Reducing the occurrence of inner curve corrugations

Design options to delay the formation of corrugations on the inner rail of tight curves

Florian Auer

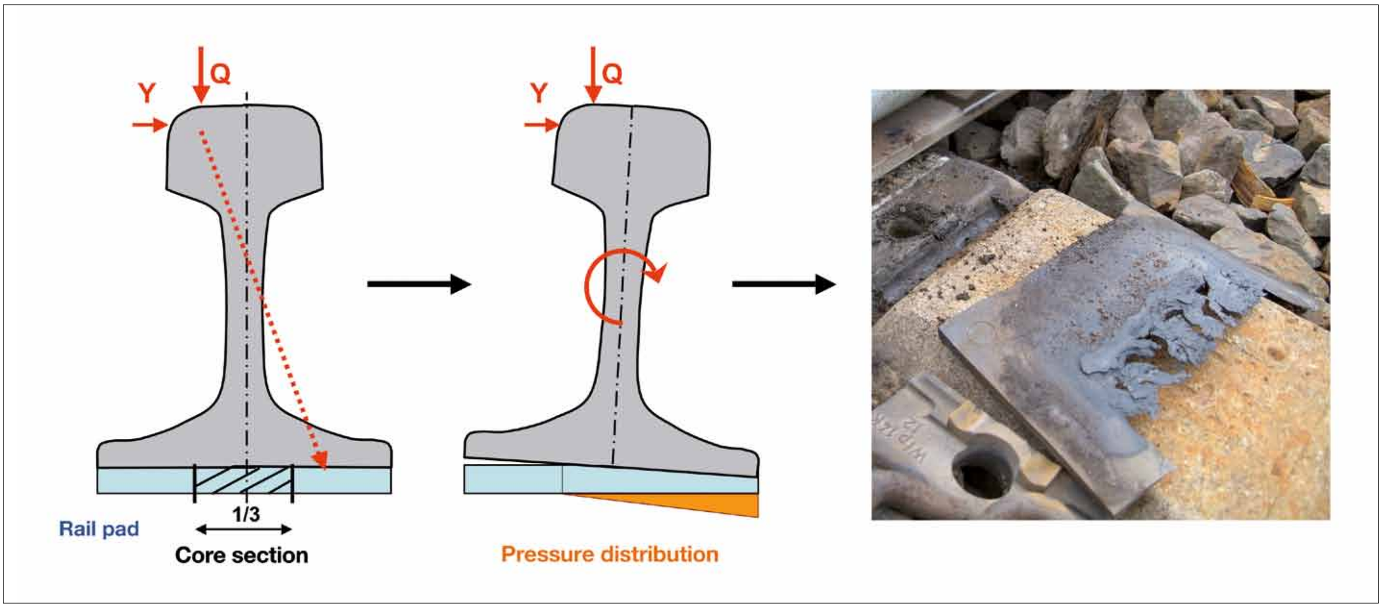

Fig. 1: High edge pressure on rail pads in curves

Due to the Austrian topography, the network of the Austrian Railways (ÖBB) has a high percentage of curved track. Many lines were laid out with a standard curve radius between 250 and 300 m.

The additional lateral forces and bending moments caused by the curve lead to a disproportionately greater stress on the track components and cause wear and tear which does not arise on straight track.

The outer rail in curves with a radius R < 600 m experiences a higher level of wear on the side, the inner rail frequently exhibits an increased tendency to form corrugations. The dynamic deformation of the track panel due to the formation of corrugations leads to an increase in crack growth in the sleepers and the ballast, too, can be overstressed. Curved track with corrugations is also noisier by up to 15 dB. Increased wear of the side rail foot guide elements also results from the lateral forces in the curve. The rail pads experience a higher pressure at the edges due to the tilt in the rails and thus wear prematurely on one side.

In the last few years there has been a general trend to design the rails to be more flexible. The stress on the track components below the rail is reduced by better load distribution of a higher, but more uniform stress on the rail. Various reasons, among them the increase in rolling contact fatigue problems and the reduction in the formation of corrugations, have led to the use of the head-hardened steel type R 350 HT in curves.

This article specifically discusses the effect of flexible track components on the slowing down of the formation of corrugations in tight curves.

Design changes

Curved track to a lower radius limit of R = 250 m is continuously welded (applicable to concrete sleepers) by Austrian Railways. Based on life cycle costings (sustainability criteria), the use of concrete sleepers has been pushed in the main network and thus also in tight curves for about 30 years. Unfortunately, the life of various components, in particular the rail fasteners, was initially not able to keep up with the target life of concrete sleepers of 40 years and more. The railway engineers had to carry out several design changes to the fasteners over time.

Even though the lateral resistance to displacement was always sufficiently dimensioned for the concrete sleepers used, some of the individual fasteners had a noticeably higher level of wear and thus short service lives. Maybe the robust and proven ribbed plate design was discarded too early. Later fasteners and the Hermann Meier fasteners – the later direct or W fastener – may have several benefits, in particular with regard to price, however, they were initially not designed for long-term use in tight curves (see [1] and [2]).

One aspect is of particular importance: the lateral wheel forces cause an additional two-part stress in the track panel. The force resulting from the vertical wheel load Q and the horizontal guide force Y is frequently located to the side of the core section of the rail pads in curves (Fig. 1). The system of clips and pads must, therefore, be designed for the elastic tilt of the rail including lifting off of the section of the rail foot pointing towards the track centre in addition to taking up the lateral forces in the rail foot level. Thus in curves, stiff rail pads in particular experience high pressure at the edges and thus wear prematurely. In case of a high traffic density, the rail pads of rubber/plastic compound, which were previously used as standard by ÖBB, had to be replaced after about only five years in curves with R ≈ 300 m. If the rail pads are replaced too late, lastingly negative wear, such as penetration and destruction, occur

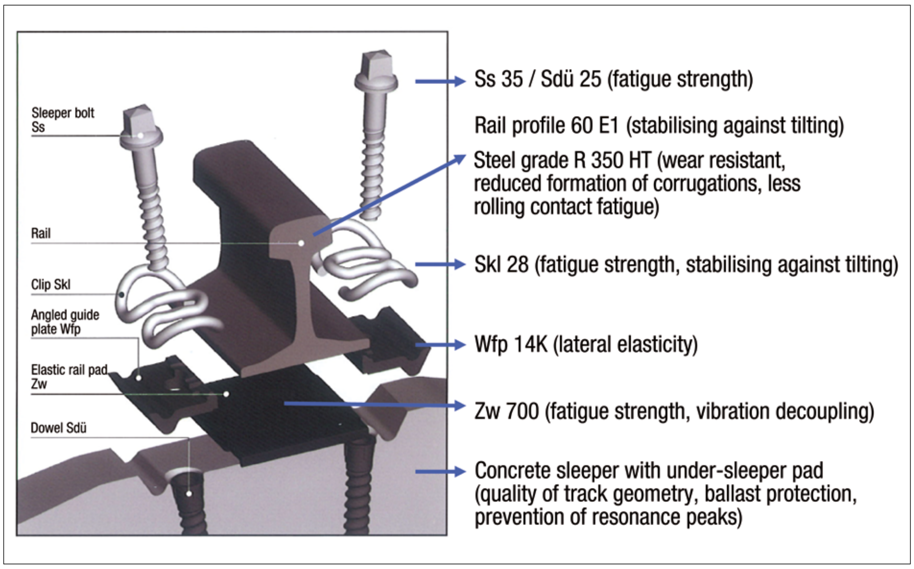

Fig. 2: Optimum curved track configuration, standard at ÖBB since 2007 (source: Vossloh Fastenings System, adapted)

in the fastening system and in the area of the rail supports. In addition to the adjustments to the rail pads, further adaptations had to be carried out:

- Modern angled guide plates are made of glass-fibre reinforced plastic. These have a horizontal elasticity of about 50 kN/mm and thus the wheel forces are transferred flexibly to the concrete sleepers with a deformation of the side rail foot guide. This contrasts with the old steel angled guide plates; their deformation-free transfer of energy led to concrete sleepers flaking over time.
- The screw/dowel pairing $S_{screw}25 – S_{dowel}21$ used up to 2005, had to be altered with regard to their geometric form (the old V-thread causes stress peaks) and the material used (HDPE tends to creep in curves). ÖBB was involved in the development of the new screw/dowel pairing $S_{screw}35 – S_{dowel}25$. This is now used as the general standard on track with concrete sleepers.
- At ÖBB rail profile 54 E2 (“narrow” rail with 161 mm height and “only” 125 mm foot width) was replaced with profile 60 E1 relatively late. The narrow rail foot width of 125 mm has proved detrimental in curves as it requires larger rail pads and leads to higher stresses on the dowels. Although the logistics costs were reduced with rail profile 54 E2 – the previously used standard rail 49 E1 also had a foot width of 125 mm – this was at the cost of increased stress on the rail fasteners. With hindsight, the decision not to use the geometrically balanced profile 54 E1 with a foot width of 140 mm for the 54 kg rail profile in the curvy ÖBB network can be regarded as less than ideal for the long term.
- In the early 1990s, tests with head-hardened rails (designation at that time HSH grade, today R 350 HT) were carried out in the ÖBB network. The use of R 350 HT grade became mandatory in 2001 for the use in tight curves (R < 350 m) after the fatigue strength of the welding method used was documented in addition to the reduction in wear (a factor of 3 in tight curves compared to R 260 grade steel described as “wear resistant” at that time). The head-hardened rails also provide greater wear resistance against the formation of corrugations.

This curved track configuration optimised for wear and, as described later, also for corrugations is now used as standard in tight curves (R < 600 m) in the ÖBB network (Fig. 2).

Stephanides inner curve corrugation hypothesis

A good opportunity to experimentally study the vehicle/track interaction when travelling through a test curve was provided by the test drives carried out during the joint DB AG / ÖBB / SBB programme “Goods wagons running stability” in the Brixental valley in July 2001. ÖBB / SBB together with Innsbruck University’s Institute for Railway Engineering selected a curve in the Brixental valley (known among experts for its corrugations) because a steel bridge with track without corrugations is part of the curve.

Stephanides summarised the results of the test runs in his final report [3]. According to his hypothesis, corrugations are self-excited vibrations in the wheel/rail system which arise due to beat frequency effects due to frequency proximities. Thus, corrugations exhibit a higher frequency component or base vibration (about 150 to 180 Hz) and an enveloping vibration with a wavelength which is a multiple of the sleeper distance.

Therefore corrugations are formed when certain natural vibrations of the wheelsets (harmonic component of bending and torsional natural vibrations) within specific frequency ranges meet resonance peaks in the track. Individual wheels of unladen goods wagons start to lift off the rail surface on the inside of the curve in a highly dynamic manner and to touch down again repeatedly in a regular manner. The corrugation pattern starts to form if the wear resistance at the rail surface is smaller than the dynamic loading. However, the vibration mechanisms of the vehicle on their own are not able to cause the dynamic rail wear in the form of corrugations. Otherwise, sections free from corrugations, such as that on the steel bridge examined, should not occur.

Natural vibrations and resonance peaks of the track occur in various frequency ranges. The mode crucial for the formation of corrugations is at about 150 Hz (usually it is between 150 Hz and 180 Hz for the components used by ÖBB). In this frequency range, rail and sleeper vibrate in phase [4] (Fig. 3). In the “Brixental corrugation measurement” final report the following point is made several times. Voids under sleepers play an important role for the formation of corrugations. The first in-phase vibration mode between rail and sleeper (about 150 Hz to 180 Hz) develops even more strongly where voids exist and is thus a trigger for increased deformation of the track panel; this in turn promotes the beat frequency effects mentioned above. Fig. 4 shows a typical corrugation pattern.

As the voids under the concrete sleepers change over time, it is possible that the corrugation peaks move in a lengthwise direction over time. However, they remain stable and grow together from a corrugation amplitude of about 0.2 mm (peak to peak value). The enveloping vibration (with a wavelength which is a multiple of the sleeper distance) can no longer be recognised as such.

Conclusions: The hypothesis of Stephanides describes the process of corrugation formation well as it considers the wheelset vibrations combined with the track panel vibrations and thus enables an integrated description. According to this hypothesis, corrugations are formed by beat frequency effects due to the frequency proximity of wheelsets and track panel. Voids have a special effect as they increase these beats. The formation of corrugations can be stopped if the two partial effects of resonance peaks in the track between 150 Hz and 180 Hz (system rigidity adjustment) and the formation of voids (support quality of concrete sleepers) are skilfully changed or eliminated. This is done, as will be described later, by adjusting the rigidity of the rail pads and by installing under-sleeper pads.

Effect of the rigidity of rail pads

An ideal corrugation test section is available to ÖBB on a track section at Scheifling at the border between Styria and Carinthia. The double track section between Scheifling and Mariahof has numerous curves with a radius R ≈ 280 m and a slope of about 1.5 % over a length of about 7 km with roughly identical subsoil conditions. On new track, concrete sleepers of type L2 without under-sleeper pads and with rigid plastic rail pads were laid.

Track 1 (mainly downhill travel) was renewed in 1999. After seven years, the rail pads had to be replaced in curves due to their wear. During the replacement of the rail pads in October 2006, 22 different rail pads from five different manufacturers were installed on sections of at least 90 m length each (Fig. 5).

The geometric shape of the rail pads was specified to the manufacturers, but they had a certain amount of leeway with regard to the selection of the rigidity. In the test section, the static rigidity of the rail pads varied between 55 kN/mm and 241 kN/mm (secant between 18 kN and 68 kN) and their dynamic rigidity varied between 79 kN/mm and 300 kN/mm (evaluation range 18 kN to 68 kN; 5 Hz). An exception is the reference rail pad with a static rigidity of about 500 kN/mm. Using this extensive test setup, it is possible to determine the effect of the rail pad rigidity on the formation of corrugations on the track in service.

The test installation of the rail pads in October 2006 was followed by an intensive programme of measurements. The wear of the rail pads and the formation of corrugations, in particular, were examined in detail. At selected points, measurements (deformation of sleepers and rails, lateral movement of rail and sleeper while a train was passing over, acceleration measurements at rails and sleepers, corrugation amplitude measurements, decay rate determination etc.) were

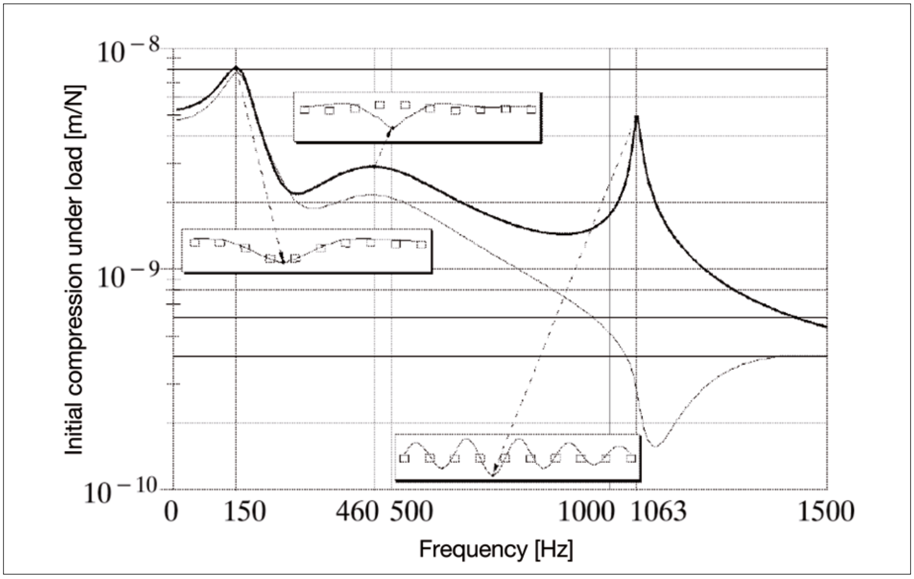

Fig. 3: Vertical frequency response of track [4]

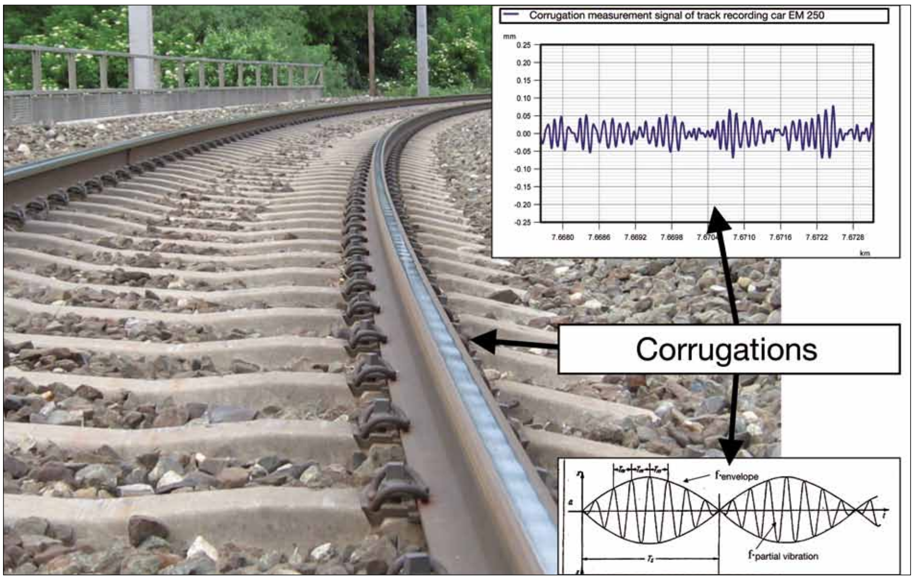

Fig. 4: Typical corrugation pattern

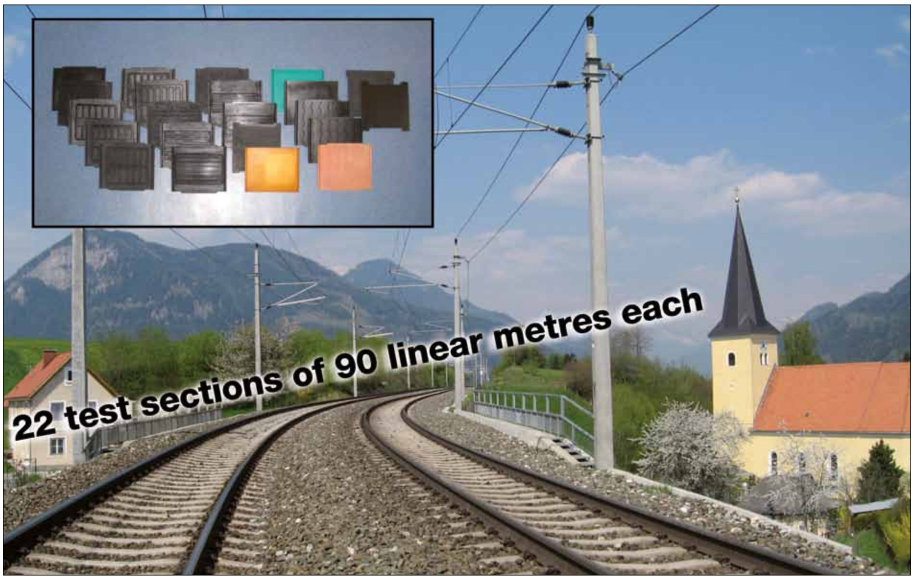

Fig. 5: Test section for rail pads near Scheifling (Styria): 22 test sections of 90 linear metres each

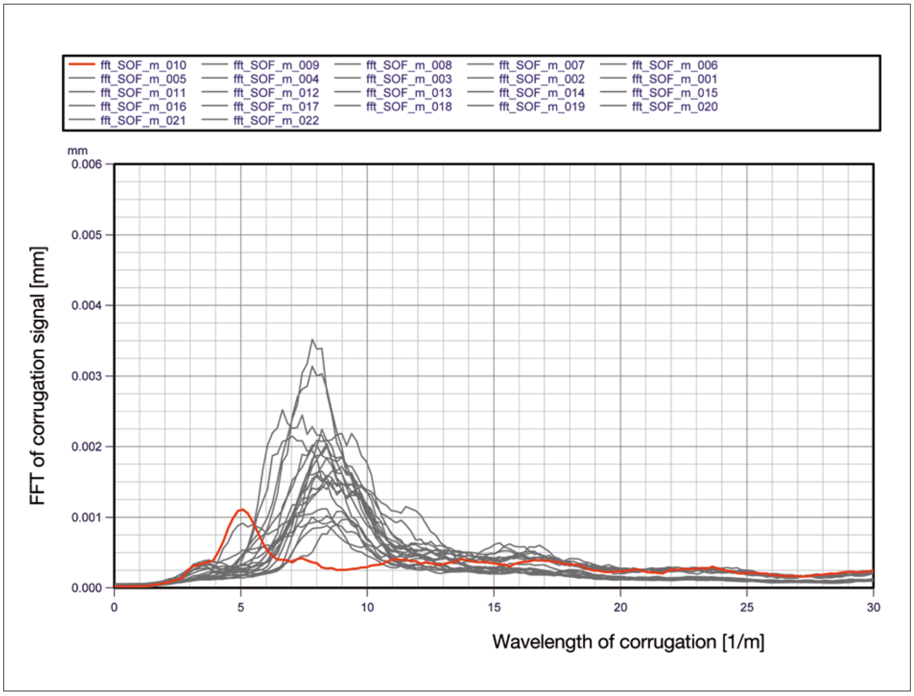

Fig. 6: FFT analysis of corrugation amplitude in test section A10

carried out which were helpful in answering detailed questions.

The most important measured signals came from the track recording car EM 250. On average, the track recording car travelled over the test section three times per year. The rail inclination measurement signal enabled inference of the wear of the rail pads [5]. The corrugation depth signals (the centre of the rail head was scanned with a three-point laser and the versine determined in this way was converted into the actual surface waviness) and the axle bearing acceleration enabled detection of the growth of the corrugations and determination of the effect of the rail pad rigidity.

Fast Fourier Transform (FFT) analyses of the corrugation signal provided initial information on the corrugation growth in the individual test sections. Fig. 6 shows the detailed analysis of subsection A 10; the comparison sections are shown in grey. It can be seen that the amplitude of the enveloping spectrum as well as the corrugation frequency clearly differ from the others. The smaller enveloping amplitude points to smaller corrugation amplitudes and the frequency reduction to larger corrugation wavelengths. Section A 10 has particularly soft rail pads with a dynamic rigidity of 85 kN/mm. Soft rail pads thus demonstrably lead to a change in the system's natural frequency and lead to a lower formation of corrugations.

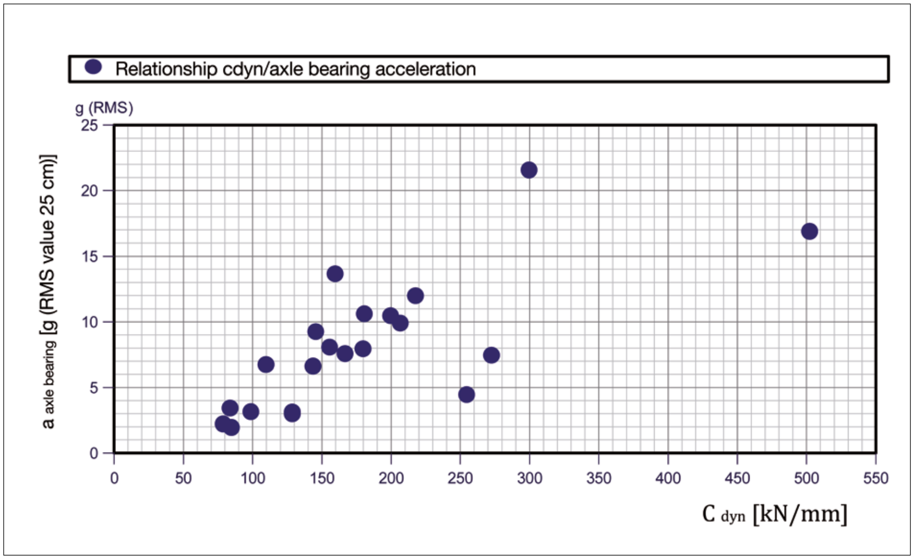

Fig. 7: Relationship between dynamic rigidity of rail pads and axle bearing acceleration

The importance of the axle bearing acceleration track measurement signal (RMS value above 25 cm) has increased overall over the last few years. In addition to assessing the quality of rail welds and the crossings, the magnitude of corrugations is defined more and more by this signal and not just by the corrugation depth signal used previously.

Fig. 7 shows the relationship between axle bearing acceleration and dynamic rigidity of the rail pads for the 22 test sections. Here, too, the following can be seen: a reduction in the rail pad rigidity (applies to the range 85 kN/mm < C_{dyn} < 300 kN/mm) leads to a lower corrugation amplitude, here expressed as axle bearing acceleration of the track recording car.

Fig. 8 provides a physical explanation for the stronger formation of corrugations when more rigid rail pads are used. This plots the correlation between the relationship corrugation depth/axle bearing acceleration and the dynamic rigidity of the rail pads. A larger value for C_{dyn}/aaxlebearing points to a greater decoupling of sleeper vibrations and wheelset vibrations. Even if the actual value of the relationship is of minor importance, the following relationship can be clearly seen: If the vibrations of the sleepers (and this applies in particular to asymmetrically supported sleepers which can thus vibrate freely) and the wheelsets are to be decoupled, rail pads with a dynamic rigidity of C_{dyn} < 150 kN/mm are required. In this way the formation of corrugations and the effect of flat spots is reduced.

The results of the rail pad test installation at Scheifling are as follows:

Soft rail pads lead to a frequency shift of the track panel to a small extent. The characteristic frequency is reduced by about 20 Hz (180 Hz ➞ 160 Hz) when soft rail pads are used.

Softer rail pads lead to a delay in the formation of corrugations. For the same traffic, smaller corrugation amplitudes are forming than for the reference section with more rigid rail pads.

Tracks fitted with rail pads of a smaller dynamic rigidity behave more favourably with regard to the formation of corrugations. Rail pad material with higher damping favours the growth of corrugations.

Rail pads with a static rigidity C_{stat} ≈ 60 kN/mm (evaluation range between 16 and 68 kN) and a dynamic rigidity of C_{dyn} ≈ 85 kN/mm can be regarded as particularly good at slowing down the formation of corrugations.

However, the softer rail pads on their own do not completely prevent corrugations (the steel type and the under-sleeper pads are also influencing factors).

The greater rail head deflections are transferred to the angled guide plates by fastening system W 14 without a greater than linear increase in wear.

The outcome of the wear examinations was favourable to the soft rail pads. Softer rail pads tend to have a longer service life, too.

The optimised rail pads are also of great advantage for straight track. A certain track elasticity is required to absorb the dynamic stress of flat spots onto the rails. Soft rail pads with a dynamic rigidity of $C_{dyn} < 150$ kN/mm reduce the risk of rail breaks significantly. Thus, the elastic rail pad not only helps to protect the rail, but also the concrete sleeper and the ballast bed. Therefore, ÖBB now uses only rail pads of type Zw 700 with the above characteristics ($C_{dyn} = 85$ kN/mm) in replacements and for new track.

Effect of sleeper voids

Since the installation of the first under-sleeper pads in the ÖBB network in 1997 (proof of concept tests from 1989), the positional behaviour of concrete sleepers sitting on a plastic layer (the under-sleeper pad) has been examined intensively and compared to the results of test sections without under-sleeper pads. The extensive measurement series showed sometimes surprising results. In particular, an almost systematic accumulation of voids below the concrete sleepers can be found in sections without under-sleeper pads. One of the most important characteristics of concrete sleepers with under-sleeper pads is the more uniform support in the ballast bed (resulting in more uniform subsidence) and together with this the almost complete suppression of voids.

There are several possibilities of determining the support quality of track with concrete sleepers. Using precision levelling, it is possible (at individual locations) to determine the absolute settling behaviour of the track. The track measurement signals for longitudinal level and direction are relative parameters; however, they are available for complete sections. Furthermore, (relative and absolute) subsidence under load can be determined by means of deformation measurements on site. Precision levelling and deformation measurements are resource intensive; the measurement signals of the track recording car are available digitally for complete track sections and can thus be easily processed.

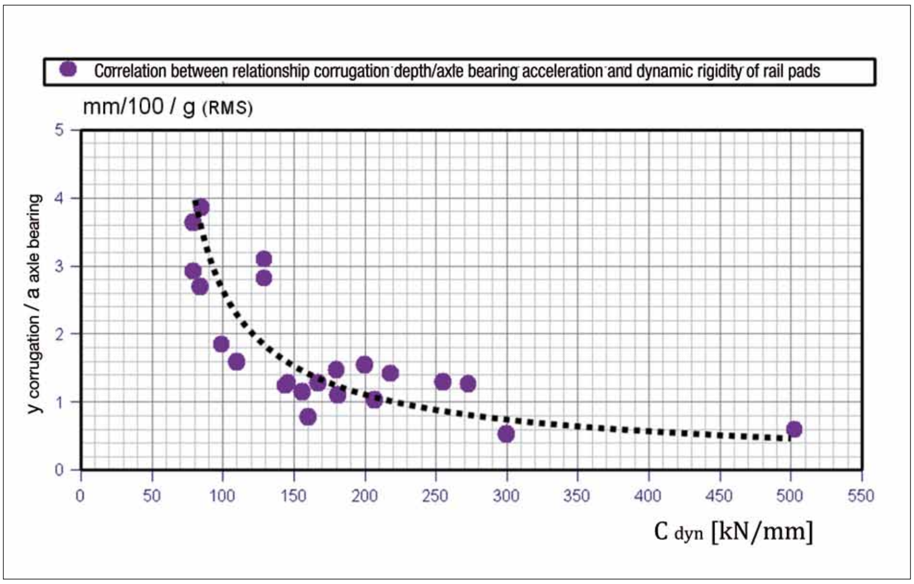

Fig. 8: Correlation between relationship corrugation depth/axle bearing acceleration and dynamic rigidity of rail pads

Even on the first test installations of concrete sleepers with under-sleeper pads, the track concerned showed a noticeable reduction in vertical settlement and also a more stable longitudinal level signal. The doctoral thesis of Monaco [6] also dealt with the lateral displacement resistance of concrete sleepers with under-sleeper pads. Based on this, ÖBB extended the tests with concrete sleepers with under-sleeper pads.

To determine the effects of different pad materials, it became necessary to carry out subsidence measurements at many locations. ÖBB decided to use a very simple and compact measurement system. Fig. 9 shows several measurement frames including the distance transducers placed on the ballast bed. As these are quick to install, it is possible to install transducers at several points of the sleeper and to determine the subsidence. ÖBB carries out these measurements on at least three points of a sleeper, i.e. at the two sleeper ends and in the centre of the sleeper. It is possible to measure five sleepers simultaneously.

To assess the differences in subsidence, it became necessary to develop a classification system for the positional behaviour of sleepers. ÖBB uses a two-dimensional subsidence diagram which exactly portrays the positional behaviour of the concrete sleepers in the ballast bed. The sleeper subsidence of one of the two sleeper ends is plotted on the X-axis and the vertical subsidence in the centre of the sleeper is plotted on the Y-axis for one crossing by locomotive (normally standard loco 1016/1116/1216). Using this type of representation, it is possible to easily and quickly see the deflection of the sleeper, the formation of a void and the size of the take-off wave. Fig. 10 shows two typical diagrams. On the left-hand side, the subsidence behaviour of a concrete sleeper with voids is plotted; on the right-hand side is a typical diagram of a concrete sleeper with under-sleeper pads with very uniform vertical subsidence in the sleeper centre and at the sleeper end.

In her dissertation, Schöpp [7] examined the existing ÖBB subsidence diagrams and measurement results. Based on this, concrete sleepers with under-sleeper pads only rarely form voids (and then only small ones). Concrete sleepers without under-sleeper pads, however, show an almost systematic formation of voids over time. Frequently, for ten consecutive concrete sleepers, three sleepers can be found with partial voids and four neighbouring sleepers which are completely unsupported and are thus freely suspended from the rails. In her dissertation, Schöpp also developed a calculation method to determine a void index. By analysing the energy density spectrum of the track measurement signal for longitudinal level, it is possible to "detect the probability of voids under concrete sleepers from the recording car or at the office desk". The positive effect of the under-sleeper pads on the prevention of voids was confirmed again.

This positive effect of the under-sleeper pads on the positional quality also leads to a reduction in the sleeper stress. The bending moments in the centre of the sleeper are reduced by about 50 % for track with under-sleeper pads. It can be assumed that

Fig. 9: Measurement setup to determine the relative vertical sleeper subsidence (Manufacturer of measurement equipment: PJM)

the life of the concrete sleepers used can also be extended by under-sleeper pads.

Due to the extensive measurements in the ÖBB network it was possible to clearly prove the positive effect of under-sleeper pads. The formation of voids is slowed down significantly or completely suppressed. This applies to all materials used for under-sleeper pads so far, i.e. softer and more rigid types [8].

Curves free from corrugations

If the design changes listed above and leading to a longer life of components in curves are combined with the optimisation of system rigidity and positional behaviour of the track

- sufficient dimensioning of the rail fasteners,
- use of rail pads with a dynamic rigidity of C_{dyn} = 85 kN/mm,
- use of under-sleeper pads,
- installation of rail profile 60 E1 with steel type R 350 HT,

a curved track can be achieved which is almost completely free from corrugations. The individual positive effects are superimposed on each other. The track measurement signals for corrugation amplitude and axle bearing acceleration document the facts on various curves with radii between 250 m and 400 m [9]. Corrugations normally do not arise in larger radii of curvature.

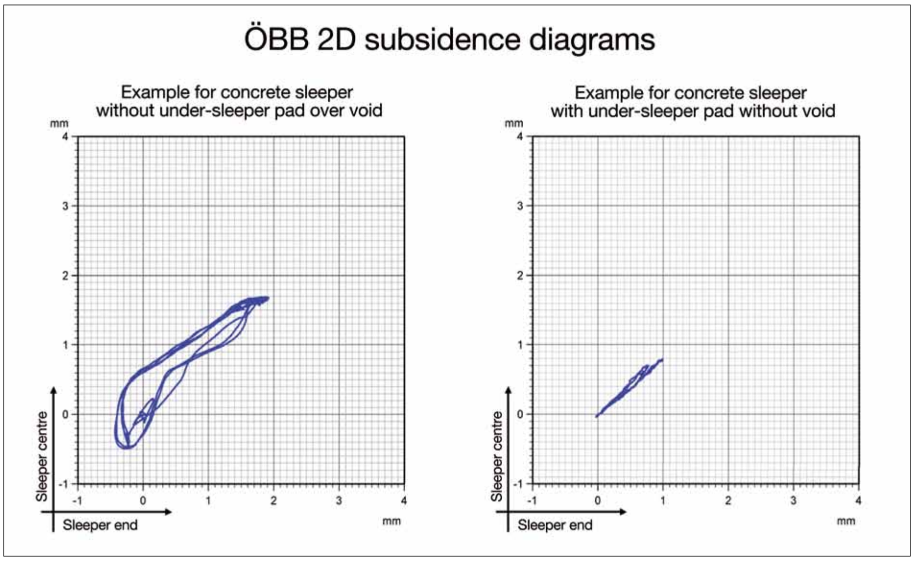

Fig. 10: Examples of 2D subsidence diagrams

Although it cannot be ruled out that stiffening of elastic components (in particular the rail pads) will also lead to some formation of corrugations in the long term, the formation of corrugations is almost completely eliminated in this way compared to the track design with concrete sleepers still used 20 years ago. Modern curved track requires less maintenance and has a longer service life. A fact which does not only entail a reduction in life-cycle costs, but is also very valuable for lineside residents.

In curves with 250 m < R < 600 m, the following track type is standard at ÖBB: rail profile 60 E1 (steel type R 350 HT) – continuously welded – concrete sleeper with under-sleeper pad (the type of pad has little effect on the formation of corrugations) – rail fastener system W 28 (Skl 28, Wfp 14) – Zw 700 (C_{dyn} = 85 kN/mm) – 600 mm sleeper distance.

The so-called High Duty Sleeper ("HD sleeper"; as a divided frame sleeper) was successfully tested in tight curves with radii R ≈ 200 m. It is possible with this sleeper type (increased lateral displacement resistance) to continuously weld curves with radii R > 180 m (possibly smaller radii can also be implemented). It is also possible to provide two support point levels for each sleeper (the rail fastener is definitely no longer the "weakest link" in this case). After more than three years, a test curve near St. Pölten does not exhibit any signs of corrugations (Fig. 11) despite the very small curve radius of R = 214 m and the high traffic volume (the East-West goods traffic traverses this curve).

In addition, the characteristics of the test curve were also examined with extensive measurements. Thus, distance transducers were fitted at several points of the track panel and, in particular, of the rail. Fig. 12 shows the relative rail head deflection (vertical and lateral movement of the rail head) in relation to the rail support. The top diagram shows the situation for a locomotive of type 1016/1116/1216 travelling over it. The vertical subsidence under the four wheelsets and the pronounced lateral deflection of the first and third wheelset can be seen. However, no additional dynamic vibrations are superimposed on the deformations.

The situation is different for the unladen goods wagon in the bottom diagram. Obviously, the beat frequency effects described arise here (and precisely for this wheelset).

Wheelset and track panel exhibit a coupled vibration. However, the amplitude is too small for corrugations to have formed in this specific curve so far. The corrugation hypothesis presented in the section "Stephanides inner curve corrugation hypothesis" is confirmed here too.

Note: The low deformation values result from the use of double rail fasteners (in total eight clips per sleeper).

Summary

This article presents measures to reduce the formation of corrugations on the inner rail in a curve with conventional ballasted track. Building on the corrugation hypotheses of Stephanides according to which the corrugations are formed by beat frequency effects due to the frequency proximity of wheelsets and track panel with the additional effect of voids under the sleepers, the following was found:

Corrugations are formed to a greater extent on rails with concrete sleepers with rigid rail pads as these do not cause a decoupling of the vibrations at the wheels and in the track panel in contrast to soft rubber rail pads. To reduce the occurrence of corrugations, the use of rail pads with a dynamic rigidity of $C_{dyn} < 150$ kN/mm is recommended. This leads to a reduction in corrugations for concrete sleepers without under-sleeper pads and in particular for concrete sleepers with under-sleeper pads.

Measurements in the ÖBB network show frequent "riding up" of concrete sleepers in the sleeper centre with simultaneous increased formation of voids under the rail supports or sleeper ends. This phenomenon occurs in particular for rails on concrete sleepers without under-sleeper pads and with rigid rail pads. The unsupported sleeper ends can, amongst other things, vibrate with the corrugation frequency and simultaneously increase the formation of corrugations. Partial voids underneath the sleeper ends thus increase the formation of corrugations.

Under-sleeper pads prevent the formation of partial voids underneath the sleeper ends. Apart from a more even support of the sleepers and better settling behaviour, the formation of corrugations can be slowed down significantly by the use of under-sleeper pads and the beat frequency effects between the wheelsets and the track panel are suppressed.

Steel grade R 350 HT is more (contact) wear resistant than steel grade R 260. Track with R 260 rails thus exhibits a faster formation of corrugations.

Fig. 11: Curve with HD sleepers at Sankt Pölten

The wear condition of the rail pad and the holding down force of the clip – which can be reduced by material fatigue, dowel creep and incorrect tightening torque – also have an effect which increases the formation of corrugations. By using sufficiently dimensioned rail fasteners, soft rail pads, concrete sleepers with under-sleeper pads and rail profile 60 E1 with steel grade R 350 HT, ÖBB has achieved an optimum of wear

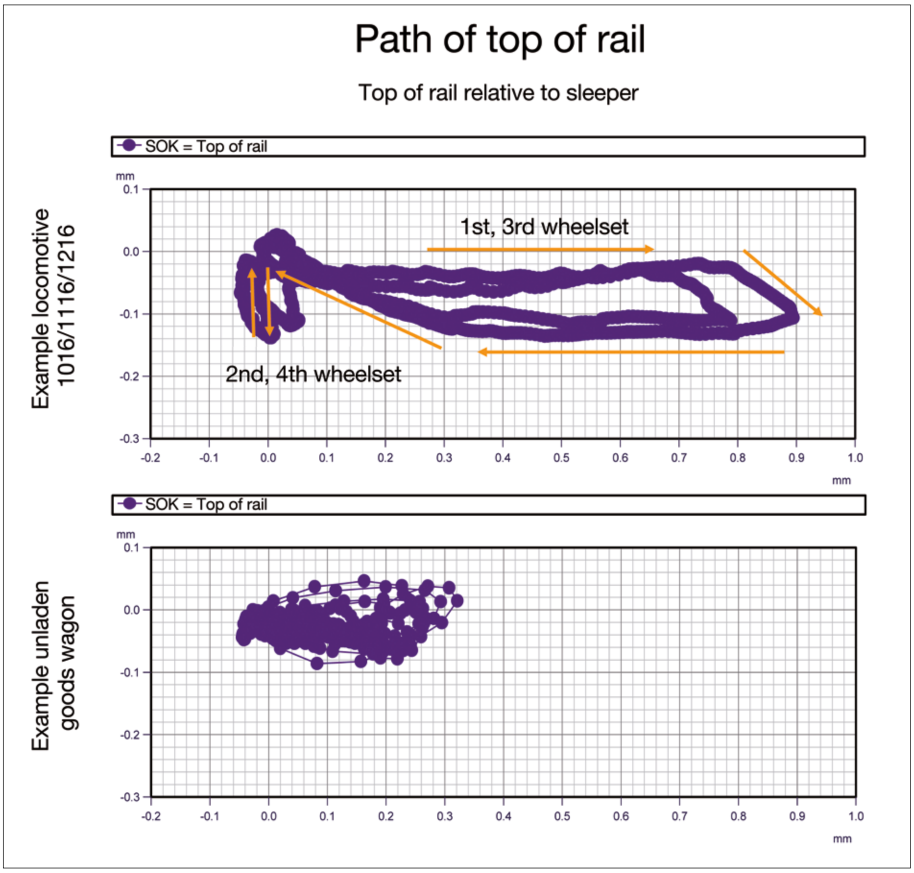

Fig. 12: Examples for the relative movements of the rail head in curves with HD sleepers (figures without source are taken from the doctoral thesis of Florian Auer)

resistance and long service life. The positive effects are superimposed on each other and in combination result in a track which is almost free from corrugations:

- Rail profile 60 E1 (steel grade R 350 HT),
- continuously welded,
- concrete sleeper with under-sleeper pads,
- rail fastening system W 28,
- Zw 700 (C_{dyn} = 85 kN/mm),
- sleeper distance 600 mm.

This article has shown that it is possible to almost completely eliminate the formation of corrugations in tight curves, even for high traffic volumes, for many years. ÖBB has been using this low maintenance and quieter curved track configuration since 2007 as standard in its main network.

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Summary

Reducing the formation of long-wave corrugations

Intensive studies carried out in the ÖBB network show the advantage of elastic components and the rail grade R 350 HT with regard to the wear behaviour on tracks in tight curves. Firstly, the new components have a far longer service life and secondly, an optimised dimensioning of the track system can almost completely prevent the formation of long-wave corrugations in track curves with a radius R < 400 m. In curved tracks with an advanced state of corrugation, the service life of the track components will be greatly reduced – this applies to the ballast bed in particular – and also these tracks are up to 15 dB louder than uncorrugated tracks. Under sleeper pads help to reduce the formation of sleeper voids, elastic rail fastenings lead to decoupling of the occasionally freely oscillating sleepers and the wheelset, and the rail grade R 350 HT leads to a general reduction of wear. If these elements are combined together correctly when dimensioning the curved tracks and if the system behaviour of the track is optimised as a whole, it is possible to eliminate the formation of long-wave corrugations almost completely.