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Investigation of track stiffness quality based on rail foot bending strain utilizing structure optimization methods

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Abstract

Track stiffness variation is one of the major sources of track quality deviation. To investigate track stiffness, it is common to install trackside sensors to measure track answer under extern excitation. In this research, rail foot bending strain at the middle of rail seats along the track under normal train runs is recorded by strain gauge to investigate track stiffness quality. To determine track stiffness quality based on the measurement strain result, there exists two difficulties: firstly, the dynamic wheel load is time-variant and unknown; secondly, the relationship between rail seat stiffness and rail bending strain is a multi-input-multi-output function, which makes a direct analytical solution difficult.

The first issue is solved by introducing the concept of the strain-location curve. The second issue is solved by transferring the problem to a structural optimization problem. The commercial structure optimization software Ansys Designxplorer® is used to processing field measurement result and a good match is achieved.

Keywords: track stiffness; rail bending strain; structure optimization.

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1. Introduction

Track stiffness is a term to describe the track deformation under given external load. An ideal track should have a constant stiffness distribution to limit additional dynamic wheel-rail-interaction load. However, due to initial design and build imperfection, component variation as well as track deterioration during its lifetime track in real life would always show track stiffness variation. Strong variation of track stiffness could lead to declined track safety and passenger comfort, increased dynamic vehicle-track-interaction load and rise of maintenance activities. Therefore, it is important to monitor track stiffness deterioration in operation.

With the development of technique, plentiful track stiffness monitoring methods have been developed. Generally, track stiffness measurement methods could be divided into two groups: standstill measurement methods and continuous measurement methods (Wang et al., 2016).

The standstill measurement methods measure track answer by preinstalled sensor on the track under externally introduced load. Sensors for such measurement could be:

- inductive transducers to record the track deflection,
- velocity transducers or geophones to record track deflection velocity,
- accelerometer to record track acceleration.

The continuous measurement methods are designed for continuous track stiffness measurements along long sections. Such measurements are performed utilizing special designed measurement wagon, for example the Track stiffness measurement vehicle of Swiss Federal Railways (SBB), the track modulus measurement system developed by University of Nebraska (USA), the Rolling Stiffness Measurement Vehicle (RSMV) developed by Banverket, Sweden (Berggren, 2009) and so on. The SBB measurement vehicle determines track stiffness by comparing track deflection under different axle loads when the vehicle runs by. RSMV investigates track stiffness by measuring the axle acceleration under dynamic excitation introduced by the vehicle.

For small-scale research purpose, the standstill measurement methods are more suitable without the need of special measurement vehicles. In this research, track stiffness is measured using strain gauge to measure the rail bending strain at the middle of rail seats under normal train runs. Comparing with inductive transducer, it has the advantage that it does not require extra reference measurement base, which must have no deflection under train runs to ensure the accuracy of the measurement result. Comparing with the Falling Weight Deflectometer method and impact hammer method it has the advantage that the measurement results reflect the “real” track answer under true load situation. Considering the non-linearity characteristic of track stiffness, the stiffness under different preload could vary greatly.

However, two problems come together with this approach:

Firstly, the exact load introduced by normal train is unknown. Therefore, it is not possible to determine the absolute track stiffness by this method. However, considering the fact that what really influence the track stiffness quality is the track stiffness deviation rather than the absolute track stiffness value, it is enough to evaluate the track stiffness quality by determining the distribution of relative rail seat stiffness along the section.

Secondly, it is more difficult to determine relative rail seat stiffness by rail bending strain comparing with by rail seat deflection. The relationship between rail seat stiffness and rail seat deflection could be considered as one-input-one-output function, which could be solved using iteration method (Liu, 2015). However, the relationship between rail seat stiffness and rail bending strain at the middle of two rail seats is multi-input-multi-output (MIMO) function. To solve this issue, it is turned to the structural optimization method.

2. Field measurement and data processing

2.1. Choose of measurement section

In the scope of EU research project DESTination RAIL, Technical University Munich (TUM) initiated meetings with Deutsche Bahn (DB) representatives in 2015 to receive support. DB helped TUM to select a track section of a railway line in the south of the city of Munich, which is an old, conventional ballasted line with the superstructure component of Rail S 54, K rail fastening system and concrete sleeper B 58. This section was chosen based on following consideration:

- The radius of the section is larger than 2000 m, which could be considered as straight track; The line is horizontal, train speed (V_{max} = 140 km/h) is constant and traction force is low (no station/stop close to the pilot section),
- The section show no discontinuities along the superstructure (track form) or substructure type like transitions, bridge decks, under crossing etc., and can be considered as a homogenous section,
- Previous investigation has identified two locations, which show low and high track stiffness variation respectively.

In conclusion, this section is characteristic for a straight, homogenous section of normal track quality with problematic location (location 1) and reference location (location 2). Thus, it is an ideal starting section to study the feasibility of this approach.

Location 1 lies 130 m ahead of location 2. On both location 1 and location 2, 9 strain gauges are installed at bottom of rail in the middle of rail seats continuously. The rail bending strain at the two sections are measured under same train runs.

2.2. Processing of rail bending strain measurement results

The process of data processing for both locations are the same. Firstly, the measured bending strain under the last bogie was filtered with 500 Hz Butterworth low pass filter to eliminate the measurement noise and then ordered according to time sequence. Then the peak values of each strain gauge are picked up. Meanwhile the measured strains from all other strain gauges, when one strain gauge arrives its peak value, are also plotted. In this way the continuous measurement results curves are discretized with respect to the axis of rail seat sequence and time sequence axis.

In this way, a strain matrix is established:

$$\varepsilon_{ij} = \begin{bmatrix} \varepsilon_{11} & \cdots & \varepsilon_{1n} \\ \vdots & \ddots & \vdots \\ \varepsilon_{n1} & \cdots & \varepsilon_{nn} \end{bmatrix}$$

with:
ε_{ij} = the strain measured at position i, when the strain at position j arrives its peak value, i, j $\leq$ n,
n = the number of installed strain gauge.

A 3-D plot of rail bending strain (ε) matrix with respect to rail seat sequence (s) as well as to time sequence (t) is showed in Figure 1.

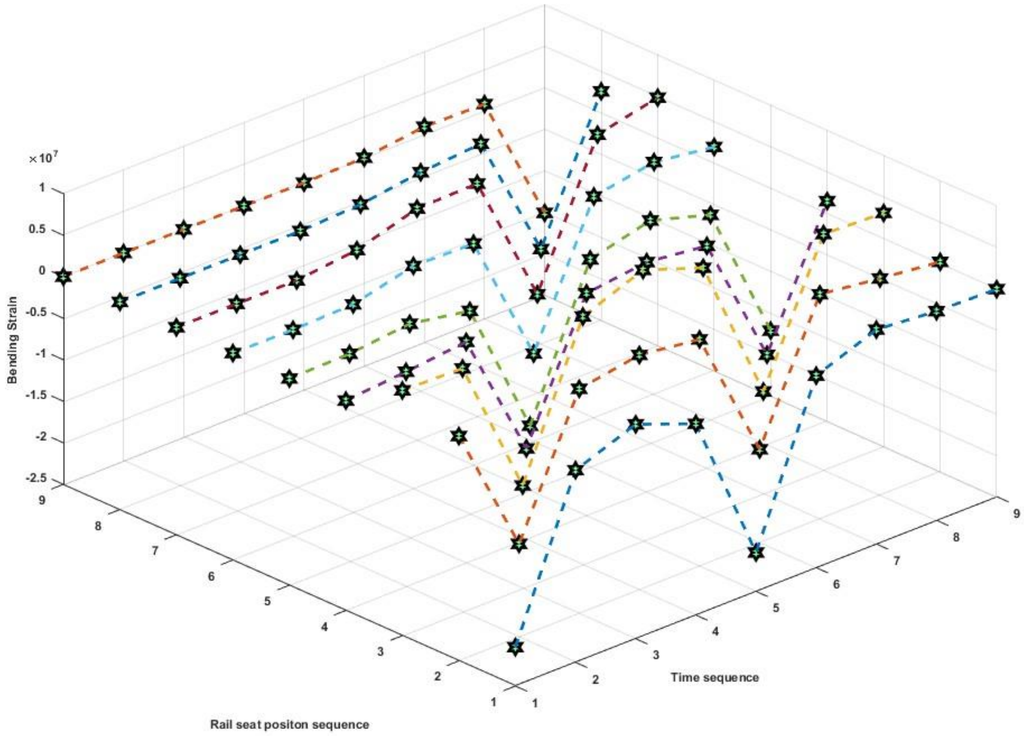

Fig. 1 3-D plot of rail bending strain

It is self-evidence, that the measurement result of a strain gauge arrives its maximal value, when the wheel is exactly above it. Accordingly, the train speed could be calculated based on rail seat distance and the time interval, in which two neighbor stain gauges arrive its peak values respectively. Graphically train speed is the tangential ration of the peak value in s-t plane in Figure 1. With the sleeper space of 0.63 m, the average train speed at the two sections are calculated as 139.4 km/h and 140.8 km/h respectively, which fits with the information from DB that the train speed in the section is 140 km/h. When comparing the two locations, the influence of speed variance is thus eliminated.

When Figure 1 is cut by plane parallel to ε-t plane at $s = s_0$, it shows the strain history of the chosen rail seat s_0 during the train runs. Such a line is showed in Figure 2.

Similarly when Figure 1 is cut by plane parallel to ε-s plane at $t = t_0$, it shows the distribution of rail bending strain along the measured section at this selected time point t_0. An example line in strain-space plane is showed in Figure 3.

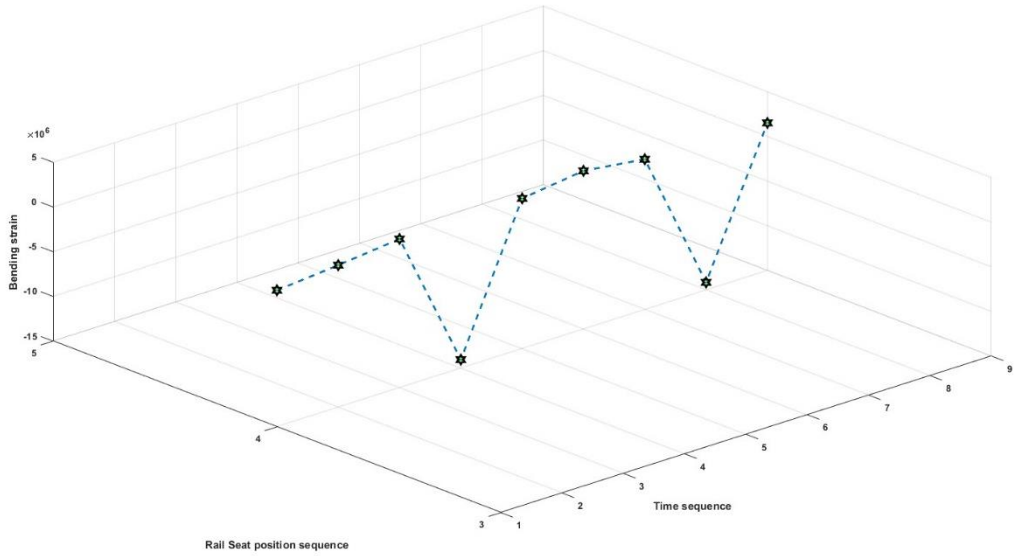

Fig. 2 Strain-time (ε-t) curve of 4th rail seat

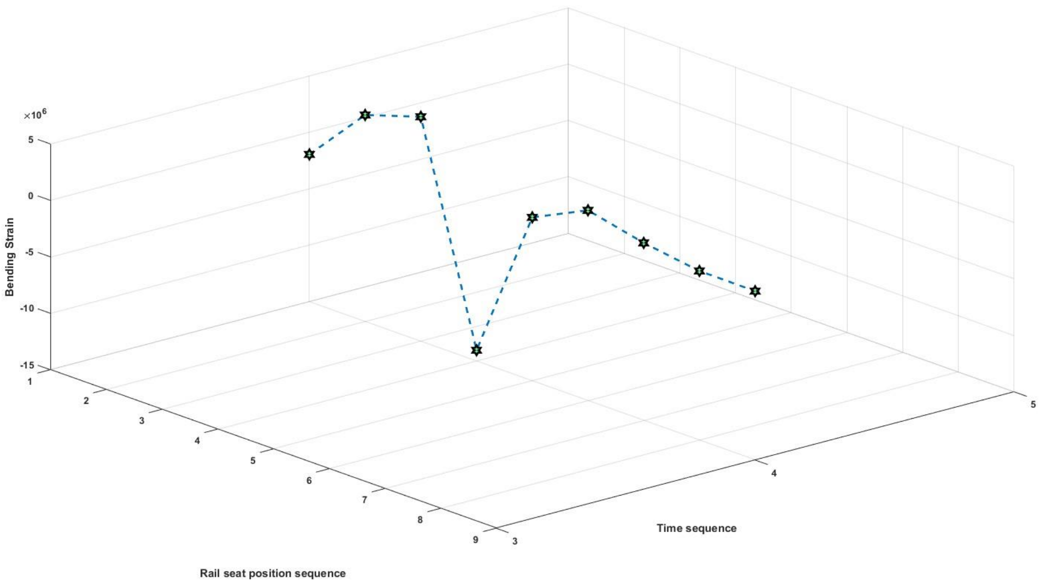

Fig. 3 Strain-space (ε-s) curve at time sequence 4

It makes less sense to compare the maximal bending stress at different locations, i.e. in different ε-t curves, because the introduced wheelset force at different time could or in most case actually must be different due to the dynamic vehicle-track-interaction. In contrast, ε-s curve is free of this time-variable load influence, while at each time instance, the wheel-rail- contact force could be assumed as constant, although its absolute value is unknown. Under the assumption that high-frequency vibration of rail is filtered by the low-pass-filter, only low frequency motion is remaining, so the bending strain in only related with rail deflection at the selected time instant.

It could therefore be concluded that a ε-s curve is reflecting the distribution of rail seat stiffness along the section, thus the relative rail seat stiffness could be determined.

3. Determination of relative rail seat stiffness based on rail bending strain

As mentioned above, the relationship between rail bending strain and relative rail stiffness is a multi -input-multi- output function, which makes a direct analytical solution difficult. The problem is solved by using Ansys DesignXplorer® studying the ε-s curve, which provide algorithms to reveal the MIMO relationship among input and output parameters of mechanical structures.

3.1. Idealization of track structure

Following idealization of track components are performed:

- Stiffness of all track components are considered as linear-elastic.
- Only the wheel-rail-interaction in vertical direction is considered. The interaction in horizontal direction is not considered here. It is assumed that the behaviour of vehicle and track are symmetric with respect to the track centre line. So only half of the system is considered in the modelling.

Rail is simulated as a beam with exact rail S 54 cross section, which are connected by linear springs at every rail seat to simulate the supporting stiffness. To eliminate the boundary effect, the beam contains 31 rail seats. However, only the rail seat stiffness at the center 10 rail seats have been set as variable (since along each section 9 strain gauges have been installed), others would be considered as constant. Therefore, the measured result from the first two and last two stain gauges could not be fitted totally and would not be considered as criterion.

3.2. Introduction of structure optimization method

Ansys DesignXplorer® is originally designed for structure optimization problems. A typical structure optimization problem could be described as:

Minimize f(x) subject to

$$G_j(x_i) > 0$$
$$x_i \subseteq X_i$$

with:
f (x) is the object function to be optimized
x_i are the design variables
X_i are the feasible domain of x_i,
$G_j(x_i)$ are the constraints

To find the optimized f(x) in the feasible domain under given constraints, it is essential in structure optimization to reveal the correlation between the design parameters and object function. Due to this consideration, many algorithms including reaction surface, neural network etc. are developed especially to simplify the optimization process under MIMO implicit relationship. Those methods could be implemented here to find the relationship between rail bending strains and rail seat stiffness:

$$Minimize\ abs([\varepsilon_i - \varepsilon_{i,meas}])$$

$$with\ k_j \subseteq K$$

with:

ε_i = simulated rail bending strain at position i,
$\varepsilon_{i,meas}$ = measured rail bending strain at position i,
k_i = rail seat stiffness at rail seat j,
K = feasible domain of rail seat stiffness, here as $[0.01 * k_{standard}, 10 * k_{standard}]$

The relationship between object parameters and design parameters are not given explicit, but implicit defined by the mechanic behavior of the above-mentioned idealized structure.

While the exact dynamic load is unknown, it is not possible to determine the exact rail seat stiffness, which is however not a problem, because the focus here is the relative track stiffness distribution along the section to get track stiffness quality. While the system is linear-elastic, a unit point load is considered as input load.

3.3. Calculation and calibration

Principally there are 9 strain-location curves that could serve as the object. However, to eliminate the influence of boundary conditions, take section 1 as example, only the strain-location curve at time sequence 4, 5 and 6 are chosen as 3 independent objective sets.

To calibrate the relative rail seat stiffness determined from this method, retroactive calculation must be performed: a set of determined relative rail seat stiffness is only then considered as valid, when the rail bending strain calculated from it fit all the 5 curves. The investigation process is described as in Figure 4.

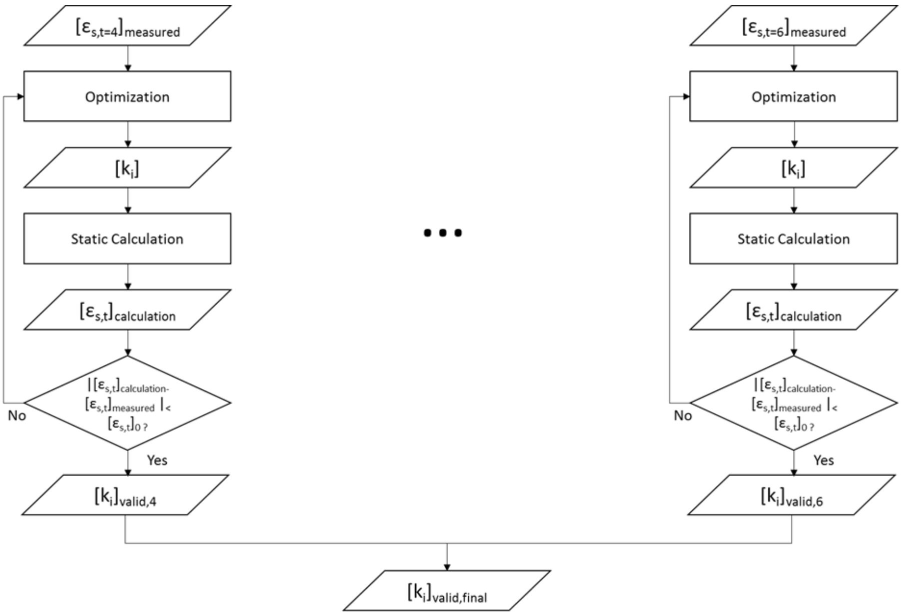

Fig. 4 flow chart to determine relative rail seat stiffness

As a first approach, the relationship between rail seat stiffness and rail bending strain has been investigated by direct optimization utilizing the Screening algorithms, which is a non-iterative direct sampling method by a quasi-random number generator based on the Hammersley algorithm. The simulated bending moment under the relative track stiffness, which has been determined using the above-mentioned method, are listed in figure 5. Calculation based on different curves leads to the same parameter selection, and the results fit for every situation, so it could be concluded the numerical calculated results fit together with the measured results.

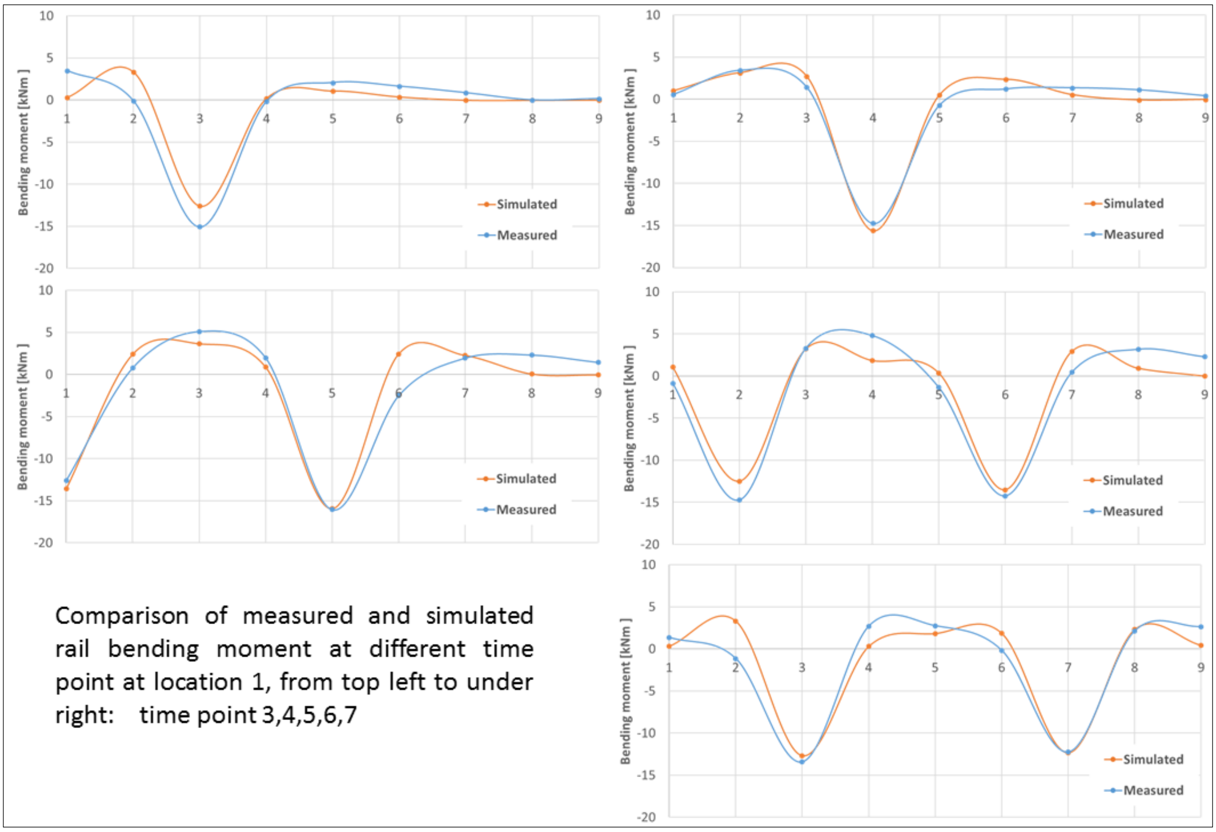

Fig. 5 comparison of rail bending moment from measurements and from the calculated relative track stiffness

Under the same way the relative track stiffness at location 2 is determined, a comparison of the relative rail seat stiffness at the two sections normalized with respect to average track stiffness along each section is showed in figure 6.

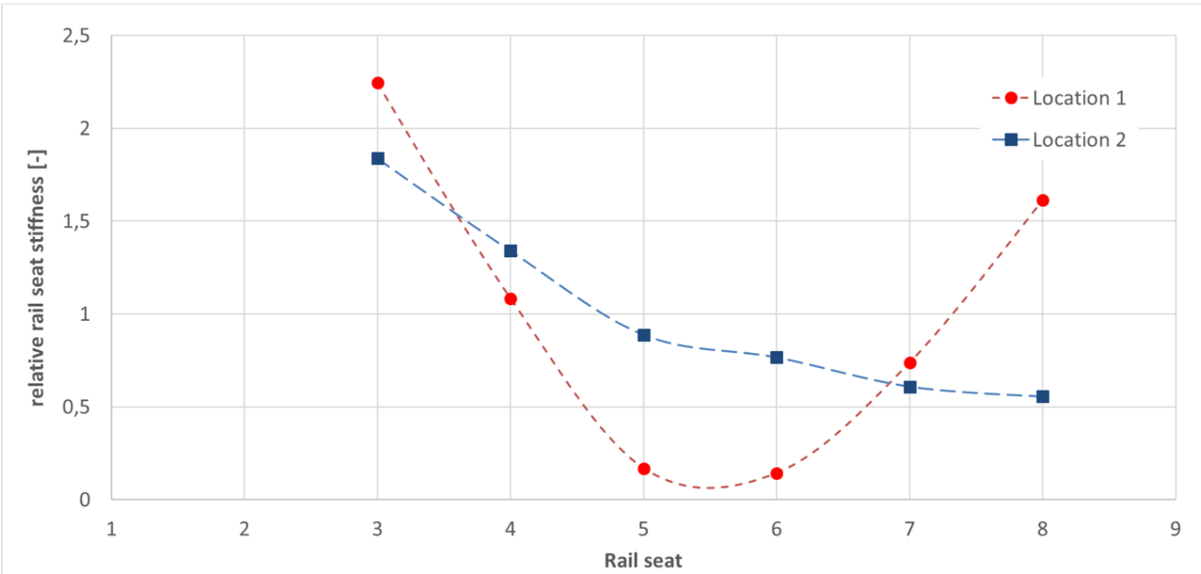

Fig. 6 compare of relative track stiffness at location 1 and 2

The variation of track relative stiffness is apparently high at location 1 compared with location 2, which fits the result of preliminary investigation.

4. Conclusion

In this paper, an approach utilizing the numerical tool Ansys DesignXplorer® to process rail bending strain to investigate relative track stiffness is established.

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5. References

BERGGREN, E. G. 2009. Railway Track Stiffness: Dynamic Measurements and Evaluation for Efficient Maintenance. 2009:17, KTH.

LIU, D. 2015. The influence of track quality to the performance of vehicle-track interaction. München, Technische Universität München, Diss., 2015.

WANG, P., WANG, L., CHEN, R., XU, J., XU, J. & GAO, M. 2016. Overview and outlook on railway track stiffness measurement. Journal of Modern Transportation, 24**,** 89-102.