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Modelling of slab track systems for design purposes

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Abstract

Slab track is a recent technology used to cope up with the train high axle loads and speed, it has replaced the ballast material in classical ballasted track with either reinforced concrete slab or asphalt layer in order to increase both stability and durability of the railway lines. This paper aims to propose a new slab track design model which can be used to design/analyze any slab track systems under vertical loads using AREMA and EN specifications for high-speed systems (300 kmph). This model has been validated through experimental work held in Heriot-Watt University then applied to the most common slab track systems (BÖGL, Shinkansen, and RHEDA 2000) in the world. The standard section of RHEDA 2000 slab track has shown the best structural performance and efficiency compared with BÖGL and Shinkansen standard sections regarding the rail deflection, stresses of rails, and stress of replacement soil layer and subgrade soil. This paper has concluded the rail deflection is the most critical factor for the slab track design regarding EN specifications while the subgrade stresses is the vital criterion concerning AREMA specifications. Furthermore, EN-Specifications are found to be more conservative than AREMA specifications for the design or analysis of all the slab track types.

Keywords: Railway slab track, Slab track design, AREMA and EN-Specifications, Midas GTS NX, Nonlinear analysis

Introduction

The rapid growth of axle loads and high speed in railway transportation systems increases the maintenance costs for railway lines [4, 18]. Thus, new solutions have been introduced to overcome these issues. Some solutions tend to improve the quality of the subgrade soil by replacement soil or geosynthetics such as geotextile [1]. One of the most recent solutions is to employ a slab track system.

The slab track system consists of two main parts, namely: the superstructure, and the substructure. The superstructure elements of the slab track are rails, sleepers or blocks, concrete bearing layer (CBL), or asphalt bearing layer (ABL) and hydraulic bonded layer (HBL). The substructure elements of the ballastless track are the frost protective layer (FPL), formation (replacement if required) and subgrade [5, 10, 13].

Investigating a slab track design model manually is time-consuming and daunting to be implemented. Therefore, the use of finite element analysis (FEA) is a must for studying slab track systems. The slab track has been studied over the last few decades through numerical computerized models and experimental physical tests. G. Michas has built a finite element model with ABAQUS to investigate the static linear behavior of RHEDA 2000 slab track using EN loads [13], and this model was verified by a model built by H. Feng which was a ballasted track of the same dimensions [9]. Michas has found that the slab track deformation is smoother than ballasted track because of distributing the loads in much larger areas. On the other side, the ballasted track deformation is sharper near the points where the loads are located and almost undeformed at the areas far from the loads. Slab track has shown less rail top level displacement than ballasted track by approximately 60%.

S. Matias has studied a static comparison between Stedef slab track system and ballasted track system to predict their structural behavior for design purposes utilizing ANSYS software. His work was validated through experimental campaigns conducted by SNCF [12]. Also, a parametric study has been held in order to optimize the design. Matias has found decreasing HBL to Stedef slab track thickness from 28 to 20 cm increases the subgrade vertical stress by 10%.

T. Čebašek et al. have tested the slab track (BÖGL) and ballasted track to investigate their behavior under static and cyclic loading using GRAFT apparatus in Heriot-Watt University [11]. Čebašek has figured out that the concrete slab track performed significantly better in terms of cumulative settlement and rail deformation when compared to the ballasted track (80% reduction due to slab track). Čebašek has found out that the ballasted track produces higher displacement measured at rail top level than BÖGL slab track. The major reason for the observed higher displacement of the ballasted track was caused by the unbound nature of ballast.

A. Ramos et al. have performed numerical models to calibrate with the experimental physical tests held by T. Čebašek et al. [11] in Heriot University laboratory [16]. These numerical models have shown great match with the experimental tests of T. Čebašek. The main aim of this work was to develop an empirical model for predicting long-term track deformation for ballasted and slab track.

M. Atalan et al. have investigated the behavior of slab track with asphalt bearing layer using analytical and numerical in order to study the effect of dynamic forces on high-speed railway lines (HSL) [2]. They have found that the use of asphalt bearing layer in railway slab tracks has beneficial impacts, such as increasing the bearing capacity of the soil, increasing the vertical stiffness of the track, improving the slab track dynamic performance, and its responses for HSLs [2].

The slab track systems are utilized worldwide with different percentages, the most common slab track systems are illustrated in Fig. 1. These slab track systems are BÖGL, Shinkansen, and RHEDA 2000. These railway slab track systems form approximately 76.20% of the worldwide use of slab track [5, 10, 13].

BÖGL slab track system is made of precast slab panels, the slab panels are 6.45 m long and 2.55 m in width with a thickness of 200 mm, it weighs around 9 tons, the reinforcement utilized in these panels is steel fibers, and grade of concrete is taken C45/55 [3]. Shinkansen slab track system is precast slab panels, the precast slabs are 4950 mm long

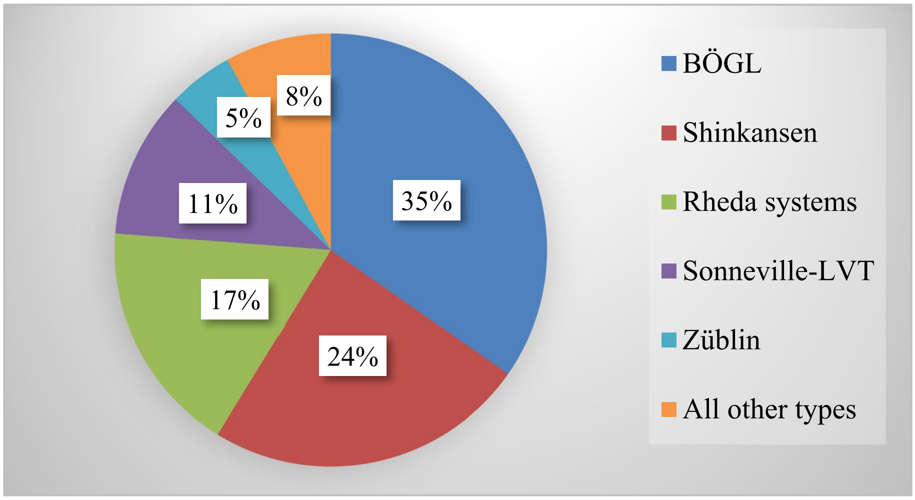


Fig. 1 The most common slab track systems [13]

and 2340 mm wide and the thickness varies from 160 mm in tunnels (to provide less height) to 190 mm on roadbed. There are short and vertical cylindrical concrete dowels (400 mm diameter and 200 mm height) to provide the lateral and longitudinal resistance [3, 10, 18]. RHEDA 2000 is cast in situ with reinforced concrete. RHEDA 2000 uses sleeper of B350 and it has a CBL of 240 mm, a HBL of 300 mm, and FPL of 500 mm to 700 mm in height. The dimensions of this slab can be changed according to the project specification (i.e., flexible slab track) [5, 10, 13].

The vertical loads and specifications utilized in this research follow two international codes, namely American Railway Engineering and Maintenance of the Way (AREMA), and European Norms (EN).

The type of loads utilized in AREMA is COOPER E80 [15], Cooper E80 includes two steamed locomotives with 4 axles of 355.8 kN, two leading axles of 177.9 kN and also two tender wagons comprise of 4 axles of 231.3 kN. In addition, the trailing linearly distributed load is about 116.8 kN/m as depicted in Fig. 2. Also, AREMA recommends the use of impact factor according to Eq. 1 [6]:

$$I = 1 + \frac{D_{33} * V}{D_{wheel} * 100} \quad (1)$$

where V is speed in mph, D_{33} is the standard diameter of a 33 inches wheel and D_{wheel} is the actual train wheel diameter in inches.

For speed of 300 km/h, $D_{33}=33$ inches, and $D_{\text{wheel}}=36$ inches, the impact factor according to AREMA = 2.70. Eccentricity of vertical loads according to AREMA,

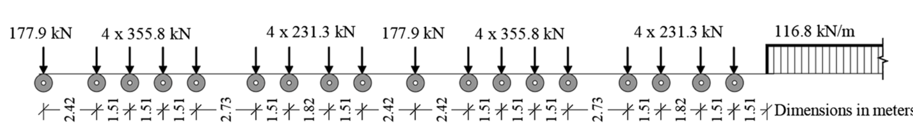


Fig. 2 Cooper E80 load model [7, 15]

must be taken as 20% of train loads on one rail and − 20% on the other rail. In addition, AREMA slab track design must include these specifications [6, 7, 18]:

- Allowed rail vertical displacement–6.35 mm (i.e., 0.25 inch).
- The reinforcement steel of the slab shall be 0.7 to 0.8% of the slab cross-section.
- Allowed rail bending stress (σ_{all}) can be obtained from the following equation:

$$\sigma_{all} = \frac{\sigma_y - \sigma_t}{(1 + A) * (1 + B) * (1 + C) * (1 + D)} \tag{2}$$

Where σ_y is the yield stress of steel in MPa, σ_t is the thermal stress of the rail in MPa, *A* is a factor based on lateral bending (0 to 0.15), *B* is a factor based on rail wear (0 to 0.1), *C* is dependent on track quality (0 to 0.25) and *D* is dependent on horizontal curve's super elevation (0 to 0.15). Thus, the allowable can be taken as 482 MPa for $\sigma_y = 780MPa, \sigma_t = 138$MPa, $A = 0.15$, $B = 0.10$, $C = 0.15$, and $D = 0$.

The loading cases used in this paper according to AREMA are.

A1: D.L + L.L (AREMA Cooper E80 + impact).
A2: D.L + L.L (AREMA Cooper E80 + impact + eccentricity).

There are five loading models in EN specifications; namely LM71 (UIC71), SW/0, SW/2, unloaded train model, and highspeed load models (HSLM-A and HSLM-B) [17]. The load model "LM 71" (Fig. 3) represents the static vertical effect of normal rail traffic loads, this load consists of 4 axles of 250 kN and a continuous distributed load of 80 kN/m along the track [17].

The loading models "SW/0 and SW/2" (Fig. 4) are continuous distributed loads over a finite length. The load model SW/0 is used to represent the normal rail traffic loads while SW/2 is utilized to represent the heavy rail traffic in each national code [17].

The "Unloaded train loading model "is only used to check stability against wind loads for railway bridges while the" high speed load model (HSLM)" is used in dynamic analysis whenever train speed exceeds 200 kmph especially on bridges. These types of loads are

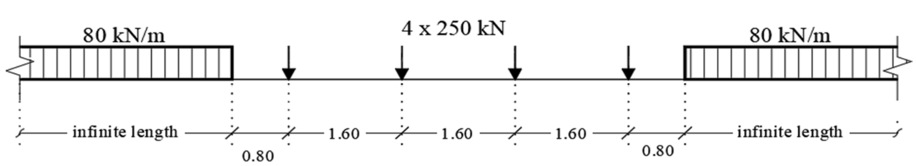
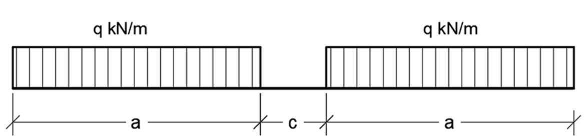


Fig. 3 Load model LM71 [17]



Load Model	q (kN/m)	a(m)	c(m)
SW/0	133	15	5.3
SW/2	150	25	7

Fig. 4 Load model SW/0 and SW/2 [17]

out of this paper scope. The EN specifications recommend the use of Eisenmann dynamic impact factor which is taken according to equation (Eq. 3) [6].

$$I = 1 + \phi * t * s \tag{3}$$

$$\phi = 1 + \frac{V - 60}{380}, for 200 < speed \leq 300 km/hr \tag{4}$$

The parameter "t" can be taken as 0.1, 0.2, or 0.3 depending on track quality, "s" can be assumed 1, 2, or 3 based on the selected confidence level for obtaining the maximum rail deflection (84.1%, 97.7%, and 99.9%), ϕ is a factor depends on the train speed where V is the speed in kmph.

In case of speed of 300 km/h, $t = 0.1$, and $s = 3$, the Eisenmann dynamic impact factor "I" according to EN is taken equal to 1.5. Eccentricity of vertical loads according to EN, must be taken as 11% of train loads on one rail and − 11% on the other rail [17]. Another factor "α" is employed to adjust the loading model to match the lighter or heavier traffic loads for EN only [17], the "α" is mostly taken as 1.33 across European nations. In addition, European slab track design must include the following specifications [6, 8, 10, 13]:

- The maximum allowable rail deflection is about 2.00 mm.
- The minimum reinforcement ratio for slabs is taken as 0.8 to 0.9% from cross-section.
- Allowed rail bending for welded rails is 0.31 ultimate strength (for steel–ultimate strength 1130 MPa- the allowable rail bending shall be 350 MPa).

In this paper, the used loading cases according to EN are.

- E1: D.L + L.L (EN LM71 + impact + α).
- E2: D.L + L.L (EN LM71 + impact + eccentricity + α).
- E3: D.L + L.L (EN SW/0 + impact + α).
- E4: D.L + L.L (EN SW/0 + impact + ecc + α).
- E5: D.L + L.L (EN SW/2 + impact).

The bearing capacity has been assumed according to the soils used in the validation experimental tests [11, 19]. These tests used a replacement of well graded limestones with bearing capacity of 400 kPa, and a subgrade layer of clayey sand with bearing capacity of 175 kPa.

The lack of a reliable design method for the slab track systems has been a daunting issue for developers and engineers. Therefore, this research aims to build a precise and effective nonlinear Finite Element model which can be used for different slab track systems, this model has been validated through experimental work. Moreover, this research compares between the most common slab track systems (BÖGL, Shinkansen, and RHEDA 2000) to determine the most efficient slab track system applying EN and American (AREMA) specifications, and to find the worst case of loading for each design code.

Methods

This paper is concerned with investigating the nonlinear behavior of the most common slab track systems (BÖGL, Shinkansen, and RHEDA 2000) under EN and AREMA specifications for design/analysis purposes and to suggest the most structurally efficient slab track system in the world. To achieve the aforementioned objectives, five sequential steps have been taken as shown in Fig. 5. The 1st step is to introduce the most worldwide common slab track systems. In the 2nd step, the loads and specifications of each design code (EN and AREMA) are discussed. The 3rd step is to introduce the stages of 3D nonlinear finite element model through Midas GTS NX. The 4th step is to validate this model through experimental work held in Heriot-Watt University using GRAFT II apparatus. Regarding the 5th step, the most common slab track systems nonlinear behavior is investigated under EN and AREMA specifications to study their nonlinear structural behavior and select the most efficient slab track.

The proposed finite element model

The proposed slab track design model consists of six different stages using MIDAS GTS NX software as shown in Fig. 6. The mechanical properties for the materials of slab track systems used in the finite element analysis are illustrated in Table 1, similar to the materials properties used in experimental validation tests [11, 19]. Subgrade soil has been assumed to be clayey sand with modulus of elasticity equal to 60 MPa (minimum accepted value for new tracks according to European specifications [10], and the cohesion (C) for FPL and replacement (cohesion-less soils in general) has been taken as 0.1 kPa not 0 in order to avoid misleading in the software [14].

The track superstructure (Rails, HBL, and CAM-Cemented Asphalt Mixture) has been simulated as linear materials (following Hooks law model). At the beginning, CBL and

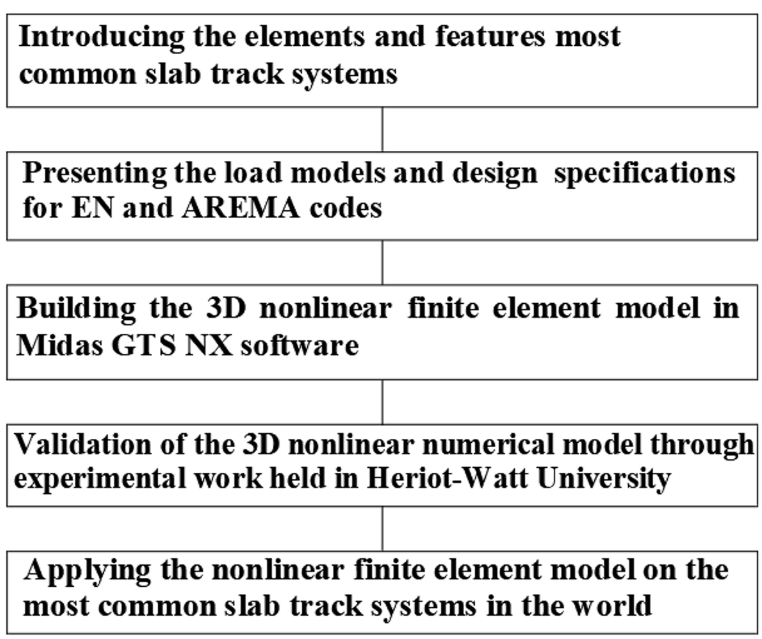


Fig. 5 Research methodology program

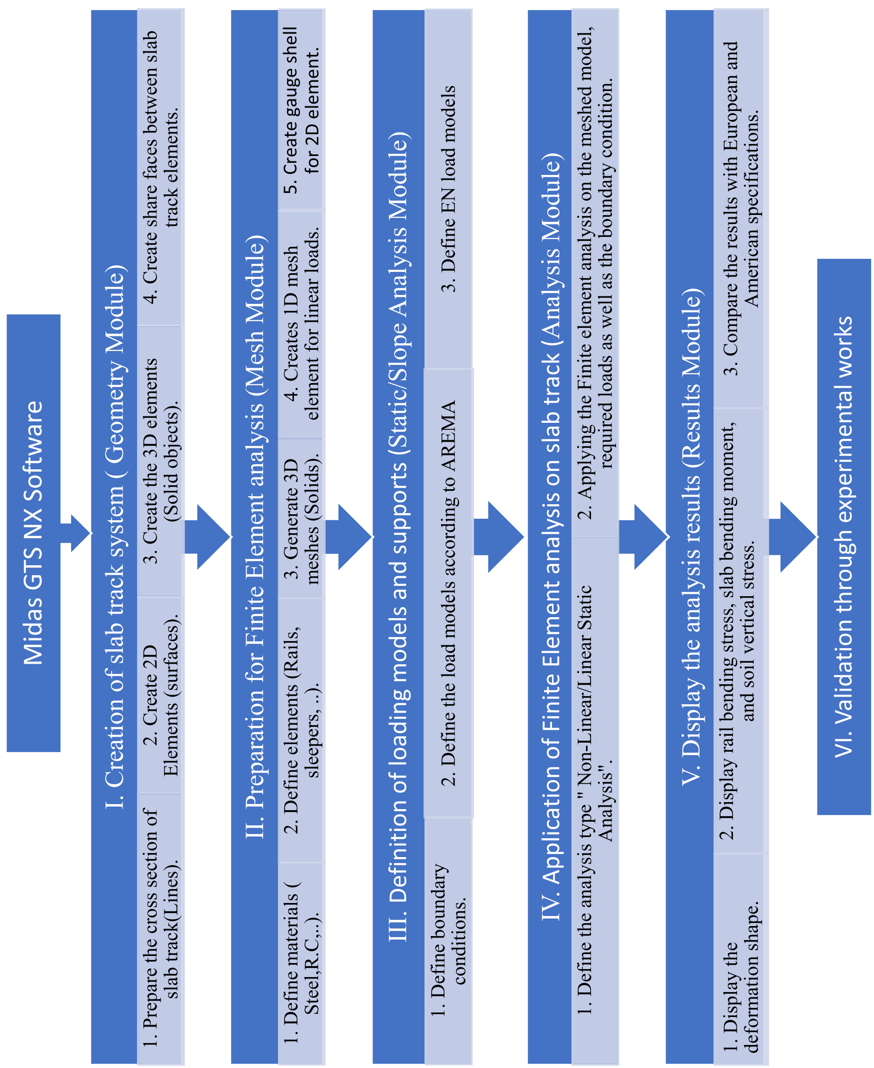


Fig. 6 The proposed slab track design model

Table 1 The mechanical properties for the materials of slab track system

Elements	Modelling type	Mesh size (m)	γ (kN/m^3)	E (MPa)	υ	Φ	C (kPa)
Rail	Linear elastic	0.10	78.5	210,000	0.30	–	–
CBL		0.20	25.0	36,000	0.20	–	–
Slab shoulders		0.20	25.0	36,000	0.20	–	–
CAM (grouting)		0.30	23.0	22,500	0.25	–	–
HBL		0.30	24.0	17,870	0.20	–	–
FPL	Nonlinear (Mohr–Coulomb)	0.50	21.44	400	0.30	35	0.1
Replacement		0.60	20.91	400	0.30	35	0.1
Subgrade soil		0.70	20.91	60	0.30	25	5

Where the meshes size are in meters. γ is the unit weight in kN/m^3, *E* represents modulus of elasticity in MPa, υ is the Poisson's ratio (unitless), φ is the angle of the internal friction, *C* is the cohesion (kPa)

R.C sleepers were modelled twice, one as linear material and the other one as nonlinear material. Negligible differences were observed between the two models as the tensile stress in the concrete were less than the rupture tensile strength of concrete (F_{ctr}). Thus, to decrease the model computational costs and efforts, the CBL and R.C. sleepers were modelled as linear materials. On the other hand, the track substructure (FPL, formation, and subgrade) has been represented as nonlinear materials (following Mohr–Coulomb model).

The type of meshes used are "Hybrid Mesher" which uses a combination of hexahedrons (8 nodes) and tetrahedrons (4 nodes) because "Hybrid Mesher" is more accurate in stress analysis than "Tetra Mesher" which uses only tetrahedrons [14].

The suitable mesh size for each element has been selected based on a mesh study (only half of the model has been built due to symmetry as per Fig. 7), this mesh study has been carried out including three models of 2.5, 5.0, and 10.0 cm mesh size. The displacement (at rail top level) difference between the models of 10 cm and 5 cm mesh sizes is about 0.6% meanwhile the displacement difference between 2.5 and 5.0 cm models is less than 0.1%. Because of this insignificant difference, it was found that the mesh size is not necessary to be less than 10 cm. Hence, the meshing sizes were selected as per Table 2.

The boundary conditions for the finite element models have been set to simulate the surrounding soil, which means that "*x*" direction displacement is constrained for the left/right side, "y" direction displacement is constrained for the front/back side while "*x*, *y*, and *z*" direction displacement is constrained for the bottom of the model. The type of analysis used has been set as nonlinear static analysis.

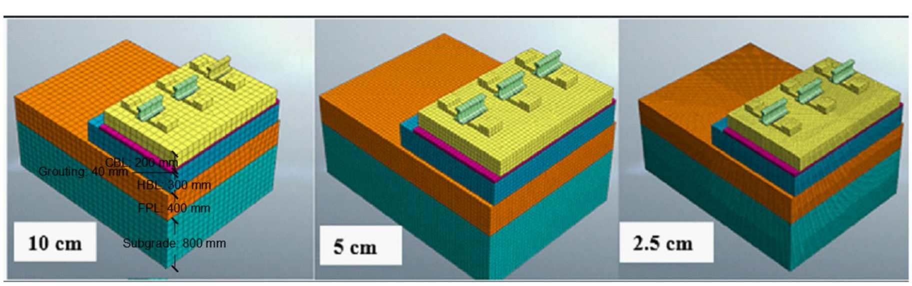


Fig. 7 FE Models used for mesh convergence investigation

Validation of the finite element model

Description of the experimental test

The results of the numerical slab track design model have been validated only for BÖGL slab track. These results have been compared with the results of a static experimental test held in Heriot-Watt university laboratory by D. Thölken et al. [19]. The experimental test has evaluated the rail and slab displacements of the BÖGL slab track systems under specific loading system. This test has been performed utilizing GRAFT II apparatus (Geo-pavement and Railways Accelerated Fatigue Testing II) as depicted in Fig. 8. The main dimensions of the used slab track in the experiment are shown in Fig. 9.

Validation result analysis

The numerical models built for the validation have employed the same material properties and meshing sizes (as per Table 1) and the nonlinear analysis, which are the same as the material properties used in the validation experiments [19]. This experimental test consists of three different scenarios (S_1, S_2, and S_3). The 1st scenario has employed an axle load of 130 kN divided onto three sleepers as 25%, 50% and 25%. The 2nd scenario is to use an axle load of 170 kN distributed on three sleepers as 25%, 50%, and 25%. The 3rd scenario is to apply an axle load of 258 kN with equal percentages for each sleeper (33.3% for each one). The goodness of fit has been calculated to investigate the agreement between the numerical and experimental outputs, R^2 value has been found to be 0.87 which means that the numerical models have an excellent match with the experimental results. Figure 10 shows the comparison between

Fig. 8 GRAFT II apparatus used in the experimental test [11, 19];

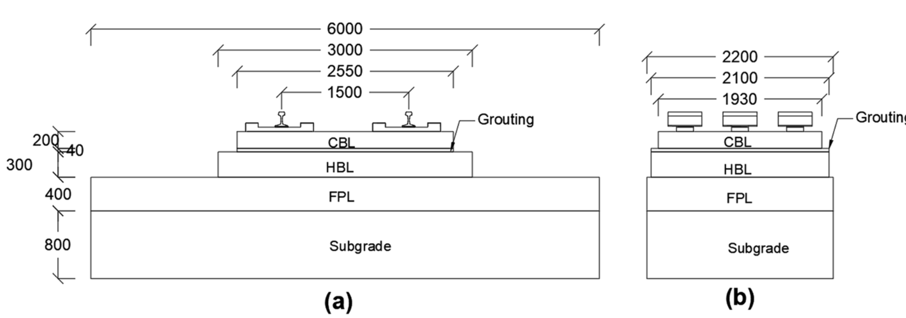


Fig. 9 Main dimensions and levels for GRAFT II. **a** Cross section view. **b** Longitudinal view

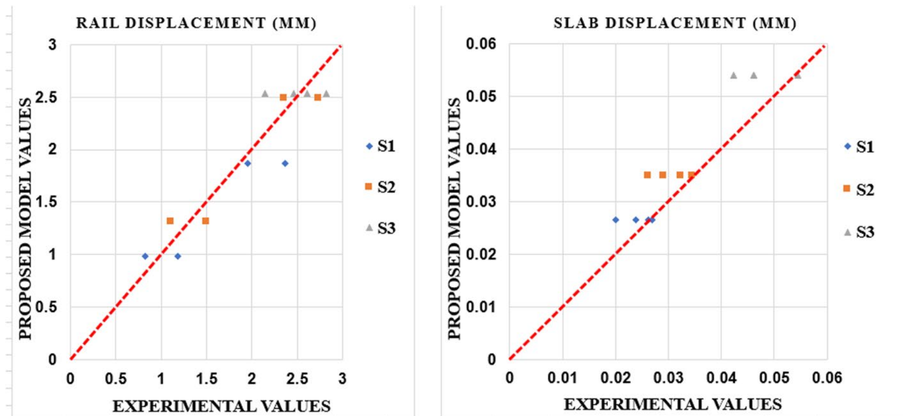


Fig. 10 Comparison between D. Thölken test and the numerical slab track design model

the displacement obtained from the numerical model (the numerical slab track design model) and the experimental test measured at the actuators and LVDTs (linear variable differential transformer).

According to this validation with Thölken experimental test, it's obvious that the slab track design model can mimic the actual behavior of ballastless tracks. Therefore, the utilized finite element model has been employed to design the most common slab track systems and to extend the studied design parameters.

Applications of the proposed model on the most common slab track systems

The nonlinear proposed slab track design model can be used for several purposes such as evaluating an existing slab track system, design a new slab track system, and optimization purposes. Regarding designing of a new track system, this model can be utilized to make a parametric study to achieve the required design specifications. The nonlinear numerical model has been applied on the most common slab track systems (BÖGL, Shinkansen, and RHEDA 2000) with their standard sections were studied according to both of AREMA and EN specifications.

BÖGL slab track model

The geometric model for BÖGL slab track is built according to its standard dimensions as shown in Fig. 11 (3D view is depicted in Fig. 12). The superstructure consists of UIC (60) rails, concrete shoulders of R.C slab are $0.75 \times 0.30 \times 0.10$ m spaced at 650 mm, CBL is prefabricated slabs of $6.45 \times 2.55 \times 0.20$ m, HBL has height of 30 cm and width of 3.55 m. On the other hand, the substructure contains FPL with height of 50 cm and width of 5.55 m, the replacement layer thickness is assumed 80 cm as per validation experiments, the subgrade is laterally extended 3 m from each side and with thickness of 1.70 m.

Shinkansen slab track model

Shinkansen slab track which is built according to the standard section as shown in Fig. 13. The superstructure includes rails of UIC (60), steel plates for fastening rails

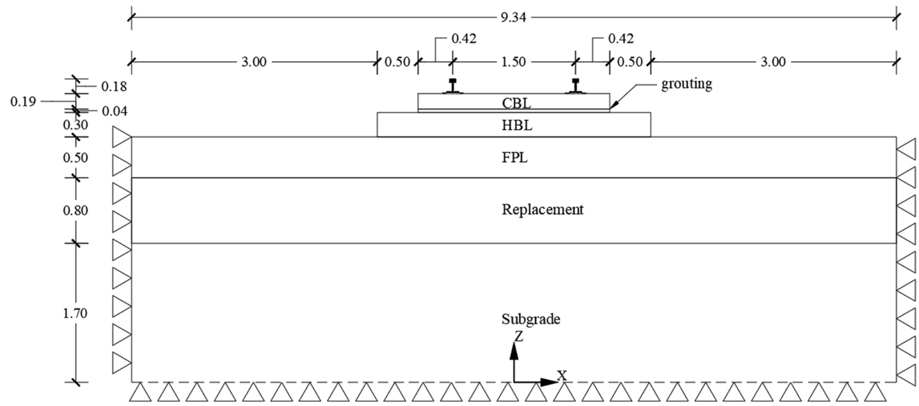


Fig. 11 BÖGL slab track standard cross-section (dimensions in meters)

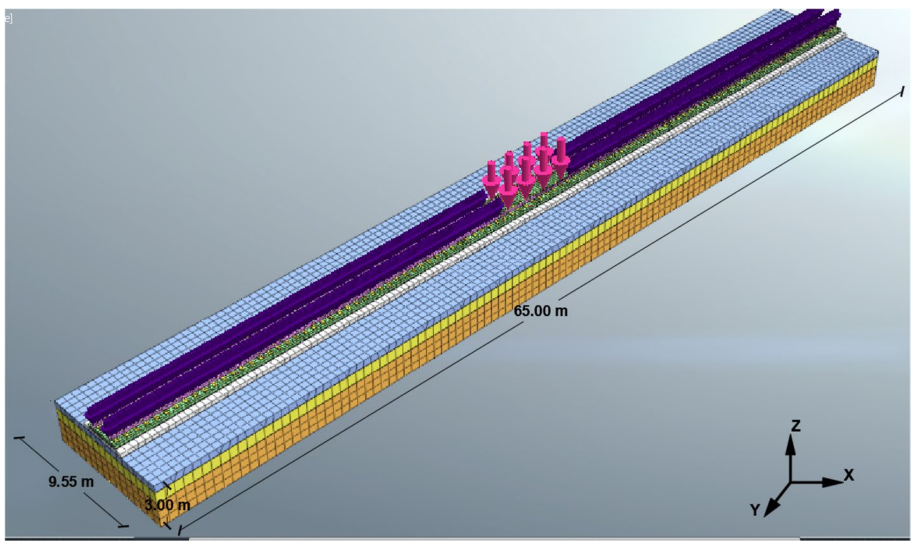


Fig. 12 BOGL slab track model 3D-view

with dimensions of 250 × 150 × 10 mm spaced at 625 mm, CBL is prefabricated slabs of 4.90 × 2.34 × 0.19 m while HBL has a height of 300 mm and width of 3.34 m. On the other hand, the sub-structure consists of FPL with height of 500 mm and width of 5.34 m, the replacement layer is taken 80 cm, the subgrade is laterally extended 3.0 m from each side and with thickness of 1.70 m. The materials, meshing size, required loads, boundary conditions, and analysis type used for Shinkansen slab track design model are the same as BÖGL model.

RHEDA 2000 slab track model

The geometric model for the RHEDA 2000 slab track system is built according to its standard section as shown in Fig. 14. The superstructure includes rails of UIC (60), R.C sleepers (B355) are twin block of 0.91 × 0.29 × 0.19 m, CBL is casted in-situ with

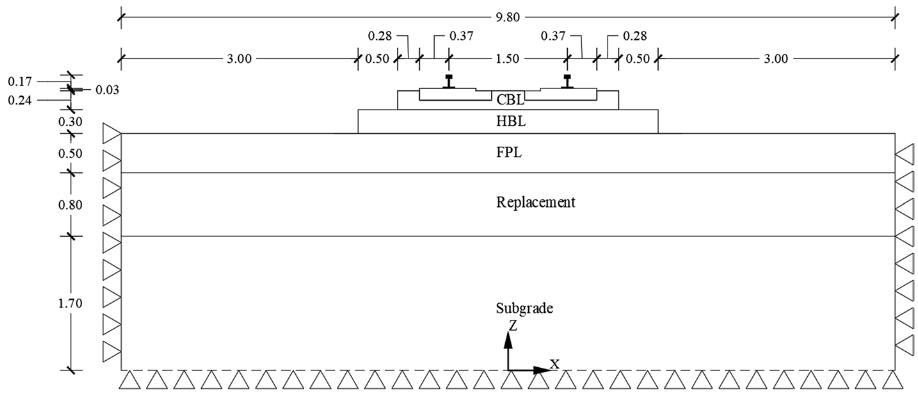


Fig. 13 Shinkansen slab track standard cross-section (dimensions in meters)

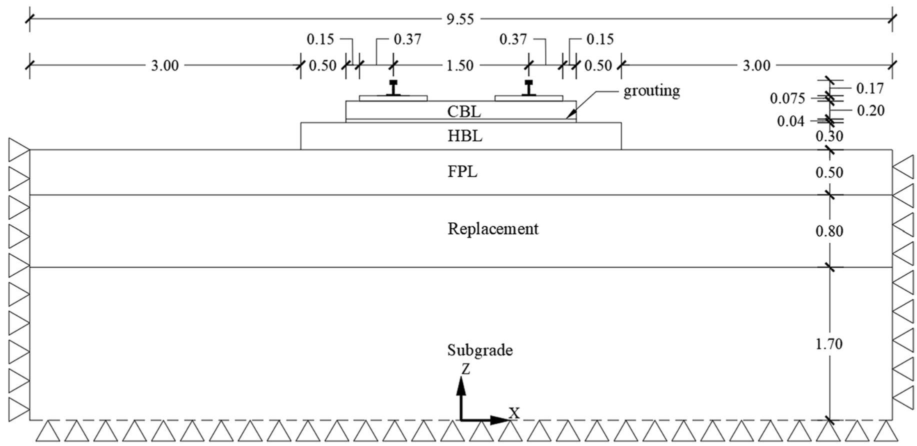


Fig. 14 RHEDA 2000 slab track standard cross-section (dimensions in meters)

a height of 0.24 m and width of 2.80 m, HBL has height of 0.30 m and width of 3.40 m. On the other hand, the sub-structure contains FPL with height of 0.50 m and width of 5.40 m, the replacement layer is taken 80 cm, and the subgrade height is 1.70 m.

The elements and materials properties used for RHEDA slab track are the same as BÖGL and Shinkansen slab track except for reinforced concrete and CAM. The reinforced concrete has modulus of elasticity of 34,000 MPa and 50,000 MPa for slab and sleepers, respectively. RHEDA 2000 does not include CAM layer. The meshing size, loads, and analysis type are the same as per BÖGL, and Shinkansen models.

Results and discussion

The proposed slab track design model has been applied on the three studied slab track systems; the results can be shown in Table 2. For all slabs, it was found that the worst-case scenario for the slab track design in American specifications (AREMA) is case A2 and in European specifications (EN) is case E2. Furthermore, it was found that bending moments in reinforced concrete slabs are less than their cracking moment (M_{cr} = 34.6, 31.13., and 41. kN.m/m for BÖGL, Shinkansen, and RHEDA 2000,

Table 2 The nonlinear static analysis results for the most common slab track systems

Type	Load case	Disp	$F_{bending}$	$M_{xx}+ve$	$M_{yy}+ve$	$M_{xx}-ve$	$M_{yy}-ve$	σ_{sub}	σ_{rep}
BÖGL	A1	3.99	−228.2	10.3	10.3	−7.4	−8.8	164	300.1
	A2	4.22	−270.6	11.6	12.1	−7.7	−8.7	165.8	355.1
	E1	2.50	−118.4	6.5	6.4	−3.4	−3.6	110.3	161.9
	E2	2.55	−123.0	6.5	6.3	−3.3	−3.7	110.5	174.0
	E3	2.45	−15.7	5.1	5.1	−3.1	−2.8	114.1	161.7
	E4	2.48	−15.5	5.2	5.6	−3.3	−2.6	114.4	174.9
	E5	2.22	−12.35	4.6	4.7	−2.7	−3.0	105.2	141.9
Shinkansen	A1	4.18	190.0	10.1	11.2	−7.6	−7.5	173.8	314.0
	A2	4.42	−223.9	12.7	12.7	−7.3	−7.9	175.2	381.9
	E1	2.70	−61.1	7.2	7.3	−1.9	−2.3	120.1	160.4
	E2	2.75	−67.2	6.7	7.9	−2.0	−2.6	120.1	177.1
	E3	2.56	−17.8	5.7	6.1	−3.5	−3.7	118.2	162.3
	E4	2.59	−15.6	6.3	6.7	−3.6	−3.3	118.6	180.6
	E5	2.31	−15.1	5.1	5.3	−2.4	−2.7	108.9	140.4
RHEDA 2000	A1	3.83	−167.6	14.4	12.9	−14.8	−11.1	158.4	255.2
	A2	4.06	+167.0	12.7	12.9	−12.4	−10.7	161.5	291.8
	E1	2.55	−75.1	6.5	6.3	−1.9	−4.7	113.9	140.2
	E2	2.61	+80.8	6.5	5.8	−2.0	−5.4	115.3	147.9
	E3	2.46	−14.3	6.5	6.3	−5.2	−4.4	113.5	137.04
	E4	2.48	−15.6	6.4	5.8	−5.3	−4.5	114.2	144.7
	E5	2.22	14.7	5.3	5.4	−3.9	−3.3	105.3	122.1

respectively) under both of AREMA and EN cases of loading. Thus, the CBL can be considered as uncracked section and modelling this layer as linear material can be acceptable. Also, the required slab reinforcement for CBL may be assigned as the minimum required reinforcement according to the corresponding design code. The proposed design model can be used as follow to conclude an acceptable design considering AREMA and EN standards. It is clear that choosing the appropriate replacement soil thickness and properties has a major effect on the slab track system.

BÖGL slab track standard section model

- The standard BÖGL slab track with slab track components properties mentioned in Table 2 (sample of the results can be found in Additional file 1) and using AREMA cases of loading has fulfilled AREMA requirements as the maximum normal stress in rails is − 270. 6 kPa which is less than the allowable stress of $f_{all}=482$ kPa, the max rail deflection is 4.22 mm which is less than the allowable deflection of 6.30 mm, the maximum replacement soil stress is equal to 355.1 kPa which is less than the allowable stress of $\sigma_{all}=400$ kPa and the maximum subgrade stress = 165.8 kPa which is less than the allowable stress of $\sigma_{all}=175$ kPa. Thus, according to AREMA the design of the standard BÖGL slab track system is acceptable.
- On the other hand, the same BÖGL slab track with the same slab track components properties and using EN cases of loading has failed according to EN specifications to achieve the required max rail deflection of 2 mm as the maximum rail deflection is 2.55 mm. However, the maximum normal stress in rails is

only − 123.5 kPa which is less than $f_{all} = 350$ kPa, the maximum replacement stress equals to 174.0 kPa which is less than $\sigma_{all} = 400$ kPa, and maximum subgrade stress is equal to 110.5 kPa which is less than $\sigma_{all} = 175$ kPa. Using the proposed design model, designer can increase the thickness of the replacement from 0.80 m to 1.53 m to achieve the allowable rail deflection.

Shinkansen slab track standard section model

- The design for Shinkansen slab track with its standard dimensions according to AREMA has failed to fulfill the specifications requirements as the maximum subgrade stress = 175.2 kPa is a little bit more than its allowable stress $\sigma_{all} = 175$ kPa. However, the maximum normal stress in rails is − 223.9 kPa which is less than the allowable stress $f_{all} = 482$ kPa, the max rail deflection is 4.42 mm which is less than the allowable deflection of 6.30 mm, and the maximum replacement stress equals to 381.9 kPa which is less than $\sigma_{all} = 400$ kPa. Therefore, in order to achieve the allowable rail deflection according to AREMA specifications, the designer can increased the thickness of replacement soil in the design model until all AREMA requirements are achieved and it was found that increasing it from 0.80 m to 0.90 m will do so.
- The design for the same Shinkansen slab track using EN cases of loading has failed to achieve the requirements of EN specifications as the maximum rail deflection equals to 2.75 mm which is greater than the maximum allowable deflection of 2.00 mm. However, the maximum bending stress in rails is − 67.2 kPa which is less than $f_{all} = 350$ kPa, the maximum replacement stress equals 177.1 kPa which is less than $\sigma_{all} = 400$ kPa and maximum subgrade stress is equal to 120.1 kPa which is less than $\sigma_{all} = 175$ kPa. In order to fulfil EN specifications, the designer may increase the depth of the replacement soil from 0.80 m to 1.72 m in the design model, and the allowable rail deflection according to EN specifications will be achieved.

RHEDA 2000 slab track standard section model

- The design for RHEDA 2000 slab track with its standard dimensions according to AREMA has fulfilled the specifications requirements as the maximum normal stress in rails is 167.04 kPa which is less than the allowable stress $f_{all} = 482$ kPa, the max rail deflection is 4.06 mm which is less than the maximum allowable deflection of 6.30 mm, the maximum replacement soil stress is equal to 291.6 kPa which is less than $\sigma_{all} = 400$ kPa and the maximum subgrade stress equals 161.5 kPa which is less than $\sigma_{all} = 175$ kPa. Thus, according to AREMA the design of the standard RHEDA 2000 slab track system is acceptable.
- The design for the same RHEDA 2000 slab track according to EN cases of loading has failed to achieve the requirements of EN specifications as the max rail deflection is equal to 2.61 mm which is greater than the maximum allowable deflection of 2.00 mm. However, the maximum bending stress in rails is + 80.8 kPa which is less

than $f_{all} = 350$ kPa, the maximum replacement soil stress equals 147.9 kPa which is less than $\sigma_{all} = 400$ kPa and the maximum subgrade stress is equal to 115.3 kPa which is less than σ_{all} 175 kPa. In order to fulfill the EN specifications, the designer may increase the depth of the replacement soil from 0.80 m to 1.55 m in order to achieve the allowable rail deflection according to EN specifications.

Comparison between BÖGL, Shinkansen, and RHEDA 2000 slab tracks systems

A comparison between the results obtained from BÖGL, Shinkansen and RHEDA 2000 slab tracks standard section has been held to determine the most structurally efficient slab track system. From the previous analysis, it was found that AREMA A2 and EN E2 loading cases are the most critical cases of loading for all the studied systems. Thus, they have been utilized in this comparison.

Comparing the results shown in Table 2 altogether, it is obvious that the standard section of RHEDA 2000 is the most efficient slab track system compared to the other two system with their standard section, because it produces the least values in rail displacement, rail stresses, replacement stresses and subgrade stress regarding both of AREMA and EN specifications. This can be interpreted by the increased CBL thickness of RHEDA 2000 compared to the other two systems as well as the use of twin-block sleepers which guarantees more vertical stiffness.

Concerning rail displacement, Shinkansen gives the highest values because its thickness equals 190 mm while RHEDA 2000 has decreased the rail deflection by 8% and 5% for AREMA and EN, respectively compared to shinkansen. For rail stresses, BÖGL gives the highest values, RHEDA has reduced the rail stress by 38% and 34% for AREMA and EN, respectively compared to BÖGL because it has twin-block sleepers unlike BÖGL.

Regarding replacement soil stresses, shinkansen slab track produces the highest stresses on the replacement soil top level. Employing RHEDA 2000 slab track has decreased replacement soil stresses by 26% and 16% for AREMA and EN, respectively compared to shinkansen. Apropos of the subgrade stresses, shinkansen slab track produces the highest stresses on the subgrade top level. Employing RHEDA 2000 has decreased subgrade stresses by 11% and 4% for AREMA and EN, respectively compared to shinkansen. BÖGL has intermediate results (rail displacement, replacement soil stresses, and subgrade soil stresses) between both Shinkansen and RHEDA 2000. Therefore, RHEDA 2000 can be considered the most structurally efficient slab track system.

Conclusions

In this paper, a proposed slab track design model has been introduced to evaluate the nonlinear behavior of the most common slab track systems (BÖGL, Shinkansen, and RHEDA 2000) in order to design/analysis these systems and to select the most structurally efficient slab track system in the world. These facts have been drawn:

- The EN standards are more conservative than AREMA standard for the design of different slab track systems.
- The eccentricity loading cases of AREMA and EN must be taken into consideration in slab track design, specially, in case of studying the replacement soil thick-

ness and properties. The most critical case of loading for slab track design is A2 (Dead load + Cooper E80 + impact + ecc) from AREMA specifications and E2 (Dead load + LM71 + impact + ecc + α) from EN specifications.

- Rail deflection is the most effective criteria for designing slab track systems for EN specifications. However, the subgrade vertical stress is the most vital factor for AREMA specifications.
- The bending moments in the R.C. slabs (CBL) of the most common slab track systems (BÖGL, Shinkansen, and RHEDA 2000) for both AREMA and EN loading cases are less than the cracking moments. Therefore, the required reinforcement steel can be taken as minimum reinforcement steel.
- The standard section of RHEDA 2000 performs better than the standard section of BÖGL and Shinkansen regarding deflection of rails, stresses of rails, and stress of soil layers (i.e., replacement and subgrade soils).
- The proposed design model can be used to design/analysis any slab track system by selecting the most appropriate replacement soil thickness and its properties as replacement soil has a major effect on slab track systems.

Abbreviations

EN	European norms
AREMA	American Railway Engineering and Maintenance of the Way Association
CBL	Concrete bearing layer
HBL	Hydraulic bonded layer
FPL	Frost Protective layer
CAM	Cemented asphalt mixture
V	Train speed in km/h (EN) or mile/h (American)
D_{33}	Diameter of a standard train wheel of 33 inches
D	Diameter of the actual train wheel in inches
γ	Soil unit weight in kNm^3
E	Modulus of elasticity in MPa
C	Soil cohesion in kPa
υ	Poisson's ratio (unitless)
Φ	Angle of internal friction for soils
Disp	Displacement at rail level in mm
$F_{bending}$	Bending stress at rail in kPa
M_{xx}	Bending moment in xx direction at CBL kN.m/m
M_{yy}	Bending moment in yy direction at CBL kN.m/m
$σ_{FPL}$	Vertical compressive stress at the top level of FPL in kPa
$σ_{sub}$	Vertical compressive stress at the top level of subgrade in kPa

Supplementary Information

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Additional file 1: Appendix A-1. Rail displacement for BÖGL slab track (AREMA A2). **Appendix A-2.** Rail vertical stress for BÖGL slab track (AREMA A2). **Appendix A-3.** Bending Moment M_{xx} in slabs for BÖGL slab track (AREMA A2). **Appendix A-4.** Bending Moment M_{yy} in slabs for BÖGL slab track (AREMA A2). **Appendix A-5.** Replacement vertical stresses for BÖGL slab track (AREMA A2). **Appendix A-6.** Subgrade vertical stresses for BÖGL slab track (AREMA A2). **Appendix A-7.** Rail displacement for BÖGL slab track (EN E2). **Appendix A-8.** Rail vertical stress for BÖGL slab track (EN E2). **Appendix A-9.** Bending moment Mxx in slabs for BÖGL slab track (EN E2). **Appendix A-10.** Bending moment Myy in slabs for BÖGL slab track (EN E2). **Appendix A-11.** Replacement vertical stress for BÖGL slab track (EN E2). **Appendix A-12.** Subgrade vertical stress for BÖGL slab track (EN E2).

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Authors' contributions
MHA: conceptualization, methodology, reviewing, and editing. IMA: supervising, reviewing, and editing. AAE: methodology, modelling, interpretation, writing, and editing. MAD: conceptualization, methodology, interpretation, reviewing, and editing. All authors have read and approved the manuscript.

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The author declare that they have no competing interests.

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