, the length of measurement at one measuring spot can be estimated as one minute. It is necessary to count with a longer time if the track is intensively operated and must be cleared more often between the measurements or if the measurement is performed during freezing weather. The latter requires melting the connection between the protective tube and the polyurethane foam cube by gas burner. This can be accelerated if more workers are available for the work.

7.2 Possible Economic Assets

7.2.1 At the time of release of this methodology, the authors do not have information on the CWR axial forces management costs from the Czech Republic at disposal. Nevertheless, they try to compile an estimation of the economic assets of the methodology based on available information in the following paragraphs.

7.2.2 According to Koob [6], the CWR axial forces management costs in the USA reach the level of 134 million USD annually. Division per particular items is presented in the Table 4.

Table 4 – Annual CWR Axial Forces Management Costs in the USA [6]

Costs [mil. USD]	Item
15	Track Buckle Repair
28	Buckle Derailments
51	Slow Orders
40	Destressing

7.2.3 Table 5 shows the length of tracks (not railway lines) in the Czech Republic in 2020 and in the USA in 2003, i. e. in year to which the data of costs from the Table 4 are related. The data origin from a statistics of the International Union of Railways [11]. For the USA of 2003, the date were calculated by linear extrapolation from available data of the period from 2013 to 2020.

Table 5 – Length of Tracks in the CZ (2020) and in the USA (2003, Extrapolation from 2013 to 2020). [11]

Length of Tracks [km]	Country
15 189	Czech Republic
267 751	United States of America

7.2.4 Assuming the same ratio of buckle derailments and track buckle repair in the Czech Republic and the USA, it can be estimated by comparison of the data from the Tables 4 and 5 that the costs connected to buckle derailments and track buckle repair are in the Czech Republic currently approximately 2.4 million USD in prices of 2003. Upon recalculation of the CZK/USD exchange rate from 2003 (an approximate value of 28 Kč [12] was used in the calculation) and involvement of the past inflation to 2003 in aggregate level of approximately 50 % [13], the orientation recalculation of buckle derailments and track buckle repair results in approximately 100 million CZK annually. The authors do not have necessary data for a more precise cost estimation.

7.2.5 It can be derived out of the estimation presented in the preceding paragraphs that a potential decrease by 10 % in average annual costs of buckle derailments and track buckle repair in the Czech Republic shall lead to financial savings of 10 million CZK. This would significantly overweight the investment and measurement costs. Moreover, it needs to be noted that the application of this methodology is not bound to the area of the Czech Republic and upon involvement of foreign railway networks, the financial savings would significantly increase.

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9 Annexes

9.1 Complete List of Items for Installation and Measurements Used by the Authors

9.1.1 The authors used following devices and aids for installation of approximately 50 measuring set track units:

- strain gauges HBM K-CLY4-0060-1-350-4-005-Y (50 pcs + 30 pcs spare ones)
- covering foil with kneading compound HBM ABM75 (2 packages)
- cleaning agent with cleaning pads HBM RMS1 (2 l of agent and 200 pcs of pads)
- last for cleaning pads (can be made e. g. out of wide flat screwdriver)
- spare sanding belts of 9 mm width (10 pcs)
- wire brushes for drill (2 pcs)
- steel brush (1 pcs)
- sandcloth of grit size 180 (10 pcs)
- sandpaper of grit size 400 (6 pcs)
- rail neutral axis gauges (4 pcs, own production in 3D printer)
- thin permanent markers (4 pcs, oil markers can be applied)
- pencils (3 pcs)
- tape measure of 5 m length (2 pcs)
- steel ruler (2 pcs)
- penknife (1 pcs)
- power strips of 5 m length with five sockets (2 pcs)
- cable ties (200 pcs)
- cable tie holders (200 pcs)
- contact adhesive (5 pcs)
- polypropylene tubes HTEM DN 40 of 150 mm length (60 pcs)
- end caps to polypropylene tubes HTEM DN 40 (60 pcs)
- scissors (3 pcs)
- black (3 pcs) and red (3 pcs) electrical insulation tapes
- AA batteries (18 pcs)
- LED torch (1 pcs)
- basic tools (spanners, pliers, screwdrivers) and cloths
- marking spray paints (4 pcs)

continues from the previous page

- polyurethane foam cube of 5 cm length edge (60 pcs)
- spatulas (1 pcs)
- work gloves
- polyurethane lacquer HBM PU140 (3 pcs)
- strain gauge adhesive HBM Z70 (3 pcs)
- head torch (1 pcs)
- connecting cable D-Sub 15 pin male/RJ11 female (2 pcs, own production)
- pens (2 pcs)
- notebooks
- recording sheet for measurement results
- strain gauge installation plan
- data acquisition system power cable for connection to 12 V maintenance-free car battery (1 pcs)
- computer power cable for connection to 12 V maintenance-free car battery (1 pcs)
- data acquisition system HBM QuantumX MX840A
- computer with Catman Easy software
- reflective vests
- copy of K-03 certificate of work supervisor
- copy of monitoring contract agreed with the infrastructure manager
- entry to the railway area passes
- 12 V maintenance-free car batteries (2 pcs)
- surface thermometer Testo 905-T2
- belt grinders (3 pcs)
- drills (2 pcs)
- hot air gun
- 10 kg propane-butane cylinder (2 pcs)
- petrol generator
- 20 l petrol can
- 50 m extension cord on cylinder
- knee pads (6 pairs)
- protective tents (2 pcs)
- gas space heater

9.1.2 The authors used following devices and aids for measurements:

- connecting cable D-Sub 15 pin male/RJ11 female (2 pcs, own production)
- pens (2 pcs)
- notebooks
- recording sheet for measurement results
- strain gauge installation plan
- head torch (1 pcs)
- data acquisition system power cable for connection to 12 V maintenance-free car battery (1 pcs)
- computer power cable for connection to 12 V maintenance-free car battery (1 pcs)
- cable ties (200 pcs)
- cable tie holders (200 pcs)
- contact adhesive (5 pcs)
- data acquisition system HBM QuantumX MX840A
- computer with Catman Easy software
- AA batteries (18 pcs)
- digital radios (6 pcs)
- reflective vests
- entry to the railway area passes
- 12 V maintenance-free car batteries (2 pcs)
- surface thermometer Testo 905-T2
- dust pan and hand brush
- cloth
- gas burner
- gas cartridges for gas burner (2 pcs)
- red electrical insulation tape
- polyurethane foam cube of 5 cm length edge (3 pcs)

9.2 Example of Methodology Application – Bezpráví Locality

9.2.1 Bezpráví locality is a part of the I. and III. railway corridor line of the Czech Republic. It lies between Ústí nad Orlicí and Brandýs nad Orlicí station. The monitored section is in the 1st track in km 260.8 to 261.4. 16 measuring spots are located in the section, always four in four stationings in spacing of 160 m. The total length of the monitored section is 480 m. The Bezpráví locality strain gauge installation scheme is a separate annex of this methodology. Measuring set track units were installed into the monitored section on the 31st August 2021, stress-controlled rail welding was made on the 1st September 2021.

9.2.2 The right-hand side rail was welded in km 261.233 on the 1st September around noon. Before the welding, the rail from the direction of Ústí nad Orlicí was pulled by 14 mm and the rail from the direction of Brandýs nad Orlicí by 7 mm. The rail anchorage section in the direction of Brandýs nad Orlicí started after the measuring spot in the fourth stationing with the measuring set track unit installed (km 261.328). 95 meters of rail was prolonged by 7 mm. Rollers under the rail foot were used by this rail pulling. The average relative prolongation is 74 μm/m on average. Measurement after the rail release and placing of rollers under the rail foot, and after the required prolongation and fastening was made in the profile of the fourth stationing (km 112.010). Measured values are summarized in the Tables 6 and 7.

Table 6 – Record of Measured Data from Bezpráví Locality before Rail Pulling.

Monitored Section: Bezpráví			**Date: 01 September 2021**
Measuring Spot	**Time [hh.mm]**	**Rail Temperature [°C]**	**Strain [μm/m]**
D.IV.3	10.26	19.9	1699
D.IV.4	10.27	19.5	1776

Table 7 – Record of Measured Data from Bezpráví Locality after Rail Pulling.

Monitored Section: Bezpráví				**Date: 01 September 2021**
Measuring Spot	**Time [hh.mm]**	**Rail Temperature [°C]**	**Strain [μm/m]**	**Relative Strain [μm/m]**
D.IV.3	11.44	21.6	1764	65
D.IV.4	11.45	21.6	1856	80

9.2.3 Upon comparison of the values from the Tables 6 and 7, it can be seen that the average prolongation of the rail by pulling is 73 μm/m in the monitored section. This corresponds the expected value (the difference in the order of magnitude of single digits of μm/m corresponds the noise of the measurement) very precisely. The measured data show that the prolongation of the 95 m long rail (not counting the anchorage block) placed on rollers under the rail foot by 7 mm was very uniform. It needs to be added that more measuring spots would increase the level of certainty of this conclusion. However, this was not possible due to the limited number of research team members and restricted time allocated for installation.

9.2.4 The complete record of measured values after stress-controlled rail welding in the Bezpráví locality is presented in the Table 8.

Table 8 – Record of Measured Data from Bezpráví Locality after Stress-Controlled Rail Welding.

Monitored Section: Bezpráví			**Date: 01 September 2021**
Measuring Spot	**Time [hh.mm]**	**Rail Temperature [°C]**	**Strain [μm/m]**
D.I.1	13.47	30.3	1546
D.I.2	13.48	31.2	1511
D.I.3	13.50	31.0	1198
D.I.4	13.51	31.2	1677
D.II.1	13.57	28.5	2103
D.II.2	13.58	28.2	2030
D.II.3	13.59	28.4	2024
D.II.4	14.00	28.0	2183
D.III.1	11.50	19.1	1621
D.III.2	11.51	19.8	1301
D.III.3	11.52	19.8	1576
D.III.4	11.53	19.9	1293
D.IV.1	11.41	22.3	1503
D.IV.2	11.42	21.5	1694
D.IV.3	11.44	21.6	1764
D.IV.4	11.45	21.6	1856

9.2.5 Figure 10 shows strain development in measuring spots daily and monthly, after stress-controlled rail welding. Values presented in both graphs are related to the measurement after rail welding, i. e. to the values from the Table 8.

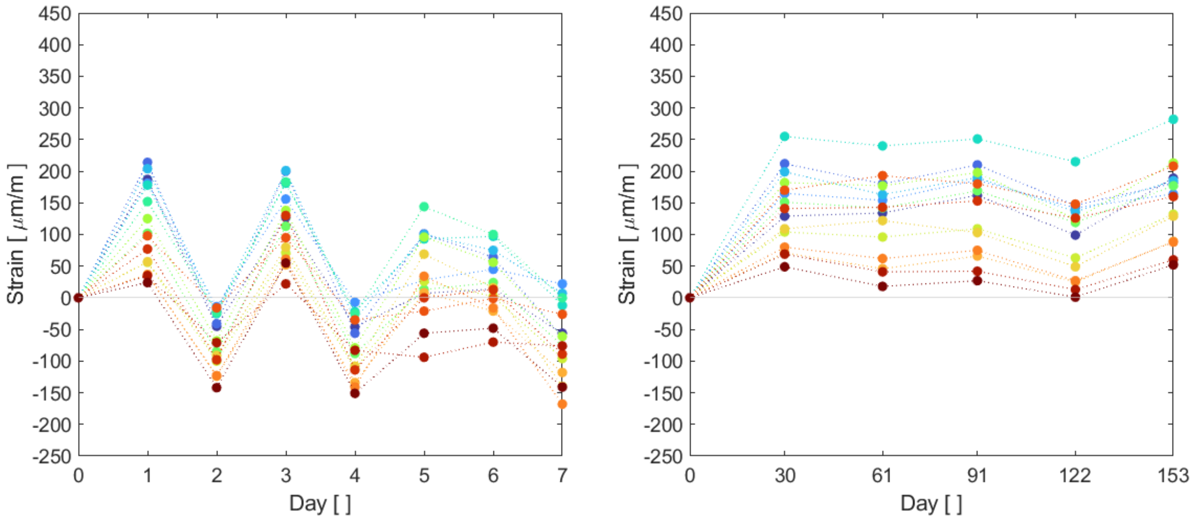


Figure 10 – Development of Measured Deformation Values by Measuring Spots in Bezpráví Locality over the First Days and Months after the Stress-Controlled Rail Welding.

9.2.6 Comparison of the graphs shows that significant changes of deformation values occur shortly after the stress-controlled rail welding. The tonnes carried, which are significant in the monitored section, stabilise the recorded strain afterwards, corresponding to the phases presented in the Figure 6. The prolongation of the rails after the stress-controlled rail welding is apparent in all the measuring points what corresponds to an increase of neutral temperature in this locality. As an example, values measured in the profile of the third stationing in km 261.168 from the 1st February 2022, i. e. five months after the stress-controlled rail welding, can be shown. These values are presented in the Table 9.

Table 9 – Record of Measured Data from km 261.168 of the Bezpráví Locality on the 1st February 2022.

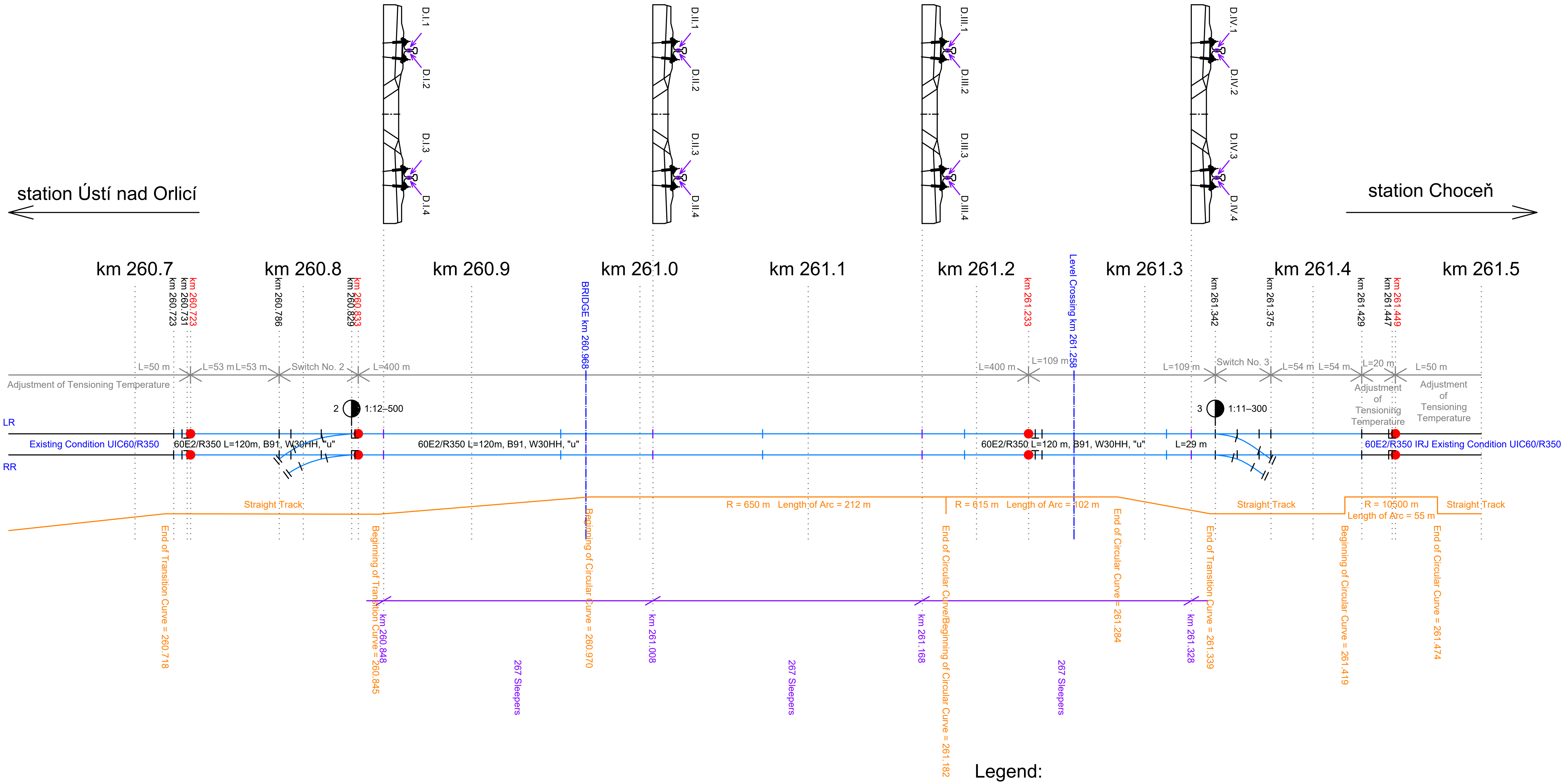
Monitored Section: Bezpráví				**Date: 01 February 2022**
Measuring Spot	**Time [hh.mm]**	**Rail Temperature [°C]**	**Strain [μm/m]**	**Relative Strain [μm/m]**
D.III.1	12.13	3.4	1753	132
D.III.2	12.14	3.5	1430	129
D.III.3	12.14	4.0	1665	89
D.III.4	12.15	4.0	1381	88

9.2.7 The average value of relative strain in comparison to the state after the stress-controlled rail welding in the km 261.168 stationing five months after the welding is 131 μm/m in the left-hand side rail and 89 μm/m in the right-hand side rail, as it is visible from the Table 9. Based on the Formula 6, it corresponds to the neutral temperature increase by approximately 11, or 7,5 °C respectively, from the tensioning temperature. The instant value of axial stress in the inspected stationing in the left-hand side rail is approximately 76,5 MPa and in the right-hand side rail 66,5 MPa, according to the Formula 7.

9.3 Other Annexes

Other annexes to this methodology comprise

- Scheme of Strain Gauge Installation in Bezpráví Locality and
- Documentation of the Functional Sample TJ04000301-V2 *Measuring Set for Diagnostics of Time-Based Development of Stress States in Continuous Welded Rail*, which is an outcome of research performed within the scope of investigation of the TACR TJ04000301 project *Non-Destructive Determination of Mechanical Stress in Continuous Welded Rail.*



Legend:

sleeper spacing „u"

- stress-controlled rail weld
- stress-free rail weld
- strain gauge positioning (from both sides of the rail web)

Workplace	Designed by	Document Type	Document State	Format
FTE-ERCT/DTS	Petr Vnenk	Strain Gauge Installation Scheme	Released	A3
UNIVERSITY OF PARDUBICE FACULTY OF TRANSPORT ENGINEERING	Made by: Petr Vnenk	Name, Additional Name: Strain Gauge Installation State, Bezprávi Locality, TJ04000301, WP1	Document No.: 2	Scale: -
	Controlled by		Version: 2; Release Date: 14 Jul 2022	Lang.: en; Sheet: 1/1

Measuring set for diagnostics of time-based development of stress states in continuous welded rail

Functioning sample

UNIVERSITY OF PARDUBICE
FACULTY OF TRANSPORT ENGINEERING

Functioning sample identification

Name: Measuring set for diagnostics of time-based development of stress states in continuous welded rail
Identification code: TJ04000301-V2
Project No.: TJ04000301
Authors: Petr Vnenk, Özgür Yurdakul, Ph.D., Jiří Šlapák, Vladimír Suchánek, Ph.D., Assoc. Prof. Bohumil Culek, Ph.D., Assoc. Prof. Ladislav Řoutil, Ph.D., Ondřej Sadílek, Ph.D., Filip Klejch, Zdeněk Sháněl, Karel Suchý, Tadeáš Šustr, Miloš Šula
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Technical specifications

The measuring set was developed within the investigation of the project No. TJ04000301 Non-destructive determination of mechanical stress in continuous welded rail supported by a grant from the ZETA programme of the Technological Agency of the Czech Republic.

The measuring set is composed out of a track and a mobile part. The track part contains a K-CLY4-0060-1-350-4-050-Y strain gauge type produced by HBM, polypropylene tube of length of 150 mm and outer diameter of 40 mm, and a polyurethane foam cube of an edge length of 50 mm. The strain gauge is connected to the investigated rail at its neutral axis with the main axis of the strain gauge being parallel to the neutral axis of the rail. Corresponding area of the rail surface must be cleaned from rust and unevennesses and degreased. Strain gauge is attached by 1-Z70 fast-acting superglue and, after drying, painted over by 1-PU140 polyurethane lacquer, both produced by HBM. After the covering material is dry, the strain gauge is covered by 1-ABM75 aluminium foil coated with kneadable putty produced by HBM, too. The polypropylene tube is attached to the lower part of the rail web by a pair of cable ties and cable ties holders and Chemopren Extreme glue. Strain gauge conductors with RJ male connector are placed into the polypropylene tube closed from one end, while the other end of the tube is plugged by the polyurethane foam cube. Mobile part contains an MX840A data acquisition system and a SCM-SG350 quarter bridge adaptor produced by HBM, a connecting cable and an RJ11 female connector produced by ENCITECH. Mechanical deformation is measured directly by the MX840A data acquisition system.

The track part of the measuring set is currently installed in 44 spots in the Hostinné – Pilníkov railway line section and in 16 spots in the Ústí nad Orlicí – Brandýs nad Orlicí railway line section. Former development stages of the track part of the measuring set were installed in the Mostek – Horka u Staré Paky and Brno-Horní Heršpice – Střelice railway line sections. One specimen of the measuring set is permanently placed in the area of the Educational and Research Centre in Transport, Faculty of Transport Engineering, in Doubravice.

Economical parameters

Economical asset of the measuring set resides in the ability of continuous and discrete logging of the value of longitudinal deformation of rail, which enables prediction of continuous welded rail failures – rail breaks and track bucklings. Timely prediction of such failures can lead to a modification of operational loading of rail and minimize economical loss.

Description

The measuring set is in use at regular measurements of longitudinal deformations of continuous welded rail in operated railway lines. Its asset is a very precise determination of rail deformation in the location of track part installation. This accuracy ranges up to μm·m^{-1}. Further assets are the lifetime of at least 1 year and no limitations for the use of track maintenance technology, except for ballast profiling and distributing machines. It is necessary to lift the brushes of the ballast profiling and distributing machine in order to save the track part of the measuring set while riding over the spot of installation.

Figures

Figure 1: Track part of the measuring set.

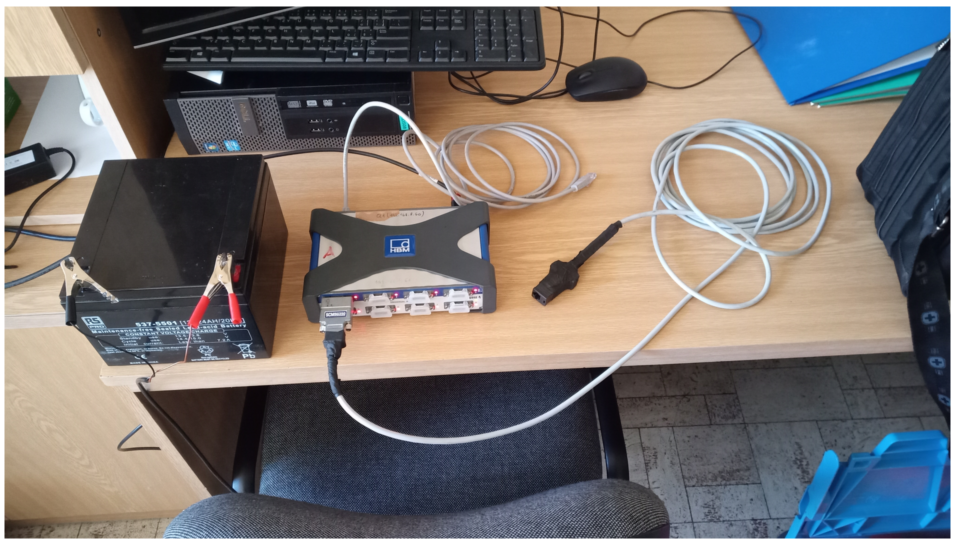

Figure 2: Mobile part of the measuring set.

Figure 3: Strain gauge attachment by 1-70 fast-acting superglue.

Figure 4: Connection of track and mobile part of the measuring set during measurement.