GENERAL REQUIREMENTS FOR BALLASTLESS RAIL-TRACKFORMS
ASPHALT AND CONCRETE PAVEMENT DESIGN

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ABSTRACT: Ballastless railway track-forms use long term experience from road pavement design and construction. Like other special pavements, e.g. airside pavements, the impact of load regimes with respect to service conditions and design life must be carefully studied and reflected by a sound and sustainable pavement design approach. Ballastless track design has to implement rail infrastructure requirements with respect to reliability, availability, maintainability and safety. Ballastless track design must study static and dynamic train loads, load distribution within the structure, environmental impacts, substructure performance as well as interactions with safety and signaling equipment. General requirements and recommendations are highlighted for design and installation of such pavements used as a subsystem to provide long-term bearing capacity for rail track-forms.

KEYWORDS: Railtrack, Design, Pavement, Concrete, Asphalt, Ballast

1. GENERAL

Conventional ballasted tracks require less investment costs compared to other track-forms. They bear very high axle loads at moderate speed and corrections or adjustment of the vertical and horizontal alignment can be applied thanks to the flexible interface between sleeper panel and ballast bed. Efficient machinery is available for all the maintenance work needed.

Increased maintenance needs caused by ballast degradation had been observed during the last decades especially if ballast is laid on a stiff layer [1]. Ballast on concrete slabs like bridge decks or tunnel floors, suffered much quicker degradation than when laid directly on a soil surface. Along high speed lines in Japan, France and Germany the durability of the ballast was approximately halved, and ballast renewal was needed after about 15 years. There is no contribution to overall track elasticity by a stiff substructure, so higher vertical contact stresses are acting between sleepers and ballast. Lack of track elasticity and damping will also increase dynamic loads and vibrations. Today high speed line service requires high track quality while availability requirements are in conflict with necessary track closures for maintenance needs e.g. for track re-alignment, tamping or ballast renewal.

Based on long term experience in road applications concrete pavements and asphalt layers or combined multi-layered structures offer high bearing capacity and safe and sound alignment (see figure 1). Integration of such layers into rail superstructure requires knowledge of track performance requirements such as durable track geometry, track elasticity and track stability which are discussed in this paper. This paper collects the decisive requirements and parameters which are important for safe and sound ballastless track design and construction. Due to the wide variation of possible ballastless track application dependent on the specific combination of operational requirements, train loads and environmental impacts fixed for individual projects most of the requirements must be handled as general requirements.
2. BALLASTLESS TRACK SYSTEMS

Actual in-service ballastless track systems along high speed lines as well as short test sections in revenue lines can be grouped as follows. All of them are multi-layered structures:

- supporting rails connected to sleepers (e.g. see figure 1)
- with prefabricated slabs or frames supporting the rails
- with integrated sleepers supporting the rails (monolithic structure)
- with embedded rails or discrete rail seats

2.1 Concrete or asphalt pavements supporting rails connected to sleepers

Such systems are reflecting the basic concept to use road pavement expertise as a supporting structure for sleepers and rails. With respect to geometrical tolerances and to achieve uniform contact pressure between sleeper-bottom and pavement-surface an interlayer which offers small elastic and plastic deformations should be used. Using sleepers with a large contact area (minimum length 2,4 m) to the pavement the pressure between sleeper and pavement by rail seat loading will be reduced to a level which is much lower than the contact pressure of conventional truck-tires. Therefore asphalt pavements can be used to serve as supporting structures for ballastless tracks (see figure 1). But in addition to the thickness design according to bearing capacity the occurrence of deformations caused by the time and temperature dependent visco-elastic behaviour of asphalt must be taken into consideration.

Requirements for concrete and asphalt layers for ballastless tracks are in respect to some design parameters much higher and sharper, respectively. The maximum cant for German high speed rail tracks is 180 mm which is equivalent to cross-fall of about 12,5 %. Design speed up to 330 km/h or more requires tracks with accurate and durable alignment. High centripetal and guiding forces are activated to control the train wheel-sets along curves. Those must be transferred to the substructure as well as longitudinal forces generated by braking or accelerating the train. Horizontal forces caused by changes of temperature within the continuously welded rails shall be safely controlled to avoid track buckling. Suitable connectors to handle all those horizontal forces shall be inserted at the sleeper and pavement interface (see figure 2).
2.2 Pavements with prefabricated slabs or frames supporting the rails

Prefabricated slabs (see figure 3) in a length of about 6.5m and connected to a cement treated base (CTB) had been installed along thousands of kilometres of high speed lines worldwide. The slabs are segmented into 10 sections and prestressed in transversal direction designed like a set of wide-base sleepers. A first test section had been built 1977 close to Munich, the Max Bögl company took the long term experience of this system and did a re-design to offer a competitive ballastless track system. The innovative approach to achieve an economic production procedure was to integrate the exact track alignment by individual grinding of the rail seats, while the slab is always the same. At the construction side the slabs are exactly positioned by special lift quoins and coupled in longitudinal direction. After filling the horizontal gap between the slab and the treated base, which can be 30 cm asphalt or cement treated base layer, the coupled joints between the slabs are working as smoothly prestressed joints.

2.3 Multi-layered structures with integrated sleepers supporting the rails (monolithic structure)

Actual system designs were derived from the original Rheda system which used a Continuously Reinforced Concrete Pavement (CRCP) supporting the sleepers. The monolithic structure had been achieved by concrete poured between and below sleepers. For good long term behaviour it was evident to achieve full bond between sleepers, filled concrete and CRCP. Actual design is the "Rheda 2000" by company rail-one integrating the lattice girder sleepers directly within the CRCP (see figure 4). A first section has been constructed within the new line Erfurt - Leipzig/Halle in year 2000 followed by thousands of kilometres built world-wide.
Cracks are controlled by the prefabricated concrete elements for the rail seats which are integrated in the CRCP. With respect to durability of the ballastless track system the crack width shall be limited to max. 0.5mm. This requires respective amount of longitudinal reinforcement, which is typically 0.8% to 0.9% of concrete cross section.

2.4 Multi-layered structures with embedded rails or discrete rail seats

Embedded rail technology is aimed to a continuous rail support without any rail fastening systems. Continuously elastic rail pads and rails itself are inserted in u-shaped pockets/trough of the pavement structure (see figure 5), fixed in the exact height, position and cant. It must be guaranteed, that horizontal and vertical loading to the rail causing tensile and shear stresses will be transferred between rail and pavement structure by the elastic bed and respective bond conditions. This requires a CRCP to be used as a supporting structure.

Alternatively the elastic rail-fastening-systems can be directly connected to a CRCP (see figure 6). But it is essential to avoid transversal cracks at the positions of the dowels of the fasteners, which requires controlled cracking by kerbs cut into the concrete pavement every e.g. third rail seat. Modifications of the CRCP design is needed to end up with required functions of such a Jointed Continuously Reinforced Concrete Pavement. With respect to durability of the system joints should be sealed.
3. BALLASTLESS TRACK SYSTEM DESIGN

3.1 Requirements

Due to economic boundaries a design life of at least 50 years, usually 60 years is applied for ballastless track systems. Subsystems and components, which are subject to a shorter life span due to wear or fatigue, e.g. rails, shall have adequate provision for replacement (Maintainability). Sustainability of ballastless track systems primarily concerns ecological impact like energy consumption and CO$_2$ emission during construction and recycle-ability at the end of service life.

Due to the fact that high un-sprung masses (axles plus power line of locos or power cars) are running with high speed, safely guided and supported by the rails the track must be able to distribute the load into the substructure and to control vibrations. Therefore resilient rail support is essential; according to the German requirements for ballastless track system design \[2\] spring coefficient of rail seat (e.g. fastening system) shall be \(22.5\text{kN/mm} +/\!-\! 2.5\text{kN/mm}\) (standard rail seat distance 65cm). This approach gives rail deflection of about 1.5mm if loaded by 20t axle load.

Rail stresses must be carefully controlled. In addition to flexural stresses activated by axle loads, thermal tensile stresses due to cooling of the continuously welded rails (CWR) in addition to restrain forces activated by the substructure behaviour (e.g. bridge decks), train braking etc. must be taken into account. Track-forms with CWR shall demonstrate high safety against the risk of horizontal track buckling. Resistance against transversal track movements must be > 25kN/m along the track according to \[2\].

Vertical, plastic deformations within track superstructure shall be limited; asphalt pavements used to support sleepers show some deformations along the sleeper contact area which is helpful to smooth the load transfer at this interface. Such kind of adaptation effects should not lead to lower riding quality. Due to certain risks of substructure settlement or heaving along cut sections the ballastless track superstructure design must come up with proposals concerning height adjustments of at least 20mm which is usually done in the fastening system.

The design of ballastless track systems shall accommodate all equipment required (loops, balises, axle counters, track circuits, noise absorbing panels, level crossings, guard rails), and their connection to the track. Local changes in the track cross-section shall be accommodated in the track design. All loads arising from fixing of equipment shall be taken into account, e.g. guard rails. Aerodynamics loads on the equipment shall be considered.

The design of the track system shall consider the effects on the system due to the actions of errant wheels and the likelihood and consequences of tipping of a derailed train. The renewal procedures for components potentially effected by derailment must be part of the track design.
3.2 Design Loads
Ballastless track structures have to handle different kind of forces acting within vertical and horizontal (longitudinal and transversal) direction to safely guide the vehicle and to distribute the loads caused by traffic and/or environmental impacts to a bearable level for the relevant systems.

Loads could be:
- Static or quasi static (acting as repeated / fatigue loads) axle loads;
- Dynamic (in addition to static loads due to excitations);
- Exceptional (in terms of load cycles or temporarily limited).

Loads acting between running vehicle and rail are always a combination of static and dynamic loading.
Exceptional loads are singular load actions, e.g. derailment. Other loads associated with the construction maintenance and emergency access must be considered.

For track design axle load configuration given by the load model 71 is used, which gives a maximum axle load of 250 kN. Maximum axle loads of actual high speed trains are about 170 kN (ICE 3) and further reduction is expected. Alternatively the relevant load schemes according to line category or real vehicles can be used for system design.

Vertical static loads may act unequally on the inner and outer rails due to centrifugal effects in curves or non-uniform load distribution. Such effects are determined on the basis of a suitable vehicle model, taking into account track alignment parameters like cant and cant deficiency. If track alignment parameters are not specified the load distribution between inner and outer wheel is ± 20% [2].

Dynamic vertical loads are dependent on vehicle speed and quality of vehicle and track. A dynamic factor of 1.5 should be applied to all static and quasi-static loads according to the maximum safety limit of 5,0m/s² vertical car body acceleration set in vehicle approval procedures.

Alternative tools to determine dynamic loads are:
- Track quality characterized by normal distribution using rail deflection. The coefficient of variation must be limited to 10%, the confidence level at least 99.7% .
- Power Spectrum Density (PSD) function describing vehicle response (e.g. by Multi Body Simulation) according to specified limits
- Other models describing vehicle-track interaction in combination with acceptance criteria

In addition to vehicle and environmental loading ballastless track system design has to include impact from the signaling system (induction effects, interference from reinforcement etc.), the substructure performance (tunnels, bridges, embankments), electrical power system (stray current requirements, cable access etc.), safety and telecommunications installations and operational needs like maintainability and accessibility.

4. LOAD DISTRIBUTION WITHIN TRACK SUB-SYSTEMS

4.1 Vertical load distribution
The assembled rail, fastening system (discrete or embedded rail system) and concrete sleeper (if used) and can be considered as a beam on a continuous or discrete resilient support. The moment of inertia of the rail profile (usually 60 kg/m), the spacing of the fastening systems (usually 65cm) as well as the elasticity of the whole assembly on its support, have an influence on the longitudinal distribution of the vertical loads (see figure 7) and horizontal loads applied on the rail.

The rail supporting structure which is made by prefabricated structures and/or pavements (single or multi layered) is designed to distribute the load by bending (beams and frames mainly in longitudinal direction; slabs in longitudinal and transversal direction) into substructure. Bending behavior shall be elastic without or with
limited plastic deformations e.g. asphalt layers used as an intermediate or leveling layer on tunnel floor. By the bending behaviour of the rail additional, small negative rail seat loads are activated.

![Diagram of Lift-up forces](image)

Figure 7: Dynamic rail seat loads [kN] activated by an ICE 1 boogie (static axle load 196 kN)

4.2 Transversal loads
Also transversal loads will be longitudinally distributed along the rail in accordance with the horizontal elasticity of the track system. Horizontal elasticity must be within certain limits to control the wheel rail interface (mainly gauge) but it is actually not exactly specified. The elastic and plastic gauge widening recorded during repeated load test for approval of new fastening systems according to actual European Norms are not used as acceptance criteria. If horizontal elasticity is not determined the load distribution can be assumed as follows:

- 60% horizontal wheel loading acting on rail seat below wheel
- Each 20% horizontal wheel loading acting on rail seats before and after wheel

For embedded rail systems rail seat loads may be distributed to respective sections, each 65cm long.

Railway lines with ballastless track systems are usually prepared to accept trains equipped with eddy current brake systems. Effects of eddy current braking systems if used as regular, service breaking systems are dependent on activated brake force and sequence of trains. Effects activated by emergency braking are significantly higher and shall be handled as exceptional loading.

The maximum vertical attractive force activated by magnets may interfere with movable track components (e.g. turnouts, lift of tongue rail) and track equipment.

Temperature increase by eddy current braking must be determined based on specified performance of brake set up and configuration (e.g. gap between rail and brake), maximum contribution (e.g. 0.3 m/s²) of eddy current brake to operational deceleration (e.g. 0.5m/s²) and sequence of trains (e.g. 10min). Alternatively maximum allowable rail temperature increase due to Eddy current brake shall be specified. This requires a vehicle or track based rail temperature control system for acceptance of eddy current brakes as operational braking systems.

5. PAVEMENT DESIGN

5.1 Calculation models and limits
Design criteria for all layered structures/pavements distributing the loading by bending (flexural resistance) are the maximum tensile flexural stresses acting in the layer(s). Loading of supporting layers (base layers) made by unbound materials shall be evaluated using vertical compressive stresses. Decisive combination of rail seat loads
shall be used to determine the maximum bending moment acting in the pavement structure. Rail seat loads which cause a reduction in bending moment must be removed from the model. Decisive tensile flexural stress (bending tensile stress) of all layers of a multilayered system shall be calculated. Stresses shall not exceed tensile flexural fatigue strength. It is recommended that vertical stresses acting on subsoil or subgrade shall not exceed $\sigma_z = 0.050\ \text{N/mm}^2$.

5.2 Substructure requirements

For ballastless track systems it is necessary to control permanent deformations (settlement or heave) as well as elastic deformations due to variable loading. Ballastless track systems do not admit significant permanent deformations of the substructure. Permanent deformation, e.g. due to settlement or heave, shall be specified, and it should be ensured that the rate of deformation will not be larger than the limit taken into account for the design. Due to this it is essential that any deformation of the substructure is nearly finished before the installation of a ballastless track system starts.

The elasticity of the substructure should be defined, in order to design the ballastless track. Unless otherwise specified a deformation modulus on the formation equivalent to $E_{z2} = 45\ \text{N/mm}^2$ should be used for the ballastless track design.

The interaction between ballastless track systems and bridges should be taken into account. An integrated bridge-track design shall be executed where appropriate. If the bridge and the track are designed separately, the relevant characteristics of the ballastless track system shall be verified according to the bridge design.

Provision shall be made for

- the curvature of the bridge deck due to deformation dependent on the bridge deck stiffness and decisive load combination as well as rotation of the adjacent bridge decks at intermediate and end supports shall be made for each ballastless track system.

- to avoid high differential lateral movements between adjacent superstructures and between superstructure and abutment. Such movements may be caused by temperature, traffic or other variable loads. The calculation of movements shall take the bearing conditions of the superstructure into account (internal play of bearings, deflection of bearings).

- the differential vertical bridge deflections at bridge joints from temperature, traffic or other variable loads, shall be made for each ballastless track system. The use of rail expansion joints may be necessary for long bridges.

Foundations of railway bridges are usually less susceptible to settlements than the embankments around. Therefore, provisions against differential settlements at transitions between railway bridges and earthworks besides shall be made.

Transitions between earthworks, bridges and tunnels will usually ensure a gradual transition with respect to track geometry and track elasticity. Ballastless track systems shall be able to compensate remaining differences (settlements and elastic properties) in the substructure, e.g. by variation in support stiffness and geometrical adjustment capacity, to minimize the dynamic response in the vehicle. The length of the transition zone depends on the design speed and the differences in behaviour between the adjacent structures and substructures.

6. CONCLUSIONS

Ballastless track superstructures require sound and safe structural design with respect to thickness of rail supporting structures (e.g. pavements) as well as proper cross-section design. Designers should use proven pavement-technologies already applied for road infrastructure. Concrete and asphalt pavements are able to meet the requirements concerning the bearing capacity, accuracy and durability needed for ballastless tracks. Such synergetic effects in road and railway superstructure design and construction are useful but requirements for railway tracks especially on high speed are specific. Experience generated during the last decades on ballastless track design, construction and track performance confirms that the interface between the pavement structure and rail track components should be carefully studied. Beside special high loadings also tight limits concerning track
geometry with respect to high design speeds, up to more than 300km/h, must be covered by the design as well as by high quality of track works during construction. Higher initial costs for ballastless tracks compared with improved ballasted track systems will push further activities in research and development.

REFERENCES: