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Innovative Concepts for Fatigue-Resistant, Durable and Safe Fixed Railway Tracks in UHPFRC

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Abstract

This paper outlines novel concepts to address structural shortcomings in modern fixed railway track systems made of concrete, focusing on enhancing structural safety, durability, and fatigue resistance. It introduces Ultra-High Performance Fibre Reinforced Cemetitious Composite (UHPFRC) as a novel building material, known for its dense, fine-grained matrix strengthened with a high amount of short slender steel fibers. UHPFRC has the capacity to transmit tensile stresses up to 7-10 MPa in the elastic and 10-16 MPa in the strain-hardening domains while maintaining fatigue resistance up to 70% in the elastic and 45% in the strain-hardening domain. UHPFRC remains crack-free under service conditions. This contribution presents three concepts of the high-performance fixed railway tracks built in UHPFRC: 1. Fixed track with a slab thickness of 100 mm. It has been developed to reduce the self-weight of the railway track on bridges and to increase the clearance in the cross-section of existing tunnels. 2. Fixed track for the rapid replacement of damaged sleepers. The concept guarantees a high track alignment quality. It can also be applied for constructing new fixed tracks designed as mass-spring systems. 3. Single-span bridge girder with an integrated fixed railway track.

Keywords: fixed railway track, ballastless railway track, UHPFRC, uncracked structural elements, rail fastener, crack free

1 Introduction

Approximately half a century ago, the first ballastless railway tracks, built in concrete, were taken into operation in Europe. These track systems, characterised by their rigid load-bearing structure, include elastic components such as rail and sleeper pads that guarantee the required elasticity and ensure stable behaviour.

Ballastless tracks led to an increase in the running speed and ensured a better riding comfort. Various ballastless track systems have been developed and built since the introduction of this railway track type. Concrete, reinforced concrete, bituminous and rubber materials are often used to construct ballastless railway tracks.

Advanced railway track systems such as mass-spring systems made it possible to reduce noise and vibration and to route railway lines underground through densely populated cities and urbanised areas.

Novel high-performance, fatigue-resistant building materials with ductile behaviour are now available to improve the safety and reliability of railway systems including high speed trains.

Due to the development of Ultra-High Performance Fibre Reinforced Cemetitious Composite materials (UHPFRC) and the related technology, ballastless track systems can now be further optimised and improved using this ductile high-performance cementitious material that remains crack-free during the entire service duration, which is extended to at least 100 years. This represents a significant progress when compared to traditional concrete.

2 Concepts of fixed railway tracks in UHPFRC

The proposed concepts were developed after analysis of characteristic damage often identified on traditional fixed track systems made in concrete.

2.1 Shortcomings identified in current railway track systems

Inspections and condition assessments of existing ballastless railway tracks provide information about shortcomings and characteristic damage occurring on track systems made in concrete.

In Europe, slab-like railway track systems exhibit transverse cracks in the load-bearing slab and in the grouted concrete on the top, some of which are located in the area of the rail fasteners [5] [6]. Although the grouting concrete is primarily used just to fix the sleepers, these cracks in the grouting concrete are at the origin of unexpected degrees of freedom in the entire structural system of the slab track and then lead to overstressing and subsequent damage of the sleepers and rail fastenings. This is the main reason why the sleepers are classified as so-called "wear components" of the railway track and thus need to be replaced periodically. However, the 1:1 replacement of sleepers within the remaining surrounded grouted concrete does not meet quality requirements, since experience shows that the same track geometry accuracy can no longer be guranteed. The consequence is overstressing of the rail fasteners and increased rail wear, affecting travel comfort and necessitating more important maintenance work.

In China, three slab-like fixed track systems, i.e. CRTS I, CRTS II and CRTS III, have been introduced with mass-spring systems that reduce noise and vibration. Condition assessment of these railway track systems revealed that these systems possess structural shortcomings [1] [2] [4], for example, debonding between individual layers of the load-bearing slab built as composite slab.

2.2 UHPFRC in railway infrastructure

The assessment of damage confirms that the crack opening in the structural parts of existing reinforced concrete fixed tracks is nothing unusual and corresponds to basic rules of reinforced concrete construction, i.e. in order to transmit tensile stress in reinforced concrete components, the concrete must crack to induce deformation necessary to activate the steel reinforcement bar. However, cracks in the concrete and fracture of structural parts of fixed railway tracks is a main reason for replacing fixed tracks.

When studying the application of UHPFRC in the field of railway infrastructure [8], it is crucial to highlight its technical advantages over traditional reinforced concrete. First of all, fixed railway tracks should be understood as load-bearing structures for which it is required that they are rigid, crack-free and fatigue-resistant. These requirements are analysed and verified just in the same way like for any other structure, irrespective of the building material.

Ultra-High Performance Fibre Reinforced Cemetitious Composite (UHPFRC) is a novel building material consisting of a dense, fine-grained matrix strengthened with a high amount of short slender steel fibers. UHPFRC has a compressive strength of about 150 MPa and the capacity to transmit tensile stresses up to 7-10 MPa in the elastic and 12-16 MPa in the strain-hardening domains. The tensile fatigue endurance limit is at 70% of the elastic stress limit and 45% of the tensile strength. UHPFRC remains crack-free under service conditions.

Due to its relatively high strength and ductility, UHPFRC has the potential to resist mechanical stress occurring in zones of direct force introduction. Moreover, thanks to its optimised compactness and its potential to remain crack-free under service conditions, UHPFRC is impermeable for water and is thus durable, i.e. damage mechanisms known from reinforced concrete (such as steel rebar corrosion, alkali-agregate reaction, frost spalling) cannot occur.

Furthermore, fresh UHPFRC exhibits good workability making it ideal for fixing prefabricated sleepers on top of load-bearing slabs or fixing rail fasteners. Owing to the rapid strength development after casting, i.e. typically reaching about 5 MPa at 5°C and 25 MPa at 20°C within 12 hours, railway tracks built with UHPFRC can be put in service by light vehicles already 12 hours after casting.

The targeted use of UHPFRC in the parts of the ballastless railway track that are subjected to tensile or cyclic loading, eliminates fatigue damage due to cracking, and thus, significantly increases the service duration of the ballastless railway track. The use of UHPFRC in the zone of rail fasteners improves the resistance and safety of anchorage because backlash and subsequent fracture of the rail fasteners are prevented.

2.3 Concept 1: thin slab-track-system

The proposed concept of fixed railway track consists of a 100 mm thin UHPFRC full slab cast on-site (without incorporating steel reinforcement bars) and 100-150 mm high sleeper blocks. The principle is shown in Figure 1:

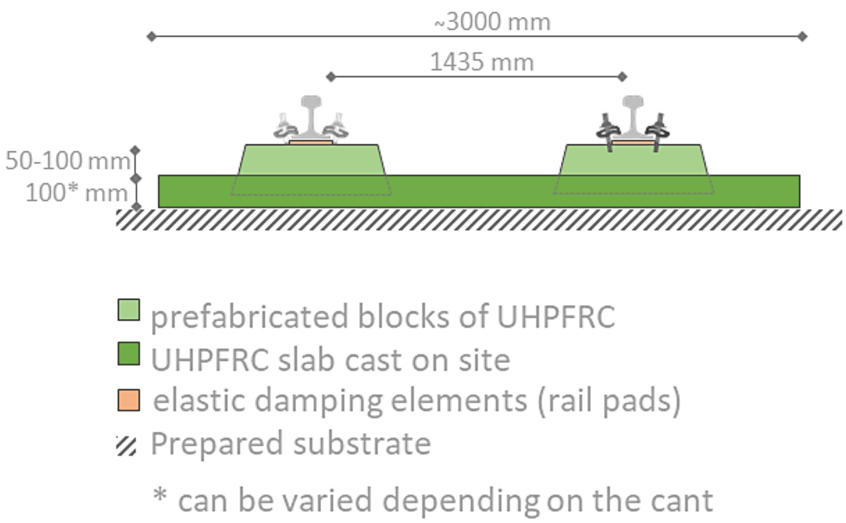

Figure 1: Concept 1 thin slab-track-system

The construction process consists of 2 stages:

1. In the first stage, the substrate (compacting, levelling, blinding layer) will be prepared.
2. In the second stage, the prefabricated rail panels equipped with the prefabricated blocks will be aligned with a tolerance of ±1 mm and embedded in the 100 mm thin layer of the fresh UHPFRC in the target track geometry.

The truncated pyramid shape of the blocks contributes to a better embedding of the blocks in the load-bearing slab cast in UHPFRC. The required elasticity of the fixed railway track will be achieved by using a direct rail fastening system with elastic pads. Railway track sections in curves with transverse slopes are cast using fresh UHPFRC with thixotropic workability.

This concept is intended to increase the clearance profile in existing tunnels. The track system is placed on a ground in concrete or rock. Since UHPFRC transmits tensile stress over the entire cross-section, a stiffness inconsistency of the rock substrate can be bridged.
Furthermore, this type of fixed railway track enables reducing the dead load of the railway track on the existing railway bridges and viaducts.

2.4 Concept 2: mass-spring system with an optimised construction process

The proposed improved railway slab track as a mass-spring system will be constructed as follows (Fig. 2):

1. Depending on the required degree of damping, elastic full-surface, strip, or point supports are used, on which the prefabricated formwork elements made of UHPFRC incorporating rebars are placed. The vertical prefabricated formwork elements made of UHPFRC are optional.
2. In the next step, the massive railway slab track is reinforced with rebar cages and cast, and the gauge channels on the top are recessed.
3. Prefabricated rail panels, including direct rail fasteners, are placed according to the target railway track geometry in the gauge channels and fixed using UHPFRC. Since mass-spring systems require the weight of individual track elements, the structural parts that are not directly stressed, are realised in reinforced concrete. Optionally, approximately 20 mm of UHPFRC can be added on the surface of the massive railway slab track to seal and prevent the formation of cracks on the top surface of the concrete.

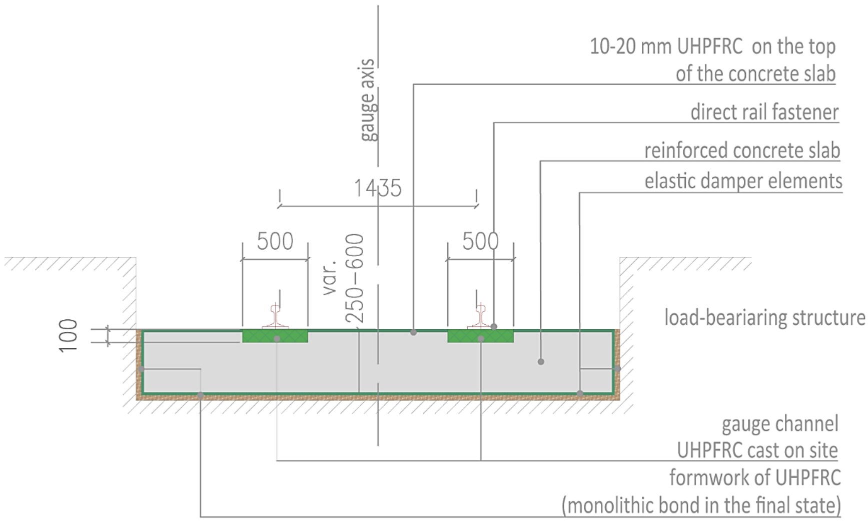

Figure 2: Concept 2 mass-spring systems

By using the formwork elements made of UHPFRC as permanent structural elements, higher resistance of the fixed railway track in the final state is achieved. The amount of steel reinforcement bars in the structural part made of reinforced concrete can be reduced, and thus, the rebar layout is simplified, and the concrete cover in the adjacent reinforced concrete components will be reduced. The zones with direct force introduction from the rails through rail fastening into the railway track are realised in UHPFRC.

This track system and its construction method allow for accelerated replacement of damaged rail fastenings in case of an accident or other operational reasons. Using core drilling of about 80-100 mm diameter, previous plastic dowels of the rail screws are removed, and new ones inserted and cast with UHPFRC. Monolithic bond between existing and new UHPFRC is obtained.
Furthermore, the horizontal force produced by the torque of the wheels leads to tensile stresses in the near-top-surface area, which is resisted by the UHPFRC thanks to its relatively high tensile strength. This ensures a durable connection of the rails to the load-bearing slab and prevents unwanted backlash.

2.5 Concept 3: bridge girder with the integrated fixed railway track

Figure 3 shows the cross-section of a single track railway bridge girder of prestressed UHPFRC with the integrated fixed railway track for a span of up to 15 m (transport length for the prefabricated girder). The bridge cross-section is designed for a gauge width of 1435 mm, structure gauge EBV 4 in a curve according to European standards, considering a railway track widening of 20 mm, and structure gauge expansion in the inner curve of 231 mm.

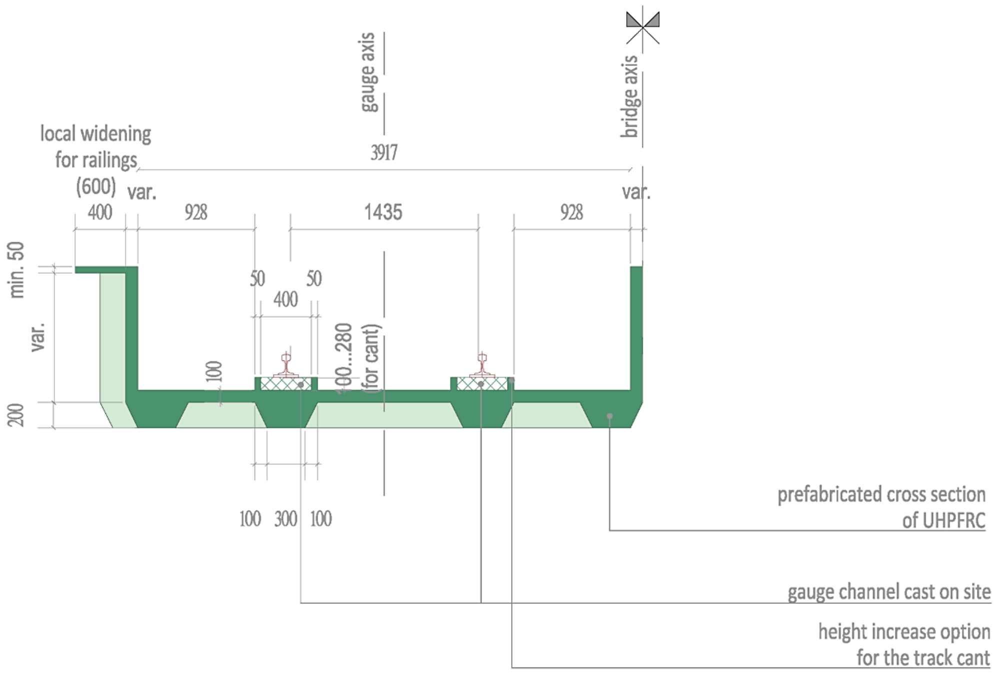

Figure 3: Concept 3 bridge girder with integrated fixed railway track

The railway bridges up to about 15 m span can be prefabricated in the factory and placed on the prepared abutment at the construction site. This concept is intended for situations of required limited construction height of the bridge slab and limited clearance height under the bridge. In the case of overpassing a river, the main challenge is to ensure the freeboard over the water and a sufficiently smooth underside of the bridge girder so that no driftwood obstructs the water flow under the bridge.
At the same time, the specifications for the route of the railway line set strict requirements, and changes in the elevation of the railway line lead to significant changes in a large area. These factors demand a slender structure that fulfils all requirements.

The height of the trough base is variable between 100 mm and 300 mm, and in the area of the gauge channels, 400 mm. The webs and the height of the trough base under the rails can be varied depending on axial loading and the span. Moreover, additional prestressing is possible under the gauge channels. For the cant in the curve, the walls of the gauge channels in the prefabricated girder can be extended. After aligning the rails in the gauge channels, they are fixed together with the rail direct fastening on site using the fresh UHPFRC.

3 Validation

The three proposed concepts are currently validated by stress analysis using the finite element program ATENA [7], which allows to model the mechanical behaviour of UHPFC. The material properties of typical UHPFRC are introduced in the numerical model. The numerical model is calibrated using measured monitoring data collected from existing fixed tracks. Subgrade stiffness is calibrated by means of separate numerical models allowing to numerically simulate compression stress and to verify the force-displacement behaviour.

The rail accuracy is ±1mm. The rails will be aligned first and then embedded in UHPFRC in all concepts. This method is known as the "Top-Down" method in railway track construction, and it allows the required accuracy to be achieved.
In general, ballastless railway track systems are built on a substrate with limited settlement. Small local differential settlements of up to 18 mm can be corrected by means of levelling plates.

4 Conclusions

The three presented concepts show how the targeted use of the high performance building material UHPFRC can eliminate shortcomings of conventional ballastless track systems made in concrete. UHPFRC is a building material that meets all railway track requirements: fatigue-resistant, homogeneous, ductile, crack-free and with workability that fulfils the needs of the construction process.

The use of UHPFRC allows to reduce the height and, therefore, the dead load of the railway track, increase the load-bearing capacity, simplify and accelerate the construction process, and construct during operation with only short closure phases.

In addition, the use of UHPFRC significantly has the potential to reduce the environmental impact. The experience of a executed project showed a 70% reduction in CO_2 emissions compared to the conventional solution.
The use of UHPFRC increases the service duration of the fixed railway track beyond 100 years compared to the current systems with a durability of 30 to 50 years.

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