Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 25 (2017) 443–450

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2016 Shanghai. 10-15 July 2016

Estimating clamping force of rail fastener system by experimental and numerical methods

Q.T. LI[a], Y. LUO [a]*, Y. LIU [a]

[a] *Institute of Rail Transit, Tongji University, No. 4800 Cao'an Road, Shanghai, 201804, China*

Abstract

Higher demand on security of passenger railway nowadays leads to a trend of field testing method tried on the existing lines. Features of rail fastener are important parameters relevant to safety of railway track structure. Numerical model calculated to predict lateral features of rail fastening system investigates the relation between applied load and displacement of rail in order to provide a new idea of experiment design. The displacement of rail caused by torsional deformation is also considered. Nonlinear relationship of displacement response and load excitation discovered from experimental validation of a numerical model mainly lies in rail bending due to the dynamic response hardening (DRH). Consequently, clamping force which is only measured in the laboratory can be evaluated by both numerical and experimental analysis in this paper. Displacement distribution in longitudinal direction is also mentioned.

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.

Keywords: clamping force, numerical model, rail fastening system, nonlinearity

1. Introduction

Growing axle loads of train and increasing high speed has placed significantly demand on rail infrastructure in China, especially on rail security. Structural safety is of paramount importance in rail transport industry thus there have been continuing efforts in design and testing of rail structure. Rail fastening system fixes rail to sleeper by tensioning rail through spring-actuation as a result of the long elastic spring deflection of the tension clamp. The

* Y. Luo. Tel.: +86 21 69585815; fax: +86 21 69584704.
E-mail address: yyluo15@163.com

2352-1465 © 2017 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.
10.1016/j.trpro.2017.05.424

tension clamps combine exceptional clamping force, superior dynamic fatigue strength and stable creep resistance all in one. Clamping force of rail fastener is an essential parameter relevant to the safety of railway track structure but also is hard to test on site.

Though field testing of clamping force in the existing line has not done before, some laboratory tests have performed by manufacturers and other researchers. In Europe, experimentalists measure clamping force of fastening system according to the standard of EN 13146-7-2002 which is applicable to complete fastening systems assembly. In the test procedure, an increasing tensile load is applied to rail until rail pad can just be moved, then remove pad and decrease load until the average of displacement transducers is zero. Clamping force is the value at d=0 read off from load-displacement diagram, whereas rail fastening system installed on the existing railway is impractical to evaluate its clamping force by means mentioned above while the reliability and security of rail could not be ensured enough.

Some basic numerical methods have gradually been developed as guidance to carry experiments on the field test. Discrepancy of lateral force in aspect of direction and magnitude on two rails results in a numerical method utilized on lateral mechanical behaviour of two rails set up by D. Tong(1988). In addition, Y. Zhang and S. Lian (1997) considered the twist of rail when analysing lateral displacement due to non-ignorable torsion deformation on the top of rail. B. Tesfa et al. (2012) proposed a means of automatically measuring the clamping force of bolted joint independently on railway track joints and points.

In order to determine clamping force of fastener above-mentioned in the practical use which are continuous distributed and hardly obtained, a set of experimental tests is designed and carried out on the base of static lateral mechanical model of rail structural system in Suzhou city, China in this present study. Fastener properties observed from testing results are studied and explained through numerical model analysis conducted by Matlab, which is used to evaluate lateral stiffness of rail fastening system from the calculated relationship between applied load input and lateral displacement response of track. Analysing results of both numerical simulation and experiments are believed to indicate an approximate value of clamping force, to reduce lateral displacement of rail and to enhance security of rail structural system.

2. Numerical Model

Aiming at defining the clamping force of fastening system accurately by numerical method, mechanical model must be established in lateral direction since lateral stiffness of rail is much larger than vertical in all types on account of geometry properties. Displacement range of rail in lateral direction is also wider enough to distinguish evidently. As a result, static lateral mechanical model of rail is finally selected for estimating clamping force of rail fastening system, see Fig.1.

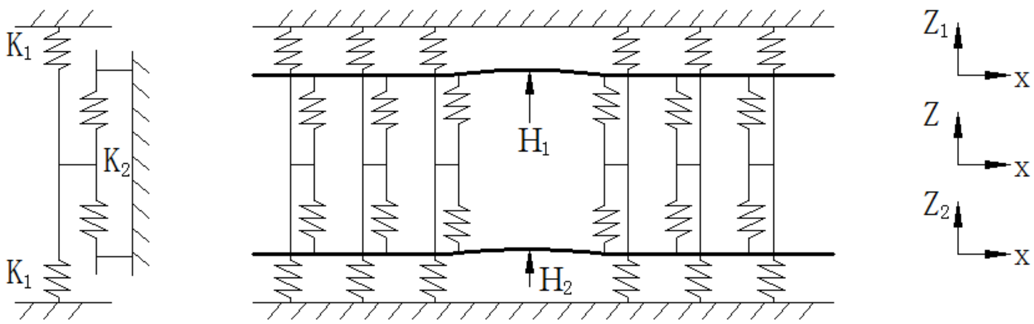


Fig.1. static lateral mechanical model of rail

In this present study, the two rails are modelled as Winkler beams with a bending stiffness EJ_y. The rail displacements resulted from bending are denoted as Z_1 and Z_2. The rail fastening systems are modelled as continuous spring connections. The fasteners stiffness k_1 of a single rail fastening system is used to calculate an equivalent stiffness $\overline{k_1}=k_1/d$ which is a certain number in the continuous model, where d is the fastener distance. The track slab is assumed to be connected to ground through continuous spring whose equivalent stiffness is denoted as a constant number $\overline{k_2}$ while the lateral displacement of track slab along the track is determined by Z . The track-soil ground is assumed to be rigid in the plane of rail cross section. The lateral displacement Z_1 and Z_2 induced by bending deflection of rail can be written in the following general form:

$$Z_1=\frac{1}{16EJ_y}\left[\frac{H_1+H_2}{\beta_2^3}\varphi_1\left(\beta_2 x\right)+\frac{H_1-H_2}{\beta_1^3}\varphi_1\left(\beta_1 x\right)\right] \tag{1}$$

$$Z_2=\frac{1}{16EJ_y}\left[\frac{H_1+H_2}{\beta_2^3}\varphi_1\left(\beta_2 x\right)-\frac{H_1-H_2}{\beta_1^3}\varphi_1\left(\beta_1 x\right)\right] \tag{2}$$

where $\varphi_1(\beta x)=e^{-\beta x}\left(\cos\beta x+\sin\beta x\right)$, $\beta_1=\left(\frac{\overline{k_1}}{4EJ_y}\right)^{1/4}$, $\beta_2=\left(\frac{\overline{k_1}\,\overline{k_2}}{4\left(\overline{k_1}+\overline{k_2}\right)EJ_y}\right)^{1/4}$, H_1 and H_2 are lateral load inputs.

Considering torque of rail arising from lateral load excitation, the lateral displacement is actually caused by bending deformation and torsion deformation. The latter is considerable thus cannot be ignored. As a result, numerical model in this paper definitely takes the twist of rail into consideration. The rails are also modelled as continuous elastic supported beams of infinite length affected from torque induced by fastening system. It brings rise to lateral displacement of rail head when centre of rail axis is assumed as torsional centre

$$d=\overline{OD}\times\alpha=\overline{OD}\times\frac{M_t\gamma}{2K_\theta}e^{-\gamma x} \tag{3}$$

where $\overline{OD}$ is the displacement from load point to torsional center, α is torsion angle, M_t is denoted as torque , K_θ is a torsional factor relative to lateral equivalent stiffness of fastener $\overline{k_1}$, equivalent stiffness of track slab $\overline{k_2}$ and geometrical dimension of rail, $\gamma=\left(K_\theta/\left(GI\right)\right)^{1/2}$, GI is the torsional stiffness of rail.

Consequently, the whole displacement of rail loaded all the time is given by the expression

$$Y=Z_1+d \tag{4}$$

In Fig.2, we can see numerical displacement increasing linearly with the growing load when $\overline{k_1}$ is a constant. For depicting feature of rail fastening, lateral stiffness of fastener $\overline{k_1}$ can be defined from numerical method above with experiment at a site of existing line.

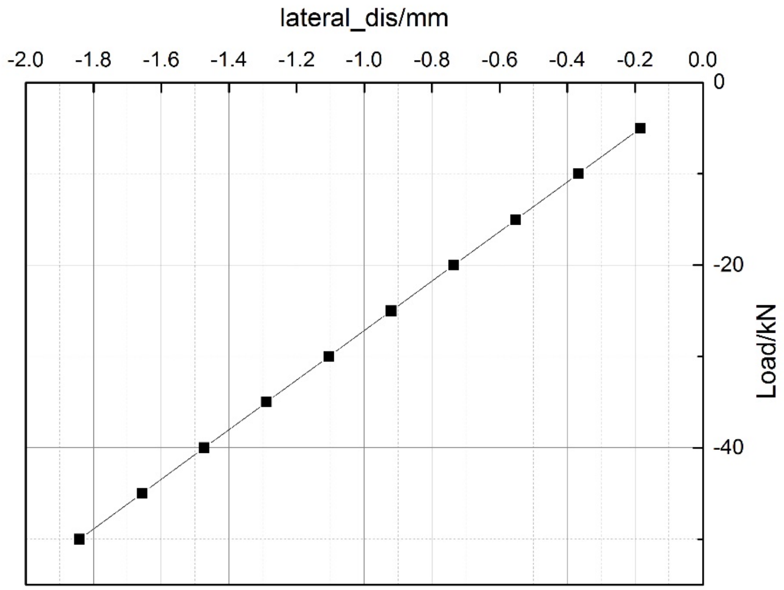


Fig.2 displacement-load curve of numerical model

3. Experiment and Result

3.1. Experiment design

In the following, numerical model noted above is validated by means of experiments which have been performed at a site in Suzhou city. The track on this site is a classical ballastless track with a whole support of rail by track slab. Aiming at evaluating characteristics of rail fastener, load should be applied to rail which is stressed only by fasteners. Since rail fasteners uniform distribute along the direction of rail at 0.6m intervals on the test field in Suzhou city, load is placed onto rail head in the middle of two fastening systems which can bring rise to the largest response displacement of fasteners symmetrically, as can be seen in Fig.3.

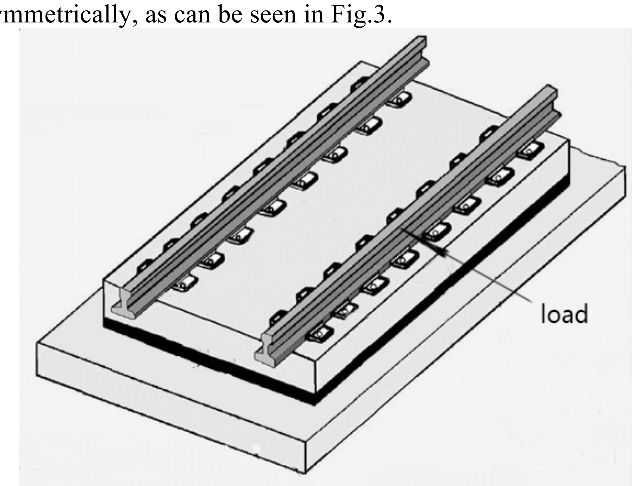


Fig.3. clamping force test

For this static test, measured rail is loaded laterally from 5kN to 50kN by the spacing of 5kN. CCD laser sensors installed at the cross section where the fastener is closed to load point measure lateral displacement of rail head in order to calculating stiffness of rail fastener by numerical model noted earlier. Apparatus is also test vertical displacement of rail support (fastening system) relevant to rail due to clamping force. Repeating the procedure twice more leads to accurate and reliable database. Different relations of displacement-load are recorded and analysed to calculate clamping force.

3.2. Result

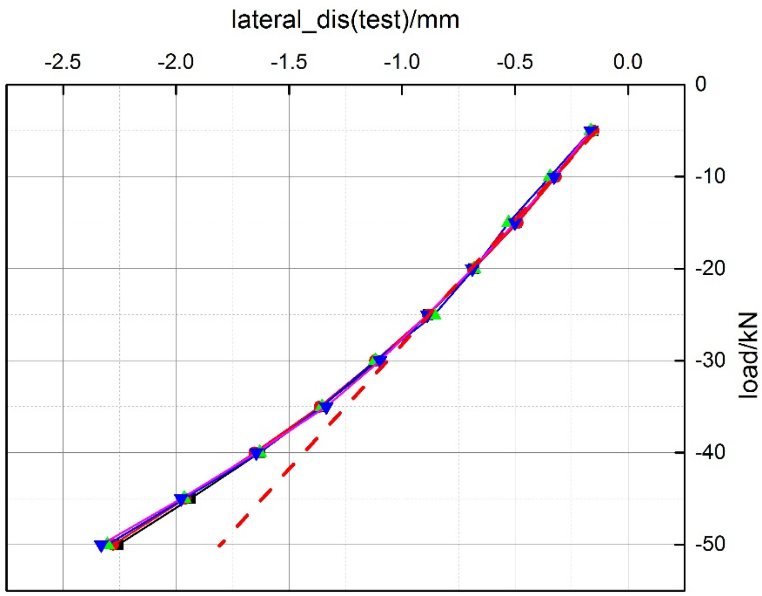


Fig. 4. lateral feature of rail head.

The distinct feature shown in lateral displacement-load curve of rail head is shown in Fig.4. Lateral displacement increases consistently along with growing load from the null point. The maximum lateral displacement on rail head appears at 2.404mm when the largest load (50kN) applied. However, displacement-load relation of rail displays nonlinearity instead of a linear relationship when variation trend of displacement lags behind load input. It indicated apparently that the whole lateral stiffness of rail structure K is by no means a constant while a function $K(t)$ can be depicted as it. In order to reveal the change law and influence factors of $K(t)$, analysis resulted from experiment measurement by using numerical model will be shared below. Related parameters are listed as shown in table 1.

Table1 Related parameters of rail structure

Related parameters	value
equivalent lateral stiffness of spring under track slab $\overline{k_2}$ / MPa	200
bending stiffness of rail EJ_y /(N m^2)	$1.08X10^6$
displacement from load point to torsional center $\overline{OD}$ /mm	94.77
torsional stiffness of rail GI //(/(N m^2))	$1.424X10^5$

4. Analysis

4.1. Stiffness characteristics of single fastener

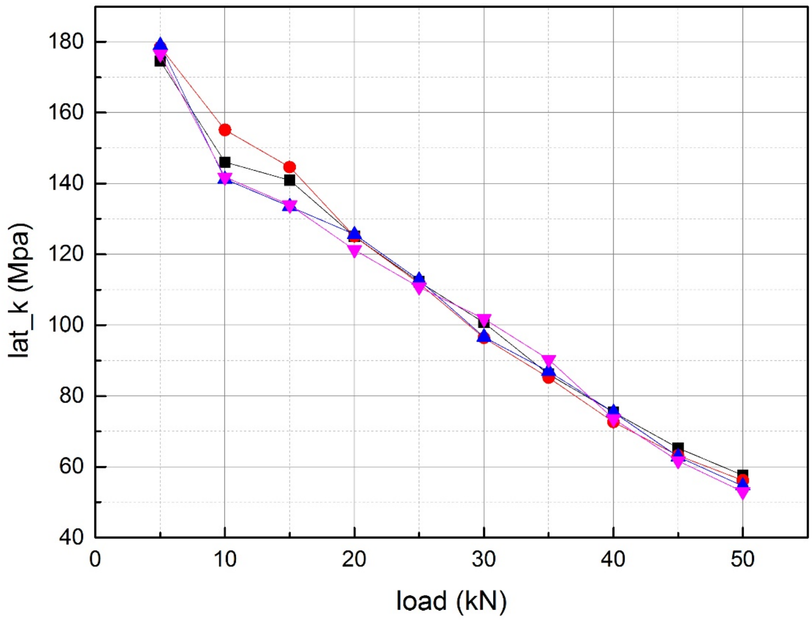
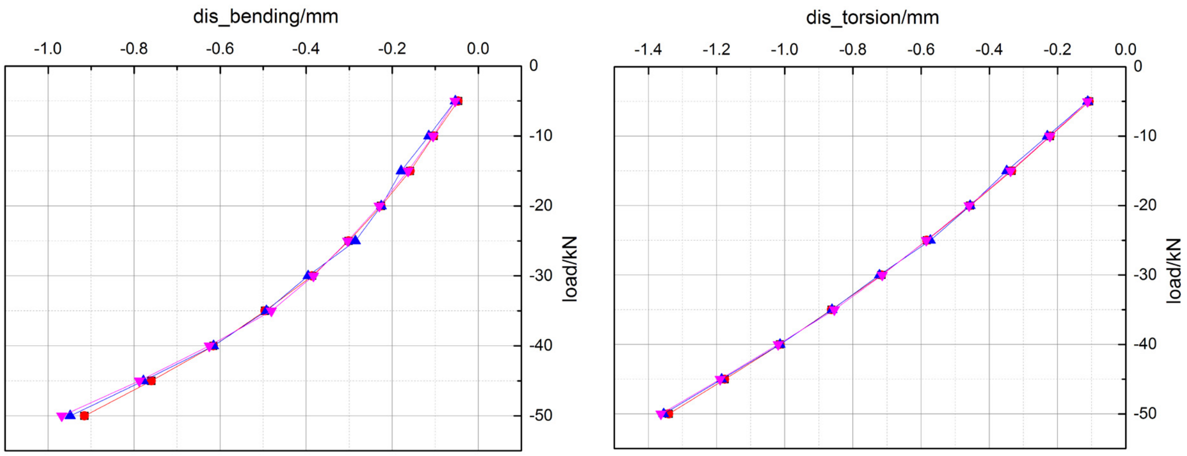


Fig.5 lateral stiffness k_1

From the testing results as shown in Fig.5 we can see value of lateral stiffness decreases steadily with increasing f applied instead of a constant referred in session 2. Also, it gives a reasonable interpretation about distinct nonlinearity of relation between displacement response and load input which is not given rise by numerical model in Fig.2, but in connection with a changing lateral stiffness of rail fastening system k_1 .



(a) bending deformation (b) torsional deformation

Fig.6 displacement-load curves of experiment

Compared with deformation induced by torsion accounting for 60% in all, nonlinearity of displacement affected by rail bending is outstanding as shown in Fig.6, where slope of curve denoted as stiffness apparently descends due to the dynamic response hardening (DRH) which results in the difference between kinetic and static friction. Since rail is static, load input is supported by elastic deformation and the real area of contact is large; while dynamic response force holds part of load excitation in order to diminish elastic force and the real area in motion.

4.2. Clamping force estimation

On the basis of both numerical calculation and test analysis, clamping force will be approximately obtained on existing line while experiments are commonly done in the lab by vertical tensile loading. This approach of prediction is helpful in reducing lateral displacement of rail and enhancing the security of rail structural system. The analysis of lateral stiffness k_1 confirms that nonlinearity is inevitable because of the DRH. Numerous studies indicate that lateral stiffness of fastener is a little lower than vertical whose value is hypothetically K_v=$1.5k_1$ when measured railway is a straight line without any curves as the test site in session 2. Clamping force P can be figured out through vertical displacement of rail support (fastening system) and k_1 when rail is stressed only by clamping force on loading side in vertical direction, can be given by the expression

$$P = K_v \ y = 1.5k_1 y \tag{4}$$

Fig.2 shows linear relationship of displacement-load curve when deformation is small, thus the approximation of clamping force is 10.95kN fitting curves of multiple tests by Bisquare equation. This value is a little lower than measured value offered by manufacturer. Rail fastening system distributed uniformly and continuously for a long time gives rise to clamping force descending. Hence, comparison show good agreement between the measured value and estimated force, which indicates a reliable method process.

4.3. longitudinal distribution of rail displacement

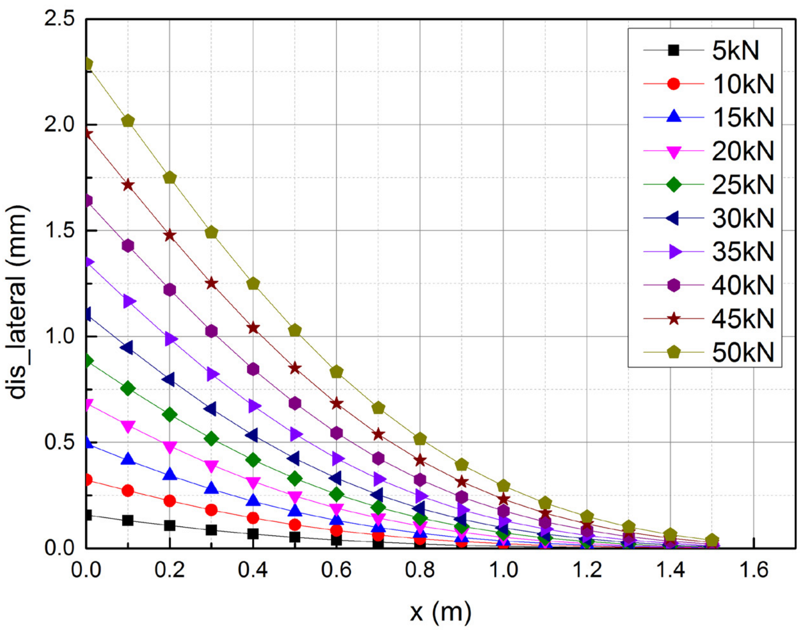


Fig.7 longitudinal distribution of rail displacement

Numerical analysis is also performed to explain lateral displacement distribution along the rail. Fig. 7 shows that lateral displacement experiences a sharp drop as x goes up. But the smaller lateral load is, the slower attenuation of displacement is. Displacement falls to 0.05mm by loading 50kN and 5kN when $x = 1.5m$ and $x = 0.7m$, respectively. Ratio of attenuation along rail line increases first and then decreases to zero regardless of loading value.

5. COCLUSION

Numerical model calculated to predict lateral features of rail fastening system indicates displacement caused by both bending deformation and torsion deformation grows linearly as load increases, whereas validation test designed for estimating clamping force is analysed obvious nonlinear relationship between them especially when large deformation appears. Nonlinearity lies mainly in rail bending due to the dynamic response hardening (DRH) that dynamic response force holds part of load excitation in order to diminish elastic force and the real area in motion. Clamping force can be derived from vertical displacement of rail support (fastening system) and lateral stiffness k_1 by fitting curves of this tests. Predicted value of clamping force is approximately equal to measured value offered from manufacturer. In addition, ratio of displacement attenuation in longitudinal direction increases first and then decreases to zero regardless of loading value. As a consequence, clamping force of rail fastener on existing line presented by numerical and experimental analysis in this paper provides a new idea of experiment which can be simple, convenient and enhance the security of railway.

References

[1] D. Tong, Railway Track [M]. Shanghai: China Railway Publishing House, 1998:53-55

[2] Y. Zhang and S. Lian. Analysis of Lateral Displacement of Rail while Considering the Twist of Rail [J]. Journal of Shanghai Tiedao University(Natural Science), 1997, 18(3): 18-23

[3] Jin Changshan, Study on Stick-Slip Transition Process within Dry Friction Pairs [J]. Lubrication Engineering, 2013, 38(5): 1-6

[4] LIAN Song-liang, TheoreticaI Calculation of the Track Structure Stiffness [J]. China Railway Science, 2004, 25(1): 67-71

[5] Chakherlou T N, Oskouei R H, Vogwell J. Experimental and numerical investigation of the effect of clamping force on the fatigue behaviour of bolted plates [J]. Engineering Failure Analysis, 2008, 15(5): 563-574.

[6] Lombaert G, Degrande G, Kogut J, et al. The experimental validation of a numerical model for the prediction of railway induced vibrations[J]. Journal of Sound and Vibration, 2006, 297(3): 512-535.

[7] Ishida M, Moto T, Takikawa M. The effect of lateral creepage force on rail corrugation on low rail at sharp curves[J]. Wear, 2002, 253(1): 172-177.

[8] D. Clouteau, G. Degrande, G. Lombaert, Numerical modelling of traffic induced vibrations, Meccanica 36 (4) (2001) 401–420.

[9] G. Lombaert, S. Franc- ois, G. Degrande, J. Kogut, Validation of a numerical model for railway induced vibrations, Proceedings of the sixth National Congress on Theoretical and Applied Mechanics, Ghent, Belgium, National Committee for Theoretical and Applied Mechanics, May 2003.