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RESEARCH ARTICLE

Solutions of Omitting Rail Expansion Joints in Case of Steel Railway Bridges with Wooden Sleepers

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Abstract

The Technical Specifications of D.12/H. of Hungarian State Railways (MÁV) specifies that a continuously welded rail (CWR) track can be constructed through a bridge without being interrupted if the expansion length of the bridge is not longer than 40 m. If the expansion length of a bridge is greater than 40 m, the continuously welded rail should normally be interrupted; a rail expansion joint has to be constructed. The goal of this research is to provide technical solutions of track structures on bridges so a continuously welded rail can be constructed through the bridge from an earthwork without interruption, so rail expansion joints can be omitted.

Keywords

rail expansion joint · heat expansion · rail · steel bridge · wooden sleepers · rail restraint

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1 Introduction

A finite-element (FEM) model has been developed to determine the normal, axial forces in the rail, bridge structure and the bearing in case of a two-span-bridge with an expansion length of 40 m, where forces occur from the change of rail temperature and braking and acceleration of trains. Following this, the model has been converted into bridges with 70 m and 100 m expansion lengths with the purpose to find technical solutions, with their application the resultant normal forces in the rail, bridge and the bearing do not exceed — or exceed to a lesser extent — those values resulting in bridges with expansion length of 40 m. By the application of these solutions, the CWR track can be constructed through the bridge without interruption, rail expansion joints can be omitted.

Only the joining of CWR tracks from earthworks to steel bridges with wooden sleepers are discussed in this research.

There are technical solutions in bridges where the continuously welded rail is constructed through a bridge without interruption, and longitudinal beams of the bridge can move independently from the rails, within certain boundaries. These solutions are not part of this article.

2 Laboratory testings of longitudinal rail restraint of rail fastenings

Test series have been carried out in the Laboratory of the Department of Highway and Railway Engineering, Budapest University of Technology and Economics, in order to determine the longitudinal stiffness and the longitudinal rail restraint of different rail fastenings to model the interaction of the rail and bridges precisely.

The tests were carried out according to standard EN 13146-1:2012 [3]. The test arrangement is shown in Figs. 1 - 2. The concrete sleeper, the rail and the fastening assembly were fixed to a horizontal base. A tensile load at a constant rate of 10 kN/min was applied to one end of the rail, while the load and the displacement were measured. When the rail slipped in the fastening, the load was reduced to zero rapidly and the rail displacement was measured for two minutes. Without removing or adjusting the fastening, the cycle was repeated further three times with three minute intervals in the unloaded condition between each cycle.

The rail displacement was measured with inductive transducer of type Hottinger Baldwin Messtechnik (HBM) WA 20 mm, and the load was measured with force transducer of type HBM C9B 50 kN. The data acquisition unit and measuring amplifier was HBM Quantum MX 840, evaluation software was Catman AP. The sampling rate frequency was 10 Hz.

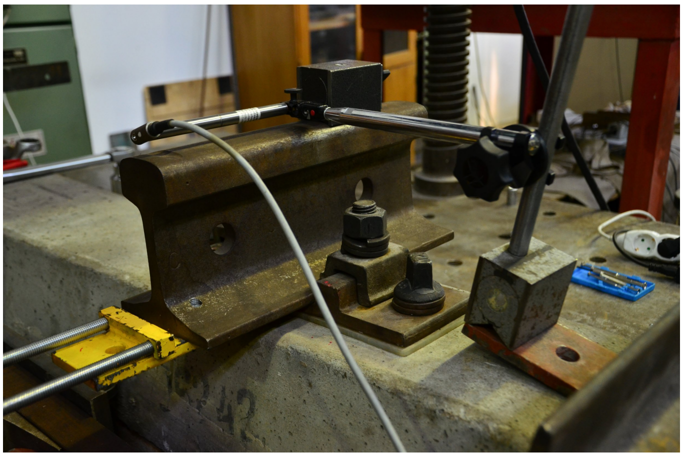

Fig. 1. Longitudinal rail restraint test (1)

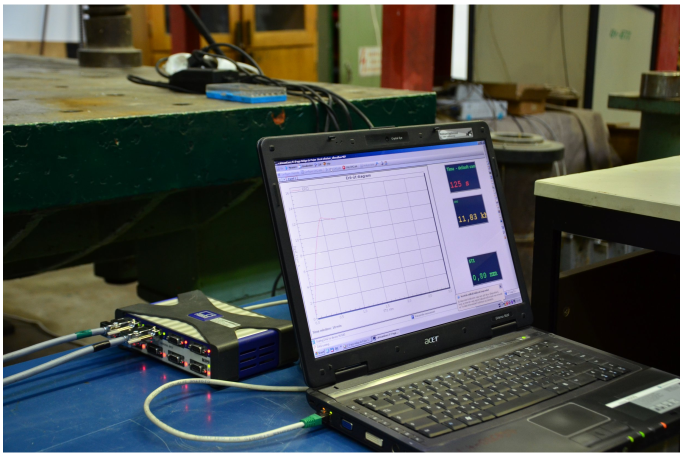

Fig. 2. Longitudinal rail restraint test (2)

The maximum load to produce an initial elastic displacement was determined in each cycle. The value of the first cycle was discarded. The average of the second, third and fourth cycles was calculated and considered to be the longitudinal rail restraint. The fastening assembly is unable to take on higher forces, the rail will slip in the fastening longitudinally.

The longitudinal stiffness of the fastening is defined as ratio of the force producing the initial elastic displacement and the elastic displacement.

The load – displacement diagram measured on the *K* (Geo) fastening with Fe6 washer tensioned with a torque of 250 mm is illustrated in Fig. 3 as an example. In this case there was no railpad under the railfoot. The longitudinal rail restraint is obtained to be 20,52 kN, and the longitudinal stiffness has been found to be 40000 N/mm.

The tests were carried out on *K* (Geo) fastening, and on Vossloh KS (Skl-12) and W14 fastenings. The results are summarized in Table 1.

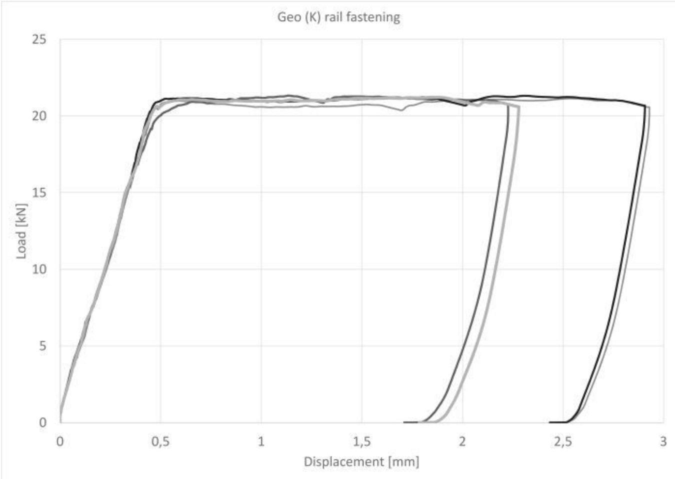

Fig. 3. Load – displacement diagram of *K* (GEO) fastening with Fe6 washer

3 Structure of the FEM model

The finite-element software of AxisVM 12 was used for model. Two different types of beams are possible to be defined in the software. One of them is the Euler-Bernoulli beam that assumes the cross-sections are perpendicular to the longitudinal axis of the loaded beam. The other one is the Timoshenko beam that takes into effect the shear deformations, therefore resulting in a softer structure. Our model comprises two dimensional Euler-Bernoulli beams.

The model structures consist of one rail of section 60E1 and half of the cross-sectional area of the bridge. For interest of the comparability of different models, each model has got the same material and cross-sectional properties.

3.1 Bridge structure

The beam modelling the half-cross-sectional area of the bridge are the following:

- cross-sectional area: 1000 cm^2
- elasticity modulus: 210000 N/mm^2
- linear heat expansion modulus: $1{,}20 \cdot 10^{-5}$ 1/°C

The static model of the bridge is illustrated in Fig. 4. A fix support is located at the left hand-side and there are moving supports at mid-span and at the right hand end, therefore the expansion length of the bridge is equal to its structural length.

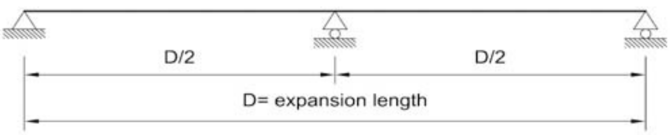

Fig. 4. The static model of the railway bridge

Tab. 1. Longitudinal rail restraint and stiffness of rail fastenings

Type of fastening	Longitudinal rail restraint [kN]	Longitudinal stiffness [N/mm]
K (Geo) with flat EVA railpad under the rail	26,51	51 400
K (Geo) without any railpad	20,52	40 000
KS, Skl-12 with flat EVA railpad under the rail	16,58	36 000
KS, Skl-12 without any railpad	10,47	14 000
W 14, with flat EVA railpad	11,79	28 000

Tab. 2. Maximum values of normal forces and relative displacements in case of bridges with expansion length of $D = 40$ m, without any rail expansion joints (longitudinal ballast resistance in joining track sections $p = 5$ N/mm/rail)

	Structure	Season	K (GEO) restraint 30,0 kN	K (GEO) restraint 20,52 kN	KS Skl-12 restraint 10,47 kN
Maximum normal force [kN]	Fixed bearing	winter	1581	1375	701
		summer	-1581	-1375	-701
	Bridge structure	winter	1581	1375	701
		summer	-1581	-1375	-701
	CWR track	winter	2009	1966	1930
		summer	-1761	-1720	-1684
Relative displacement of bridge and rail (at sliding bearing) [mm]		winter	17,3	23,4	47,5
		summer	-17,3	-23,4	-47,5

3.2 Modelling CWR ballasted tracks

It has been assumed in the model that a ballasted track with continuously welded rail (CWR) joins the bridge at its both ends. The ballasted CWR tracks are modelled with continuously elastically supported beams, whose properties are equal to those of the rail section of 60E1:

- area of cross section: 7670 mm^2
- elasticity modulus: 215000 N/mm^2
- linear coefficient of thermal expansion: $1{,}15 \cdot 10^{-5}$ 1/°C

The longitudinal resistance of a consolidated and well maintained ballast can be 8 to 10 N/mm, whereas that of a newly laid ballast can be considered to be 5 N/mm in respect of one rail. In accordance with this, the limiting longitudinal load of the continuous support of the ballasted track has been assumed to be 9 N/mm for the consolidated ballast and 5 N/mm for the newly laid ballast. The model does not take into consideration that the longitudinal ballast resistance of the track increases under the load of a train. It is suggested to deal with the case of the loaded track in another article in the future.

3.3 Modelling the track – bridge interaction

The spacing between the wooden sleepers on the bridge is 0.60 m, therefore the beams substituting the rail and that modelling the bridge are connected with non-linear springs every 0.60 m. Due to the non-linear behaviour, it is necessary to carry out second-rank theory computations. The properties of the springs are defined on the basis of the laboratory tests defined in chapter 2 and their results summarized in Table 1.

Major in ref. [4] and Birk and Ruge in ref [5] also apply non-linear elastic relationship between the displacement difference in the track - bridge interaction and the longitudinal restoring force.

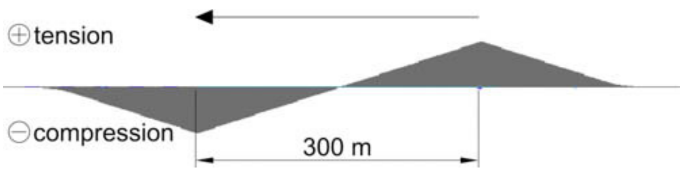

Fig. 5. Normal force generated by braking in the rail

3.4 Load cases and combinations

The neutral temperature and the linear coefficient of thermal expansion of the bridge and the rail are different, therefore relative displacement is generated between the rail and the bridge. According to the Technical Specifications of D.12/H. of Hungarian State Railways (MÁV), the neutral temperature of the rail is 20^{+8}_{-5} °C. The temperature of the rail can reach even 60°C in the summer due to direct sunshine, and as low as -30°C in the winter. The neutral temperature of the steel bridge is 10°C that can be changed by ±40°C under extreme weather conditions [6].

European Standard EN 1991-2 require that the braking effect of the trains onto the rails be substituted by a longitudinally uniformly distributed load of 20 kN/m per two rails that is 10 kN/m per one rail through a total length of 300 m. It has a maximum value of 6000 kN on the bridge. The acceleration of the trains is to be taken into consideration by an evenly distributed longitudinal load of 33 kN/m with a total value of 1000 kN [7]. Of the two effects, it is the braking that produces higher force, therefore this is critical.

The normal forces generated in the rail by a braking effect is illustrated in Fig. 5. The braking takes place over the distance and in the direction indicated by the arrow [8].

Tab. 3. Maximum values of normal forces and relative displacements in case of bridges with expansion length of $D = 40$ m, without any rail expansion joints (longitudinal ballast resistance in joining track sections $p = 9$ N/mm/rail)

	Struc-ture	Season	K (GEO) restraint 30,0 kN	K (GEO) restraint 20,52 kN	KS Skl-12 restraint 10,47 kN
Maximum normal force [kN]	**Fixed bearing**	winter	1219	1064	689
		summer	-1224	-1065	-689
	Bridge structure	winter	1440	1169	689
		summer	-1441	-1170	-689
	CWR track	winter	1734	1626	1557
		summer	-1487	-1379	-1311
Relative displacement of bridge and rail (at sliding bearing) [mm]		winter	12,6	23,4	47,5
		summer	-12,6	-23,4	-47,5

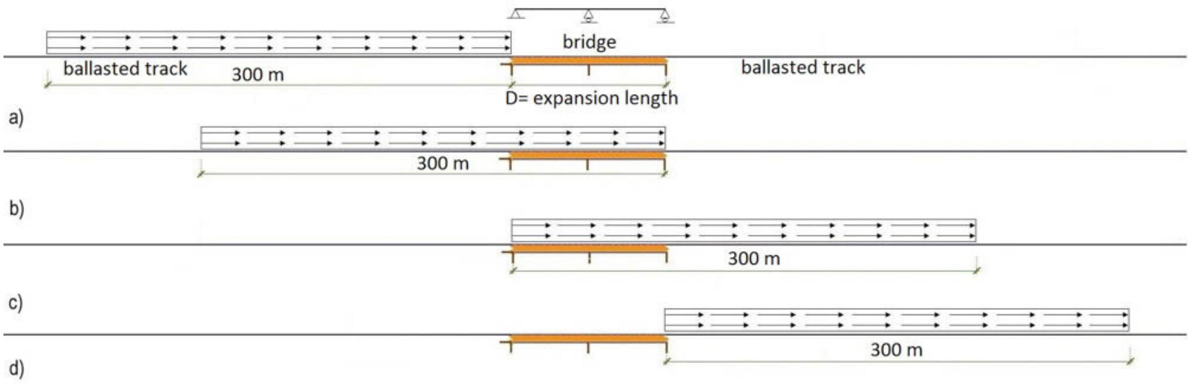

Fig. 6. Special positions of braking load

In case of critical load combination the position of maximum values of normal forces generated by the change of temperature and by braking should coincide.

The combination of loads comprise of the kinematic load of change of temperature in winter, that in summer and the braking effect over a distance of 300 m. In order to determine the position of loads generating the greatest normal force in the structures, the braking force has been moved from the position indicated in Fig. 6a gradually in steps of 10 m through the positions in Figs. 6b and 6c to the position shown in Fig. 6d. Braking to the right and to the left are mirrors of each other. Each braking load position has been combined with kinematic load of change of temperature both in summer and in winter.

If the rail temperature is lower than the neutral temperature, tensile force will arise in the rail that may result in fracture of the rail and if it is higher than the neutral temperature then compressive force will be induced that may lead to buckling of the track. The latter is more dangerous in respect of traffic safety.

4 Determination of normal forces in bridges with expansion length of $D = 40$ m without rail expansion joints

As it has already been mentioned in the introduction, according to Technical Specifications of D.12/H. of MÁV, continuously welded rail track can be joined to the bridge structure without a rail expansion joint if the expansion length of the bridge is equal or less than 40 m, therefore the normal forces generated in the structural elements are permitted. As a consequence, as first step of the research we have determined the normal forces induced in the rail, bridge structure and the bearing.

The model of the bridge and the continuously welded rail track has been built in the way described in Chapter 3. The computations have been carried out in the following cases:

- *K* (Geo) rail fastening with longitudinal rail restraint of 30,0 kN,
- *K* (Geo) rail fastening with longitudinal rail restraint of 20,52 kN,
- KS Skl-12 rail fastening with longitudinal rail restraint of 10,47 kN.

The longitudinal stiffness of the fastenings is summarized in Table 1.

The normal forces resulting from the load combinations are summarized in Table 2 in case of a longitudinal ballast resistance of 5 N/mm/rail and in Table 3 in case of 9 N/mm/rail.

The normal internal force diagrams are illustrated in Figs. 7 - 10. They indicate the cases when the greatest normal forces are generated in the bridge, the fixed bearing and the rail. The 300 m long section with the uniformly distributed load of braking is indicated. They arise with the application of a rail fastening with a longitudinal rail restraint of 30,0 kN and a longitudinal ballast resistance of 5 kN/m/rail. The force diagram in red colour indicates the normal force in the bridge and that in blue colour indicates the normal force in the rail.

It has been obtained that the lower the rail restraint is the lower the normal forces are in the rail and the bridge.

The direction of the maximum normal force is irrelevant in respect of the bridge and the bearing, the one with the higher absolute value is considered to be critical.

The technical specifications do not limit the maximum value of the longitudinal rail restraint and stiffness of the fastening. If an EVA railpad is inserted under the railfoot in the *K* (Geo) fastening and the nut is pulled by slightly higher torque than specified, the longitudinal rail restraint of this fastening can reach a value of 30 kN. The longitudinal stiffness is 51400 kN/mm. In this case the maximum longitudinal force in the bridge and the fixed bearing is 1581 kN both in compression and tension. The maximum value of the tensile force in the rail is 2009 kN and that of the compressive force is 1761 kN. Taking these values into consideration and the maximum limit values of 3000 kN of braking force per one rail, Table 4 summarizes the maximum permissible normal forces.

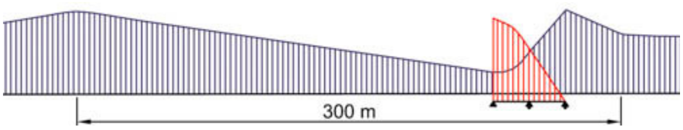

Fig. 7. Normal internal force diagram, when the greatest force is generated in the fixed bearing and the bridge ($D = 40$ m)

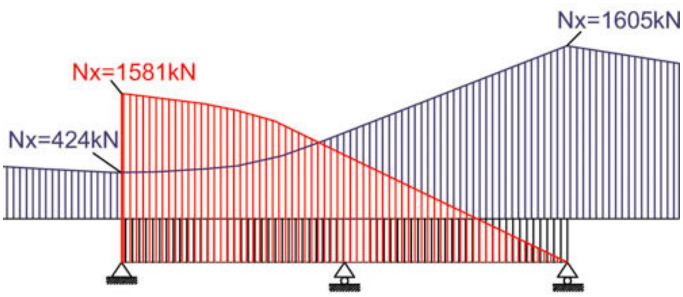

Fig. 8. Normal internal force diagram, when the greatest force is generated in the fixed bearing and the bridge (zoom of Fig. 7)

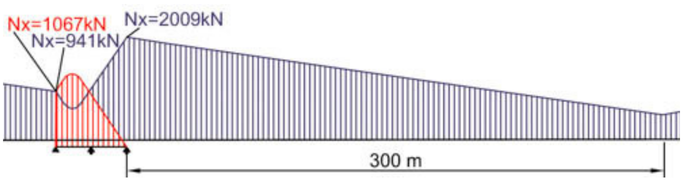

Fig. 9. Normal internal force diagram, when the greatest tensile force is generated in the rail ($D = 40$ m)

5 Analysis of bridges with expansion length of greater than $D = 40$ m without rail expansion joints

According to present regulations an expansion joint has to be constructed between the ballasted CWR track and the bridge if the expansion length of the bridge is greater than $D = 40$ m. As

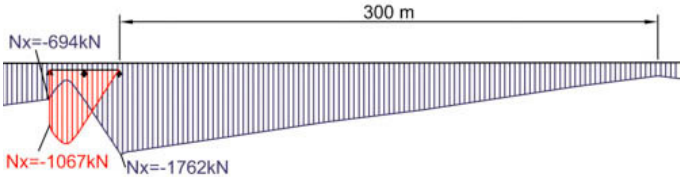

Fig. 10. Normal internal force diagram, when the greatest compressive force is generated in the rail ($D = 40$ m)

Tab. 4. Maximum permissible normal forces

Structure	Maximum permissible normal force	
Fixed bearing	3000 kN	-3000 kN
Bridge structure	3000 kN	-3000 kN
CWR track	2009 kN	-1761 kN

a consequence the bridge can change its length due to change of temperature, however the longitudinal forces resulting from braking of the trains whose maximum value is 3000 kN on one rail according to standard of Eurocode 1991-2 have to be taken on by the fixed bearing of the bridge.

We have carried out analyses to determine the normal forces generated in the continuously welded rail, the bridge structure and the fixed bearing in cases of bridges with expansion length of 70 m and 100 m.

5.1 Bridges with expansion length of 70 m

The results of our computations carried out on bridges with expansion length of 70 m without any rail expansion joints are summarized in Table 5 that contains the longitudinal normal forces in the rail, the bridge structure and in the fixed bearing and the maximum relative displacements between the bridge and the rail, in function of the longitudinal rail restraint of the fastening and the ballast resistance.

In case of application of the same rail fastening, on bridges with longer expansion length higher normal internal forces are generated from the same loads.

Rail fastenings with lower longitudinal rail restraint will allow higher relative displacements between the bridge and the rail and will convey lower longitudinal forces from the rail onto the bridge and vice versa. The rail restraint of Skl-12 fastening is much less than that of the *K* (Geo) fastening, therefore much lower longitudinal internal forces will be generated with its application.

By comparing the data of Tables 4 and 5, it is obtained that the internal normal forces generated in the rail in case of a bridge with an expansion length of 70 m and fastening assembly of Skl-12 will not exceed the normal forces generated in the rail in case of an expansion length of 40 m and *K* (Geo) fastening assembly, even if an EVA railpad is inserted under the rail and the nut is drawn slightly higher than specified in the assembly regulations.

In case of a bridge with an expansion length of 70 m and a fastening assembly with a longitudinal rail restraint of 13 kN, similar longitudinal normal forces are generated in the bridge structure and the bearing as in case of 40 m of expansion length

Tab. 5. Maximum values of normal forces and relative displacements in case of bridges with expansion length of $D = 70$ m, without any rail expansion joints

	Structure	Season	Geo rail restraint of 20,52 kN	Skl-12 rail restraint of 16,58 kN	Skl-12 rail restraint of 12,56 kN	Skl-12 rail restraint of 10,47 kN
longitudinal ballast resistance in joining track sections $p = 5$ N/mm/rail						
Maximum normal force [kN]	Fixed bearing	winter	1881	1787	1469	1225
		summer	-1881	-1787	-1469	-1225
	Bridge structure	winter	1890	1787	1469	1225
		summer	-1890	-1787	-1469	-1225
	CWR track	winter	2075	2009	1963	1947
		summer	-1829	-1762	-1716	-1700
Relative displacement of bridge and rail (at sliding bearing) [mm]		winter	27,4	31,6	40,7	46,5
		summer	-27,4	-31,6	-40,7	-46,5
longitudinal ballast resistance in joining track sections $p = 9$ N/mm/rail						
Maximum normal force [kN]	Fixed bearing	winter	1615	1500	1306	1159
		summer	-1619	-1502	-1306	-1159
	Bridge structure	winter	1823	1653	1345	1170
		summer	-1823	-1654	-1345	-1170
	CWR track	winter	1890	1811	1746	1733
		summer	-1644	-1565	-1500	-1486
Relative displacement of bridge and rail (at sliding bearing) [mm]		winter	23,2	26,1	29,1	30,5
		summer	-23,2	-26,1	-29,1	-30,5

and overdrawn K (Geo) fastening assembly. For a 70 m expansion length and 16 kN rail restraint, the internal normal forces in the bridge and in the bearing are higher than in case of 40 m expansion length, however they are much lower than 3000 kN, and still lower than 2000 kN.

The application of K (Geo) fastening is not suggested on bridges with an expansion length greater than 40 m.

Continuously welded rail track can be constructed through bridges with expansion length of $D = 70$ m without rail expansion joints if the rail fastening has got a maximum longitudinal rail restraint of 15 to 16 kN, supposing that ballasted CWR track is joined at both ends of the bridge. In these cases rail expansion joints can be omitted.

5.2 Bridges with expansion length of 100 m

The results of our calculations carried out on bridges with expansion length of 100 m and without any rail expansion joints are summarized in Table 6. It can be determined that with the application of a rail fastening with a rail restraint of 10,5 kN, the normal internal force in the rail will not exceed the value generated in the rail on a 40 m expansion length (2009 kN). If the rail restraint of the fastening assembly is greater than this value, the normal internal force in the rail will be higher, especially in case of a K (Geo) fastening.

The longitudinal internal forces in the bridge and in the bearing do not exceed the limit of 3000 kN. In case of a rail restraint of 10,5 kN the longitudinal internal forces are approximately 10% higher than in case of a 40 m expansion length.

The maximum relative displacement between the rail and the bridge is +/- 55 mm (Table 6). This is +/- 40 mm on a 40 m expansion length. This difference is negligible regarding the fatigue strength of the rail clip, because the rail starts slipping in the fastening after an initial elastic displacement of 0,5 to 1,5 mm.

Based on our analysis, the continuously welded rail can be constructed through a bridge with an expansion length of $D = 100$ m without any rail expansion joints, if the rail restraint is maximum of 11 kN, if ballasted CWR track is joined at both ends of the bridge. Special attention has to be paid to correct construction of the fastening, if it has a screw or nut it may not be overtensioned. In case of the construction of a rail fastening with a rail restraint of greater than 11 kN, a more detailed analysis is necessary.

It can be concluded that the longitudinal rail restraint of fastening assembly has a dominant influence on the interaction of the bridge and the rail in respect of the normal internal forces.

6 Bridges with expansion length of 100 m and with rail expansion joints

The major goal of our publication, as it has already been mentioned at the beginning of this paper, is to provide technical solutions with their application a continuously welded rail track can be constructed through a bridge without interruption, without any rail expansion joints. This case in this chapter has been modelled to compare these results with those obtained without expansion joints.

We have built models also for the cases where there are rail expansion joints at both ends of the bridge. The models were built in a similar method discussed in previous chapters. In order to simulate expansion joints, non-linear springs have been inserted in the model at the ends of the bridge, altogether 10

Tab. 6. Maximum values of normal forces and relative displacements in case of bridges with expansion length of $D = 100$ m, without any rail expansion joints

	Structure	Season	Geo rail restraint of 20,52 kN	Skl-12 rail restraint of 16,58 kN	Skl-12 rail restraint of 10,47 kN	rail restraint of 7,0 kN
longitudinal ballast resistance in joining track sections $p = 5$ N/mm/rail						
Maximum normal force [kN]	Fixed bearing	winter	2243	2151	1748	1169
		summer	-2249	-2151	-1748	-1169
	Bridge structure	winter	2304	2182	1748	1169
		summer	-2304	-2182	-1748	-1169
	CWR track	winter	2220	2148	1977	1929
		summer	-1974	-1902	-1731	-1682
Relative displacement of bridge and rail (at sliding bearing) [mm]		winter	33,2	38,1	54,5	71,6
		summer	-33,2	-38,1	-54,5	-71,6
longitudinal ballast resistance in joining track sections $p = 9$ N/mm/rail						
Maximum normal force [kN]	Fixed bearing	winter	2092	1970	1602	1169
		summer	-2094	-1972	-1602	-1169
	Bridge structure	winter	2291	2157	1644	1169
		summer	-2291	-2157	-1644	-1169
	CWR track	winter	2099	2015	1884	1855
		summer	-1853	-1768	-1637	-1608
Relative displacement of bridge and rail (at sliding bearing) [mm]		winter	30,0	34,1	41,9	46,0
		summer	-30,0	-34,1	-41,9	-46,0

Tab. 7. Maximum values of normal forces in units of kN's in case of bridges with expansion length of 100 m, with expansion joints at both ends of the bridge, longitudinal ballast resistance in joining track sections $p = 5$ N/mm/rail

Structure	Season	Geo rail restraint 20,52 kN	Skl-12 rail restraint 10,47 kN
Fixed bearing	winter	876	876
	summer	-876	-876
Bridge structure	winter	-966	-925
	summer	895	895
CWR track	winter	1504	1504
	summer	-1543	-1543

of them with longitudinal stiffness of 5 kN/mm and a limiting load of 1,9 kN [9]. Above a total horizontal load 19 kN the springs will slide longitudinally, they are not able to take on higher forces.

Only rail fastening assemblies of K (Geo) with rail restraint of 20,52 kN and Skl-12 with 10,47 kN have been modelled in case of a ballast resistance of $p = 5$ N/mm/rail. The results are summarized in Table 7. Comparing the values of Tables 6 and 7, it can be concluded that much higher normal internal forces are generated in the rail, bridge structure and the bearing if rail expansion joints are omitted at both ends of the bridge. This has to be taken into consideration during the design, also at considering the stability of the CWR track against buckling at the joint of the bridge and the ballasted track.

7 Conclusions

Research has been carried out with the purpose to find technical solutions to construct continuously welded rail through bridges with expansion length of greater than 40 m without interruption that joins ballasted CWR tracks at both ends. In these cases rail expansion joints can be omitted. Conclusions are the followings:

- In case of expansion length of $D > 40$ m, the normal internal forces in the bridge structure, the bearing and the rail will be higher than in case of expansion length of $D = 40$ m. With increasing expansion length of bridge, the normal internal forces will increase. This has to be taken into consideration during the design, also at considering the stability of the CWR track against buckling at the joint of the bridge and the ballasted track.
- The normal internal forces in the bridge structure, the bearing and the rail can be decreased by reducing the longitudinal rail restraint of the fastening assembly. It can however result in excessive opening of a gap in case of rail fracture in winter.
- The continuously welded rail can be constructed through a steel bridge with an expansion length of 70 m without any rail expansion joint if a fastening assembly with a longitudinal rail restraint of maximum of 15 to 16 kN is applied. In these cases the normal internal forces in the rail will not exceed those generated in case of an expansion length of 40 m with K (Geo) fastening of 30 kN of rail restraint. Normal internal

forces in the bridge and bearing will be approx. 10% higher than in case of 40 m expansion length.

- The continuously welded rail can be constructed through a steel bridge with an expansion length of 100 m without any rail expansion devices if a fastening assembly with a longitudinal rail restraint of maximum of 11 kN is applied. In these cases the normal internal forces in the bridge and the bearing will slightly exceed those generated in a bridge with an expansion length of 40 m with K (Geo) fastening, however the normal force in the rail will be less than those in case of 40 m of expansion length.
- It can be concluded that the longitudinal rail restraint of fastening assembly has a dominant influence on the resultant normal internal forces in the bridge and the rail. The less the rail restraint is, the lower internal forces will be generated in the structural elements.
- The consolidation of the ballast, that is higher ballast resistance value will serve in favour of safety. In case of higher ballast resistance less internal forces will be generated in the rail and the bridge.

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