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Procedia Structural Integrity 64 (2024) 301–310

Structural Integrity Procedia

www.elsevier.com/locate/procedia

SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

Load-Bearing Capacity Assessment of Traffic Superstructures for Roads and Tramways

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Abstract

The load-bearing capacity of traffic superstructures is usually assessed based on deformation measurements. The bearing capacity is defined as the superstructure's resistance to short-term deformations. However, different measurement concepts and evaluation methods are required for different superstructures to assess the bearing capacity. Therefore, this paper will present various methods for road and tramway superstructures and illustrate them with practical examples.
The bearing capacity of road pavements is typically assessed by deflection measurements using the falling weight deflectometer (FWD). This dynamic measurement method applies a falling weight to the road surface, and the resulting deflection basin is recorded briefly. This can then be evaluated. Evaluations of various measurements in Germany are presented.
The assessment of load-bearing capacity in the tramway sector is not currently established in German regulations. An individual measurement concept was developed and applied to assess the load-bearing capacity in urban transportation. The measurements aimed to determine the in-situ deformations of the grooved rail with a selected type of fastening during the passing of trams. In addition, the serviceability during operation was checked. The measurements were carried out on an open construction (grass track) and a closed construction (asphalt), as well as in tight curves and on straight track sections. Based on the deformations determined, conclusions can also be drawn about the service life.

Keywords: Non-destructive testing; pavement; tramway; load-bearing capacity; deflection

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Peer-review under responsibility of SMAR 2024 Organizers
10.1016/j.prostr.2024.09.251

1. Introduction

In the case of traffic fastenings, condition assessment and evaluation play a decisive role in good maintenance management. One part of maintenance management is the assessment of the existing fastening's load-bearing capacity. In general, load-bearing capacity is defined as the mechanical resistance of a traffic fastening to short-term deformations (FGSV 2003). Therefore, the traffic load-induced deflection of the traffic fastening and the metrological determination of the resulting deflection basin play a decisive role.

The load-bearing capacity of road pavements is usually assessed using measurements with the Falling Weight Deflectometer (FWD). This involves applying a load to the road surface with a drop weight and measuring the resulting deflection. The procedure has been established for years and is already listed in national regulations. However, the evaluation methods used may differ from country to country.

In inner-city areas, tram tracks can also be embedded in the road pavement. In this case, the road's pavement is in direct contact with the grooved rail. Tramway superstructures can have different types of fastenings. For example, closed (e.g. with asphalt) or open construction methods (e.g. grass track) are used. The deflection behaviour differs significantly due to the embedded grooved rail and the different load types. For this reason, the methods established in road construction for assessing load-bearing capacity cannot be applied per se to tram pavements. In Germany, a DIN standard covers the assessment of the performance of tramway pavement systems. However, this standard only contains laboratory tests, which cannot simulate realistic loads. For this reason, a measurement method was developed to measure the actual deformations in situ.

2. Load-bearing capacity assessment of asphalt pavements

2.1. Falling Weight Deflectometer (FWD) and Darmstadt FWD evaluation method

Nowadays, the load-bearing capacity of asphalt pavements is usually assessed with the help of FWD measurements. The FWD is a dynamic measurement method in which a force impulse is applied to the road surface employing a drop weight. The resulting short-term vertical deformation of the pavement is measured indirectly via geophones at the load application point and various distances from this point and summarised to form a deflection basin. The measuring principle is shown in Fig. 1a. With knowledge of the deflection basin and the material properties of the pavement, the quality of the load-bearing capacity of the bound and unbound layers can be determined using back-calculation methods. Predicting the quality of the layer bond between the different asphalt layers is also possible. (Čičković & Bald 2017). The layer bond significantly influences the load-bearing capacity of asphalt pavements (Middendorf et al. 2021, Middendorf et al. 2023).

Various ways of analysing deflections measured with the FWD and evaluating the results exist. Internationally, the Young's moduli of the individual layers are often back-calculated. In Germany, characteristic values obtained directly from the deflection basin are generally used. The German regulations “AP Trag” (English: regulation draft for the load bearing capacity of road pavements) provides two options for analysing FWD data (FGSV 2014):

- geometry based evaluation method according to Jendia (1995)
- mechanics based method according to Grätz (1999) (also: Darmstadt FWD evaluation method)

The mechanics-based evaluation method according to Gräz (1999) and the Darmstadt evaluation method developed from it will be briefly explained in the following paragraph. According to Grätz (1999), assessing the load-bearing capacity of the bound and unbound layers is possible using the mechanical parameters M_0 and l. The method is based on the approach of the slab on elastic-isotropic half-space (see Fig. 1b). It is assumed that the slab is very stiff compared to the base and that the slab thickness is negligible compared to the other dimensions. (Gräz 2009) The aforementioned requirements can be considered fulfilled for today's asphalt pavements (Nguyen & Bald 2016).

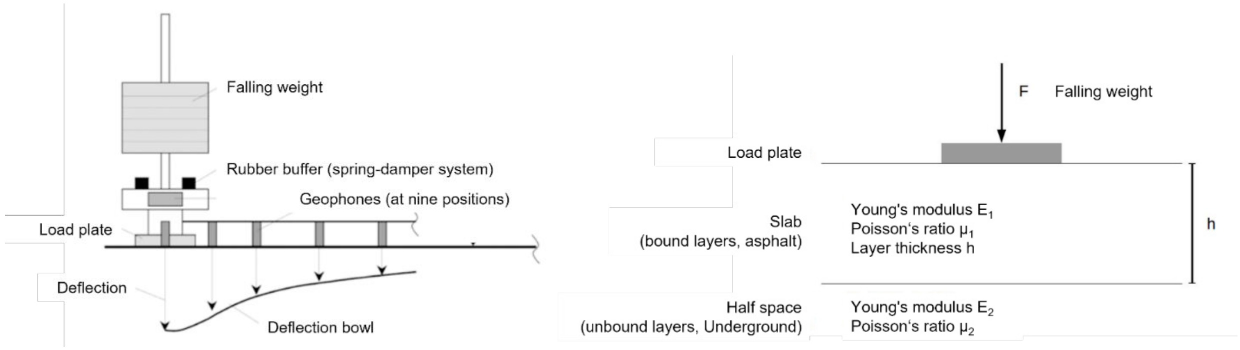

Fig. 1. (a) Principle sketch FWD (FGSV 2008); (b) Calculation model "Slab on elastic-isotropic half-space" (Gräz 2009)

To calculate the layer modulus M_0 and the elastic length l, the deflection basin from the deflections measured with the FWD must first be normalised to a load of 50 kN and a temperature of 20 °C. The normalised deflection basin is then approximated using a regression equation. The following load-bearing capacity parameters can be determined from the regression parameters:

- M_0 Stiffness modulus of the half-space (consisting of the unbound base courses and the subsoil) [MPa]
- l elastic length (Stiffness ratio between unbound and bound layers) [mm]
- M_1h^3 characteristic stiffness of the load distributing layer (e.g. asphalt slab) [MNm]

Therefore, the assessment of the half-space (unbound layers) is based on the characteristic value M_0, while the assessment of the load-bearing capacity of the asphalt pavement is based on the characteristic stiffness of the load-distributing layer M_1h^3. M_1h^3 is understood as the slab stiffness of the load-distributing layer increased by a factor of twelve (Čičković & Bald 2017). The load-bearing capacity parameters and the formulas required to determine them are explained in detail in Čičković & Bald (2017).

To assess the results for M_0 and l, the AP Trag (FGSV 2014) provides orientation values (minimum values) for the different load classes. These can also be used to calculate an orientation value for M_1h^3. By comparing the calculated load-bearing capacity parameters with the orientation values of the regulations, it is now possible to assess for each measuring point whether the load-bearing capacity at the time of measurement is at the level of the load class realised during construction. In Germany, roads are divided into seven load classes by RStO 12 (FGSV 2020). The classification is based on the dimensioning-relevant load (Mio 10-ton axle transitions). A load class Bk 100 is used for the highest loads (e.g. motorways). The lowest load class (e.g. for low-traffic residential roads) is Bk 0.3.

The advantages of investigating asphalt pavements using FWD and analysing the data using the Darmstadt FWD evaluation method can be summarised as follows:

- Non-destructive testing and assessment of load-bearing capacity and layer bonding
- No information on layer formation (layer thicknesses) or material parameters is required for the assessment
- Assessment of the load-bearing capacity of the overall structure based on the back-calculated load class
- Separate assessment of slab or bound layers (asphalt layers) and half-space or unbound layers (substructure, subgrade) is possible

Examples of applications of the Darmstadt evaluation method in relation to method development and verification (Böhm, et al. 2011) and the assessment of the quality of the layer bond (Nguyen & Bald 2016, Nguyen 2023) can be found in the sources mentioned. There are also studies on the application of the method including the time history (Cickovic 2022). The results of two sample measurements are presented below.

2.2. Example 1: Assessment of the load-bearing capacity of the bound layers (asphalt layers)

Example 1 illustrates the assessment of the load-bearing capacity of the bound layers of a road pavement. In the case shown, the condition of the load-bearing capacity of a road in a German city was to be determined as part of the condition assessment and evaluation using FWD measurements. The measurement was carried out in 2023 on both road lanes in the respective direction of travel. The distance between the two measuring points was approx. 100 metres.

No data is available on the existing structure of the asphalt pavement. Therefore, there is no information on the material used, the layer structure, thicknesses or the unbound layers beneath the asphalt. As the road is located in an inner-city area, it is also possible that there is at least a partial cobblestone surface beneath the asphalt layers. Such a historically grown structure may increase the load-bearing capacity of the analysed measuring point enormously. Therefore, it is possible that the load-bearing capacity back-calculated from the deflection measurements for the analysed measuring point shows, for example, a load-bearing effect equivalent to load class Bk 100 according to RStO 12. However, load class Bk 100 is usually realised for motorways and is rather unusually high for urban roads. Accordingly, due to the historically grown fastening structure, significantly increased back-calculated load-bearing capacities can also be determined at individual measuring points under certain circumstances. Due to the lack of knowledge about the existing layer structure, it is difficult to assess the measured deflection basin by recalculating Young's moduli. With this evaluation approach, it would be essential to specify layer thicknesses for which drill cores would have to be taken from the road due to the lack of data, which would damage the structure. Therefore, the Darmstadt FWD evaluation method is particularly suitable, based solely on the measured defection values. The condition of the road pavement was apparently good when the measurements were taken. Cracks and potholes were detected in isolated instances.

After carrying out the FWD measurements, the load-bearing capacity parameters already explained were determined using the measured deflection values. The following will discuss only the load-bearing capacity parameters of the bound layers (asphalt slab). Accordingly, the results are only presented concerning the load-bearing capacity parameter M_1h^3. The results of the load classes of the various measuring points back-calculated based on the M_1h^3 values are shown in Fig. 2. As shown, the measurement route can be divided into six homogeneous sections, each with a comparable load-bearing capacity. Section 4, in particular, should be prioritised for maintenance planning, as it has a comparatively low back-calculated load-bearing capacity.

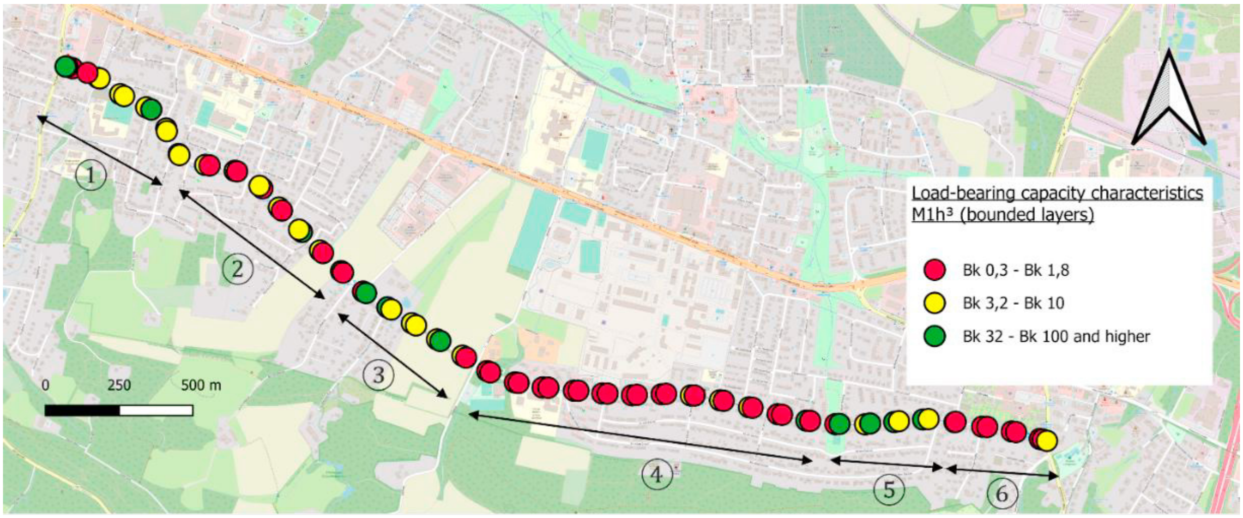

Fig. 2. Back-calculated load class in relation to the bound layers (example 1)

To summarise, the Darmstadt FWD evaluation method described above enables a network-wide assessment of the load-bearing capacity of the bound layers. As shown in this example, homogeneous sections with comparable load-bearing capacity can be formed on the basis of the calculated load-bearing capacity parameters and the back-calculated load classes. This is particularly important for maintenance management. Based on the homogeneous sections formed, renewal measures can be prioritised section by section as the need arises.

2.3. Example 2: Assessment of the load-bearing capacity of the unbound layers

Example 2 illustrates the assessment of the load-bearing capacity of the unbound layers (substructure and subgrade) of a road pavement. In this case, an FWD measurement was carried out due to cracking observed in the longitudinal direction on the upper side of the asphalt surface course. Therefore, the measurements aimed to determine whether the observed damage was due to the load-bearing capacity of the unbound layers being too low in some areas. The road under investigation has a single-lane cross-section without separate directional lanes. It is a path in a park, which is used very occasionally by vehicles. There is no regular vehicle traffic. The measurement was carried out in 2024 in both directions of travel. The distance between two measuring points was approx. 5-8 metres.

The path under investigation has a coloured asphalt pavement. According to the client, the layer structure shown below was realised. This structure corresponds approximately to a load class Bk 0.3 (assumption) according to RStO 12:

- Asphalt surface course (coloured asphalt): 3 cm
- Asphalt base course: 8 cm
- Crushed rock base course: 20-25 cm
- Frost blanket course: 15-30 cm

After carrying out the FWD measurements, the bearing capacity parameters were determined using the measured deflection values. Firstly, the bearing capacity parameters M_1h^3 of the bound layers were analysed. These turned out to be very homogeneous. A load class Bk 0.3 according to RStO 12 could be calculated for the entire area (for damaged and damage-free areas). As the existing structure of the pavement also corresponds approximately to this load class, the load-bearing capacity of the bound layers can be categorised as sufficiently high. The damage observed, therefore, cannot be attributed to the load-bearing capacity of the asphalt layers being too low.

The following will discuss in more detail the load-bearing capacity parameters of the half-space and, thus, the load-bearing capacity of the unbound layers. The back-calculated stiffness moduli of the half-space M_0 are therefore considered. Fig. 3 shows the determined M_0 values by stationing. The red line represents the orientation value (minimum value) for a load class Bk 0.3 according to AP Trag (FGSV 2014). The vertical black line separates damage-free (left) and damaged areas (right).

It can be seen very quickly that the stiffness moduli of the half-space M_0 are significantly lower in the damaged areas (stationing 77 m to 160 m). In contrast, substantially higher stiffness moduli of the half-space can be determined in the damage-free areas (stationing 0 m to 77 m). The load classes back-calculated in the damage-free areas correspond to at least a load class Bk 1.0 or higher. It can, therefore, be concluded that the damage found is very likely the result of the inadequate load-bearing capacity of the unbound layers (crushed rock base course, frost blanket course and/or subgrade).

To summarise, the Darmstadt FWD evaluation method described above also allows the load-bearing capacity of the unbound layers to be assessed very well. The evaluation presented leads to a realistic result that justifies the observed damage pattern.

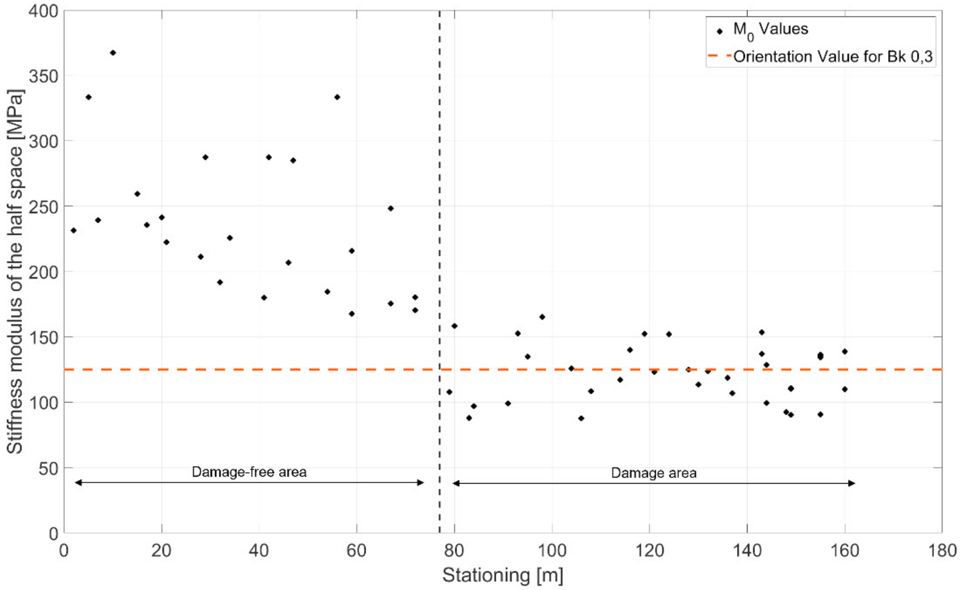

Fig. 3. Results of the back-calculated stiffness modulus of the unbound layers along the stationing (example 2)

3. Research into the deformation behaviour of grooved rail tracks using in situ measurements

3.1. Problem and objective

Trams are an essential part of local public transport in cities. Similar to the railway, the tram can transport many passengers efficiently in short cycle times. The tram can only realise this function if the infrastructure it uses functions perfectly and is, therefore, fit for the purpose. (Kempf & Liu 2023)

Tests can be done in the laboratory for components of the superstructure system to verify the usability of tram traffic routes, and the deformations of the components can be measured in the field. The research project aimed to measure the real deformations of grooved rail tracks in the field for a transport company in a city in Germany to determine the serviceability of a rail fastening system. Superstructure systems planned for new constructions and modifications are subject to testing in accordance with the relevant standard EN 17319. In addition to a series of tests, a continuous vibration test with a certain number of load cycles is carried out to simulate the real load. However, it was determined for the traffic company's system that the laboratory tests on the existing fastening systems often do not reach the required number of load cycles. This contradicted the system's many years of error-free operation in the city's network. It was essential for the usability of the fastening system in this case to know the real deformations of such superstructure systems in the field.

For this reason, the Institute of Transportation Infrastructure Engineering at the Technical University of Darmstadt was asked to record the real deformations at five measuring points with different framework conditions in this city's network.

3.2. Measuring stations

The superstructure system to be measured consists of two covered grooved rails fastened to a continuous concrete support plate and/or longitudinal concrete beam. At the support point, this fastening consists of anchors, clamping plates, elastomer intermediate layers, rubber press plates and, if necessary, height levelling plates (see Fig. 4a). In the intermediate rail area, the rail is continuously cast underneath. There are track rods between the rail mountings to increase frame stiffness.

The measuring points differ in cover, radius, superelevation and load already absorbed. The measuring points shown in Table 1 were selected for the measurement.

Table 1. Boundary conditions of the analysed measuring points

Measuring point	Superstructure type according to VDV 600	Covers	Radius [m]	Super-elevation [mm]	Planned lateral acceleration [m/s²]	Equivalent 13-tonne axle load transfers [million] (acc. to DIN EN 13146)	Equivalent 10-tonne axle load transfers [million] (acc. to DIN EN 1731)
1	With planned vegetation	Grass	20.5	40	0.59	0.70	1.96
2	With planned vegetation	Grass	∞ (straight)	0	0	0.70	1.96
3	Closed	Asphalt & fibre concrete	22	0	0.59	0.43	1.21
4	With planned vegetation	Grass	20	0	0.87	0.32	0.92
5	Open	Ballast	25	0	0.70	1.70	4.86

The selection criteria for the measuring points were sections of track with a high lateral load effect and sections of track with and without cover. The measuring points were located in narrow curves. A statically relevant covering is only present at measuring point 3, as the covering of the closed superstructure consists of asphalt and fibre concrete. All other measuring points had a structurally irrelevant covering (open superstructure or superstructure with planned vegetation). A measurement on a straight section served as a reference section for the sections with narrow curves.

3.3. Methodology

Measurements were taken at the track rod and at the support point to determine the influence of these two positions. Measurements were also taken on the outer and inner rails. As the behaviour of the tram axles in tight curves is not completely known, it makes sense to analyse both rails simultaneously.

During a tram crossing, a grooved rail can experience the following movements:

- Vertical deflection
- Lateral displacement
- Twisting of the grooved rail
- Torsion at the railhead

The measurement concept used detected the above movements using only inductive displacement sensors. The linearity deviation of the inductive displacement sensors is ≤ 0,1 % (HBM 2021). The sensors were geometrically attached to the rail head, rail web, and rail foot so that the movements could be determined using simple mathematical calculations. The measuring system also included a measuring booster and a laptop for the initial digital testing of the measured values and for saving the data. The measuring system was set up at the track rod and the support point. The measurement technology (sensor types, measuring booster, etc.) is classically common, as it is very robust and has proven itself. Possible measurement errors are therefore manageable and can be eliminated quickly. Fig. 4b systematically shows the measuring positions for each measuring point:

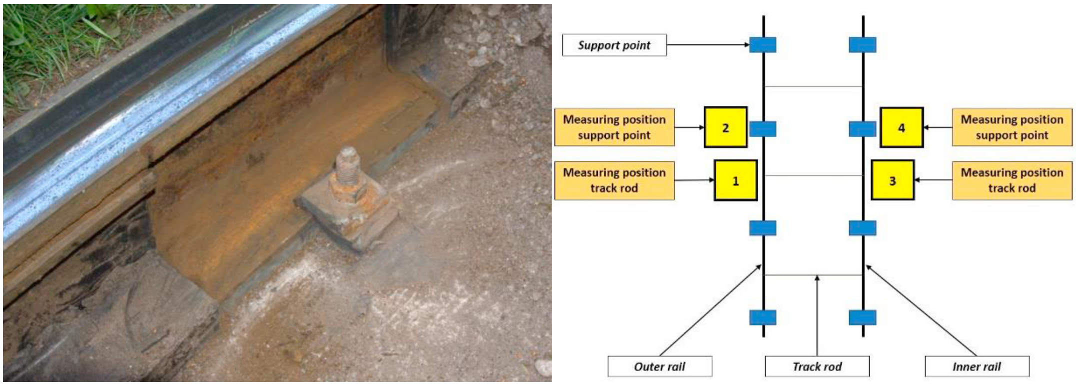

Fig. 4. (a) analysed rail fastening system; (b) Principle sketch of the measuring positions per measuring point

3.4. Vehicles

During the measurement, the passes of different vehicle types were registered in terms of their weight, number of axles and axle distances. The vehicles had six or eight axles and drove over the measuring point at different speeds. The measured speeds were between around 5 km/h and 14 km/h. The axle loads varied between 6.5 tonnes and 12 tonnes. The most recorded axle load was 11 tonnes.

The time intervals were similar at all measuring points (every 10 minutes). It was taken care to include all vehicle types in the city's network in the measurement of all types of vehicles to exclude possible influences from the design of the vehicles. A maximum number of crossings per rail was measured at each measuring point to be able to make statistically verified statements. The measurement was recorded at a defined frequency.

3.5. Results and outlook

All five measurement sections were free of functional damage. The lateral accelerations of the vehicles that happened were significantly lower than the planning requirements. The tram superstructure shows a generally high equivalent support point stiffness (exception: measuring point 5). This means that the rails deform very little during the passes. This is independent of the fact that the superstructure system is designed with a statically relevant covering.

The equivalent support point stiffness is the lowest at measuring point 5. The most significant deformations are found here. A maximum rail sinking of 1.67 mm and a maximum rail head displacement of 1.51 mm were measured on the outer rail. These comparatively high sinks are the result of the design. At the time of the construction of measuring point 5, a significantly softer polyurethane base casting was used at this point to reduce the vibrations. This method of construction was not continued in practice for other reasons, according to the operator. This section was important for the measurement project because of the long service life (17 years) and the comparatively high deformation values. According to the operator and his experience - up to the time of the investigation - no functionally relevant errors were detected with the track. As the deformations of measuring points 1 to 4 are significantly lower than those of measuring point 5, error-free operation is also ensured for these.

The measurements and results describe the differences between the requirements of the standard and the actual usability in practice. The measured deformations depend on the forces applied to the grooved rail, meaning on the vehicles used in practice. The main difference was the value of the rail head deflection. In the track, the rail shows minimal lateral movement and therefore a minimal lateral displacement of rail head. However, a test according to the relevant standard requirements with the same rail fastening leads to lateral displacement of rail head and even system failure. We suspect that this was due to the load assumption of the lateral force in the standard requirements, which may be too high. This is merely an assumption, which still needs to be analysed in more detail. This finding shows the potential for more research. Especially with long-term use in mind, the continued research of rail fastenings in traffic routes for trams is recommended. For example, an extended measurement concept is possible, installed at the measuring points over a significantly longer period. This would allow the seasonal influences to be recorded to analyse the effects of temperature on the superstructure components. At the moment, (at least) one preferred concept for long-term measurement is being developed and tested at the Institute of Transportation Infrastructure Engineering of Technical University of Darmstadt. As it is still in the testing phase, it is not yet possible to go into more detail. However, of course other important parameters (e.g. temperature effects) will be taken into account.

4. Summary

Assessing the load-bearing capacity of traffic fastenings is crucial for good maintenance management. The traffic load-induced deflection of the fastening plays a decisive role. For this reason, deformation measurements are usually carried out to assess the load-bearing capacity.

The assessment of road pavements concerning load-bearing capacity is usually carried out with the help of measurements with the FWD. The method has been established for years and is regularly used successfully. This paper presents and explains the Darmstadt FWD evaluation method, listed in German regulations. The advantages of the Darmstadt FWD evaluation method are demonstrated and illustrated using two example measurements. In addition to non-destructive testing, the method's main advantage is the separate assessment of slab or bound layers (asphalt layers) and half-space or unbound layers (substructure, subgrade). This allows the causes of damage to be easily assigned and evaluated, and repair measures can be determined. Furthermore, no information on layer structure or material parameters is required for the assessment. This is particularly helpful in inner-city areas, some of which have historically evolved pavement structures.

The deflection behaviour of tramway pavements differs significantly from that of road pavements because of the embedded grooved rail and the different load types. Therefore, the load-bearing capacity assessment methods established in road construction cannot be applied automatically to tramway pavements. The laboratory tests in the current regulations for evaluating the fatigue strength of rail fastenings cannot be used for field measurements. Therefore, the actual deformations in the field must be measured and assessed using a qualified methodology. A first approach for such a methodology is presented and applied in the field for different superstructure types (open and closed construction). The application was carried out on a straight line, in tight curves, and with different vehicles (type, speeds and axle loads). The listed measurement methodology must be developed further (e.g. via a long-term measurement considering different temperatures) and established in the regulations.

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