A Drivable Slab Track Cover System For Railway Tunnels

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Abstract

Technical and economic reasons are the driving factors for the increasing importance of slab tracks compared with traditional ballasted tracks. Modern railway tunnels require complex safety concepts regarding evacuation and rescue measures. In Germany, for instance, in case of emergency, the drivability of adjacent independent tunnel tubes is required. This is the motivation for the present contribution, dealing with the development of a drivable slab track cover system. Requirements with regard to function, economy and maintenance lead to a proposal for a drivable slab track cover system, consisting of two element types: a relatively small side element and a much larger middle element. As the European standard does not provide realistic load assumptions, technical data on several fire-fighting vehicles and their respective tire loads are collected. Based on the latter, numerical and experimental investigations of the side element, which is the crucial part of the cover system, are carried out.

Keywords

Slab track, drivability, railway tunnel, code requirements, reinforced concrete, experimental investigation, smeared crack model
1 Introduction

In fact, Non-ballasted railway tracks, also called “slab tracks”, are gaining more and more in importance compared with the traditional ballasted tracks. This can be attributed to various technical and economic reasons.

Although the construction costs for slab track systems are approximately 30% to 50% higher than those for ballasted tracks (Bilow and Randich, 2000; Darr and Fiebig, 2006), lower maintenance costs represent a significant advantage of slab track systems against ballasted tracks. For example, during operation of the latter, non-uniform settlement of the ballast requires costly works for the track system (Eisenmann and Leykauf, 2000). Moreover, current developments within the European rail network show increasing train speeds and axle loads, which both considerably reduce the maintenance intervals of ballasted tracks (Bilow and Randich, 2000; Ren et al., 2008; Zicha, 1989; Eisenmann and Leykauf, 2000). Reduced maintenance intervals in combination with the increasing traffic intensity in the European network lead to a decrease of availability of ballasted track systems (Esveld, 2003) and to higher operation costs. Hence, in order to assess the economic efficiency of a rail track in an objective way, it is important to consider the life cycle costs and not only the investment costs.

A technical advantage of non-ballasted track systems is the higher lateral track resistance, which allows either smaller radii of the railroad, when postulating a defined velocity, or higher train speeds, when postulating a particular curve radius (Ren et al., 2008). The reduction of structure height and the fact that during high-speed operation churning of ballast particles is not possible, represent further technical advantages (Ren et al., 2008; Esveld, 2003) of non-ballasted track systems.

Within the last four decades several types of slab track systems have been developed. These include the German systems Rheda, Bögl, Gertrac and Züblin, the Austrian system ÖBB-Porr, the Japanese Shinkansen slab track, the English Pact-Track system, the Netherlands Embedded Rail System (ERS), the American Long Island Railroad Slab Track, the French Stedef system or the Sonneville system Low Vibration Track (LVT), which is used in the Eurotunnel under the English Channel (Eisenmann and Leykauf, 2000; Bilow and Randich, 2000; Esveld, 2001; Markine, 1999).

Due to the advantages mentioned above, slab track systems today have been established as the standard solution for railway tunnels.

Modern tunnels require complex safety concepts. In the European Union, standards concerning safety in railway tunnels are based on a Technical Specification of Interoperability (TSI) (TSI, 2008). The purpose of TSI is to prescribe tunnel-specific measures concerning all subsystems of a railway track, such as infrastructure, energy, command-control etc. Thereby, the main focus is laid on increasing the safety level by considering special rules for preventing or mitigating accidents but also for evacuation and rescue measures. TSI only specifies minimum requirements, as many measures depend on local conditions for a particular tunnel project. Hence, all member states have the possibility to enact stricter rules for increasing the safety level. For example, in the subsystem infrastructure, on the one hand TSI does not prescribe the possibility of driving along a slab track by road vehicles. On the other hand, in Germany, the document of the
federal railway organisation (EBA, 2001) stipulates the drivability of adjacent independent tunnel tubes in case of emergency. Details concerning the drivability of slab track systems are summarized in a report compiled by the Institute of Highway and Railroad Engineering of the Karlsruhe Institute of Technology (Hohnecker, 2008). In order to provide uniform planning criteria, the requirements summarized in that report will be included in the catalogue of requirements for the construction of slab tracks of the German railway network (AKFF, 2002).

Up to now, there has been no standard solution for a drivable cover system for all different types of slab tracks. Hence, in the course of such a design process, the respective type of slab track has to be considered. In the following, the development of a drivable cover system, based on the Austrian slab track system ÖBB-Porr, is presented. Whereas in Andreatta et al. (2012a) and Andreatta et al. (2012b) first proposals for a drivable slab track cover system were presented, based on a plain concrete solution, in the present contribution a completely revised solution concerning the geometry, the material and the structural behaviour is described. Thereby all technical and economic requirements concerning fabrication, installation, function and maintenance are considered. As the European standard does not provide realistic load assumptions, appropriate load arrangements will have to be set up. Based on the determined loadings, experimental and non-linear numerical investigations are carried out in order to comply with the code requirements regarding the ultimate limit state.

2 Design process

The report of the Institute of Highway and Railroad Engineering of the Karlsruhe Institute of Technology (Hohnecker, 2008) provides the basis for the development of the drivable slab track cover system for the Austrian slab track system ÖBB-Porr, described in this contribution. The latter is based on a prefabricated reinforced concrete plate with eight pairs of track-supporting components which are integrated on the surface of the slab track at intervals of 65 cm (Fig. 1)
The main topics of the report, concerning inspection, drivability, maintenance and functionality during train operation, are briefly presented.

2.1 Geometric Requirements

All the requirements described in detail in the following lead to a concept for a drivable slab track cover system consisting of two element types. Relatively small, removable side elements are placed on both sides of the rails, and much larger middle elements are placed between the rails in the middle of the slab track (Fig. 2).

![Figure 2. Arrangement of the side and middle elements and detail of the geometry and support of the side elements.](image)

As effective quality management requires inspections of tracks at regular intervals, slab tracks and slab track cover systems have to be designed such that security-relevant parts, e.g. rail fastenings, can be checked at any time and without restrictions. Hence, a gap width of at least 180 mm between the edge of the rail head and the side element is required (Fig. 2). However, for small passenger cars, a constant gap of 180 mm would increase the risk of jammed or even damaged tires. Hence, the gap width is not uniform along the rail, but is reduced to 100 mm in the area between the track-supporting components (Fig. 2).

In the case of performing maintenance works such as, for example, the welding of rails, a working space of at least 250 mm must be kept entirely clear on both sides of the rail (Fig. 2). The latter demand can only be met by removing parts of the slab track cover system, namely the side elements. Removal of those parts should be possible with man power alone...
(maximum 2 persons) without any lifting equipment. Hence, the weight has to be low, requiring small dimensions for the side elements. The drag forces generated by the airstream of passing railway vehicles may result in vertical separation of the cover system from the slab track. Thus, both the side and middle elements have to be fixed. For instance, openings are provided in the side elements, for installing tension anchors (Fig. 3). Moreover, the drivable cover system must not interfere with the functionality of drainage of the slab track.

2.2 Side element

Initially, for economic reasons, it was intended to make the side elements of plain concrete (Andreatta et al., 2012a; Andreatta et al., 2012b). However, numerical simulations considering linear-elastic material behaviour clearly showed that the code requirements regarding the ultimate limit state cannot be met for heavy local tyre loads. Thus, the side elements shown in this contribution are made of reinforced concrete.

As the distance between the axes of two track-supporting components is 650 mm, the length of a side element was chosen as 630 mm, resulting in a gap width of 20 mm between adjacent elements (Fig. 2). In contrast to the first proposed solution described in Andreatta et al. (2012a) and Andreatta et al. (2012b), characterized by placing the side element between two track-supporting components, the revised solution of the side element described in this contribution is characterized by enclosing each track-supporting component. Hence, side elements do not extend over the gap between two adjacent slab tracks. This is advantageous because of possible geometric irregularities in those regions. According to the required minimum working space of 250 mm on both sides of the rail, the width of a side element was determined as 292 mm and its height of 179 mm follows from the geometric requirement of a 50 mm elevation difference between the top of the rail and the top surface of the cover system. The chosen dimensions result in a weight of 620 N.

For the vertical support of the side elements, several determining factors have to be considered. On the one hand, for minimizing tensile stresses in the side elements, the spans should be as small as possible and, hence, various support areas should be provided.
ontop of the track-supporting components as well as in the region between the track-supporting components (Andreatta et al., 2012a; Andreatta et al., 2012b). On the other hand, various support areas of a side element yield a statically indeterminate support. Consequently, small irregularities of the geometry of a side element and the track-supporting components would lead to a modified support situation with not all the intended support areas actually being in contact with the slab track. Thus, in contrast to the first solution proposals, contact areas are limited to the region between the track-supporting components (Fig. 2).

Investigations regarding the transfer of breaking forces of road vehicles from the top surface of the side element to the slab track showed that they cannot be transmitted only by friction forces between the side element and slab track. Hence, the breaking forces have to be transmitted from the side elements into the shoulders of the track-supporting components (Fig. 2). Since the side element is identified as the critical part of the cover system concerning the structural performance, all further investigations in subsequent sections are restricted to the side element.

2.3 Middle element

As it is not necessary to remove the middle elements for inspection works, and for economic reasons, they were designed with dimensions of 2.58 m length and 0.65 m width, much larger than the side elements (Fig. 2). Since the middle elements are acting as single-span girders and because of transportation aspects, they are also made of reinforced concrete. Because of their higher weight of about 6600 N, they can be placed and removed only by appropriate lifting equipment. The middle elements are easily adaptable to any additional requirements for the track, such as ducts or train control devices.

3. Load arrangement

The European Standard does not provide a special load model for drivable slab track cover systems. In Eurocode 1991-2 (Eurocode 1, 2012) three load models (LM1, LM2 and LM3) especially developed for the structural analysis of bridges are described. As the side element with a drivable surface area of only 0.16 m² is small, the load models are not suitable in the present context. As the German Federal Railway Authority (EBA, 2001) stipulates the drivability of tunnels in case of emergency, it was first necessary to identify existing types of fire trucks that may be used for rescue operations in tunnels. Based on the information provided by different manufacturers, technical data on several firefighting vehicles were collected to determine the vertical and horizontal component of the force transmitted from a tire to a cover element. The resultant vertical force, on the one hand, results from the vertical component of the permanent and the service load, and, on the other hand, from the breaking force. The breaking force, which acts in a horizontal direction at the centre of gravity of the vehicle, causes a moment transferred to the surface of the cover element. This moment is supported by vertical forces, leading to an additional vertical load acting on the front axle, while the rear axles are partially unloaded. For selected types of fire-fighting vehicles, Table 1 contains an overview of the resultant values of the vertical and horizontal forces transmitted from a front tyre to a cover element.
Table 1. Vertical and horizontal tyre loads for different fire-fighting vehicles.

<table>
<thead>
<tr>
<th>Type of fire-fighting vehicle</th>
<th>Vertical force [kN]</th>
<th>Horizontal force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scania P 380 4x4</td>
<td>65.5</td>
<td>52.4</td>
</tr>
<tr>
<td>Scania 19.380 CP 131</td>
<td>58.2</td>
<td>46.6</td>
</tr>
<tr>
<td>Scania R 124 8x4x6</td>
<td>63.5</td>
<td>50.8</td>
</tr>
<tr>
<td>MAN 19.322 FA</td>
<td>68.1</td>
<td>54.5</td>
</tr>
<tr>
<td>MAN 18.400</td>
<td>69.8</td>
<td>55.8</td>
</tr>
</tbody>
</table>

Due to the shape of the top surface of the side element and to the gap between the side element and the rail (Fig. 2), load arrangements are possible for which not the whole tyre tread is in contact with the top surface of the side element. Since these load positions are decisive for the dimensioning, realistic load areas for the top surface of the side element had to be determined. These are shown in Figure 4.

Figure 4: Tyre positions and respective load areas for the top surface of the side element.

Figure 5a shows the test arrangement for determining the contact area between a tyre and the top surface of a side element, while Figure 5b shows the respective print according to position A of the tyre, described in Figure 4.
4. Code Requirements - Ultimate Limit State (ULS)

The code requirements regarding the ultimate limit state according to Eurocode 0 (Eurocode 0, 2013) are met if the design value of action $S_d$ does not exceed the design value of resistance $R_d$:

$$S_d \leq R_d$$  

(1).

In the present case, Eq. (1), supposing failure of the concrete to be decisive, yields

$$\gamma_S \cdot S_k \leq R_m \cdot 0.86 \cdot 1/\gamma_{c,R}$$  

(2),

where $S_k$ denotes the characteristic value of action and $R_m$ denotes the mean value of resistance. Considering the partial safety factor for action $\square S = 1.0$ (accidental design situation), the one for concrete $\square c,R = 1.5$ and a factor of 0.86, describing the ratio between the characteristic value and mean value of the compressive strength of the concrete used (C50/60), Eq. (2) results in:

$$R_m \geq 1.74 \cdot S_k$$  

(3).

5. Numerical model

Whereas the design process of the side element (geometry, reinforcement (Fig. 6a)) was determined by means of numerical simulations assuming linear elastic material behaviour, the structural performance is investigated by non-linear analysis. The latter is based on a three-dimensional Finite Element (FE)-model consisting of about 1.2 million degrees of freedom (Fig. 6b). The non-linear material behaviour of concrete is described by
a damage-plasticity model based on the models proposed by Lubliner et al. (1989) and Lee and Fenves (1998). The constitutive theory aims to capture different yield strengths in tension and compression, softening behaviour in tension as opposed to initial hardening followed by softening in compression, different degradation of the elastic stiffness in tension and compression as well as rate sensitivity (Abaqus, 2010). The main failure mechanism expected for the side element is cracking in tension. Hence, in order to represent the fracture process of the quasi-brittle concrete material, a classical smeared crack approach is chosen. The latter is characterized by spreading the dissipated energy along the finite width of the localization band. The crack detection is based purely on Mode I fracture considerations (simple Rankine criterion) and crack directions are stored for subsequent calculations.

For the material parameters of the selected concrete type C50/60, the respective mean values according to the Eurocode EN 1992-1-1 (Eurocode 2, 2011) are considered. The experimentally determined specific mode I fracture energy is 0.118 N/mm.

The material behaviour of the steel reinforcement is modelled by means of a von Mises-type elastic-plastic model with kinematic strain hardening. The Young’s modulus is given as 200000 N/mm², the mean value of the yield strength amounts to 560 N/mm², the ratio between the mean values of the tensile strength and yield strength is 1.08 and the strain at rupture is 5%. The reinforcement is modelled by means of the so-called embedded technique.

Thus, if a node on an embedded element, representing the rebar reinforcement, lies within a finite element representing the concrete, the degrees of freedom at the node will be eliminated by constraining them to the interpolated values of the degrees of freedom of the surrounding concrete element. Hence, a perfect bond between the reinforcing steel and concrete is assumed.

Since a thin layer of geotextile is mounted at the bottom surface of the side element, a non-linear contact model is employed for modelling the soft support. For determining
the respective material parameters of the employed Coulomb-type friction law, the geotextile layer was investigated experimentally. By means of the employed contact relationship, only shear stresses and compressive stresses can be transferred from the side element to the slab track. If the adhesive friction between the geotextile layer and the slab track is lost, then also the contact area between the side element and the shoulder of the track-supporting component is considered. In Figure 6b the thin geotextile layer and the shoulders of the track-supporting component are shown qualitatively by the respective contact planes.

6. **Numerical and experimental results**

By means of numerical investigations, the load acting on the top surface of the side element, resulting from position B (Figure 4) of a front tyre of the fire-fighting vehicle MAN 18400 (Tab. 1), is identified as critical load.

In order to fulfil Eq. (3) for this fire-fighting vehicle, the mean value of resistance \( R_m \), represented by the vertical \( RV_m \) and horizontal \( RH_m \) component of the force transmitted from the tyre to the side element has to achieve the following minimum values:

\[
R_{v,m} = 1.74 \cdot 69.8 \text{ kN} = 121.45 \text{ kN} \tag{4}
\]

\[
R_{h,m} = 1.74 \cdot 55.8 \text{ kN} = 97.09 \text{ kN} \tag{5}
\]

Hence, the side element must transfer a resultant force \( R_m \) of at least 155.5 kN.

Beside the non-linear analysis, an experimental investigation was conducted to validate the numerical results. To this end, the test set-up shown in Figure 7 was developed. It allows us to submit the given combination of vertical \( RV_m \) and horizontal \( RH_m \) load, by means of a testing machine equipped only with a single hydraulic jack acting in vertical direction. As shown in Figure 7, the test specimen is positioned on a specially produced counter-support plate, simulating the support conditions on the slab track ÖBB-Porr.

The inclination of 38° corresponds to the given ratio of the vertical \( RV_m \) and horizontal \( RH_m \) load. This test arrangement is only possible because of the negligible dead load of the side element compared with the tyre load.
Several displacement transducers were installed to record displacement components w1, u2, u3 and w3 at the measuring points MP1, MP2 and MP3, as shown in Figure 8. In total, three tests on identical specimens were performed.

Figure 7. Test set-up.

Figure 8. Displacement components measured at the measuring points MP1, MP2 and MP3 by means of displacement transducers.
In the framework of the experimental investigation, the force of the hydraulic jack was limited to the required resultant force $R_m$ ($155.5$ kN) in order to minimize a possible horizontal load transmission into the hydraulic jack in case of brittle failure of the test specimen. By contrast, in the non-linear numerical simulations (respective relationships shown in Fig. 9) the resultant force is increased until close to failure, far exceeding the required resultant force $R_m$ (1.5 times).

Figure 9 shows the comparison of the measured and predicted displacement components $w_1$ and $u_2$ (Fig. 8) in terms of the applied resultant force.

Comparison of the relationship between the resultant force and the displacement component $w_1$, measured on the three test specimens, with the respective computed relationship, shows very good agreement (Fig. 9a). Hence, the implemented non-linear contact model seems to represent the soft support of the side element by the geotextile layer in a realistic manner. Although a full bond between the reinforcement and concrete is assumed, the predicted structural behaviour agrees quite well with the measured one. Comparison of the predicted displacement component $u_2$ with the respective measured ones in terms of the resultant force (Fig. 9b) shows satisfactory agreement.

The load – displacement relationships for the three specimens investigated show that the code requirements regarding the ultimate limit state are fulfilled.

In Figure 10 the computed and observed crack paths are shown for the front surface and rear surface of the side element. Comparison of the latter for the load level of 155.5 kN shows quite good agreement. The crack paths as a result of the chosen smeared crack approach, the latter regularized by means of the characteristic length of the respective finite element, and the observed crack paths are similar.
Conclusions

This paper focused on the development of a drivable slab track cover system, taking into account the requirements concerning safety in railway tunnels according to the Technical Specification of Interoperability (TSI) that is valid in the European Union. Technical and economic requirements concerning installation, function and maintenance were considered in the course of the design process. The proposed RC drivable slab track cover system consists of two element types, a relatively small side element and a much larger middle element. As the European Standard does not provide load assumptions for drivable slab track cover systems, technical details of several fire-fighting vehicles were collected. Since the side element was identified as the critical part of the cover system, the design of the latter was assessed by non-linear analysis on the basis of a 3D Finite Element model. The numerical results were evaluated by experimental investigations. During testing, the structural behaviour of the side element was monitored by displacement transducers. Comparison of computed and measured load-displacement relationships as well as predicted and observed crack paths confirmed the simulation-based design.

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