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COMPREHENSIVE VERIFICATION OF THE BEHAVIOR OF THE CONTINUOUS WELDED RAIL ON THE BRIDGE

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Abstract. The aim of this paper is to verify the real behavior of the continuous welded rail on the bridge with a longer expansion length than allowed by Czech national regulations. Special attention is focused on the rate of interaction of the continuous welded rail and the bridge, which decisively affects the stress state in the continuous welded rail when the temperature changes. In order to improve the result and increase the accuracy of observation, two measuring methods (geodetic and strain gauge) were chosen while recording the temperature conditions of individual components of the system were simultaneously recorded.

Keywords: Continuous welded rail, longitudinal resistance, thermal expansivity.

1. Introduction

When designing new bridge structures with a continuous welded rail, it is very appropriate to avoid a solution with expansion devices (or rail joints) in the track for several reasons. This is primarily a benefit of passenger comfort in the case of exclusion crossing of these problem areas, a significant reduction of dynamic effects in transition zone and reduction of maintenance costs. Especially when replacing the permanent way on current bridge structures and in adjacent sections of a track is also the need to take into account the financial benefit of establishing a continuous welded rail in comparision with the variant with expansion devices whose acquisition costs are severalfold higher than the costs of a solution with an uninterrupted running edge of the rails. On the other hand the elimination of expansion devices in the bridge zone involve increasing of stress in terms of the combined response of the structure and track dealing with the issue in the design. From the designer's point of view, however, the current standard provisions may appear as insufficient, especially with regard to the variability of the permanent way system and bridge structures and it happens that certainty is taken into account compromise precautions in the calculations. In aspect of infrastructure serviceability of the continuous welded rail is considered the most important the spacial track stability. Its uses on bridges has drawback, therefore it is necessary to take into account especially the span of bridge structures and loads that affect the interacting system.

This work solves especially the first part of the problem, which is continuous welded rail and its role in the interaction system with a bridge. It focused particularly on the range of its dependence on a bridge structure movements and phenomena that occur when the state of the whole system changes. The design of the bridge structure and its characteristics deals only marginally, but tries to describe its behavior in detail, especially when temperature conditions changes.

A number of research projects focus on determining the combined response of the bridge structure and continuous welded rail from individual types of additional stresses in the rails, which are:

- stress from thermal changes in rails,
- stress from thermal changes in bridge structure,
- stress from traction and braking forces,
- stress from classified vertical traffic loads.

2. Methodology

2.1. Basic assumptions for a theoretical model of a CWR and bridge

When calculating the force effects in a track that is only affected by a load from a temperature changes, is based on knowledge of Hooke's law and physical law of thermal expansion material, see equation 1.

$$N_{\mathrm{x}} = EA(\frac{\mathrm{d}u}{\mathrm{d}x} - \alpha\Delta t) \qquad (1)$$

The system of horizontal springs simplifies the problem of the rigidity of the connection between bridge and rails (see Figure 1).

The system is divided into individual beams, for which the basic differential equation were defined. The beginnings of the coordinate systems are always on the left sides of the beams, except beam No. 1, which starts on the right side to maintain continuity computational model. Differential equations for beams marked with numbers 1, 2, 3, 4 in Figure 1 can be written as:

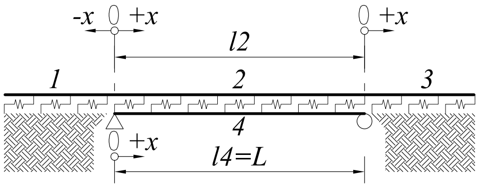

FIGURE 1. A simple girder with a fixed bearing on one side of the bridge.

$$\begin{aligned} -E_\mathrm{i}A_\mathrm{i}u_\mathrm{i}^{''} + k_\mathrm{i}u_\mathrm{i} &= 0, \quad i = 1,3, \\ -E_2A_2u_2^{''} + k_2(u_2 - u_4) &= 0, \\ -E_4A_4u_4^{''} + k_4(u_4 - u_2) &= 0. \end{aligned} \tag{2}$$

and forces in beams are calculated according to equation 1 as:

$$N_\mathrm{x} = E_\mathrm{i}A_\mathrm{i}(u_\mathrm{i}^{'} - \alpha\Delta t). \tag{3}$$

If we want to solve a system of differential equations, it is necessary to determine the boundary conditions. These are compiled based on knowledge of the behavior of the real system, where with growing distance from the ends of the bridge, the influence of the continuous welded rail by the bridge structure decreases. That is, the displacements at a sufficient distance from the bridge are zero and also the displacements and the stresses at the junction of the two beams are the same.

Then the general solution of the system of differential equations 2 can be written as:

$$\begin{aligned} u_\mathrm{i}(x) &= B_\mathrm{i}\mathrm{e}^{\lambda_\mathrm{i}x} + C_\mathrm{i}\mathrm{e}^{-\lambda_\mathrm{i}x}, \quad i = 1,3, \\ u_2(x) &= B_2\mathrm{e}^{\lambda_2x} + C_2\mathrm{e}^{-\lambda_2x} + \alpha_4\Delta t_4x. \end{aligned} \tag{4}$$

The exponential term λ takes into account the nonlinear dependence of the longitudinal resistance on the mutual displacement of the track owing to the bridge structure and is calculated according to the following relation:

$$\lambda_\mathrm{i}^2 = \frac{k_\mathrm{i}}{u_0E_\mathrm{i}A_\mathrm{i}} \tag{5}$$

A graphical representation of this nonlinear phenomenon can be seen in the Figure 2.

UIC Code 774-3[1] specifies the value of the displacement u_0 at the interface of the longitudinal linear and shear resistance and provides at least a basic overview of when approximately occurs shear behavior between the bridge and the continuous welded rail (CWR) when loaded by external forces:

- Ballasted-deck bridges:

  Displacement at the interface of longitudinal linear and shear resistance:

  $u_0 = 0,5$ mm for the resistance of the rail to sliding relative to the sleeper (frozen ballast),

  $u_0 = 2$ mm for the resistance of the sleeper in the ballast.

  Current values of the resistance in the plastic zone:

  $k = 12\ \mathrm{kN.m^{-1}}$ resistance of sleeper in ballast (unloaded track), moderate maintenance,

  $k = 20\ \mathrm{kN.m^{-1}}$ resistance of sleeper in ballast (unloaded track), good maintenance,

  $k = 60\ \mathrm{kN.m^{-1}}$ resistance of loaded track or track with frozen ballast.

- Unballasted bridges:

  Displacement at the interface of longitudinal linear and shear resistance:

  $u_0 = 0,5$ mm for the resistance of the rail due to the upper surface of the structure.

  Current values of the resistance in the plastic zone:

  $k = 40\ \mathrm{kN.m^{-1}}$ resistance of the rail due to the upper surface of the structure (unloaded track),

  $k = 60\ \mathrm{kN.m^{-1}}$ resistance of the rail due to the upper surface of the structure (loaded track).

In laboratory conditions, a number of research projects have demonstrated the validity of the scope values track resistance on bridge structures. But as other authors prove on experimental measurements directly on bridges, these recommendations may not always be generally valid and each new combination of parameters affecting the interaction CWR and the bridge can be determined by direct measurements that the degree of interaction can deviate from the submitted standards. Therefore, even this work tries to set values that will capture the bahavior of a particular interacting track and bridge system by experimental research.

3. EXPERIMENTAL MEASUREMENTS

3.1. BRIDGE AND CWR PARAMETERS

Bridge

Due to the fact that these are three independent structures whose central longitudinal joints are covered with a metal plate always welded to only one of them, so that they can move independently, only the monitored construction NK1 with the following parameters that are important to describe the behavior of the whole system will be presented below:

• Marking:	NK1,
• Description:	plate steel girder,
• Type:	continuous with 5 fields,
• Lenght:	80,3 m,
• Width:	9,5 m,

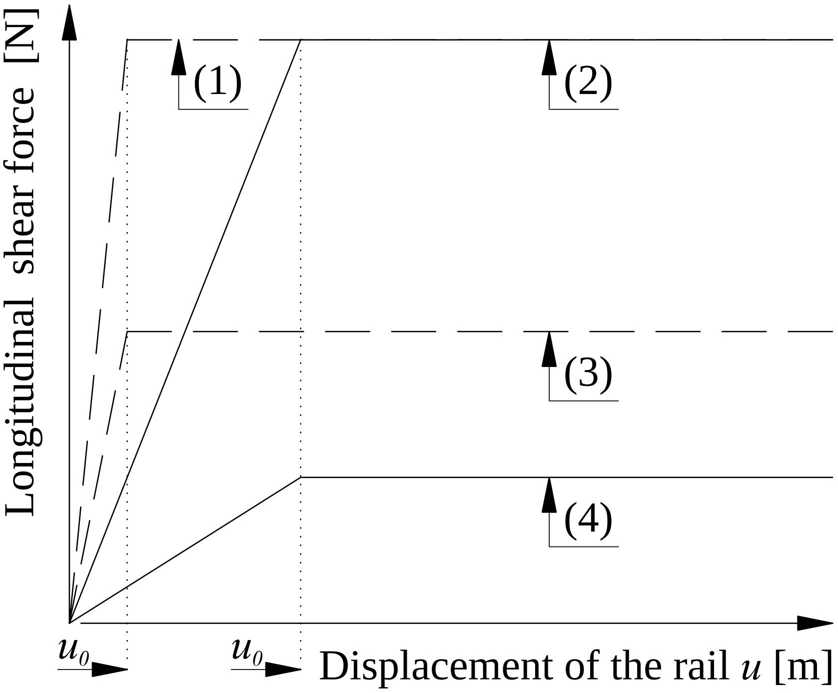

FIGURE 2. Variation of longitudinal shear force with longitudinal track displacenlellt for one track. (1) Resistance of the rail in sleeper (loaded track without ballast); (2)Resistance of sleeper in ballast (loaded track); (3) Resistance of the rail in sleeper (unloaded track without ballast); (4) Resistance of sleeper in ba11ast (unloaded track).

Span:	79,6 m,
Lenght:	80,3 m,
Number of tracks:	2.

Continuous Welded Rail

There are three different tracks on the bridge, of which two are double-track and one single track (see Figure 3). CWR is set up in all tracks on the bridge. The length of the supporting structure was adjusted to meet the requirements of regulation [2] for UIC 60 rails. However, it is located on the NK1 structure track with rails 49 E1 without any special modifications to the railway superstructure. Permanent way in this track is in the following composition in the entire length of the bridge and in the adjoining sections:

Rails:	49 E1,
Concrete sleepers:	B 91S/2,
Elastic rail fasteners:	W 14,
Sleepers spacing:	600 mm,
Deep trackbed.	

3.2. PHASES OF MEASUREMENT

The whole experiment was divided into two phases, which took place independently of each other:

- PHASE I: Geodetic measurements of the position of the bridge structure and continuous welded rail based on geodetic monitoring of bridge structure displacement and continuous welded rail depending on temperature changes.
- PHASE II: Tensometric measurements of the stress state of the continuous welded rail based on monitoring the stress state of continuous welded rail by strain gauges depending on temperature changes.

3.3. PHASE I: GEODETIC MEASUREMENTS OF THE POSITION OF THE BRIDGE STRUCTURE AND CONTINUOUS WELDED RAIL

The method of geodetic monitoring with simultaneous measurement of air, rail and bridge temperature was chosen to monitoring the movement of the bridge structure and the continuous welded rail.

The following was monitored on the bridge structure in Phase I:

- displacement of rail strings depending on rail temperature,
- displacement of the bridge load-bearing structure NK1 depending on its temperature.

The first step was to select the location of the measuring points, marked on both rail strings a total of 20 measuring profiles (20 points on the left and right rail string, numbered 1 to 20 against the direction of stationing). For monitoring displacements of the bridge structure 8 points were fitted (marked M1 to M8 - points M1 and M8 were located on abutments, other points on the bridge deck in bridge piers areas).

Figure 3. View of the track on the bridge in the direction from fixed bearing.

For monitoring the expansion behavior of the bridge structure and the permanent way depending on the temperature changes were marked observed points in selected cross-section profiles of rail strings whose positional changes in the direction of the track axis were measured in stages, together with the monitoring of other factors (especially the temperature of the rails and the bridge structure). Their stabilization was accomplished a mild hole ϕ 1 mm punched out on the outer unmoved edge of the rail heads. These points were numbered and marked in color on the rail web. Applies to both rail strings.

3.4. PHASE II: TENSOMETRIC MEASUREMENTS OF THE STRESS STATE OF THE CONTINUOUS WELDED RAIL

The aim of Phase II was to supply the geodetic monitoring of bridge and track displacements with knowledge in terms of the stress state of the continuous welded rail. During seven continuous measuring cycles, when one cycle always lasted for 3-4 days, data were collected from the installed resistance strain gauges and temperature sensors. Recording period of continuously measured quantities was 1 second.

In Phase II, data were collected from installed resistance strain gauges and temperature sensors about:

- relative deformation of rail strings depending on temperature change,
- temperature of the bridge structure and continuous welded rail.

From the data obtained from the individual phases, it was necessary to approximate the set of measured data by the given equation so that the approximation function was best matched to the measured data. Using force of the Matlab program, the parametric space was searched, discretized and seeks the optimum of the function on it. It was necessary to determine the size of the error that occurred during approximation. This was done by calculating the residue, whose sum was minimized to estimate the parameter of the regression function.

The residue calculation was used:

$$e_{\mathrm{i}} = Y_{\mathrm{i}} - \hat{Y}_{\mathrm{i}} \tag{6}$$

and to estimate the regression function parameter by minimizing the residual sum using the following relationship:

$$S_{\mathrm{e}}^2 = \sum_{\mathrm{i}=1}^{\mathrm{n}} (Y_{\mathrm{i}} - \hat{Y}_{\mathrm{i}})^2 \tag{7}$$

where

Y_i are particular displacement values determined by measurement,

$\hat{Y}_i$ are the displacement values obtained when searching for the minimum of the function on the parametric space of an unknown quantity.

4. RESULTS AND DISSCUSION

4.1. DETERMINATION OF THE EQUIVALENT COEFFICIENT OF THERMAL EXPANSION OF THE BRIDGE CONSTRUCTION

As no data were known on the stiffness of the substructure, friction in moving bearings, nor other possible effects that could also affect the longitudinal expansion bridge structure, therefore the whole phenomenon was expressed by an equivalent factor thermal expansion α_{m} (similar to [3]), which will be determined on the basis of data recorded in Phase I.

All data (longitudinal displacements) obtained by experimental measurements during nine stages (E0 - E8) were used to approximate the finding coefficient solution α_{m}. The data were interpolated with a previously known approximation function:

$$u_{\mathrm{m}} = l_{\mathrm{m}} \alpha_{\mathrm{m}} \Delta T_{\mathrm{m}} \tag{8}$$

The graph of this function is a straight line. To solve this linear approximation mathematical-statistical least squares method (LSM) was chosen.

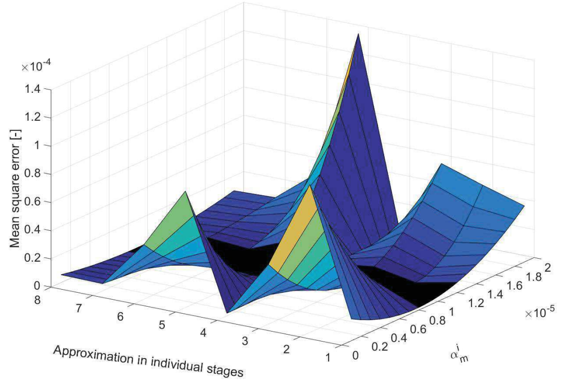

FIGURE 4. Residual sums of control functions with variable $\alpha_{\mathrm{m}}^{\mathrm{i}}$ on the searched parametric space.

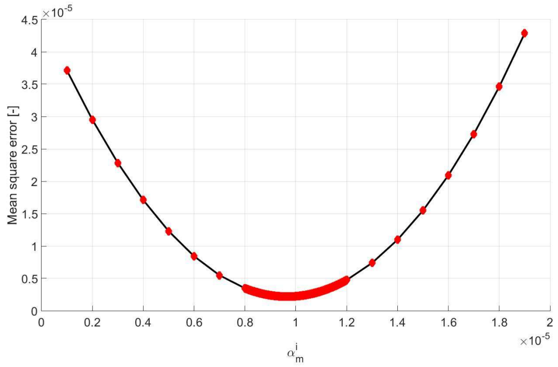

FIGURE 5. The resulting value of α_{m} as a minimum of control functions.

In general, it was a matter of approximating the set of measured data by the given equation so that the function matched the measured data as best as possible (see Figure 4).

The resulting value of α_{m} is shown on the Figure 5 as the average of the mean square errors of the functions of the individual stages over all iterated $\alpha_{\mathrm{m}}^{\mathrm{i}}$.

The resulting coefficient of thermal longitudinal expansion of the bridge structure, based on geodetic measurements and mathematical linear approximations using least square method, was determined by the value:

$$\boldsymbol{\alpha_{\mathrm{m}} = 9,66 \cdot 10^{-6}}\,\mathrm{K}^{-1}$$

.

Looking into recent experimental research (for example experimental measurements on the Znojmo viaduct or on the bridge in Kolín) it can be stated that for these three steel structures with a rail bed the bridge structures are comparable and very similar in terms of the determined equivalent coefficient of thermal expansion of the bridge structure (Znojmo – $\alpha_m = 9,7 \cdot 10^{-6}\,\mathrm{K}^{-1}$, Kolín – $\alpha_m = 8,5\ a\ 8,9 \cdot 10^{-6}\,\mathrm{K}^{-1}$).

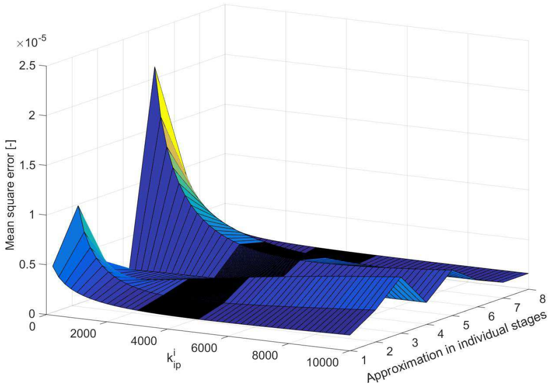

FIGURE 6. Residual sums of control functions with variable $k_{\mathrm{ip}}^{\mathrm{i}}$ on the searched parametric space.

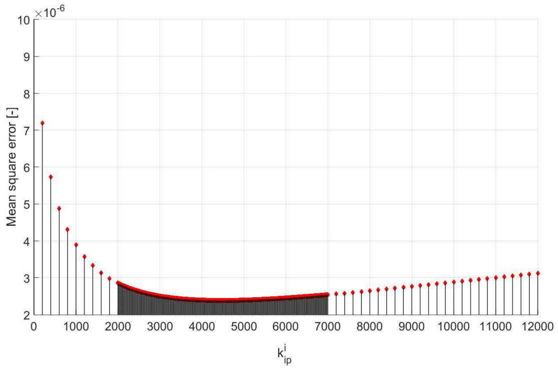

FIGURE 7. The resulting k_{ip} value from Phase I as a minimum of control functions.

4.2. DETERMINATION OF THE LONGITUDINAL RESISTANCE OF THE TRACK ON THE BRIDGE

Based on the principles described in Chapter 2.1, approximation was performed on experimental data. In this case, it is a general linear regression using general polynomials defined by differential Equations 4. For solutions In this case, too, the LSM was chosen, which helped with sufficient accuracy determine the finding values. In accordance with the requirements [4] the influence of the longitudinal shear resistance $k_{\mathrm{p}}^{\mathrm{i}}$ according to the Figure 2 was taken into account.

The approximation was further carried out by the above Equations 6 and 7, it means that after the search of the parametric space, the resulting optimized function reached the lowest residual sum. The area where the minimum mean square error of the control equations was expected is shown by a black bar in Figure 6.

The resulting value of longitudinal shear resistance of the track k_{ip} is shown in Figure 7 as the average of the mean square errors of the functions of individual stages over all iterated $k_{\mathrm{ip}}^{\mathrm{i}}$.

The resulting longitudinal resistance of the track

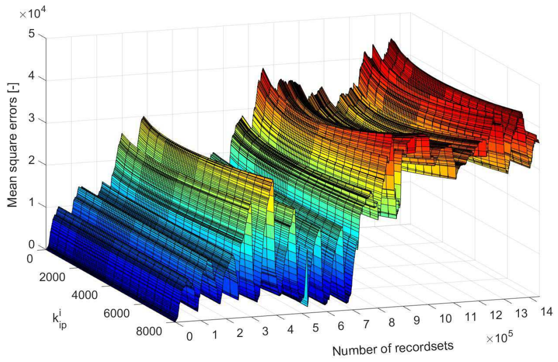

Figure 8. Residual sums of control functions with variable $k^{\mathrm{i}}_{\mathrm{ip}}$ across all recordsets.

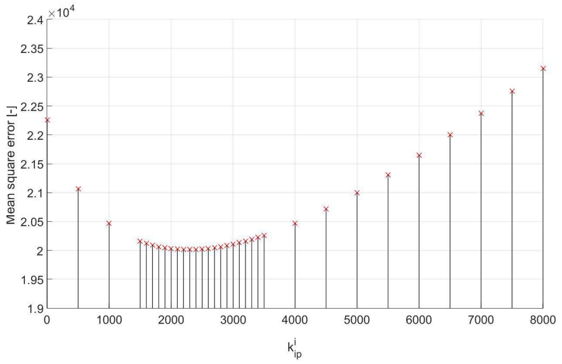

Figure 9. The resulting value of $k^{\mathrm{i}}_{\mathrm{ip}}$ from Phase II as a minimum of control functions.

on the bridge without loading by rail traffic, based on geodetic measurements of the position of the rail strings and mathematical general linear approximation using least square method, was determined by the value:

$$\boldsymbol{k}_{\mathbf{i}} = \mathbf{4,5 \cdot 10^3}\,\mathrm{N.m^{-1}}$$

.

4.3. Longitudinal resistance CWR on the bridge according to tensometric measurements

This chapter will verify the conclusions from Chapter 4.2, where the value of the longitudinal resistance CWR was determined on the bridge. The following evaluation was performed on the based of strain gauges measurement of relative deformation of rail string and measurement temperature of the bridge construction and track.

A total of $1,442,033$ values were recorded in 7 measurement cycles from each strain gauge and the same number of temperature sensors. The number of values corresponds to total measurement length in seconds.

For a purpose the same method for the evaluation was applied to as a reliable comparison of the results data from geodetic measurements, it means by minimizing the residual sum of deviations measured and approximated by LSM with the validity of Equations 6 and 7. The course of residual sums of control functions with the variable $k^{\mathrm{i}}_{\mathrm{ip}}$ across all recordsets are seen in the Figure 8.

The approximation functions are the equations of the individual axial forces. Parametric space in which the solution of the longitudinal shear resistance value was searched, was limited as follows:

- $n\langle 1; 1442025\rangle$ is the number of records,
- $k^{\mathrm{i}}_{\mathrm{ip}}\langle 1; 10000\rangle$ is the range of the vector of the searched longitudinal shear resistance of the track,
- $i\langle 1; 14\rangle$ is the number of monitored strain gauges.

In this space, based on tensometric measurements of the relative deformation of the left rail string and temperature measurements of the bridge structure and the track, it was found out that there was a good agreement with the results obtained by geodetic measurements. The right rail string is assumed to behave symmetrically in terms of tension. Therefore with a degree of simplification, based on the assumption of symmetry, is the resulting value double of the longitudinal shear resistance found out on the left rail string. By tensometric measurement of the left rail string and mathematical general linear approximation using LSM, was found out the value of longitudinal shear resistance of the track on the bridge without load by rail traffic of the size:

$$\boldsymbol{k}_{\mathbf{i}} = \mathbf{4,6 \cdot 10^3}\,\mathrm{N.m^{-1}}$$

.

5. Conclusions

It is apparent that the resulting values from both phases are in area of very low values of longitudinal shear resistance of the track. In other words, the tension in the rails due to thermal expansion of bridge structure is much less affected than might be expected. This is evident by the fact that the track on the bridge, with an expansion length of more than 20 m longer than permitted by national regulation [2] in the relevant Part XII, does not show, more than ten years of operation, anomalies in the behavior of continuous welded rail and there are no defects on permanent way of a greater extent than anywhere else on the line.

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