Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 4.1
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.4.1

Technical and Economic Advantages of Using UHPFRC for Ballastless Track Systems in Existing Tunnels with Inhomogeneous Subgrade

A. Hochuli[1], J.-G. Trouillet[2] and E. Brühwiler[3]

[1]Transport and Mobility Laboratory, Institute of Structural Engineering, EPFL - Swiss Federal Institute of Technology, Lausanne , Switzerland
[2]Railway Engineering Department, Engineering office A. Aegerter and Dr. O. Bosshardt AG, Basel, Switzerland
[3]Institute of Structural Engineering, EPFL - Swiss Federal Institute of Technology, Lausanne, Switzerland

Abstract

Existing railway tunnels often exhibit an inhomogeneous subgrade due to drill-and-blast overbreak and poorly compacted backfill. These tunnels were initially equipped with ballasted track; today, ballasted track is increasingly replaced by ballastless systems to reduce maintenance demand and improve track geometry stability. However, for conventional ballastless track in existing tunnels, an inhomogeneous subgrade typically requires additional "improvement" measures (e.g., excavation replacement, injections, levelling layers) that are difficult to implement reliably under confined tunnel logistics and that often govern both cost and long-term performance.

This paper presents the concept of *ThinCore-Track*, a thin, rigid slab-like ballastless railway track made of ultra-high-performance fibre-reinforced cementitious composite (UHPFRC), developed specifically for tunnels with inhomogeneous subgrades. The concept is based on a structured assessment of infrastructure needs and on the analysis of the shortcomings identified in existing ballastless track systems, which were taken into account for the new design. The proposed concept was assessed using 3D finite-element modelling in *ATENA*, which enables the simulation of realistic material behaviour under railway operational loads and load models in accordance with standards. The results indicate crack-free behaviour under operational loads and fatigue resistance.

Compared with current tunnel renewal solutions, the concept allows for the reduction of construction complexity by avoiding conventional reinforcement, multi-stage casting, and extensive subgrade treatment steps. Furthermore, its low construction height allows for an increase in the dimensions of the clearance profile, and in some cases, without having to mill the tunnel walls for this purpose. Economically, reconstruction costs are 22–36% lower than the analysed current solutions under comparable boundary conditions. Over a 100-year reference period, the life-cycle cost increase remains limited (mainly for wear components), while conventional approaches can incur intervention costs that are multiple times higher due to recurring repairs and replacements.

Keywords: ballastless, inhomogeneous subgrade, UHPFRC, construction logistics, life-cycle cost, maintenance strategy, clearance profile, ThinCore-Track

1 Introduction

Many railway tunnels in Switzerland were constructed more than a century ago, typically using drill-and-blast excavation. As a consequence, the tunnel invert often shows irregular overbreak zones respectively backfilled cavities, which leads to variable stiffness in the subgrade. Initially, these tunnels were equipped with ballasted railway tracks, which can accommodate local imperfections in the subgrade, such as unevenness. Nowadays, however, existing tunnels will be renewed, and ballasted railway tracks will often be replaced by ballastless track systems to reduce maintenance effort.

In practice, the change from ballast to ballastless railway track in existing tunnels is rarely a straightforward "like-for-like" replacement. The decisive challenge is the inhomogeneous subgrade: conventional ballastless railway track systems are sensitive to discontinuous support and therefore often require extensive subgrade "improvement" measures, such as subgrade material replacement, injections, levelling layers, or the construction of a concrete tunnel invert. These measures are difficult to execute reliably under confined tunnel logistics, can introduce significant schedule constraints and frequently become the dominant cost driver of the project. Moreover, even after accounting for the costs, the durability of the "improved" subgrade is not always assured under long-term cyclic railway loading, especially where the underlying backfill remains inhomogeneous.

This paper presents the concept of ThinCore-Track, a durable ballastless railway track made of Ultra-High-Performance Fibre-Reinforced Cementitious Composite (UHPFRC) developed for inhomogeneous subgrade conditions. The name *ThinCore-Track* highlights the system's key properties: "Thin" refers to the thin UHPFRC slab, and "Core" to its high rigidity. The concept was derived from a structured assessment of infrastructure needs and from the analysis of observed shortcomings in current ballastless track systems.

2 Methods

Based on an extensive literature review and practical case studies from Switzerland, the damage mechanisms and improvement potential of current ballastless railway track systems in tunnels with inhomogeneous subgrades were investigated, and the infrastructure needs were analysed in depth. On this basis, a *stable* ballastless track made of UHPFRC was developed. The developed *ThinCore-Track* was analysed using the finite-element software *ATENA Cervenka* [1], which allows the simulation of the real load behaviour of structural elements made of cementitious material. Operational loads and load models according to standards [2] were applied.

3. Specific features of existing infrastructure and lessons learned

3.1 Constraints of existing infrastructure

A railway track, as part of the entire railway infrastructure, is influenced by several factors, including the specific characteristics of the load-bearing structure and safety requirements. The design of a load-bearing structure for railway infrastructure begins with determining the usable cross-section, which depends on factors such as the number of tracks, track gauge width, speed, horizontal and vertical alignment, clearance profile, including safety spaces, and track superstructure. In the case of an existing tunnel, the clear tunnel section is predetermined and was designed based on the parameters relevant at the time of construction.

One of the key challenges of modern railway infrastructure is the updating of existing infrastructure - frequently over 100 years old - to current and future operational needs with minimal intervention. For example, railway lines are being adapted for clearance profiles with larger dimensions, which are, in some cases, necessary for international railway traffic. Furthermore, new safety requirements, such as safety spaces (service and evacuation paths), have to be implemented in existing tunnels, even though their initial dimensions did not provide for these functions.

A key feature of existing railway tunnels is the ballasted railway track. In typical cases, the superstructure of ballasted railway tracks consists of 30 cm of ballast, 150 mm high wooden sleepers, and rails. It is important to note that these tunnels were often constructed using the drill-and-blast method, and the overbreak in the tunnel invert was not structurally compensated for. Instead, this overbreak was usually filled with excavated material, which is inhomogeneous, or with railway ballast. Figure 1 (a) shows the inhomogeneity in the invert of the tunnel, built in Switzerland in 1913 using the drill-and-blast method. Another critical point for planning reconstruction and maintenance measures is the interpretation of the original execution drawings from that time, which show the tunnel invert idealized and do not document the extent of the overbreak (Figure 1(b)).

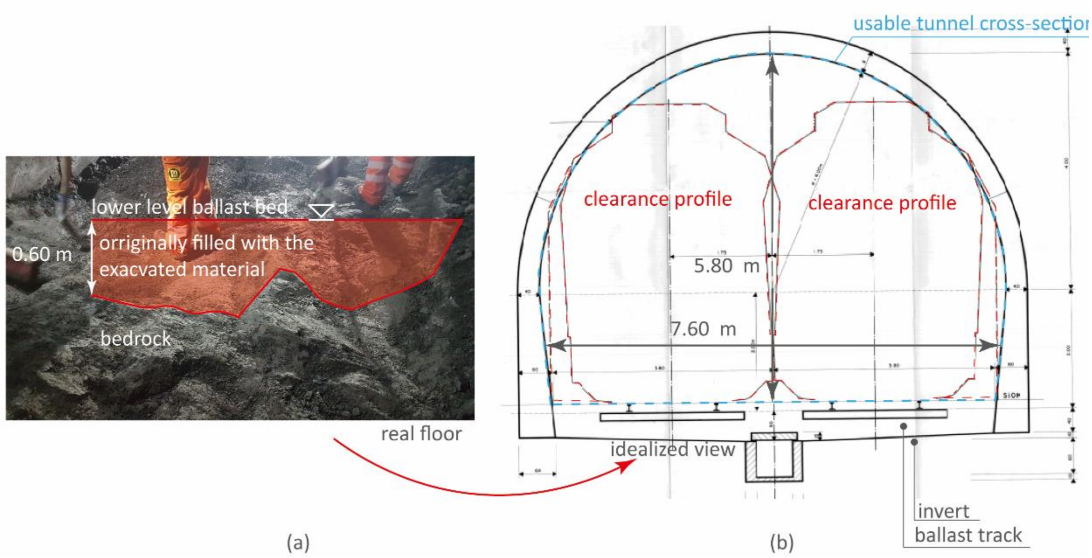

Figure 1: Tunnel floor under the ballasted track in an existing tunnel, built in 1913, Switzerland.

Further, with the introduction of ballastless railway tracks made of concrete and as experience with this type of railway tracks in tunnels grew, the replacement of ballasted by ballastless railway track was undertaken primarily in two cases:

- for the reduction of railway track maintenance time and costs
- for an increase of usable tunnel cross-section (clearance profile).

For railway tracks on a stable, homogeneous invert and on a concrete invert, this approach provides an efficient solution in both cases. Considering that any measures for the stabilization of inhomogeneity in an existing tunnel invert are expensive, time-consuming, require longer closure time, and finally, are not durable under cyclic loads induced due to railway traffic, a durable ballastless railway track on an inhomogeneous tunnel invert with a thickness of 150 mm was developed in the frame of this research. The developed concept of the ballastless railway track does not require the removal and disposal of backfill material. In addition, the reduction of the thickness of the railway track leads to an increase of the usable tunnel cross-section.
To assess the impact of the mentioned inhomogeneity in the invert on the design and structural behaviour of ballastless railway tracks, the detected inhomogeneity (Figure 1 (a)) was taken as a basis and analysed. The analysis is based on a created model of potential inhomogeneities in the tunnel invert in the longitudinal and transverse direction for both single- and double-track tunnels. The depth of the cavities in the tunnel invert, due to blasting, as detected in the case shown in Figure 1 (a), was approximately 60 cm and assumed as a basis for the analysis.

3.2. Lessons learned from current railway slab track systems

This study considers current slab track systems that are often constructed in Switzerland and consist of a load-bearing slab, grouting concrete that fixes the

sleepers or sleeper blocks embedded in the so-called rubber shoes with an elastic layer (for instance, LVT (Low Vibration Track) system).
Generally, ballastless railway track systems presuppose that the rails are fixed without backlash and that no backlash occurs during operation; in other words, the static system does not change its properties during the entire service duration. From a static point of view, a backlash is an additional degree of freedom that changes the static system, leading to a change in the structural behaviour and affecting the static system's stability.
In practice, however, the question arises as to whether the rail fasteners, fixed in the concrete of structural elements, remain backlash-free under railway traffic and whether this is technically feasible in current ballastless railway track systems made of concrete. Moreover, what is the actual service duration of the current ballastless railway tracks made of concrete? To answer these questions, attention is given to the main components of ballastless railway tracks.

3.2.1 Sleeper blocks

Tightening introduces a tensile force into the screws and compression into concrete, which leads to the formation of compressive stress fields in the concrete sleeper blocks, resulting in tensile stress fields as presented in Figure 2 (a). During train passages, compressive forces are introduced into sleeper blocks directly under wheels, which leads to tensile stresses in the bottom area of sleeper blocks, schematically as presented in Figure 2 (b).

The loading due to railway traffic is cyclic. Consequently, the components of the ballastless railway track, in which forces from railway traffic are directly introduced, must be fatigue-resistant.

Since the concrete C50 (i.e., with a characteristic compressive strength of 50 MPa) is often used for the construction of railway track elements, the fatigue resistance for this concrete is estimated according to [3], to fall in the range of low tension-compression: if $\sigma_{ct\,max}$>0.0026·I $\sigma_{c\,max}$ I then $\sigma_{ct\,fatigue}$ = 0.86 MPa and if $\sigma_{ct\,max}$≤0.0026·I $\sigma_{c\,max}$ I then $\sigma_{ct\,fatigue}$ = 2.05 MPa.

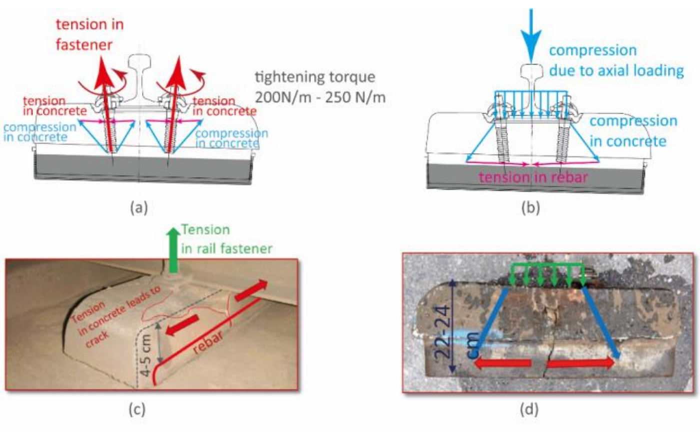

Figure 2: Cyclic loading of sleeper blocks leading to tensile and compressive stresses with subsequent typical crack formation.

It should also be noted that typical sleeper blocks are made of reinforced concrete, but straight rebars (without anchorage hooks) are placed about 40-50 mm below the top surface for various reasons, such as requirements for concrete cover in reinforced concrete structural elements according to structural standards [4] and prefabrication processes. Thus, the introduced tensile stress (Figure 2 (a)) is transmitted in the concrete cover until cracks open and then the tensile stress is supposed to be taken by the rebars, according to the fundamental rules of mechanical behaviour of reinforced concrete. However, the straight rebars are not sufficiently anchored in the concrete and can thus not fully take the tensile force. This indicate that the design of such sleepers blocks is not fully consistent with standard reinforced-concrete design rules[3], [4].
It is evident from Figure 2 (a) that the tensile fatigue resistance of concrete is reached around the rail fasteners. However, the expected crack opening according to reinforced concrete rules around the rail fasteners in such concrete sleeper blocks unavoidably leads to backlash in the rail fasteners and, thus, to overstressing and cracking damage of the sleeper block, as shown in Figure 2 (c).
Moreover, the tension force in rail fasteners increases slightly in areas of lifted rails. Thus, the cracks shown in Figure 2 (c) result from the loading shown in Figure 2 (a). As shown, an absolutely backlash-free fixation of the rail fasteners in reinforced concrete sleeper blocks is technically not feasible. The additional degrees of freedom in the static system affect the stability of the rails.

3.2.2. Grouting concrete

Next, attention is given to the grouting concrete used to fix the sleeper blocks or sleepers on the top of the load-bearing slab, the concrete invert, or the compacted substrate. A common justification for the use of grouting concrete or unreinforced concrete is that the slab is supposed to be only subjected to compression lying on the very hard subgrade, which is incorrect.
The grouting concrete is used to fix the prefabricated sleeper blocks in the target position above the top surface of the load-bearing slab or substrate at a height of 80 mm such that the grouting concrete, usually with a grain size of 8 mm, can properly fill the space under the bottom side of the sleeper blocks. The grouting concrete must also be vibrated (unless self-compacting) and de-aired. However, due to the significant size of the bottom surface, areas under the sleeper blocks are not sufficiently de-aired, resulting in voids under them. Due to the random void pattern, the contact surfaces under sleeper blocks show different textures, resulting in uneven force distribution and overloading in areas where force introduction is ensured by good contact on the contact surface. In addition, damage of grouting concrete around the sleeper blocks affects the stability of the position of the sleeper blocks, resulting in a decrease in riding comfort.

3.2.3 Bond between grouting concrete and load-bearing slab

Condition assessment of an existing ballastless railway track made of concrete [5] on drilled cores showed that the bond between the load-bearing slab and the grouting concrete was partially dissolved. This issue does not affect operational safety but should be considered in the design of ballastless railway track systems in terms of dimensioning of composite rather than monolithic cross sections.

4. Design of the ThinCore-Track system

The ThinCore-Track is a ballastless railway track made of Ultra-High-Performance Fibre-Reinforced Cementitious Composite (UHPFRC) specially developed for inhomogeneous subgrade.

4.1 Application area

The application area for the ThinCore-Track system is existing tunnels with an inhomogeneous subgrade. The primary focus lies in using this concept to increase the usable cross-section and decrease maintenance costs. Additionally, this system can be applied to new tunnels, potentially reducing the dimensions of the excavated cross-section.

4.2 Concept

The aim of the concept is to ensure the reduction of railway track height and fullfil the operational needs, such as durability and low-maintenance structures. Figure 3 shows the geometry of a new high-performance ballastless railway track using UHPFRC, developed to meet structural and operational requirements. A crucial factor in this concept is its technical feasibility in existing tunnels on an inhomogeneous substrate. The characteristic features of each element are discussed below.

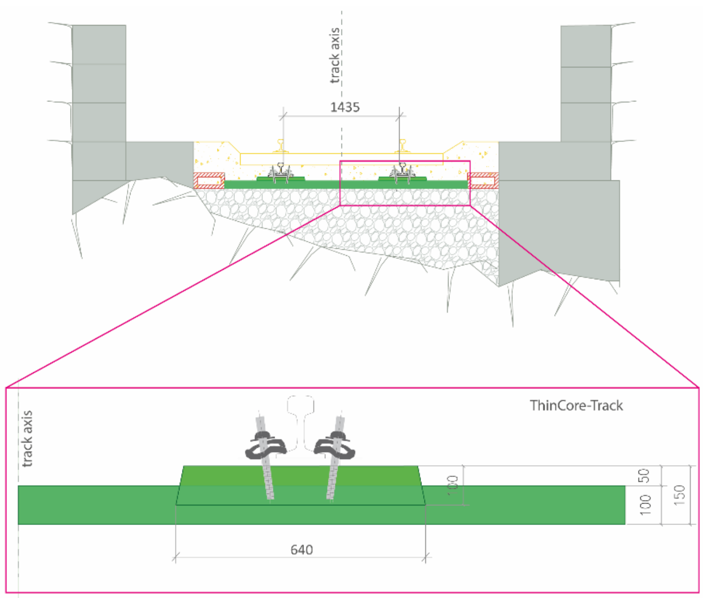

Figure 3: Concept of the ballastless railway track made of UHPFRC (ThinCore-Track).

4.2.1 Sleeper blocks in UHPFRC

This concept proposes using UHPFRC as a building material, which resists tensile stress and is fatigue-resistant when subjected to tension-compression stress reversals. Avoiding conventional rebars in sleeper blocks and providing sufficient pull-out resistance for short anchorages in UHPFRC enables the use of rail fasteners with short embedment lengths. The system is thus designed to provide sufficient tensile strength and fatigue resistance in a range of tension-compression without using conventional rebars.

According to [6], 50 mm-long threaded anchors with a 20 mm diameter in UHPFRC and a tensile strength of 11.5 MPa exhibit a pull-out resistance of approximately 230 kN. The pull-out force introduced by tightening torque of 250 Nm is around 63 kN (<30%Fu), assuming a coefficient of friction between the plastic dowel and the steel rail fastener of 0.2. According to [6], the fatigue resistance in UHPFRC subjected to tension is 70%f_{ute} in the elastic domain and 50%f_{ute} in the tensile strain hardening domain.

The short rail fasteners and the avoidance of conventional rebars allow for a significant reduction in the height of the sleeper blocks compared to traditional concrete sleeper blocks. For structural reasons (possible geometric inaccuracies during on-site casting, possible deviations from the nominal state in the substrate), the height of the sleepers of the ThinCore-Track is set at 100 mm. Depending on specific needs e.g., limited height for the construction of a ballastless railway track in an existing tunnel and the ballastless railway track's complete configuration, the sleeper block's height could be reduced to 60 mm.

The trapezoidal shape of the sleeper blocks is intended to increase resistance against the lifting in the area of the lifted rails. The force applied to the sleeper block in the area of the lifted rails is approximately 1%Q_k, where Q_k is the axial load.

Since UHPFRC sleeper blocks do not contain rebars, the de-aeration recesses are provided in the prefabricated UHPFRC sleeper blocks. These are filled using UHPFRC after slab casting but before tightening the rail fasteners.

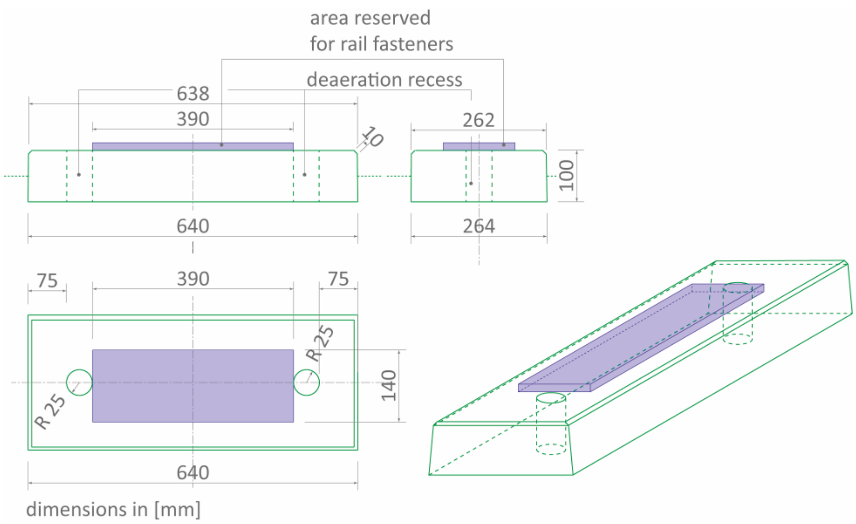

Figure 4: UHPFRC-sleeper blocks of ThinCore-Track.

4.2.2 Slab in UHPFRC

The sleepers are embedded in a 100 mm-thick UHPFRC slab using the top-down method.

The slab length of 6 m is defined considering two functions:

- bridging weak substrate areas
- transmitting the bending moment without reinforcement bars.

The potential distribution of soft areas in the subgrade under the slab is studied with respect to a slab length of 6 m.

The theoretical model of the subgrade is based on practical observations. In general, it is challenging to accurately predict the patterns of soft zones in the subgrade; the aim is to generalize the possible cases and to identify the critical cases for the design. The aim is to bridge the soft areas by means of the bending resistance of the slab.

4.2.3 Contact surface between sleepers and UHPFRC slab

Since the sleeper blocks are prefabricated, they have a smooth surface, which likely results in a weak bond between the sleeper blocks and the cast-in-place UHPFRC slab. Therefore, for the design of ThinCore-Track, it is assumed that there is no bond between the sleeper blocks and the cast-in-place UHPFRC slab and that only compression is transmitted to the contact surface.

When a wheel is above the sleeper block, a vertical load of approximately 40%$Q_{wheel\ k}$ and the horizontal force from wheel torque, braking, or acceleration, are acting. Due to rail lifting produced by passing wheel loads, the sleeper blocks are subjected to a vertical tensile uplift force of 1% Q_k. This loading case is decisive for analysing the interaction between the sleeper blocks and the UHPFRC slab, assuming no bond exists in the contact area. Due to the trapezoidal shape, pulling the sleeper blocks out of the UHPFRC slab with a force of 1% Q_k is impossible, as shown below.

For an axle load of Q_k = 250 kN, the tensile force per sleeper block in the area of the lifted rails is around 2.5 kN, resulting in a vertical compressive stress of 0.03 MPa in the inclined contact area between the sleeper block and the UHPFRC slab, which can be transmitted to the UHPFRC slab and absorbed in it according to Figure 5 and resisted in the UHPFRC slab.

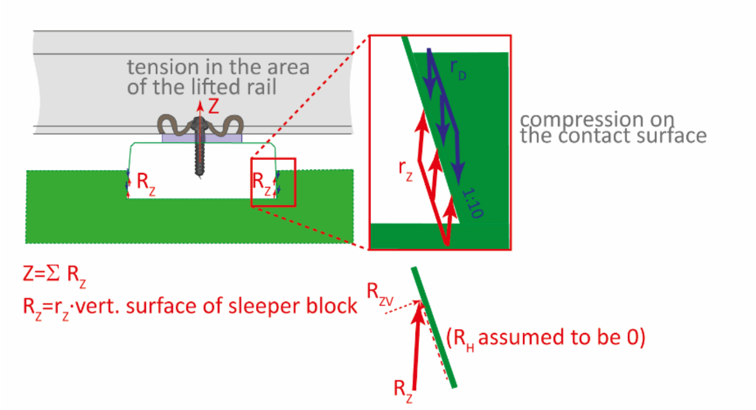

Figure 5: Tensile force introduction in the UHPFRC-slab in the area of the lifted rail. *Validation of the technical solution of the developed Concept*

4.2.4 Geometry (Height reduction)

To estimate the height reduction compared to traditional systems using concrete, the height of a typical ballasted track with 150 mm high wooden sleepers and a ballast layer thickness of 30 cm was used as a baseline, corresponding to a total height of 450 mm (100%). Figure 6 schematically illustrates the cross-sections of ballasted railway track and slab-like ballastless railway track systems.

From Figure 6, it can be observed that the ThinCore-Track allows for a height reduction of up to 67%. For the horseshoe-shaped cross-sections of existing tunnels, such as the ones shown in Figures 1 and 7, the railway track and clearance profile can be lowered by approximately 30 cm. This reduction would not only address space constraints in the upper sections of the tunnel but also contribute to increasing the height of the service and evacuation paths relative to the railway track level (level of the railhead). Consequently, this would simplify train egress in the event of an evacuation of train passengers.

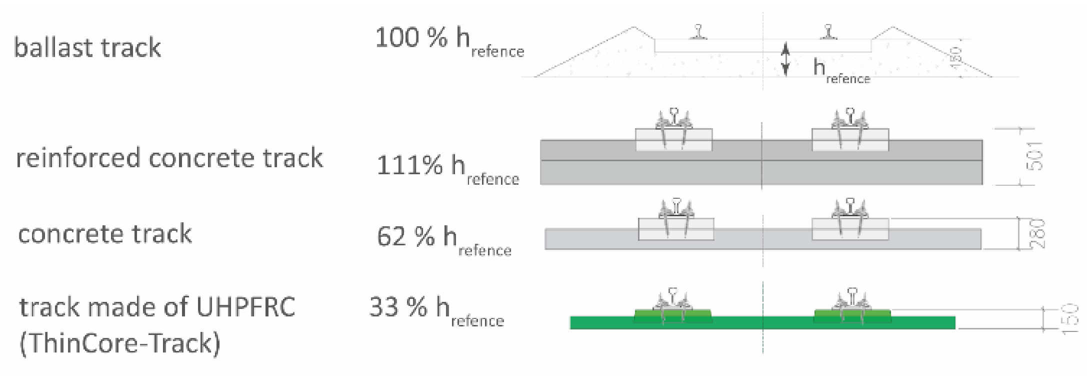

Figure 6: Quantitative assessment of the height reduction of the railway track

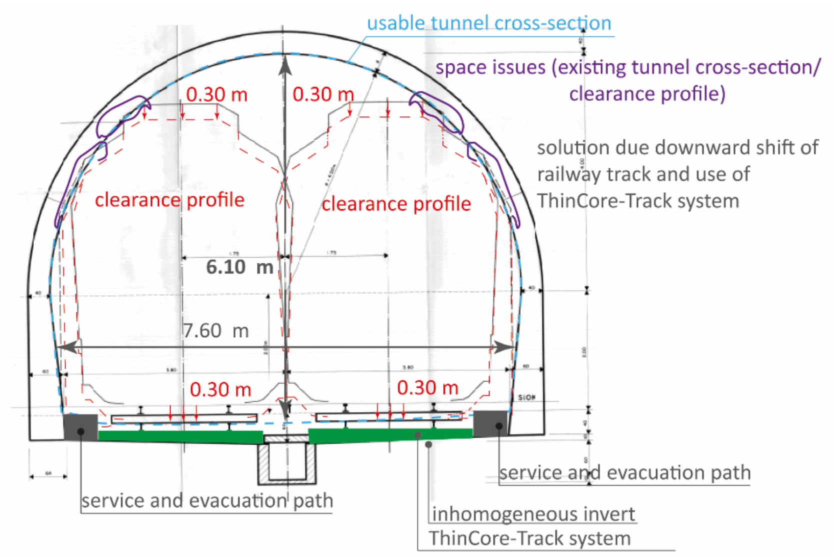

Figure 7: Increasing the usable tunnel cross-section with the ThinCore-Track

4.2.5 Service duration and fatigue resistance

The design of the ThinCore-Track enables the UHPFRC to remain within the elastic domain, with a maximum tensile stress of 50% f_{Ute} under the loads defined in the standards [1, 3]. This also ensures sufficient fatigue resistance. Consequently, the requirement of $3.2 \cdot 10^8$ load cycles or 100 years of operation is fulfilled, and backlash-free fixation of rail fasteners and avoidance of unplanned relative displacements between sleeper blocks and the slab are ensured.

4.3 Economic efficiency

Construction process duration and costs are crucial for validating the concept. However, these factors depend highly on the specific country, particularly due to variations in manpower costs and transportation logistics. For this reason, cost efficiency is evaluated by comparing cost-relevant work steps.

4.3.1 Construction costs

The cost estimate for the construction of modern ballastless railway tracks in tunnels was based on the cross-section of an existing tunnel, as shown in Figure 1 respectively Figure 7.

During the retrofit of the tunnel track shown in Figure 1, an unreinforced ballastless railway track was constructed as the "current solution", and no improvement of the subgrade was carried out. For the cost analysis, the executed project is considered, along with two additional variants in which the subgrade is improved and a ballastless railway track is constructed with a load-bearing slab made of reinforced concrete. In addition, an optional fourth case is analysed, in which both the subgrade is improved, and the ballastless railway track is constructed with the load-bearing slab made of reinforced concrete.

- Construction case I: Construction measures comprising the construction of ballastless railway track with the load-bearing slab made of unreinforced concrete and <u>without</u> subgrade improvement.
- Construction case II: Construction measures comprising the construction of ballastless railway track with the load-bearing slab made of unreinforced concrete, <u>including</u> subgrade improvement.
- Construction case III: Construction measures comprising the construction of ballastless railway track with the load-bearing slab made of reinforced concrete and <u>without</u> subgrade improvement.
- Construction case IV: Construction measures comprising the construction of ballastless railway track with the load-bearing slab made of reinforced concrete, <u>including</u> substructure improvement.

The costs of the UHPFRC concept are compared with those of the four current traditional solutions.

The pie charts in Figure 8 show the cost shares of the decisive construction process steps in the entire construction process. It can be observed that the costs for the adjustment of the tunnel vault in Cases I to IV range between 21 % and 39 % of the total construction cost. This construction process step significantly increases costs and extends the overall construction time. For instance, the process of cutting approximately 40 cm-wide areas of tunnel vault to a depth of 5 cm takes approximately 2 to 4 weeks per kilometre. As a rule, 4 such areas (2 on each side) need to be adjusted. In the case of ThinCore-Track, construction activities are concentrated in the railway track area. This means that the entire construction time can be kept significantly shorter, and no special overhead working equipment is required. As a result, the costs for "Auxiliary structures and construction logistics" are reduced.

Furthermore, the costs for subgrade improvement amount to approximately 9% to 11% of the total reconstruction cost, as shown in the diagrams in Figure 8. This corresponds to approximately 18% of the construction costs of a ballastless railway track with a reinforced concrete slab and approximately 30% of the construction costs of a ballastless railway track made of unreinforced concrete.

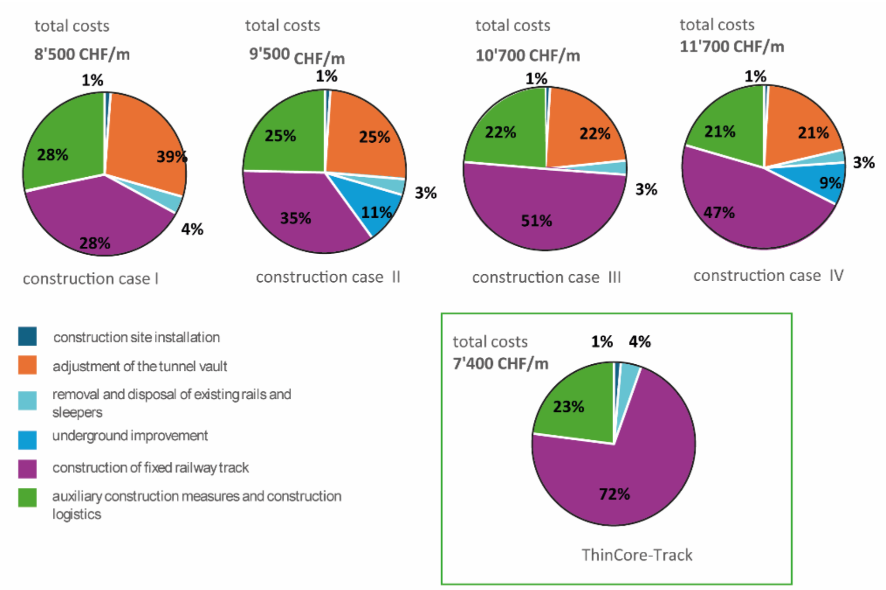

Figure 8: Share of costs for the reconstruction of existing tunnels with an inhomogeneous subgrade, including the replacement of ballasted track by ballastless railway track.

4.3.2 LCC costs

A reference period of 100 years of operation in an existing tunnel is assumed, in which a ballasted railway track is replaced by a ballastless railway track as part of a complete reconstruction measure to adjust the tunnel cross-section to meet the required clearance profile, including safety spaces, according to the assumptions for this study. For this analysis, own-project-experience-based values are used for the regular replacement of the wear components of the ballastless railway track, as well as for regular repairs and maintenance works.

The analysis is conducted for construction cases I, III, and ThinCore-Track. The selection of these cases for the life cycle cost (LCC) analysis is justified as follows:

- Construction case I, although structurally less suitable, is frequently applied in practice.

– Construction case III represents a more suitable alternative in terms of construction time compared to construction case IV.

The diagram in Figure 9 shows the total cost increase over time resulting from regular maintenance works. The total construction costs in the case of ThinCore-Track essentially include the costs for reconstruction of the ballasted railway track into ThinCore-Track and are the lowest compared to construction case I and construction case III. The diagram shows that, due to regular maintenance activities, the cumulative total costs double after only 20 years, and by the end of the 100-year reference period, these intervention costs amount to 490% for construction case I and 390% for construction case III of the total sum required for the construction of the ThinCore-Track. In the case of ThinCore-Track, the only additional costs are related to the replacement of wear components such as rails and rail fasteners, which results in a cost increase of only approximately 20% after 100 years of operation.

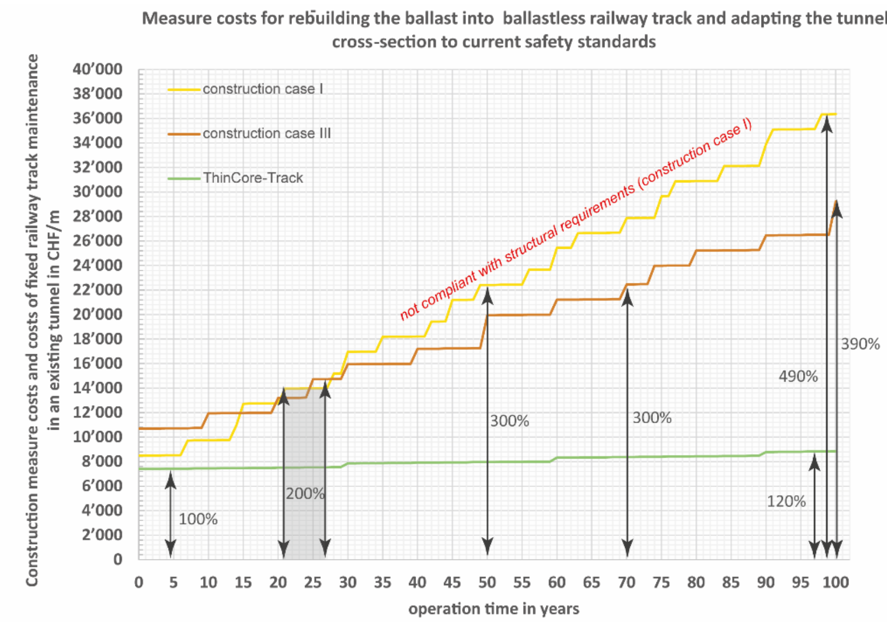

Figure 9: Total costs for (1) rebuilding the ballast into ballastless railway track and adapting the tunnel cross-section to current safety standards and (2) regular maintenance.

Conclusions and Contributions

This contribution demonstrates that the use of UHPFRC has enabled the development of a technically robust and economically viable ballastless track system for use in existing tunnels with inhomogeneous subgrade conditions. The ThinCore-Track system that has been developed eliminates the disadvantages of existing slab tracks and offers further advantages:

Technical advantages (performance and durability):

– Crack-free behaviour under operational loads: The 3D FE assessment indicates that the developed ThinCore-Track remains crack-free under operational loading.

- Fatigue resistance: ThinCore-Track is designed so that UHPFRC remains in the elastic domain, ensuring fatigue resistance for at least $3.2 \cdot 10^8$ load cycles (or more than 100 years of service).
- Backlash-free in fixation of rail fasteners: Since the construction material remains in the elastic domain, no crack appears in the area of rail fasteners, which ensures a rigid fixation of rail fasteners.
- Structural benefit through reduced height: The ThinCore-Track enables a track height reduction up to 67% compared to a typical ballasted configuration.

Economic advantages (construction and life-cycle):

- Less construction complexity: The concept reduces construction complexity by avoiding the use of conventional reinforcement, multi-stage casting, and extensive subgrade treatment measures.
- Lower construction costs: Under comparable boundary conditions, the reconstruction costs of the ThinCore-Track are 22–36% lower than the analysed current traditional solutions.
- Significantly improved life-cycle costs: Over a 100-year reference period, ThinCore-Track shows only a ~20% cost increase, compared with 290% for the current common traditional solutions.

Acknowledgements

The authors gratefully acknowledges the Structural Maintenance and Safety Laboratory (MCS) at EPFL. During 26 years of research activity, the MCS group has developed and investigated UHPFRC and related technologies for the rehabilitation and strengthening of existing reinforced concrete structures, in particular bridge and building slabs, as well as for the design and construction of new UHPFRC structures.

References

[1] *ATENA Program Documentation: Science–GiD User's Manual Interface (for ATENA ≥ v5.3).* (Sep. 02, 2022). Červenka Consulting, Prag. [Online]. Available: https://www.cervenka.cz/products/atena/

[2] Federal Office of Transport, 'The implementing provisions for the Railway Construction and Operation Ordinance (AB-EBV)'. 2024. [Online]. Available: https://www.bav.admin.ch/bav/de/home/rechtliches/rechtsgrundlagen-vorschriften/ab-ebv.html

[3] Comité euro-international du béton, Ed., *Fib model code for concrete structures 2010*. Berlin: Ernst & Sohn, 2013.

[4] *SIA 262: Betonbau*, 2013.

[5] A. Hochuli, J. Trouillet, E. Brühwiler, O. Schulz, and M. Hoffmann, 'Erneuerung einer festen Fahrbahn der Bahn unter Verwendung von UHFB – weltweit erstmaliger Einsatz von UHFB im Gleisbau – Teil 2: Übersicht der statischen Nachweise, Dimensionierung der hochleistungsfähigen Schwellensockel aus UHFB', *Bautechnik*, vol. 99, no. 1, pp. 10–17, Jan. 2022, doi: 10.1002/bate.202100040.

[6] A. Hochuli and E. Brühwiler, ‘Numerical Approach to Determine the Resistance of Threaded Anchors in Ultra-High-Performance Fiber-Reinforced Cementitious Composite’, *Buildings*, vol. 14, no. 11, p. 3669, Nov. 2024, doi: 10.3390/buildings14113669.