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To cite this article: Vojtěch Stančík et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 236 012063

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Steel bridge in interaction with modern slab track fastening systems under various vertical load levels

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Abstract. In modern slab tracks the continuously welded rail (CWR) is coupled through the fastening system with the substructure. The resulting restriction of expansion movement causes significant rail stress increments, which in the case of extreme loading may cause rail failures. These interaction phenomenon effects are naturally higher on a bridge due to different deformation capabilities of the bridge and the CWR. The presented contribution aims at investigating the state of the art European direct fastening system that is suitable for application on steel bridges. Analysis involves experimental determination of its nonlinear longitudinal interaction parameters under various vertical loads and numerical validation. During experimental procedures a two and a half meter long laboratory sample equipped with four nodes of the Vossloh DFF 300 was tested. There have been checked both DFF 300 modifications using the skl 15 tension clamps and the low resistance skl B15 tension clamps. The effects of clamping force lowering on the interaction parameters have also been investigated. Results are discussed in the paper.

1. Slab track in interaction with bridge

Ballastless track technologies can be conveniently used for constructing shallow steel bridge decks with reduced self-weight. On a steel bridge the ballastless track is formed by connecting the continuously welded rail (CWR) to the orthotropic steel deck directly through the special direct fastening system. Naturally in the CWR the longitudinal forces are rising because of the restriction of its expansion movement. On a bridge there is even more significant stress increment caused by different deflections of the bridge compared to CWR (see Figure 1).

In the case of ballastless tracks the crucial component, describing the transmission of longitudinal forces, is the fastening system. For performing a sufficiently reliable bridge/track interaction analysis it is necessary to investigate the longitudinal nonlinear stiffness of the fastening system. However values of this input parameter are quite uncertain. In the scientific literature and national codes various values of the ballastless track longitudinal resistance r_x can be found. Fundamentals in this field of study were laid by prof. Frýba and are summarized in [1]. Frýba conducted several in-situ experiments on different bridge deck types, involving the ballastless tracks. In order to obtain the values of r_0 , prof. Frýba introduced analytical solution. By solving systems of differential equations considering various values of r_0 he was able to find the most fitting value to the experimental results. However in this case

only the parameters for unloaded track were investigated. When assessing the longitudinal bridge/track interaction bridge designer must prevent reaching rail stress additional increment limits of 72 MPa in compression and 92 MPa in tension caused by live loads. These limits have been calculated for 60 E2 rail and for other rail types need to be recalculated. More recently Geissler and Freystien released a study [2] where they proposed higher stress increment limits when the bridge is arranged appropriately. Amongst other they demonstrated that ballastless tracks may resist higher stress increments in compression thanks to their rigid transversal resistance.



Figure 1. Bridge rail interaction phenomenon.

Regarding the modelling of interaction functions, general recommendations are given by UIC-774-3R [3]. Some important parameters may be found amongst other in German national codes [4] or Dutch national codes [5], while the current version of European code [6] doesn't involve recommendations for ballastless tracks. For the purposes of proper interaction analysis each node of fastening may be modelled using the nonlinear spring (Figure 3.), where the stiffness K_x refers to the recalculated value of bilinear longitudinal resistance (Figure.2) and K_z refers to vertical stiffness of elastic pads and tension clamps. Variables marked with capitals refer to one node only, while the small letters denote values recalculated for one meter of railway track length. In the before mentioned codes, values of plastic longitudinal resistance r₀ varies between 30 and 40 kN/m for unloaded track load cases, respectively 50 and 60 kN/m for loaded track load cases. According to codes the plastic resistance is reached when the relative bridge/track displacement meets the limit u_0 , which may be considered with the values in range between 0.5 and 1 mm. Thus the longitudinal stiffness k_x is significantly higher compared to standard ballasted tracks. In his publication [7] Esveld suggested slightly higher value of $r_0 = 47$ kN/m for unloaded slab tracks. Other experiments brought different results. For example evaluation of in-situ monitoring on a newly built bridge equipped with DFF 300 and the low resistance tension clamp skl B15 [8] indicated rather lower values of slab track longitudinal resistance $r_0 = 25$ kN/m. Besides that, research study carried out at the CTU Prague [9] also proved that interaction functions are temperature dependent.





Figure 2. Variations of slab tracks nonlinear longitudinal coupling functions according to [3,4,5].

Figure 3. Standard model of the bridge/track coupling interface.

2. Experiment

The aim of experimental analysis was to determine longitudinal interaction parameters of DFF 300, the state of the art direct fastening system, under various vertical loads. To meet the goals, an experiment was conducted in the laboratory of CTU Klokner Institute. Tested sample was assembled from an asymmetric 2.65 metres long steel beam with wider upper flange and four nodes of DFF 300 fastening system. In vertical direction the sample was supported by two sliding supports to achieve the sample planned spanning of 2.5 metres. Horizontal deflection was restricted by anchoring the sample with the M30 steel bars. Each DFF 300 fastening node was assembled according to Vossloh requirements using the steel base plate, elastomeric intermediate plates, steel distribution plate and the hard plastic pad that was placed under the rail toe. Testing involved both the Skl 15 tension clamp and the low resistance Skl B15 tension clamp.



Figure 4. Stress measurement on the small scale sample.



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Figure 5. Longitudinal and vertical deflection measurement on the small scale sample.



Figure 6. Experiment layout.

During the testing procedure the rail and beam stress, so as the longitudinal and vertical rail deflection were measured. The rail strain gauges were placed in the intermediate sections between the fastening nodes alike the horizontal potentiometric displacement sensors. In vertical direction the deflections were measured directly at the location of each fastening node. Arrangement of gauges is shown in Figure 6. Experimental procedures were based on EN 13481-1 code [10], nevertheless some

modifications had to be adopted, because the regulation doesn't involve recommendations for testing under vertical loads. Procedure started with vertical loading F_z . After reaching the prescribed vertical load level the rail was loaded horizontally with the force F_x . When the force increment approached the plastic resistance level, the horizontal loading was quickly reduced and plastic straining was observed. After two minutes of displacement development, the sample was horizontally and subsequently vertically unloaded. Four load cases were designed to determine the fastening interaction functions. In the first load case the interaction parameters for unloaded track were observed, while the other three load cases focused on determining interaction parameters under vertical pressure. Thus the sample was gradually tested under 0, 40, 80 and 125 kN vertical loads. Whole procedure was repeated twice. First the fastenings were equipped with Skl 15 and subsequently with Skl B15 tension clamps.

3. Numerical analysis

Generally the brief review of scientific literature showed that the longitudinal resistance of the direct fastening systems is a quite uncertain input parameter that depends on friction between the layers of different materials used within the fastening node as it depends on the elasticity of the tension clamps. Along with the verification of experimental values the numerical analysis aimed at investigating the effects of different tension clamp types and the clamping force lowering on longitudinal resistance. Effects of clamping force lowering are sometimes being discussed as the possible reason for discrepancies between the measured values of r_0 . For that case a modified model of the bridge/track coupling interface had to be developed.





Figure 8. Modified model of bridge/track coupling interface.

The global model for finite element analysis (FEA) was created in Dlubal RFEM software and is described on Figure 7. Steel plates of the asymmetric supporting beam were modelled using shell elements while the rest of the components, thus the rail, hydraulic cylinders and fastening bolts, were modelled using the Euler-Bernoulli beam elements. All the necessary eccentricities were introduced through fictive rigid beams. The most challenging task was to adopt coupling parameters of the fastening system. This was solved using the nonlinear joints at the endpoints of the corresponding beam elements. Main principle of each fastening node model is presented on Figure 8, where u_c is the nominal deflection of tension clamp caused by the fastening bolt tightening, $K_{c,z}$ is the vertical stiffness of the tension clamp, $R_{c,x}$ is the friction force between the clamp and the rail, $R_{p,x}$ is the friction force between the pad and steel parts of the fastening, $K_{p,z}$ is the vertical stiffness of the fastening elastic parts and $K_{p,x}$ is the longitudinal stiffness of the fastening elastic parts. Independent elements for tension clamps and the rest of the fastening components have been used. Therefore $R_{c,x}$ depends on the

clamping force F_c and the steel-steel friction coefficient μ_1 , while $R_{p,x}$ depends on the total vertical force $F_{tot}(1)$ and the steel-elastomer friction coefficient μ_2 .

$$F_{tot} = F_z + F_c \tag{1}$$

Table 1. Input parameters for FEA.								
clamp	$u_{\rm c} ({\rm mm})$	F_c (kN)	μ_1	μ_2	μ_3	$K_{p,z}$	$K_{c,z}$	$K_{p,x}$
Skl 15	20	22	0.1	0.55	0.05	Figure 9.	Figure 10.	rigid
Skl B15	20	12.6	0.1	0.55	0.05	Figure 9.	Figure 10.	rigid

Models of hydraulic cylinders were involved in the FEA so that the friction forces between the cylinders and the rail could be adopted. Mainly the coefficient of rolling friction μ_3 modelling the cylinder resistance against the rail longitudinal displacement was important during the FEA process to improve its accuracy. Also by using the cylinder models the loading could be controlled by horizontal displacement increments while the output was the total resistance force. Otherwise the plastic resistance values could be hardly determined by FEA. An input parameters setting is shown in Table 1. Nonlinear stiffness of the fastening components were taken from [9] and from the Vossloh DFF 300 guide [11]. It has to be mentioned that some assumptions had to be made when modelling vertical stiffness of the clamp skl B15, since there isn't presented a full description of the deflection – force behaviour in the guide.



Figure 9. Vertical stiffness of elastic pad [9].

Figure 10. Vertical stiffness of clamps [11].

4. Results

As mentioned before the experiment was inspired by EN 13481-1 [10]. However this regulation describes testing of one fastening node only, therefore the evaluation procedure was slightly modified. During the evaluation process some difficulties had to be dealt with. Obtained functions of longitudinal resistance had slightly disjointed character because of sudden irregular slipping in particular fastening nodes. Because of that a polynomic regression function was used to substitute the elastic part of the graph and a mean value was used to evaluate the plastic resistance r_0 (2). Moreover maintaining simultaneous constant vertical pressure and very small horizontal force increments during plastic displacement development was quite challenging task. For similar purposes controlling the loading procedure by displacement should be recommended. Also it may be stated that longer sample is more appropriate for experimental analysis of longitudinal interaction behavior. That is because the longer rail doesn't rotate in the fastening nodes that much and some effects of eccentricities and

second order are minimized compared to the only one fastening node testing procedures. After all no latter mentioned effects may occur in the real track.

$$r_0 = \frac{1}{n} \sum_{i=1}^{n} r_{0,i}$$
 where $r_{0,i} > r_{x,yield}$ (2)

$$r_x = 2 \cdot R_x / (4 \cdot s) \tag{3}$$

$$k_x = r_x \left(u_{x,max} - u_{x,res} \right) / \left(u_{x,max} - u_{x,res} \right)$$
(4)

$$k_x = r_x (u_{x,yield}) / u_{x,yield} \tag{5}$$

Longitudinal resistance r_x of the track was determined using the formula (3) where R_x stands for total cumulated resistance of four fastening nodes and s stands for axial spacing between the nodes. Using this formula a mean value of longitudinal resistance is obtained and recalculated for one meter length of the slab track. Values of unloaded track longitudinal stiffness k_x were evaluated using formula (4), where $u_{x,max}$ is the maximum measured displacement, $u_{x,res}$ is the residual displacement after unloading and $r_x(u_{x,max} - u_{x,res})$ is the resistance at the fictive yield point. The yield point term isn't recognized by the standards, it refers to the point where the longitudinal rail deflection increment starts to grow significantly higher due to rail slipping. Formula (4) was adopted from [10] and is appropriate to use in the case of indistinct yield point, while for the loaded track load cases, where the yield point is quite obvious, formula (5) had been used. Here the variable $u_{x,yield}$ indicates the displacement at the yield point.



Figure 11. Experimental longitudinal stiffness and plastic resistance dependence on vertical load level for DFF 300 (Skl 15).

Figure 12. Experimental longitudinal stiffness and plastic resistance dependence on vertical load level for DFF 300 (Skl B15).

Figures 11 and 12 introduce the dependence of longitudinal stiffness and resistance on vertical loading. Table 2. introduces comprehensive comparison between experimental interaction parameters r_0 , k_x and corresponding numerically simulated parameters $r_{0,F}$, $k_{x,F}$. Besides some exceptions the numerical results showed quite good accuracy, meaning the modified coupling interface model is suitable for this type of analysis. Major part of discrepancies is caused due to uncertainties in the input material parameters for FEA presented in table 1. Results demonstrate that the tension clamp is an important component, which significantly affects interaction parameters. By observing the longitudinal stiffness results it is quite interesting that the determined values are significantly lower than recommended in the codes [3,4]. Limit values of elastic deformation u_0 were found to lie in

interval between 1.2 to 1.6 mm which rather matches in situ measured values proposed in [8]. By observing the plastic resistance results it may be concluded that the unloaded track values for Skl 15 clamp correspond to the standard recommended values quite well. The same remark may be stated for the loaded track load cases, where the vertical load level is below 80 kN, referring to common rail vehicles. In the case of heavily loaded track ($F_z = 125$ kN) the track resistance value 72.5 kN/m is considerably higher than usually recommended value 60 kN/m. Latter mentioned heavily loaded track value refers to the recalculated impact of UIC 71 load model. When exploring the results of the track equipped with Skl B15 tension clamp it may be stated that the longitudinal resistance values have diminished significantly. This applies to the unloaded and quite surprisingly also to the loaded track load cases.

$F_z(kN)$	clamp	$r_{\rm O}$ (kN/m)	k_x	$r_{O,F}(kN/m)$	$k_{x,E}$	$r_{\rm O}/r_{{\rm O},F}$	$k_x/k_{x,F}$
			(kN/m/mm)		(kN/m/mm)		
0	Skl 15	42.9	27.1	41.4	30.3	1.04	0.89
40	Skl 15	60.6	42.2	56.5	37.6	1.07	1.12
80	Skl 15	59.3	41.8	61.5	40.8	0.96	1.02
125	Skl 15	73.0	55.5	72.5	43.83	1.01	1.27
0	Skl B15	23.0	18.9	25.4	19.1	0.91	0.99
40	Skl B15	40.3	31.9	45.2	29.7	0.89	1.07
80	Skl B15	45.4	30.3	48.9	31.0	0.93	0.98
125	Skl B15	55.9	35.2	61.4	32.5	0.91	1.08

Table 2. Experimentally and numerically determined interaction parameters.

Effects of clamping force lowering are demonstrated in Table 3, where u_c ' is the final clamp deflection after the fastening bolt loosening, F_c ' is the final clamping force after the fastening bolt loosening and similarly $r_{0,F}$ ' is the numerically obtained plastic longitudinal resistance after the fastening bolt loosening. To quantify these effects the validated modified coupling interface model (Figure 8.) was applied. Generally speaking it has been proven that the clamping force lowering may cause track resistance reduction. However results show that the influence isn't of big significance, at least when considering the highly elastic Skl 15 and Skl B15 tension clamps. Due to their good elastic capacity large clamp deflection change is needed for considerable clamping force lowering and subsequently for considerable longitudinal resistance reduction. Important question is how the deflection in fastening screws really reduces and what deflection change is realistic to achieve. On the other hand if we consider more rigid older types of tension clamps the effects of clamping force lowering will be considerably higher.

Table 3. Effects of clamping force lowering.

$F_{\rm z}({\rm kN})$	clamp	u_c '(mm)	u_p '/ u_p	F_c '(kN)	F_c ' / F_c	$r_{0,F}$, (kN/m)	$r_{0,F}'/r_{0,F}$
0	Skl 15	20	1.00	11.0	1.00	41.4	1.00
0	Skl 15	19	0.95	10.5	0.95	41.1	0.99
0	Skl 15	18	0.90	10.0	0.91	39.5	0.95
0	Skl 15	17	0.85	9.6	0.87	37.7	0.91
0	Skl 15	16	0.80	9.1	0.83	36.1	0.87
0	Skl 15	15	0.75	8.7	0.79	34.4	0.83
0	Skl B15	20	1.00	6.3	1.00	25.4	1.00
0	Skl B15	19	0.95	6.0	0.95	24.9	0.98
0	Skl B15	18	0.90	5.8	0.92	24.3	0.95
0	Skl B15	17	0.85	5.5	0.87	23.3	0.92
0	Skl B15	16	0.80	5.3	0.84	22.5	0.89
0	Skl B15	15	0.75	5.0	0.79	21.5	0.85

5. Conclusions

Performed study provided with useful information for practical bridge design. Detailed overview of the analysis remarks is given below:

- Modified numerical model of the coupling interface demonstrated quite good accuracy for simulating longitudinal interaction functions for ballastless tracks on a steel bridge. Using this model it is possible to predict longitudinal resistance of direct fastening, however precise knowledge of the friction coefficients and material input parameters is needed for reliable analysis.
- Dependence of longitudinal interaction parameters on vertical load for DFF 300 fastening system equipped with both the Skl 15 and the Skl B15 tension clamps is proposed in the paper. It may be stated that the tension clamp type significantly affects longitudinal interaction. Low resistance clamp Skl B15 is very convenient not only for lowering of track resistance during unloaded track load cases, but even in loaded track load cases.
- Longitudinal stiffness of the evaluated fastening system was determined to be rather lower than recommended in valid codes [3,4] while the values of plastic resistance quite matched the recommended ones.
- Effects of the clamping force lowering don't seem to be very significant. For greater influence the clamp deflection lowering would have to reach values about five millimetres. Reason for this good behaviour is the high elasticity of both tension clamps Skl 15 and Skl B15. On the other hand if the older types of tension clamps with lower elastic capacity were applied, the influence of clamping force lowering would be much higher.

Acknowledgements

Research reported in this paper was supported by Competence Centre's Program of Technology Agency of the Czech Republic (TA CR), project Centre for Effective and Sustainable Transport Infrastructure (no. TE01020168).

References

- [1] Frýba L 1996 *Dynamics of railway bridges 2nd ed.* (London: ICE Publishing)
- [2] Freystein H and Geissler K 2013 Rail/Bridge interaction on Steel Bridges with Examples *Steel Structures* **82**(2) pp 78-86 [in German]
- [3] Union Internationale des Chemins de fer (UIC) 2001 Track/bridge interaction, Recommendations for calculations (*UIC 774-3R*)
- [4] Freystein H 2010 Rail/Bridge interaction State of the Art and Examples Steel Structures 79(3) pp 220-31 (in German)
- [5] Regulations for Structures 2003 Appendix 6 Part 1: Loads (in Dutch)
- [6] European Committee for Standardization (CEN) 2003 Actions on Structures; Traffic loads on bridges *Eurocode 1, Part 2 (EN 1991-2)*
- [7] Esveld C 2001 *Modern Railway Track 2nd ed.* (Zaltbommel: MRT-Productions)
- [8] Ryjáček P and Vokáč M 2014 Long-term monitoring of steel railway bridge interaction with continuous welded rail *Journal of Constructional Steel Research* **99** pp 176-86
- [9] Stančík V and Ryjáček P 2017 Effects of biaxial and thermal loads on rail-slab track interaction behavior *Advances and Trends in Engineering Sciences and Technologies II* ed M Al Ali and P Platko (Boca Raton: Taylor & Francis Group) pp 835-40
- [10] European Committee for Standardization (CEN) 2012 Railway applications; Track; Test Methods For Fastening Systems; Part 1: Determination Of Longitudinal Rail Restraint (EN 13146-1)
- [11] Vossloh Fastening Systems GmbH 2014 Highly elastic rail fastening for high speed and conventional rail; The flexible single support point for slab track *System DFF 300*