IMPROVEMENT OF BALLASTED TRACKS USING SLEEPER PADS - INVESTIGATIONS AND EXPERIENCES IN GERMANY -

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ABSTRACT: Despite the long history of conventional, ballasted railway superstructures further development is needed. The requirements like convenient deformation behaviour (settlements), low-priced maintenance and low noise emissions (air-born and structure born) have been boosted continuously especially for high speed applications. The track-settlement behaviour is influenced by the service conditions and the ballast pressure within the contact area between sleeper and ballast. The contact pressure can be reduced by increasing the contact area or by adding additional resilient components within the superstructure to activate greater load distribution by the rails. Qualified sleeper pads (USP under sleeper pads) give possible solutions. Measurements at field tests in Germany show a better track settlement behaviour. Furthermore additional resilient elements like sleeper pads have great influence on the dynamic vibration behaviour. The vibration velocities have been measured by special ballast stones equipped with accelerometers. Results concerning tracks with additional sleeper pads are available up to 160 km/h and have been compared with measurements performed on tracks with resilient rail pads. Requirements for sleeper pads are resistance against pressure peaks by ballast stones, durable resilient properties, sufficient vibration behaviour and applicability for conventional construction and maintenance procedures. The experiences born by laboratory tests and by test sections in revenue lines have been accounted for the new composed technical delivery conditions of the German Railways DB-AG for sleepers equipped with sleeper pads.

KEY WORD: Sleeper pads, track settlement, vibration

1 INTRODUCTION

The main demands of every railway company for an optimized ballasted track structure are

- an excellent settlement behaviour
- reduction of maintenance

Both requirements ensure high availability of the track and longer service life until renewal of the ballast, as the number of necessary tamping operations causes distress of the ballast stones, too. The settlement behaviour is on the one hand influenced by the service conditions: operations with mixed traffic i.e. relatively slow freight trains at night and high speed trains during day-time, are very unfavourable. These conditions exist generally in Germany on the new high speed lines, except on the line between Frankfurt and Cologne with ballastless track. With increasing speed the vibrations in the ballast are much higher and cause wear and non-uniform settlements: measurements under the ICE 1 (InterCityExpress, German high speed train) at a speed of 250 km/h demonstrated a doubling of the effective values of vertical vibration velocity (rms-value) compared with the results at a speed of 160 km/h (Leykauf, et al. 1998). Unfavourable climatic conditions are in rainy regions and under often frost-thaw-changes available.

On the other hand the settlement behaviour is dependent on the ballast pressure in the contact area sleeper/ballast bed. Low axle loads (ICE 3 $\leq$ 170 kN compared with 198 kN for the ICE 1 and ICE 2) and low dynamic forces, which depend on unsprung mass and suspension systems as well as on maintenance intervals for reprofiling of wheel rims, are required. However, in practice the vehicle design cannot be influenced by the engineers who are responsible for track design. Therefore the track parameters have to be chosen in such a way that the acting ballast pressure is reduced to a permissible value.

The ballast pressure results from the dynamic rail seat load, acting in one fastening and hence at the bottom of half the sleeper (if the sleeper is assumed to be a rigid beam) and the respective contact area (Fig. 1). Therefore the contact pressure can be reduced by a good load distributing effect of the rail support and by a large sleeper contact area.

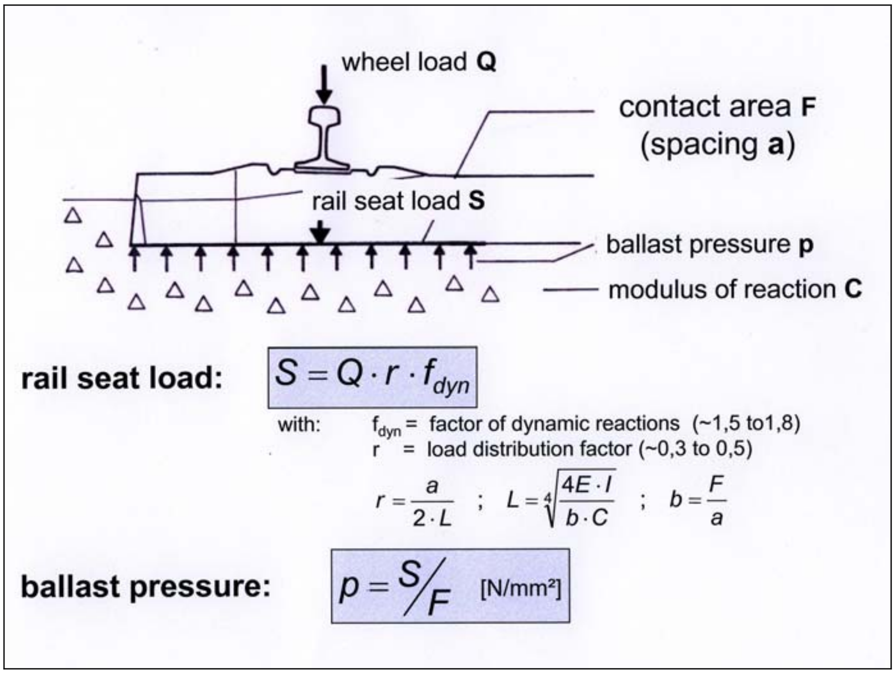

Figure 1: Calculation of ballast pressure

2 TRACK RESILIENCY

The ballast pressure does not only depend on the sleeper contact area but also on the rail seat loads as outlined in Fig. 1. The load distributing effect of the rail can be improved by a high vertical elasticity of the track, which can be introduced into the track structure in the fastening system (resilient rail pads), at the bottom of the sleepers (under sleeper pads USP) or at the bottom of the ballast bed by sub-ballast mats (Fig. 2).

The latter method is the most cost effective due to the large necessary area of the high quality resilient material and the installing costs on existing tracks. Its use is restricted in Germany mainly to bridges of the existing high speed lines were premature ballast distress was observed, caused by the rigid support of the ballast bed. Besides sub-ballast mats are in use if structure borne noise shall be reduced in sensible buildings close to the track (light floating slab track).

The most economic solution to achieve high resiliency is the use of resilient rail pads which easily can be installed by substitution. However, the spring coefficient must be limited to restrain gauge widening and high rail edge pressures which increase with tighter track radii. High elastic fastening systems require a load distributing steel pad positioned on top of the resilient pad as is in use for ballastless track systems.

The use of sleeper pads causes the exchange of the sleepers with conventional machines. But sleepers with pads can be used in track with tighter track radii.

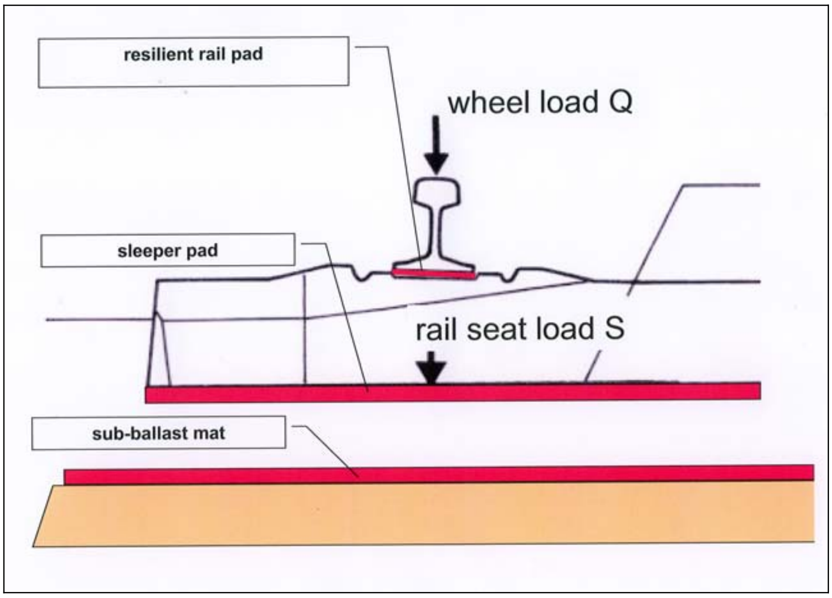

Figure 2: Possibilities to achieve required track resiliency

Dependent on the resiliency of the pad there are different application ranges:

- reduction of stress of the track superstructure
- reduction of structure borne noise
- short pitch corrugation in tight radii

3 BASIC REQUIREMENTS OF USP

The essential requirements of a resilient USP are:

- resistance against pressure peaks by ballast stones,
- durable resilient properties,
- sufficient vibration behaviour
- applicability for conventional construction and maintenance procedures

A high resistance against contact pressures resulting from ballast stones is achieved by an additional incorporated protection layer in general. Such USP were tested with a ballast-trough at the laboratory of the institute (Fig. 3).

During the first tests in the middle of the 90's the resilient behaviour of different USP was determined in a testing machine between two flat steel plates in comparison with the USP between a steel plate an the normalised ballast plate. The normalised ballast plate (DIN, 2000) is a casted steel plate with the surface of a ballast bed. Between the two steel plates more than five times larger spring coefficients were determined as a function of the thickness of the USP (8mm up to 23 mm; with larger thickness the differences are smaller). Therefore the regulation given with the technical delivery condition of the DB BN 918 145-1, this is a specification for USP (DB AG, 2004), is correct, to evaluate the static and dynamic deflection behaviour of the USP with the normalised ballast plate.

Figure 3: Ballast trough with USP

According to the technical delivery conditions of the DB-AG a fatigue test with 8 million load cycles in two stages has to be performed for the qualification test (homologation) of an USP. Fig. 4 shows the surface of two USP after this fatigue test.

Figure 4: Surface of two USP after fatigue test with 8 million load cycles

The imprints of the single ballast stones are evident. The contact area seems to be at random and is no criteria to evaluate the USP. The examined pad-materials with good behaviour (no perforation or damage), have plastic deformation with a depth of 6 mm. It is obvious, that the single ballast stones in the contact area with the USP are fixed. I. e. they are not able to move or to rotate. Movements of single ballast stones are reduced connected with a better deformation (settlement) behaviour. Dependant on the thickness and resiliency of the pad a better lateral resistance of the sleepers with USP may be expected in revenue lines (Müller-Boruttau, Kleinert, 2001).

4 TESTS IN REVENUE LINE OF DB AG

4.1 Test section Waghäusel

In 1996 a first test section of ballastless track systems was installed in Waghäusel, there are different track systems with ballasted tracks too. Two adjoining sections are equipped with USP. The first one with a “softer” pad, which is 6 mm thick with a 3 mm protection layer and a second “stiffer” one with 3 mm thickness and an 3 mm protection layer. In figure 5 the quasi-static rail deflection of the track with soft USP under a 200 kN axle load is plotted. It is evident that after 3 years of revenue service (max. speed 160 km/h, 60 million gross tonnes) there exists still excellent uniform deflection behaviour with a standard deviation of only 3.6 %, which is comparable to that value observed in perfectly installed ballastless tracks. In the adjoining section with conventional ballasted track the uniform rail deflection with a mean value of 1.09 mm after installation was disturbed after 3 years of service by two spots with vertical deflections up to 2.7 mm which caused an increase of standard deviation from 13.1 % to 50.8 %. Typical disturbtion spots in conventional tracks are caused e.g. by short bridges or by rail surface defects (Leykauf, et. al., 2002).

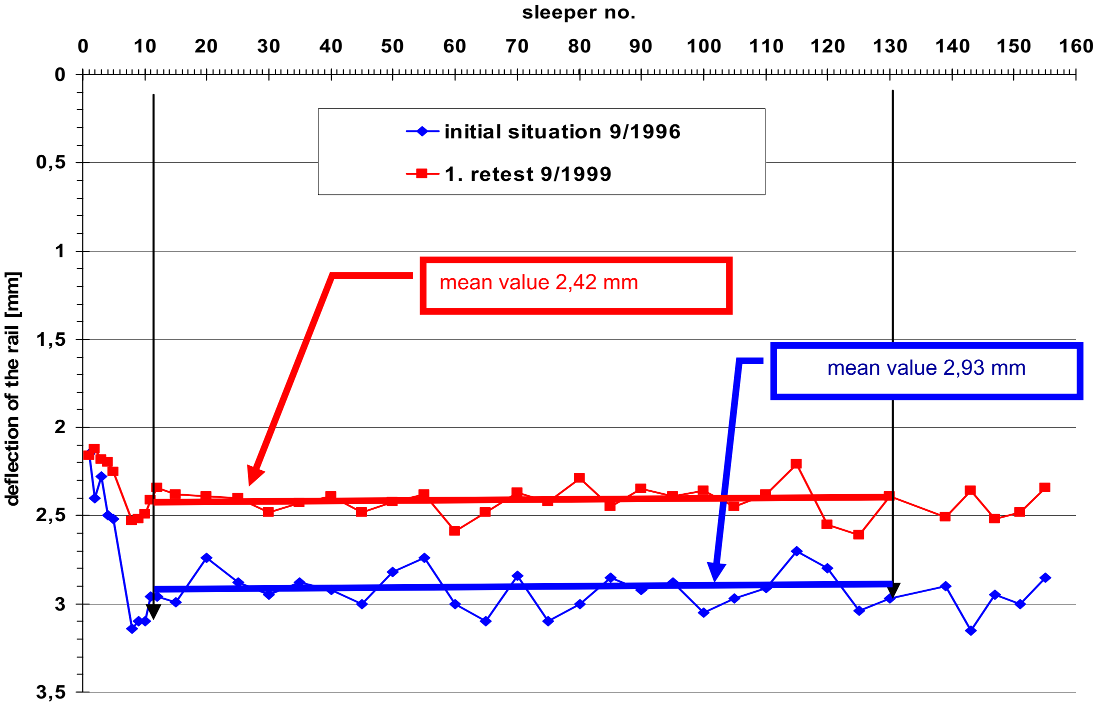

Figure 5: deflections of the rail (200 kN axle-load), test section Waghäusel with soft USP

The other track system with sleeper B70 (2.6 m standard sleeper of DB AG) and the “stiff” USP shows uniform deflection behaviour too. The rail-deflection decreases from 2.56 mm (1996) to 2.05 mm after three years in service. The standard deviation is comparable with that of a perfectly installed ballastless track too. A calculation of the spring rate c of the track shows values of:

-c = 11.5 kN/mm „soft“ USP

-c = 14.4 kN/mm „stiff“ USP

The visible inspection of the test section shows sign of abrasion of the sleeper flanks (fig. 6). This is a consequence of the high resilient USP, used for the test sections.

Figure 6: signs of abrasion of the sleeper flanks with USP

4.2 Requirements of the resiliency

On the first high speed lines of the DB AG, which were constructed conventional (sleeper B 70, W-Fastening, rigid pads) and put into service in 1991, the DB AG noticed an increased degradation of the ballast, connected with greater maintenance expenses. The measured quasi-static vertical rail deflection caused by a 200 kN-axle load amounts 0.4 mm, connected with a bedding modulus of $C = 0.3$ -0.35 N/mm³, caused by the high compaction of the earthworks and the subgrades or the rigid support of the track on bridges or tunnels. The existing lines with conventional ballasted track have a bedding modulus of $C = 0.10$ N/mm³ (Eisenmann, 1999). The vertical rail deflection caused by a 200 kN-axle load amounts 1.0 - 1.2 mm. A much better load distribution of the rail can be achieved with a quasi-static rail deflection of 1.5 mm, corresponding with a bedding modulus of $C = 0.05$ N/mm³ (spring rate $c = 14$ kN/mm). The rail deflection of about 1.5 mm should not be exceeded significantlyt to achieve permissible rail stresses of conventional tracks (Leykauf, Mattner, 1990). It is obvious that the use of USP is most effective if they are used in connection with a rigid support of the track ($C \geq 0.1$ N/mm³). Therefore the resiliency of the USP has to be adaped to the support conditions of the track to get on the one hand a good load distribution with reduced ballast pressure and on the other hand to limit the rail stresses for safety reasons. Therefore the pads of sleepers B 70 should have a spring rate of

- $c \geq 26$ kN/mm on cabable subgrade with a bedding modulus of $C = 0.1$ N/mm³
- $c \geq 16$ kN/mm on rigid support (tunnel and bridges) $C = 0.35$ N/mm³.

The spring rate of the pads has to be determined with the normalised ballast plate. According to Figure 1, an acting wheel load of 125 kN causes with a load distribution factor of 0.3 and a factor of dynamic reactions 1.5 (the factors are justifiable due to the high resilient track) a rail seat load of $S = 56$ kN. This rail seat load causes a ballast pressure of $p = 0.2$ N/mm² for the sleeper B 70. This ballast pressure is maßgebend to determine the bedding modulus or spring rate of the USP for the qualification tests according to the delivery condition of the DB AG.

It is obvious, that he USP for the test section in Waghäusel were more resilient than the derived values.

4.3 Vibration behaviour

The resilient materials introduced in different levels of the track have a great influence on the dynamic vibration behaviour and hence on the long term behaviour of the ballasted track structure (Leykauf et al. 1998). These vibration velocities have been measured by special ballast stones in which tri-axial accelerometers were introduced. (Stahl 2003).
The measuring stones were installed 5 to 10 cm below the sleeper under the rail support area. After different steps the spectrum of the oscillation velocity can be determined. The determined third octave spectra of vehicle crossings with high speed (V = 250 km/h) are plotted in Fig. 7. They were measured for different track structures:

- conventional track with sleeper B 70 and stiff pad Zw 687a (high speed line Hannover Würzburg)
- conventional track with sleeper B 70 and reslient pads Zw 700 (high speed line Hannover-Würzburg and test section Waghäusel)
- Improved track with larger sleeper B 75 and high reslilient fastening system 300 (test section on high speed line Hannover-Berlin)

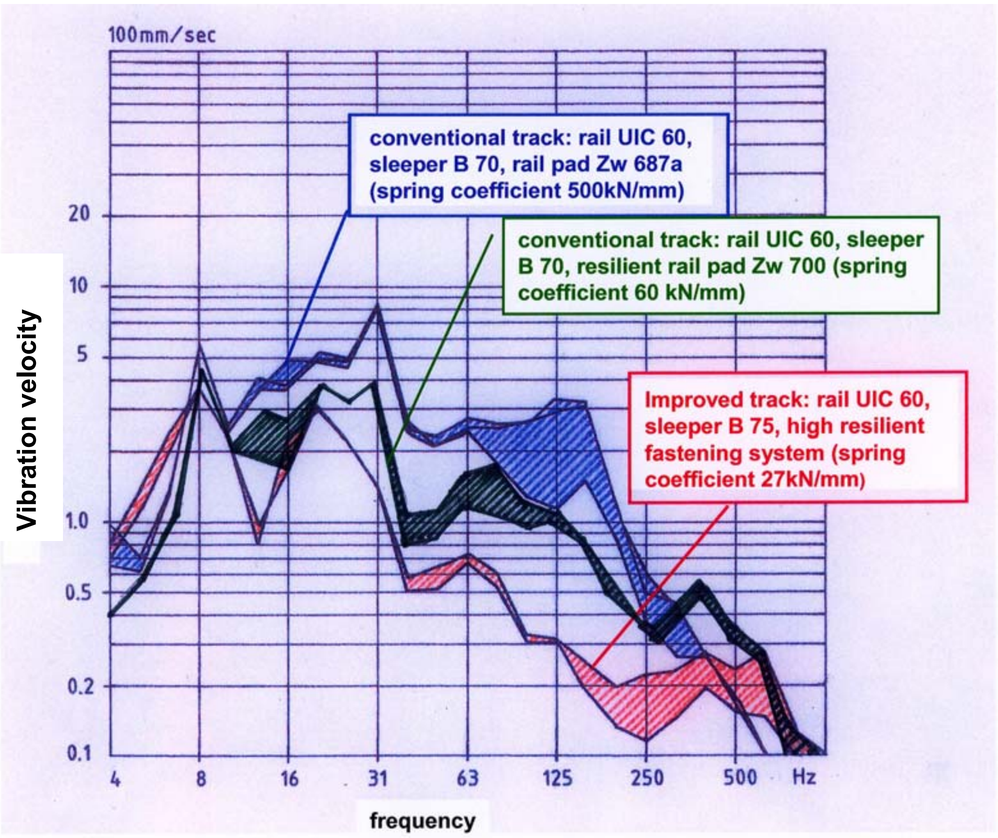

Figure 7: Recorded vertical vibration velocity for three different track structure types (V_{max} = 250 km/h)

Dependent on the running speed of the crossing vehicles, they show significant peaks at 8 Hz, 31 Hz and at the range of 60 to 125 Hz. The peaks are dedicated to the exciting frequencies caused by the distance of the boogies and axles of the ICE. With increasing resiliency the peaks are moving to lower frequencies, particularly at an area of frequencies less than 10 Hz there are significantly decreased excitations of vibrations. According to this a high resilient track system is able to reduce the excitation of vibrations and for this reason the loading of the ballasted track, particularly on high-speed lines, is reduced.

Measurement results of the vibration velocities for tracks with USP are only available for a running speed up to 160 km/h. The third octave spectra of figure 8 were recorded on the test-section Waghäusel with sleepers B70 and the "soft" USP. The results are compared with thus of the conventional track with sleeper B 70 and reslient pads Zw 700 (high speed line Hannover-Würzburg and adjoining section Waghäusel).

Subjected to the reduced velocity shows figure 8 the peaks at lower frequencies. The excitations of the boogie spacing are reflected with a peak at 5 Hz. (8 Hz at 250 km/h).The spectra of the track System with „soft „ USP are comparable with the track with resilient pads Zw 700. On the one hand the level of vibration velocity decreases at higher frequencies in comparison with resilient pads; on the other hand there are increased vibration velocities at lower frequencies. This permits the conclusion, that the improved track with resilient rail fastening system or USP gave a distinct vibration response of the boogie spacing, than the distance between the axles of a boogie. A comparative calculation of rail deflections (bending line of the rail) for an ICE power car shows a complete discharge between the axles of a boogie for the track with sleepers B 70 and rail pads Zw 687a. For the track with Zw 700 the discharge between the axles of a boogie amounts 80 % of the maximum rail deflection. This leads to the mentioned modification of the spectra characteristics to lower frequencies. The track with USP shows lower vibration velocities for the frequencies above 16 Hz.

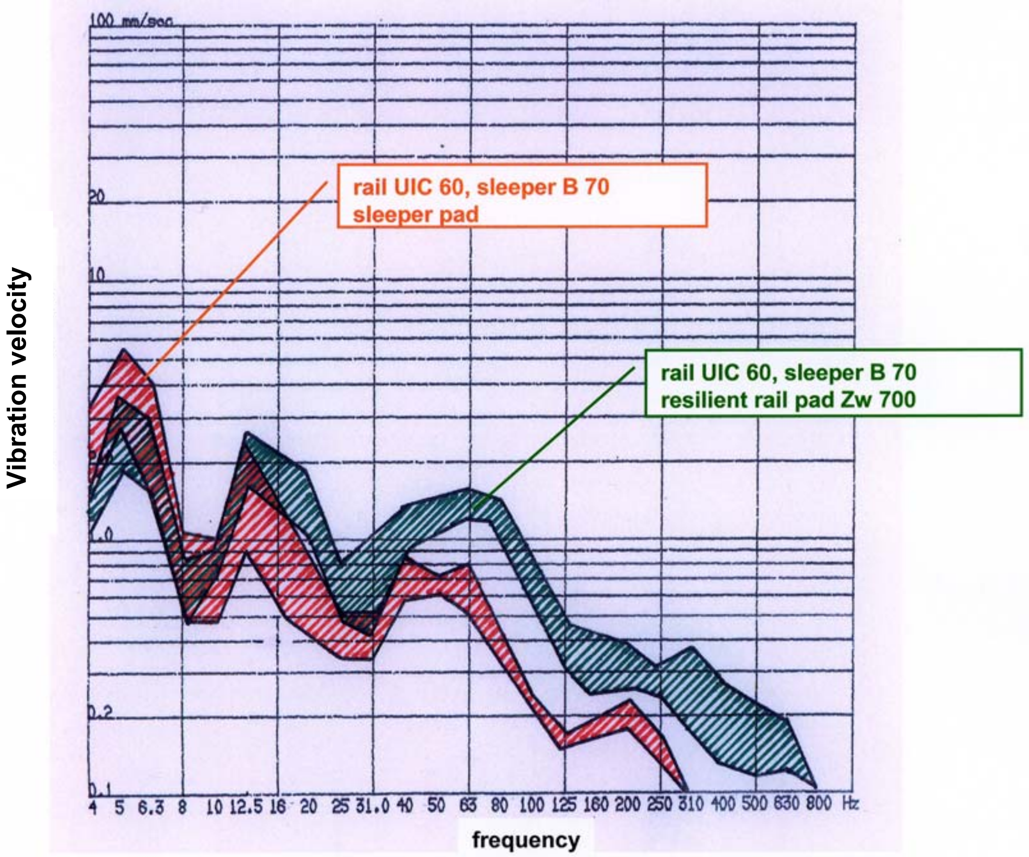

Figure 8: Recorded vertical vibration velocity for two different track structure types (V_{max} = 160 km/h)

Dependant to the method of construction of adjoining buildings, an immission reduction of structure borne noise concerning the vibrations in comparison with a conventional ballasted track can not be expected, but a substantial reduction of secondary airborne sound

5 MAINTENANCE

To avoid high negative bending moments of the sleeper in the case of settlements, the pad covers the whole bottom side. The pad has to be fixed well with the sleeper. The fixation may not be destroyed during maintenance works by conventional tamping machines. Therefore a part of the delivery conditions of DB is concerning the fixation of the pads and describes test methods for the homologation and quality management (Fig. 9).

Figure 9: pull out test for the homologation of the fixation of the USP, according to the delivery conditions of DB AG

Difficulties arising from high resilient fastening systems to fix the sleepers with tamping machines were not noticed up to now. The available experiences from different test sections of DB AG meet the expectations of the long term- and maintenance behaviour up to now.

6 CONCLUSION

The under sleeper pads (USP) should be used as substantial resilient element to activate the optimal load distribution of the rail to improve the settlement behaviour. The spring rate c of the USP in connexion with the german standard sleeper B 70 and maximum axle loads of 225 kN should be

- $c \geq 26$ kN/mm on cabable subgrade with a bedding modulus C of $C = 0.1$ N/mm³
- $c \geq 16$ kN/mm on rigid support (tunnel and bridges) $C = 0.35$ N/mm³

to limit the rail stresses for safety reasons. It has to be considered that the deflection behaviour of the USP will adjust itself after a certain time in service (adjustment effects).

With increasing resiliency of the pads, the danger exists that ballast stones suffer larger abrasion of the sleeper flanks. Therefore is recommended to support the necessary rail deflection by resilient pads in the fastening system. The spring rate of the USP can be increased.

The fatigue test, carried out with the ballast trough, shows an advantage of the USP, by the fixation of the single ballast stones in the contact area with the USP. Movements of the ballast stones are reduced connected with a better settlement behaviour. At the test section Waghäusel this was determined despite the too “soft” pads. With use of USP can be counted on a decrease of the otherwise necessary removal of disturbtion spots which are connected with destroying of ballast. Therefore economic application possibilities are present in particular with existing disturbtion spots in the track, as with changing bearing capacities, e.g. due to short bridges. Observations in the USA of tracks with rigid support conditions are showing a rapidly pulverisation of the ballast due to the high axle loads ≥ 330 kN; resilient pads in rail fastenings are overstrained. Here the USP have proven itself. It is reported from Japan, that the maintenance expenditure can be reduced by more than half on tracks with USP (Miura, 1993)

Further favourable applications for USP are in particular radii under 400 m, with those a high resilient pad in a conventional rail fastening are overstrained and for switches without resilient fastenings.

Concerning the dynamic vibration behaviour there is still need for research. The track with USP shows lower vibration velocities for the frequencies above 16 Hz. Dependant to the method of construction of adjoining buildings, an immission reduction of structure borne noise concerning the vibrations in comparison with a conventional ballasted track can not be expected, but a substantial reduction of ground-borne noise.

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