BALLAST RESISTANCE UNDER THREE DIMENSIONAL LOADING

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Samenvatting

In het kader van een internationaal onderzoeksproject werden door het Laboratorium voor Weg- en Spoorwegbouwkunde van de TU Delft een aantal driedimensionale schuifweerstandsproeven op een volledig ballastspoor werd uitgevoerd Het doel was het aanleveren van experimentele getalgegevens ten behoeve van het valideren van een recent ontwikkeld computerprogramma CWERRI, dat een volledige beschrijving geeft van het spoorspattingsgedrag van spoorconstructies.
Om te voldoen aan de strenge eisen ten aanzien van de representativiteit van het proefspoor werd een volledig nieuwe proefinstallatie gebouwd voor dit doel.
Naast het beschikbaar komen van een goed gedefinieerde set kwantitatieve gegevens betreffende het driedimensionale gedrag van ballastspoor, zoals gespecificeerd door ERRI, wordt ook enige nuttige informatie verstrekt over de selectie en behandeling van ballastmateriaal in het algemeen.

Summary

Within the framework of an international research project the Roads and Railways Research Laboratory of the TU Delft (Delft University of Technology) conducted a series of full-scale three-dimensional ballast resistance tests using a rail track panel. The aim was to provide experimental data to validate the recently developed computer program CWERRI, which gives a complete description of the buckling behaviour of railway tracks.
To meet the severe test requirements regarding the representativity of the test track a completely new test facility was built for this occasion.
Apart from the availability of a well-defined set of quantitative data concerning the three dimensional behaviour of ballast track as required by ERRI, additional useful information is given regarding the selection and handling of ballast material in general.

Contents

1. Introduction

To improve the understanding of the behaviour of Continuous Welded Rail (CWR) a theoretical research programme was initiated by ERRI/D202/WG3. Also, an experimental programme was formulated to provide the necessary input data and validation for the models. The Railway Engineering group of the TU Delft (Delft University of Technology) was invited to participate in the experimental programme according to a Test Specification. One particular result of interest was the graph relating the lateral resistance force exerted on a sleeper and the associated lateral displacement. Fig. 1 gives the assumed behaviour with some characteristic points.

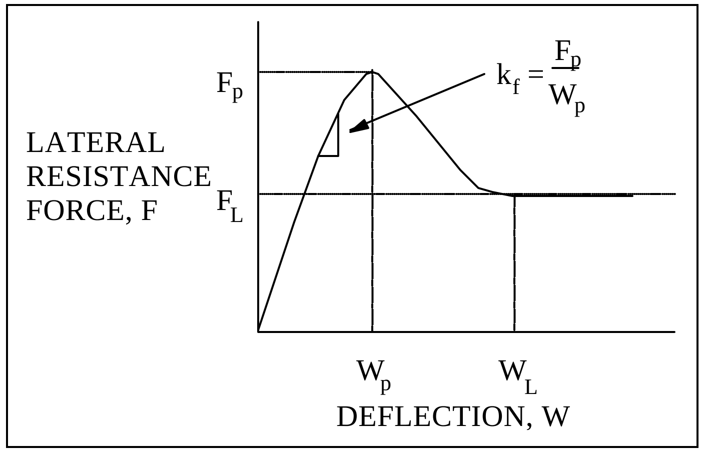

Figure 1. Lateral resistance characteristic definition

To obtain more representative results a track panel with 5 sleepers was chosen for the test rather than using a single sleeper test.

2. Test methodology and procedure

In this test the condition of the ballast in terms of geometry and compaction may have a decisive influence on the test data results. Therefore a very careful treatment of the ballast is necessary. Firstly, the boundary conditions of the ballast layer should approach the same deformation of the ballast under lateral and/or longitudinal loading as occur in practice. This means that the dimensions of a box containing the ballast should be large enough to prevent confining boundary effects. Secondly, the initial compaction state of the ballast should be maintained at the start of all tests to provide reproducible results. After each test, which is inherent destructive, the track should therefore be tamped and relined (preferably not lifted) and the ballast compacted using the same maintenance methods and procedures.

3. Description of the test conditions

A general top view of the complete test facility is given in Fig. 2. The ballast confining box is composed of four heavy beams (HEB 1000) which also function as reaction beams for the sub-systems mounting the hydraulic actuators. The position of the test track is asymmetrically chosen with respect to the ballast box to minimise possible confining effects. A revolving crane was erected to place the vertical load elements on the track and to perform the lifting operation (negative vertical load) required at some test cases.

4 Track construction

The cross section of the test track is shown in Fig. 3 and is composed of (top down):

- 2 rail lengths, section UIC54;
- 5 prestressed concrete sleepers NS90 with Vossloh fastenings Skl1 and railpad Fc9;
- ballast bed crushed stone 30/63, thickness under sleeper 30 cm;
- ballast mat James Walker type FC600/FC101;
- concrete slabs (Stelcon) 2mx2mx10cm, total 120 m^2;
- sand foundation (subgrade).

According to the classification given in D202/WG3/Activity 1, the ballast condition can be characterised as weak ('lightly consolidated or tamped track with reduced ballast shoulder'). In the lateral direction removing the ballast corresponding with a fictive next sleeper (dotted rectangle in Fig. 4) simulated the continuity in real track. Not removing the ballast on this spot would give extra volume ballast to move in longitudinal testing resulting in an extra resistance.
The elastic ballastmat underneath the ballast simulates the substructure if the supporting structure is relatively stiff as in this case.

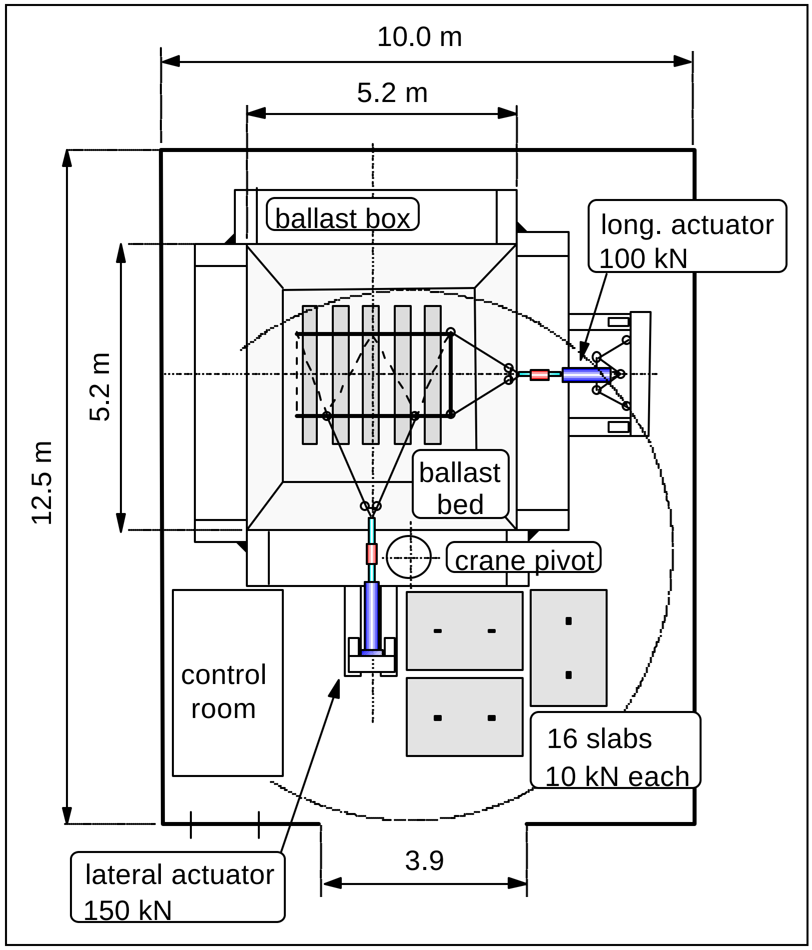

Figure 2. Top view of test facility for three-dimensional testing of ballast resistance

5. Building the test facility

As it was not possible to use existing test facilities in the laboratory building another suitable test location had to be found to perform the test programme mentioned above. After considering several options it was decided to build a temporary test facility on the testing ground available behind the laboratory building. Deciding factors in this respect were the easy availability of electric and hydraulic power resources, the direct technical support from the laboratory during the building and testing period and the easy accessibility for track maintenance operations. To be independent of the weather conditions and to protect the control and measuring equipment, it was necessary to build a temporary shed accommodating the complete test facility.

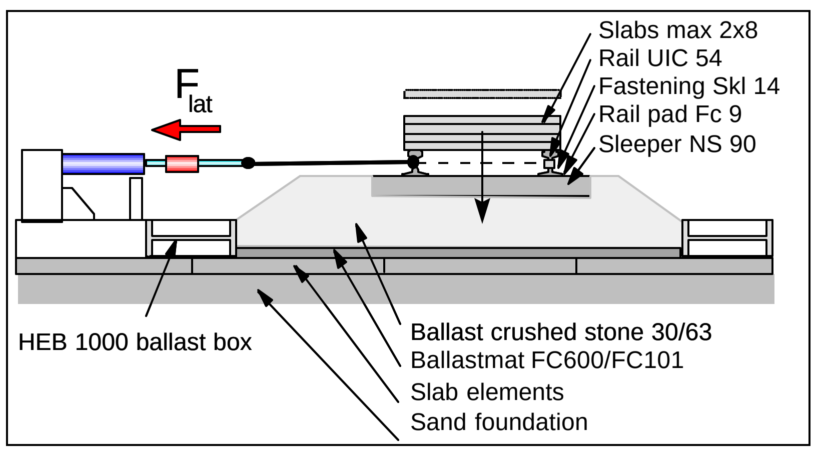

Figure 3. Cross section of test track during lateral testing with downward load.

6. Load system

At first, a hinged bar system was considered to distribute the pulling forces on the test track. On second thoughts this solution appeared too cumbersome and would increase the time window for the maintenance operations, hence would delay the progress of the test period. A better alternative is the triangle solution where the pulling force is divided over two points of the track panel.
As can be seen in Fig. 2 the load introduction in the lateral direction is achieved by means of two diagonal rods connecting the hydraulic actuator (150 kN) to the track section. Two connecting beams are welded between the rails to reinforce the track panel enabling a more uniform load introduction. In

however the longitudinal actuator was mounted in a special device allowing the longitudinal actuator to 'follow' the transversal movement without rotation during the execution of type iii tests.

Both actuators are programmed under displacement control to fulfil a complete measurement with a constant low velocity of 10 mm/min. However, in the mixed tests the longitudinal actuator, which must maintain a constant longitudinal load level, operates under load control.
The hydraulic power was acquired from a pumping house, which was located at a distance of 50 m from the testing shed.

The variable vertical load was put on the track by dead weight existing of concrete slabs with dimensions 2m x 1.5m x 10cm, weighing 9.95 kN each.

7. Measurements

According to the Test Specification, in some test cases the complete resistance relationship must be measured while in other cases it is acceptable to determine the maximum resistance force only. Because all measurements are automatically and digitally recorded it was easier to measure always the complete resistance relationship and determine the maximum value afterwards (if wanted).
Fig. 4 shows the location and direction, code, channel and application of all twelve transducers used in the test. The displacement transducers are LVDT's, except D5 and D6, which are potentiometers. These lateral and longitudinal displacements are significant (200 mm may be necessary in the lateral case, 50 mm is expected in the longitudinal case). The track related displacements are absolute. To this end the displacement holders are fixed to stiff unloaded reference beams connected to the ballast containing box. The twelve transducers and one extra channel for the power supply were automatically measured and digitally recorded simultaneously. The measuring equipment was installed in a temporary control room. The PC-system was provided with a data-acquisition board and appropriate software.
During each ballast resistance tests all thirteen measuring channels were scanned nearly simultaneously at a rate of 1 Hz. Before testing all transducers had been calibrated in the range of application. The data were processed using several software packages.

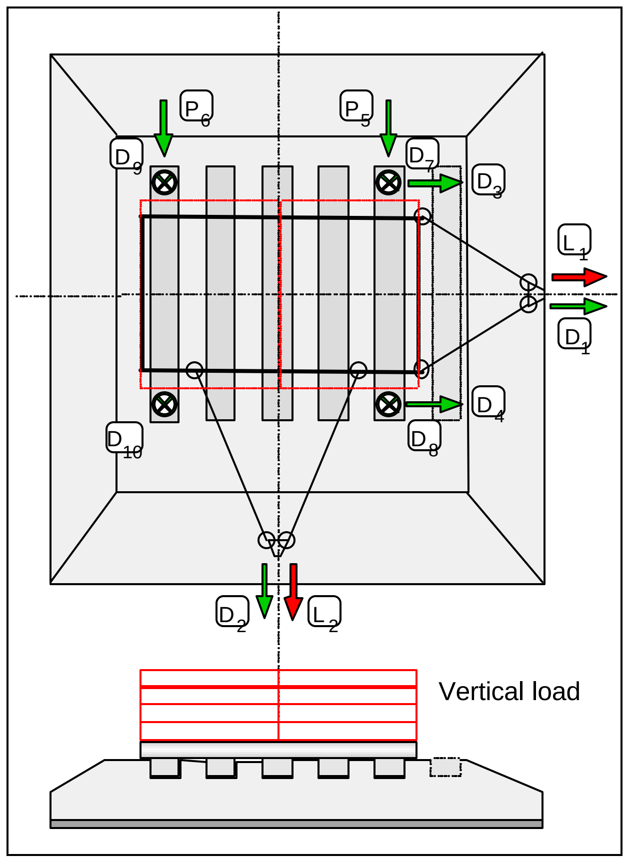

Figure 4. Location and direction of measured forces and

8. Results

8.1 Lateral resistance of the track panel in ballast

To analyse the results from the measurement data the appropriate columns for force and displacement were transferred into the Matlab environment. Here a data reduction took place and an automatic curve fitting routine was applied to produce the best fit of the data based on the formula:

$$F = c_1 x e^{-l_1 x} + c_2 (1 - e^{-l_2 x}) \qquad (1)$$

where F= the lateral force; x = the lateral displacement, c_1 and c_2 are two linear and λ_1 and λ_2 are two non-linear curve-fit parameters. It should be stressed that formula (1) is used here as a mathematical approximation only and does not claim any physical meaning.

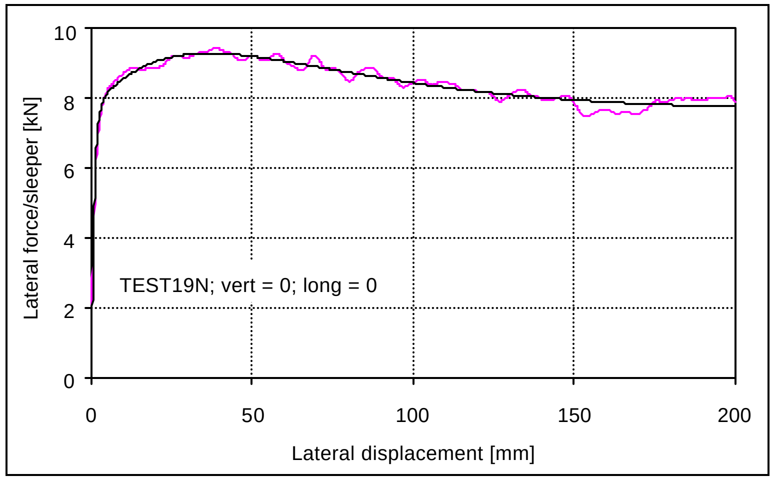

Figure 5. Lateral resistance track in ballast

Figure 5 shows one graphical result for the lateral resistance without both longitudinal and vertical load and its curve-fit approximation.
As this curve fit function gives a very good approximation of the experimental data, it is very easy now to obtain mathematically the values of the particular points Wp, Fp, FL and WL (see for definition Figure 1).
The relationship between the peak lateral resistance Fp and the minimum lateral resistance Fl is drawn in Fig. 6. Apparently, the relation is rather linear. The trendline is also given.

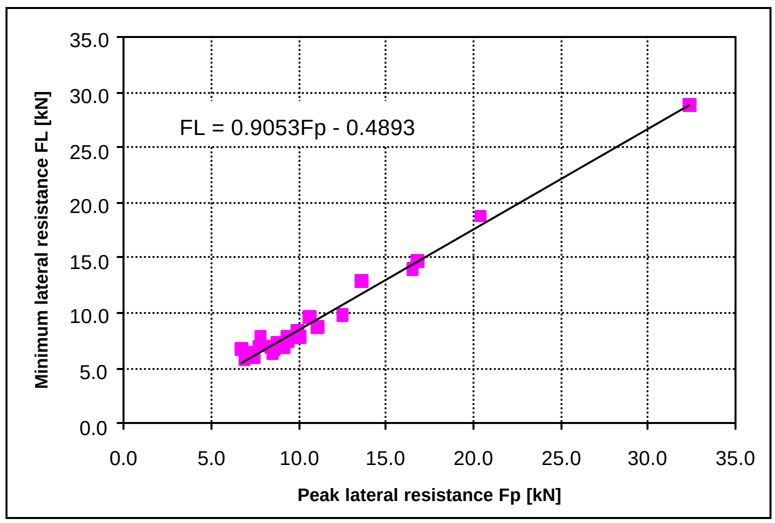

Figure 6. Relationship between peak and lateral load resistance.

Another interesting relation exists for the lateral resistance versus the vertical extra load to determine the coefficient of friction. This relation, depicted in Fig. 7, can be approximated by the following trendline:

$$Fp_{lat} = 0.7247V + 9.0119 \qquad (2)$$

This result corresponds well with the corresponding lateral results found by other researchers [1]:

BR Data :Fp = 0.665V + 8.978
TUD Data :Fp = 0.725V + 9.012
US Data :Fp = 0.860V + 6.851
DB Data :Fp:= 0.872V + 11.204

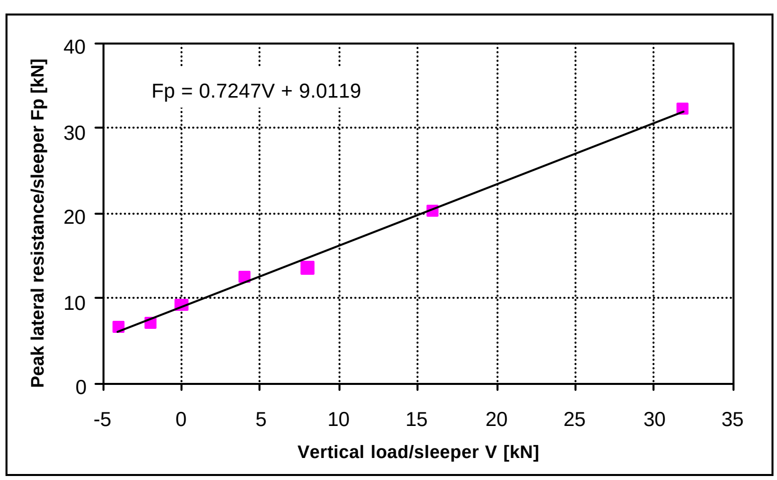

Figure 7. Peak lateral resistance versus vertical load; Longitudinal load = 0.

8.2 Longitudinal resistance of the track panel in ballast

In general, the curves of the longitudinal resistance have the same form as the lateral curves. For the analysis of the longitudinal resistance the same curve-fit formula (1) could be used. Of course, the symbols F and x now stand for the longitudinal force and displacement, respectively.
The variation in the test results is somewhat higher as is the case with the lateral tests, probably due to the variable condition of the ballast part in front of the track panel.

8.3 Lateral resistance test of the track panel with mixed Fvert/Flong

The relation between the peak lateral load and the value of the constant longitudinal force is depicted in Fig. 8 for different values of the vertical load.

This picture can be regarded as a projection of the 3D spatial points on the first quadrant of the Flat/Flong plane. The numbers in the diagram refer to the test number. The test point number 7N is found by interpolation of the test points 6 and 7.

The points from the longitudinal tests 13, 14, 15N, 17, 18 and 20N (without lateral load) are only presented in the diagram as a reference to indicate the 100 % peak value of the longitudinal tests. They should not be considered as valid lateral load point. Therefore, the lines sections, leading to these points, are dotted.

According to the expected behaviour, these relations should have an elliptical form. For low vertical loads, this behaviour is more or less confirmed, For high vertical loads, the peak lateral resistance tends to become independent of the pre-set longitudinal load

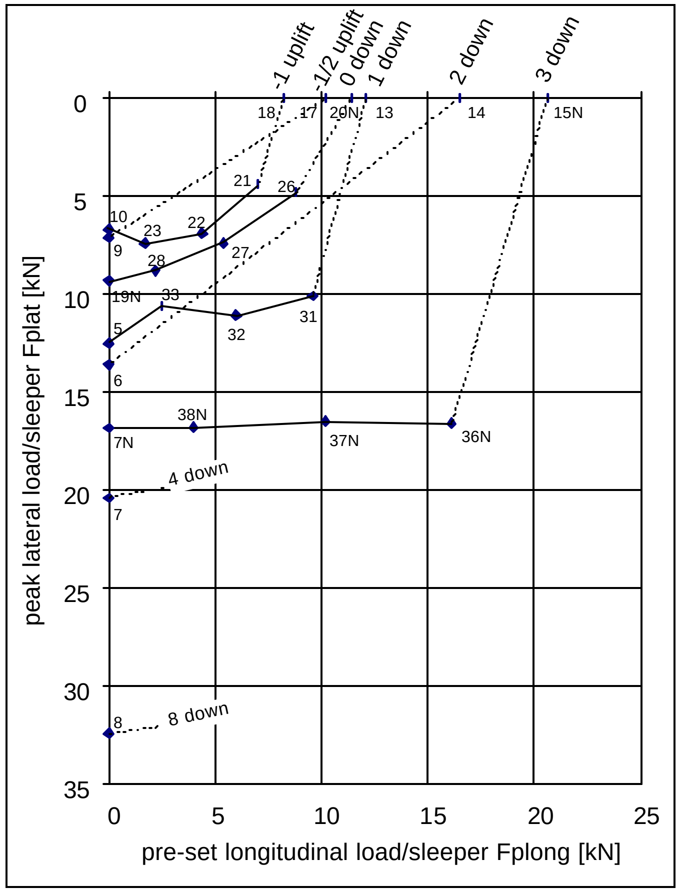

Figure 8. Lateral peak resistance points in mixed tests

8.4 Vertical displacement of the track panel with mixed Fvert/Flong

In Figure 9 a typical three-dimensional picture is given of the vertical displacement of the test track in different loading situations, based on the four vertical displacements measurements at the corners of the test track panel. The position of the rectangle, representing the track panel (consisting of 2 rails and 5 sleepers) is given at the beginning, half-way and at the end of the test period. As shown in this example, the vertical movement can be quite substantial. In some cases, as the one drawn in the figure, the vertical displacement exceeds 40 mm.

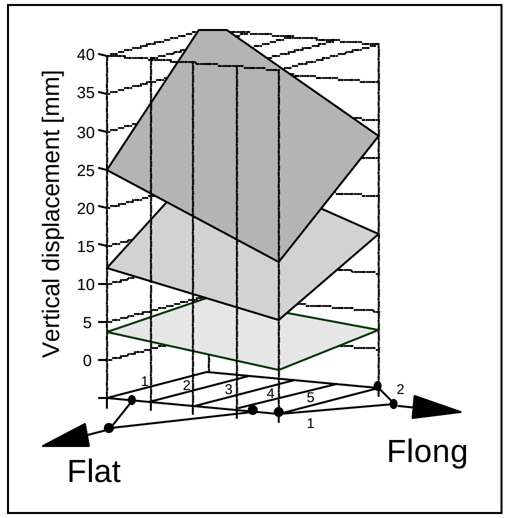

Figure 9. Example vertical displacement of track panel in ballast with mixed loads

8.5 Longitudinal resistance of rail to fixed sleeper (Flat = 0)

In a separate test rig in the laboratory the longitudinal load was also measured as a function of the longitudinal rail displacement relative to the sleeper. The same type of rail-sleeper assembly and loading conditions were applied as in the track panel in ballast.

It is interesting to compare both results with each other. In Figure 10 both results have been drawn, together with their trendlines. Apparently, for relative low vertical forces, the resistance of the fastening system is greater than the track panel in ballast. However, there is a clear indication that the two lines probably will cross each other at about V = 15 kN/sleeper (equivalent of two supports). This means under higher vertical forces the longitudinal resistance is limited by the ballast resistance and not by the fastening system. It should be noted, however, that in both experimental cases only vertical forces were acting on the railheads and no longitudinal friction forces were allowed to develop, as can be expected in practical circumstances

For the unloaded case (V=0) the resistance rail/sleeper is 1.73 higher than the corresponding resistance track panel to ballast, which is of importance in breathing zones of CWR track.

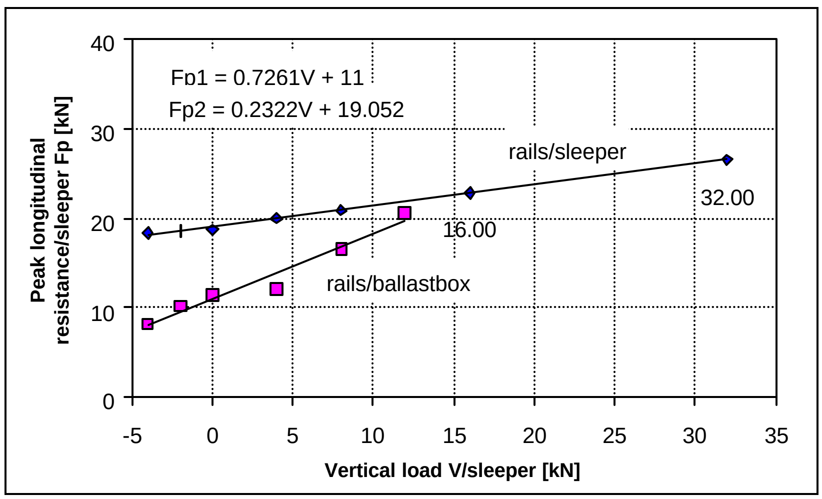

Figure 10. Comparison of the peak longitudinal resistances, measured in the track and in the separate fastening test

9. Main results and conclusions

1. The experimental programme, consisting of a series of full-scale three-dimensional ballast resistance tests, and carried out under laboratory conditions, produced new and satisfying results about lateral and longitudinal resistance characteristics, under various vertical loads.

2. The expected behaviour of a clearly defined peak value and limiting value in the lateral resistance characteristics under 'medium' ballast condition is confirmed, although the effect is little pronounced. The resistance level was found higher than was expected and may well correspond with a ballast condition 'medium' rather than 'weak'.

3. The qualifications 'weak', 'medium' etc. to express the ballast condition should be quantified, for instance in percentages of allowable minimum resistance.

4. The relation between the lateral or longitudinal force and the displacement can be very good approximated in all cases by an exponential expression with four constants.

5. Based on all tests there is a good linear relationship between the peak and minimum resistance force and between the peak resistance force and vertical load. This applies for the lateral as well as for the longitudinal resistance.

6. For negative and low positive vertical loading the expected elliptical behaviour in the lateral/longitudinal peak force plane under the combined longitudinal and vertical loading is more or less confirmed. For high vertical loads however, the peak lateral resistance tends to become independent of the pre-set longitudinal load

7. The vertical movement of the track at high uplift and longitudinal forces, while performing a lateral or longitudinal test, can be rather significant due to the vertically free movement of the track panel.

8. The separate test series to determine the longitudinal resistance of the rail on a fixed sleeper showed a bilinear behaviour. The peak resistance force corresponds well with the value supplied by the manufacturer.

9. There is a indication that for higher vertical load levels the peak longitudinal resistance may be determined by the fastening system rather than the track panel in ballast system.

10. When ballast material is involved in testing great care should be taken in obtaining the right fraction of ballast particles. The same applies for track laying in situ.

11. Repetitive tamping operations should be avoided as much as possible because of the damaging effect on ballast (crushing, pulverisation) and on concrete sleepers (fragmentation).

10. Literature

[1] Zand, J. van 't and Moraal,J., Ballast Resistance under Three Dimensional Loading. Report 7-97-103-4, Roads and Railways Research Laboratory, TU Delft, April 1997.

[2] -, Sleeper lateral resistance measurements: synthesis report (preliminary draft). BR Research, February 1997.