Performance-based Design of Slab Track

Takatada TAKAHASHI

Track Structures and Geotechnology Laboratory, Track Technology Division

Shota FUCHIGAMI

Yoshitsugu MOMOYA

Track Structures and Components Laboratory, Track Technology Division

In the development of slab track, in Japan concrete track components were designed using an allowable stress design method. Currently, they are designed using a performance-based design method according to “Design Standards for Railway Structures and Commentary (track structure)” established in 2012. In this design method, the required performances of safety and serviceability are verified by a limit state design method. This paper gives an outline of the structure of slab track and introduces the method of performance verification of the slab track using a performance-based design method.

Key words: slab track, performance-based design, performance verification, required performance, performance item

1. Introduction

The development of slab track began in 1965, and test laying was carried out, among other lines, on the Tokaido Shinkansen line and Sanyo Shinkansen line in Japan. Later, slab track was introduced to Shinkansen and conventional lines built after completion of the Sanyo Shinkansen between Okayama and Hakata, which opened in 1975.

In the development of slab track, concrete track components were designed using an allowable stress design method. Currently, they are designed using a performance-based design method in compliance with “Design Standards for Railway Structures and Commentary (track structure)” established in 2012.

This paper gives an outline of the structure of slab track and introduces the method of performance verification of slab track using a performance-based design method described in the Design Standards.

2. Structure of slab track

Track components used for slab track include track slabs, stoppers, concrete beds, filling layers, rails, rail fasteners, inter alia, as indicated in Fig. 1. The standard spacing of stoppers is 5 m. The number of rail fasteners per side of a standard slab is 7 or 8.

There are two types of rail fasteners, that is, a tie plate type, and a direct seat type, as shown in Fig. 2. A tie plate type is generally used on straight lines and curved lines in open sections and curved lines in tunnel sections. A direct seat type is used for straight lines in the tunnel section. A tie plate type is characterized by a wide range of adjustment of longitudinal level irregularity and alignment irregularity and consideration to rail-creepage. A direct seat type is characterized by a small number of parts and a low price.

A track slab is a precast concrete component manufactured in a factory. There are two different shapes of track slabs. At the time of the development of slab track, a track slab was a standard-type, as shown in Fig. 1. Since the Hokuriku Shinkansen (Takasaki-Nagano) started operation in 1997, a frame-type track slab shown in Fig. 3 has also been used. The advantage of the frame type is that the cost of this track slab is lower than the standard type, and the volume of the filling layer for a frame type is less than for a standard type.

Fig. 1 Outline of slab track

(a) Tie plate type (b) Direct seat type

Fig. 2 Types of rail fasteners

Fig. 3 Frame-type of track slab

Table 1 Performance requirement and performance item

Performance requirement	Performance item	Summary
Safety	Failure	Refers to the ability of a ballastless track to maintain load bearing capacity against all expected actions that would occur during the design life.
	Fatigue failure	Refers to the ability of a ballastless track to maintain load bearing capacity against all the expected actions (repetition of fluctuating action) expected to occur during the design life.
	Running safety	Refers to the ability to enable a vehicle to run smoothly while displacement and deformation of the track is maintained below a certain value considering expected actions to occur during the design life.
Serviceability	Appearance	Refers to the ability to prevent cracking and staining on the surface of a track structure and a track component from causing anxiety or discomfort and hindering the use of the track.
	Usability regarding riding comfort	Refers to the ability to offer a comfortable riding experience to railway passengers.
	Noise and vibration	Refers to the ability to prevent noise and vibration that occurs in a ballastless track from adversely affecting the environment and hindering the use of the track.
	Damage	Refers to the ability to maintain a ballastless track in good condition and usable without repair or suppress the damage to a level where it can be repaired within a short period.

Track slabs are classified as Reinforced Concrete (RC) and Pre-stressed Reinforced Concrete (PRC) structures. Generally, an RC structure is used in warm regions, while a PRC structure is used in cold regions. In cold regions, however, RC structures are used in tunnels where temperature changes are small, and no rainwater effect is expected (excluding tunnel exits). A PRC structure is generally used in cold regions, where prestressed concrete can prevent water penetration and, therefore, prevent deterioration due to freezing and thawing of water.

The material of a filling layer is generally Cement Asphalt Mortar (CA mortar). CA mortar is composite material of cement mortar and asphalt emulsion, and its compressive strength is about 1/10 of concrete. There are two types of CA mortars, one for warm regions and the other for cold regions.

A stopper and a concrete bed are RC structures. The reinforcing bars of a stopper are anchored to a concrete bed, and a stopper and a concrete bed are integrated. Stoppers are responsible for restraining

the movement of a track slab and holding it in place.

3. Design method of slab track [1]

3.1 Design procedure

In slab track design, performance verification is conducted on the basis of a performance verification type design method for performance requirements and performance items shown in Table 1. Design issues have not been recognized since the beginning of practical use with slab track combining individually designed track components. Accordingly, safety verification against general failure and fatigue failure and serviceability verification related to the appearance and damage of slab track as shown in Table 1 is carried out for each track component. A limit state design method is used to verify concrete track components such as track slabs, stoppers, and

Fig. 4 Design flow of track slab

Fig. 5 Flow of performance verification using limit state design method

concrete beds. The design procedure of a limit state design method is shown in Fig. 4.

First, a designer determines the required performance items for the track components based on Table 1. In general, they are safety (failure, fatigue failure) and serviceability (appearance, damage).

Secondly, “examination of durability” is carried out by assuming the dimensions and reinforcement of the components to satisfy the assumptions for verification (thickness of cover concrete, amount of reinforcing bar, the spacing of reinforcing bar, and so on.). Thus, it is possible to sustain material deterioration under environmental effects within a certain level during a design lifetime, and a verification method without considering the change of perfor-

mance over time can be conducted. The main targets for durability examinations are corrosion of reinforcing bars and PC steel rods and freezing damage of concrete.

Finally, Fig. 5 shows the procedure for performance verification. A limit state design method is used for performance verification, which compares a design response value I_{Rd} calculated by structural analysis with a design limit value I_{Ld} calculated by component’s strength. In a limit state design method, a “safety factor” is set not only for the limit value specified for each component but also for the response value calculated by structural analysis, and so on, considering various uncertainties. This design method makes it easy to reflect the designer’s ideas and new technologies. There are five

Table 2 Combination of actions and action factors

		Performance	D	L _w	L _l	B	L _{RI}	L _{Rh}	E _R	F _p	P _S	Limit value	Target	
Track Slab	In-service	Failure	1.1	1.2	1.0							1.0	Flexural capacity	Track slab body
			1.1	1.0	1.1						1.0			
			1.1	1.0	1.1	1.1	1.0	1.0			1.0	Punching shear capacity	Bolt hole for rail fastener*2	
			1.1	1.0	1.0	1.0	1.1	1.1			1.0			
		Fatigue failure	1.0	1.0	1.0						1.0	Fatigue strength of bars	Track slab body	
		Appearance*1	1.0	1.0	1.0						1.0	Limit of crack width		
	Damage	1.0	1.0	1.0							1.0	Bending yield capacity		
	In fabrication	Failure	1.1									1.0	Punching shear capacity	Lifting attachment*3
		Appearance	1.0									1.0	Limit of crack width	Track slab body
	In transportation	Failure	1.1									1.0	Punching shear capacity	Lifting attachment*3
		Appearance	1.0									1.0	Limit of crack width	Track slab body
	In laying on site	Failure	1.1							1.1		1.0	Punching shear capacity	Holding attachment*4
		Appearance	1.0							1.0		1.0	Limit of crack width	Track slab body
	Stopper	Failure	1.0	1.0		1.1	1.0	1.0		1.0			Bending capacity, Shear compression failure capacity	Stopper
			1.0	1.0	1.1		1.0	1.0		1.0				
			1.0				1.1	1.0		1.1				
			1.0				1.0	1.1		1.0				
Appearance*1		1.0				1.0	1.0		1.0			Limit of crack width		
Damage*1		1.0				1.0	1.0		1.0			Bending yield capacity		
Failure		1.0	1.0		1.1	1.0	1.0		1.0			Shear transmission capacity, Punching shear capacity	Stopper boundary*5	
		1.0	1.0	1.1		1.0	1.0		1.0					
	1.0				1.1	1.0		1.1						
	1.0				1.0	1.1		1.0						
Concrete bed	Failure*1	1.1	1.2									Bending capacity	Concrete bed	
	failure	1.0	1.0		1.1	1.0	1.0		1.0			Shear transmission capacity	Reinforcing bar for shear connection*6	
		1.0	1.0	1.1		1.0	1.0		1.0					
		1.0				1.1	1.0		1.1					
		1.0				1.0	1.1		1.0					
	Appearance*1	1.0	1.0									Limit of crack width		
Damage*1	1.0	1.0									Bending yield capacity	Concrete bed		

*1: May be generally omitted. *2: Rail fastener mounting position, *3: Bolt holes for lifting attachment at the side of track slab, *4: Track slab holding attachment during the laying of filling layer, *5: Boundary between the stopper and concrete bed, *6: Reinforcing bar for shear connections of concrete beds and structures

where D : dead load, L_w : wheel load, L_l : lateral force, B : starting and braking loads, L_{RI} : long rail longitudinal load, L_{Rh} : long rail lateral load, E_R : in-laying load, F_p : effect of temperature change, P_s : prestress force

Table 3 Fluctuating wheel load factor γ_{vw}

Performance requirement	Performance item	Conventional line	Shinkansen line
Safety	Failure	3.0	3.0
	Fatigue failure	1.3	1.45
Serviceability	Appearance	1.3	1.45
	Damage	3.0	3.0

Table 4 Fluctuating lateral force factor γ_v

Performance requirement	Performance item	Conventional line			Shinkansen line
		Straight $R \geq 800\text{m}$	$800\text{m} > R \geq 600\text{m}$	$600\text{m} \geq R$	
Safety	Failure	0.4	0.6	0.8	0.8
	Fatigue failure	0.2	0.3	0.4	0.4
Serviceability	Appearance	0.2	0.3	0.4	0.4
	Damage	0.2	0.3	0.4	0.4

types of safety factors. An action factor γ_f and a structural analysis factor γ_a are two safety factors used to calculate the design response value from the action. A material factor γ_m and a track member factor γ_b are two safety factors used to calculate the design limit values from the material properties. The track structure factor γ_t is the safety factor used to compare the design response value with the design limit.

3.2 Actions to employ for design

The designer uses dead load, wheel load, lateral force, braking and traction loads, longitudinal and lateral loads of long rails, in-laying load, effect of temperature change, and prestress force in the design. In principle, all the action combinations are verified.

Table 2 shows an example of the combinations of actions and action factors for each track component.

The force calculated by multiplying static wheel load by fluctuating wheel load factor γ_{vw} is the characteristic value of wheel load. The force calculated by multiplying static wheel load by fluctuating lateral force factor γ_v is the characteristic value of lateral force. The fluctuating wheel load factor and the fluctuating lateral force factor are shown in Table 3 and Table 4. These factors consider the results of wheel load variation measurements and so on.

4. Performance verification of concrete slab track components [1]

4.1 Track slab

Examples of verification indexes and limit values for performance requirements and performance items of track slabs are given in Table 5 and Table 6. The Table 5 is applied to the fabrication, transportation, and laying at the site of track slabs. The Table 6 is applied to the in-service period of the track slab.

During fabrication, transportation, and laying at the site, track slabs are lifted as shown in Fig. 6, transported in a stacked state as shown in Fig. 7, and held to construct a filling layer as shown in Fig. 8. For such situations, it should be verified that bending cracks do not occur in a track slab body and that punching shear failure does not occur in the bolt holes for lifting and holding attachments.

Table 5 Examples of performance requirements, performance items, verification index, and limit value in fabrication, transportation, and laying at the site of track slab

Subject of verification	Performance requirement	Performance item	Verification index	Limit value
Track slab	Body	Serviceability	Appearance	Bending moment
	Lifting attachment	Safety	Failure	Shear force
	Holding attachment			
				Flexural crack strength
				Punching shear capacity

Table 6 Examples of performance requirements, performance items, verification index, and limit value during in-service period of track slab

Subject of verification	Performance requirement	Performance item	Verification index	Limit value
Track slab	Body	Safety	Failure	Bending moment
			Fatigue failure	Stress
		Serviceability	Damage	Bending moment
			Appearance*1	Crack width
	Inserts	Safety	Failure	Sear force

*1: Generally, verification may be omitted.

During the in-service period, the designer verifies that the main body of a track slab does not undergo flexural failure, flexural fatigue failure, or flexural yielding, and that a bolt hole used to attach rail fasteners to the track slab does not undergo punching shear failure. In the case of track slabs of PRC structures, since cracking is not allowed in the fatigue failure verification, it is confirmed by verification that the stress of concrete is less than flexural crack strength. In the case of track slabs of RC structures, it is confirmed by verification that the stress of a reinforcing bar is less than the tensile fatigue strength. When calculating the response value of a track slab, the designer shall generally use a numerical analysis model using a finite element method. For example, when verifying the safety and serviceability of the track slab body during the in-service period, the train load's bending moment applied to the analytical model shown in Fig. 9 is used.

4.2 Stopper

Examples of verification indexes and limit values for a stopper's performance requirements and performance items are given in Table 7. The designer verifies that stoppers do not undergo flexural failure or shear compression failure due to horizontal loading. The designer then verifies that shear transmission failure does not occur

Fig. 6 Example of fabrication

Fig. 7 Example of transportation

Fig. 8 Example of laying at the site

in the boundary between the stoppers and the concrete to transfer the horizontal load acting on the stoppers to the concrete bed. In the case of satisfying the safety requirements for fracture, the designer can omit the verification for fatigue fractures because it has been

Fig. 9 Analytical model of track slab

Table 7 Examples of performance requirements, performance items, verification index, and limit value of stopper

Subject of verification	Performance requirement	Performance item	Verification index	Limit value
Stopper	Safety	Failure	Bending moment, Shear force	Flexural capacity, Shear compression failure capacity, Shear transmission capacity
		Fatigue failure*1	Stress	Tensile fatigue strength
	Service-ability	Damage*1	Bending moment	Flexural yielding capacity
		Appearance*1	Crack width	Omitted

*1: Generally, verification may be omitted.

confirmed that the stoppers have sufficient fatigue strength. In addition, the designer can omit the verification for appearance and damage by satisfying the safety verification for fractures.

The designer calculates the response value of a stopper as a cantilever beam. The position of a horizontal load is set considering the height of a stopper, the thickness of a track slab, and the maximum thickness of a filling layer (see Fig. 10). The total horizontal load acting on a stopper is the combined force of longitudinal and transversal force components of a rail. The acting direction of the combined force is set to the longitudinal direction of a rail in consideration of simplicity of verification and design safety. The designer then considers the friction between the track slab and the filling layer, and the coefficient of friction is generally set to 0.35.

4.3 Concrete bed

Examples of verification indexes and limit values for a concrete bed's performance requirements and performance items are given in Table 8. A bending moment occurs in a concrete roadbed when a train load acts on it. However, from experience, it has been confirmed that if concrete beds are placed on structures designed to satisfy their safety requirements, they will satisfy the safety and serviceability verification so the designer can omit verification for bending moments. Therefore, the designer verifies that punching shear failure does not occur at the edge of a concrete bed where the

Fig. 10 Position of horizontal load acting on stopper

Table 8 Examples of performance requirements, performance items, verification index, and limit value of concrete bed

Subject of verification	Performance requirement	Performance item	Verification index	Limit value
Concrete bed	Safety	Failure	Bending moment, Shear force	Flexural capacity, Punching shear capacity, Shear transmission capacity
		Fatigue failure*1	Stress	Tensile fatigue strength
	Serviceability	Damage*1	Bending moment	Flexural yielding capacity
		Appearance*1	Crack width	Omitted

*1: Generally, verification may be omitted.

Fig. 11 Punching shear failure plane at connection between stopper and concrete bed

stoppers are connected, as shown in Fig. 11. In addition, to transfer the horizontal load acting on a concrete bed to a structure, the designer verifies that a shear transmission failure does not occur at the reinforcing bar for shear connections.

5. Ending remarks

Slab track has been laid for more than 1,800 km on the Shinkansen in Japan and is also used in Taiwan and China. Improvements have been made to slab track, such as changing the shape of the track slab, increasing the rail fastening spacing, and modifying the material used for the filling layer. Further research and development for the slab tracks will be continued to improve the performance and economic efficiency.

References

- [1] Railway Technical Research Institute, *Design Standards for Railway Structures and Commentary – Track Structures*, Maruzen Publishing Co., Ltd., Tokyo, JAPAN, 2012 (in Japanese).

Authors

Takatada TAKAHASHI, Dr. Eng.
Senior Researcher, Track Structures and Geotechnology Laboratory,
Track Technology Division
Research Areas: Ballastless Track

Shota FUCHIGAMI, Dr. Eng.
Assistant Senior Researcher,
Track Structures and Geotechnology Laboratory,
Track Technology Division
Research Areas: Ballastless Track

Yoshitsugu MOMOYA, Dr. Eng.
Senior Chief Researcher, Head of Track Structures and Geotechnology Laboratory,
Track Technology Division
Research Areas: Ballastless Track, Ballasted Track