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Innovative requirements and evaluation methods for slab track design

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Abstract

With increasing train speeds and reduced time windows for maintenance work, the interest in the application of slab track technology to increase the capacity of high-speed railways has grown. Slab track may still be considered a relatively young technology, but with several different designs available on the market. Current research on slab tracks commonly focuses on improved methods. In contrast, the formulation of requirements, and evaluation towards these, are seldom investigated. In this paper, state-of-the-art simulation models are employed to illustrate and address the needs for innovative requirements in terms of structural integrity and robustness, life cycle cost (LCC) and environmental footprint of new and existing slab track designs. Based on demonstration examples, it is argued that current standards may lead to overly conservative designs inducing higher LCC and environmental footprint than necessary. Extensions of the standards in terms of LCC and environmental footprint are suggested. The conflict of interest between structural integrity and robustness, LCC and environmental footprint is discussed, and suggestions for how to optimise slab track structures are proposed.

Keywords: Slab track, structural design, requirements, life cycle analysis, life cycle cost, ballastless track.

1. Introduction

Traditionally, ballasted track has been the dominating railway track design. However, track requirements – in particular related to maintenance requirements – have become more difficult to meet with increasing axle loads and train speeds. For high-speed applications on new railway lines, the use of slab track over ballasted track has increased [1]. In general, compared to ballasted tracks, slab tracks require less maintenance work, offer higher lateral track stability and eliminate problems with ballast degradation. The main drawbacks of slab track include higher installation costs and increased emission of air-borne noise.

Slab tracks are often assumed to require little maintenance. If maintenance work on slab tracks is yet required, e.g. due to differential settlement or a foundation washout, it is often very extensive and costly.

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Thus, to minimise the risk of slab track deterioration that would require maintenance, the tracks are usually built as robust structures including several thick layers of concrete, and the requirements on the supporting foundation are rigorous to ensure that operating train speeds are well below the speeds of wave propagation in the soil. When slab tracks are designed in this fashion, there is a risk of ending up with an overdesigned solution for the track superstructure that is undesirable from life cycle cost (LCC) and environmental points of view. This motivates the search for optimised slab track designs, which may include both structural optimisation and the usage of alternative materials [2, 3]. However, before a new type of slab track can be approved, it must be ensured that the optimised solution provides substantial LCC and environmental benefits and that these do not come at the cost of reduced reliability and/or safety. To this end, clear requirements and evaluation guidelines are needed. Today, a range of advanced simulation models have been developed, cf. [4–19]. The development has mainly concerned design methodologies and analyses of application scenarios. In contrast, how the developed slab track solutions relate to demands in standards and regulations is seldom evaluated. In addition, current research often focuses on one detailed topic and there is a lack of research articles with a holistic view.

In this paper, the demands on a slab track are discussed in terms of structural integrity, structural robustness, LCC and environmental footprint. By studying these key demands, including the interaction between them, a holistic approach to the development of innovative requirements for slab track structures is established. Furthermore, evaluation procedures are proposed and demonstrated using state-of-the-art simulation models. Here, the simulation results cover two critical load cases that can be related to limit values presented in standards and regulations. Finally, areas that need further research are identified.

2. Structural integrity

Today, requirements for slab track structures are given in the European standards 16432-1 [20], 16432-2 [21] and 16432-3 [22]. The first part covers general requirements, the second part presents more detailed guidelines for the system design, subsystems and components, whereas the third part covers acceptance of slab track structures.

2.1. Demands

In the first part of the series of European standards, see Ref. [20], different areas that need to be taken into account in the design phase are identified. These areas span over different engineering disciplines including civil, structural and electrical engineering. Regarding the structural integrity of slab tracks, it is stated that static/quasi-static, dynamic and exceptional loads should be considered. However, the specified requirements that lead to limit values for different outputs/responses are few. Instead, recommendations are given on how to handle problematic issues such as risk of derailment, different types of loadings and transition zones (including connections to bridges and tunnels).

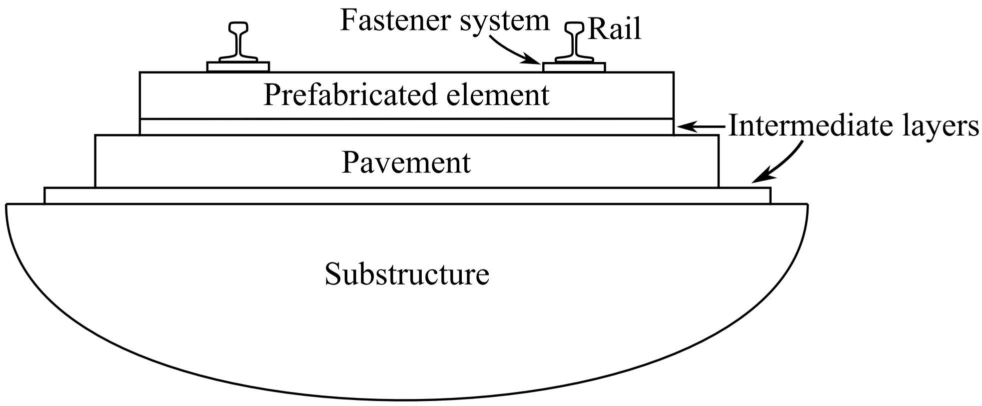


Fig. 1: Schematic cross-section of a slab track structure.

In the second part of the standard series, somewhat more detailed requirements are presented [21]. In particular, the different layers used in the structure are defined and schematically illustrated, see Fig. 1. The upper intermediate layer may work as a boot/fixation and consist of a concrete filling, whereas the lower intermediate layer may consist of a frost protection material. However, it is specified that the sequence of the layers, as well as the presence or absence of any layer or component within the slab track, is up to the individual design.

In EN 16432-2 [21], different types of slab track systems are described. In particular, prefabricated elements are distinguished from the so-called pavement. The pavement consists of one or several continuous layer(s) made of concrete (plain or reinforced), asphalt or a hydraulically bound base layer (HBL). For the pavement, different requirements are set depending on what type of material it is made of. These requirements relate to the most important physical properties, i.e. compressive strength, flexural tensile strength, water/cement ratio, and air void content. Note that the limit values presented in the standard are only recommended values and not strict requirements.

For the development of next-generation slab track structures, it is argued that a clarification of the requirements for structural integrity is necessary. Such requirements should be combined with a robustness analysis, where the impact of realistic imperfections in the vehicle, track and/or soil are considered, see Sec. 3. These requirements for structural integrity and robustness should work as constraints when slab tracks are optimised with respect to LCC and environmental impact, see Secs. 4 and 5.

2.2. Evaluation

To analyse the structural integrity according to the standard, either analytical or numerical tools can be applied [21]. In particular, an analytical calculation method is presented in the standard. This calculation uses static calculations in combination with a dynamic amplification factor (DAF) of 1.5 for the applied

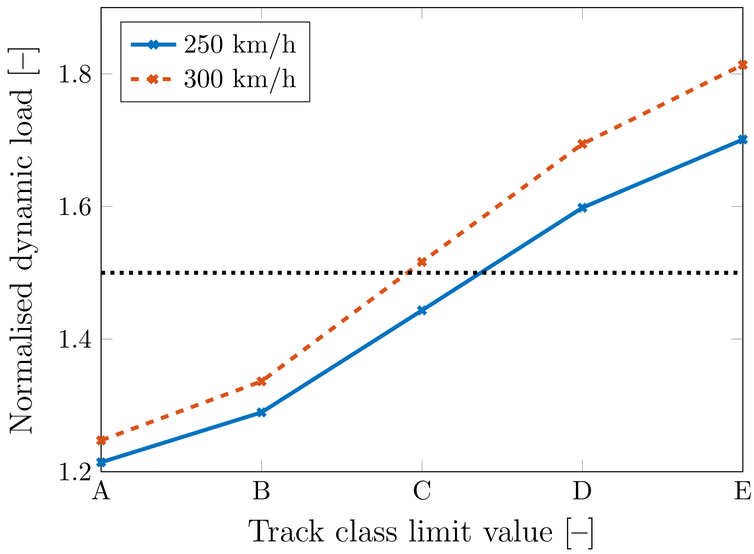


Fig. 2: Numerical example illustrating the ratio between the maximum dynamic wheel–rail contact force and the static wheel load for different track classes and train speeds. The horizontal line indicates the dynamic amplification factor used in the European standard 16432-2 [21]. From Ref. [2].

vehicle loads. However, in reality, the magnitude of these dynamic loads will vary significantly depending on train speed, unsprung vehicle mass, soil conditions, quality of track geometry, etc.

In the standard EN 13848-6 [23], requirements for track geometry are presented. In particular, depending on the evaluated standard deviation of various track irregularities, different track classes are defined spanning from class A to class E. For a given combination of vehicle and slab track design, and based on irregularities in track geometry that resulted in the limit values presented in the standard EN 13848-6, Aggestam et al. [2] applied a model for simulation of dynamic vehicle–track interaction and calculated the ratio between the maximum dynamic wheel–rail contact force and the static wheel load. Both the implementation of the applied simulation methodology and the finite element model of the slab track have been calibrated and validated against measurement data [24, 25]. Based on such simulation results, see Fig. 2, an appropriate DAF can be specified. In this example, it is observed that a lower DAF than 1.5 could be applied as long as track geometry is maintained to a certain track class (and wheel out-of-roundness is controlled).

The types of loads discussed above cover static, quasistatic and dynamic loads. Requirements for exceptional loads will vary depending on the geographical area where the slab track is installed. Typical exceptional loads may be a severe wheel flat, cf. [4], or an earthquake, cf. [5]. Independently of the type of loading, simulations of dynamic vehicle–track interaction should be carried out to assess the resulting track response. Today, there is a wide range of different calibrated and validated models that have been developed to study the structural integrity of slab tracks, cf. [6, 7, 13–16, 25]. By using such models with representative loads and performing subsequent analyses of resulting crack widths, cf. [2], the structural integrity of slab tracks can be evaluated. Such an analysis will be exemplified in Sec. 3.

3. Structural robustness

The service life of a slab track is long, but during these service years, it will degrade. Hence, it is important to investigate the robustness of the track and study how different vehicle/track imperfections would affect the track performance. In such analyses, it is important to treat the railway vehicle, track and subgrade as one integrated dynamic system and investigate how they interact.

3.1. Demands

A disadvantage of slab track compared to ballasted track is the costly maintenance that is required if excessive differential settlements of the railway track should occur. Therefore, strict requirements are usually set on the foundation. These requirements are usually formulated either directly in terms of limit values for the maximum settlement or indirectly by requirements on the stiffness of the different substructure layers. As two examples, a maximum settlement of 12.5 mm over a 20 m chord is used in the Japanese guidelines for slab track structures [17], whereas different limit values of the second deformation modulus (E_{v2}) for the frost protection layer and substructure are suggested in the European standard [21]. In this context (as pointed out above), it is also essential to ensure that operating train speeds are well below the various wave propagation speeds in the soil.

When imperfections are present in the vehicle–track–subgrade system, the dynamic loads on the track are increased. In particular, it is important to make sure that the maximum stress in the rail foot is below the fatigue limit. According to Esveld [26], it was suggested that tensile rail stresses should not exceed 220 MPa. In addition, it is important to limit the crack width in all concrete parts that contain reinforcement in order to avoid corrosion. For prefabricated concrete slabs, a crack width limit of 0.3 mm is typically used based on the requirements presented in Eurocode 2 [27]. In contrast, slightly larger crack widths (0.5 mm) are allowed for concrete pavements. Further, the influence of temperature variations may have an effect on certain track responses, e.g. interfacial stresses [28, 29]. In addition, differential settlement and ground vibrations are important in the evaluation procedure. For slab tracks, differential settlement has been studied by Guo and Zhai [9], whereas work related to ground vibrations is presented for example in Ref. [10].

3.2. Evaluation

In the current study, structural robustness is considered to be governed by the bending stresses in the rail foot and crack widths of the reinforced concrete parts. Similar to the evaluation process for structural integrity, it is recommended to apply models of dynamic vehicle–track interaction to evaluate the loads for which structural robustness needs to be ensured. The track and vehicle models described in detail in Ref. [8] have been adopted in the simulations throughout this paper. Both rails are modelled as Rayleigh–Timoshenko beams elements, while the concrete panels and pavement are modelled as shell elements. Since stresses will be evaluated in this paper, a quadratic shell element was chosen (denoted S8R in Abaqus). If not stated otherwise, train speed and axle load have been taken as 250 km/h and 17 tonnes, respectively.

The calculation of crack widths follows Aggestam et al. [2]. In this approach, simulations of dynamic vehicle–track interaction are combined with a model of reinforced concrete. Based on the study reported in Ref. [2], which included track irregularities but assumed constant soil conditions, it was concluded that the generated crack widths were very small compared to the limit value presented in Ref. [21] if the degree of external restraint was low. Here, an example of an external restraint is prevented movements of the prefabricated element due to the surrounding structures. Further, parametric studies that identified a potential to reduce the thickness of the concrete parts without resulting in unacceptable cracks in the concrete were presented. Reducing the thickness of the concrete parts would drastically reduce the environmental footprint, see Sec. 5.

The reported crack widths in Ref. [2] were calculated using non-symmetric track irregularities (irregularities between left and right rails were assumed to be uncorrelated). However, the study considered a constant bed modulus for the substructure/foundation and perfectly round wheels with no tread irregularities. The crack widths were calculated by initially using a model of reinforced concrete to determine the effective thickness and elastic modulus of the prefabricated element when the section is cracked and shrinkage is taken into account. These parameters were then used in the simulation of dynamic vehicle–track interaction to calculate the maximum bending moment in the concrete parts. In this step, also the influence of the dead weight of the track on the maximum bending moment was considered. Finally, the maximum bending moment was used as input to the model of reinforced concrete to calculate the resulting crack widths. For more information about the model of reinforced concrete and the dynamic vehicle–track interaction methodology, see Refs. [2, 8].

In the first demonstration example in this paper, the imperfection in the vehicle–track system is instead considered to be an irregularity in the substructure in the form of a foundation washout of different lengths. The washout is modelled by reducing the bed modulus of the foundation (substructure, cf. Fig. 1) along the length of the washout, see Fig. 3. Here, the nominal bed modulus $k_\mathrm{f} = 100$ MN/m^3 was reduced to either $k_\mathrm{min} = 0$ MN/m^3 or $k_\mathrm{min} = 50$ MN/m^3. Furthermore, the considered washout lengths, l_wash, were 2.6 m, 5.2 m and 10.4 m which correspond to the length of half a concrete panel, one concrete panel and two concrete panels, respectively.

In the analysed slab track design, the pavement is assumed to be an HBL. For an extreme irregularity in the foundation, such as a washout, there is a risk of generating transverse through-thickness cracks in the HBL which will influence the crack widths in the prefabricated element. Hence, the study presented here includes simulations both with or without the presence of a through-thickness pavement crack. In the simulations that included a through-thickness crack, the crack was assumed to be located in the middle of the washout, where the bending stress due to the dead weight of the track superstructure is the highest.

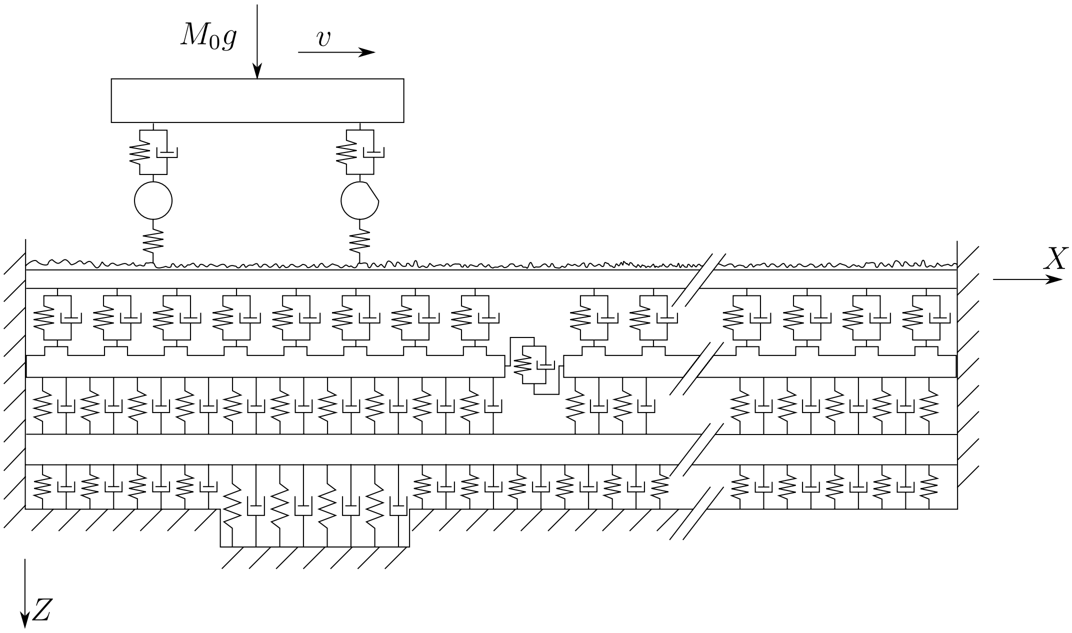
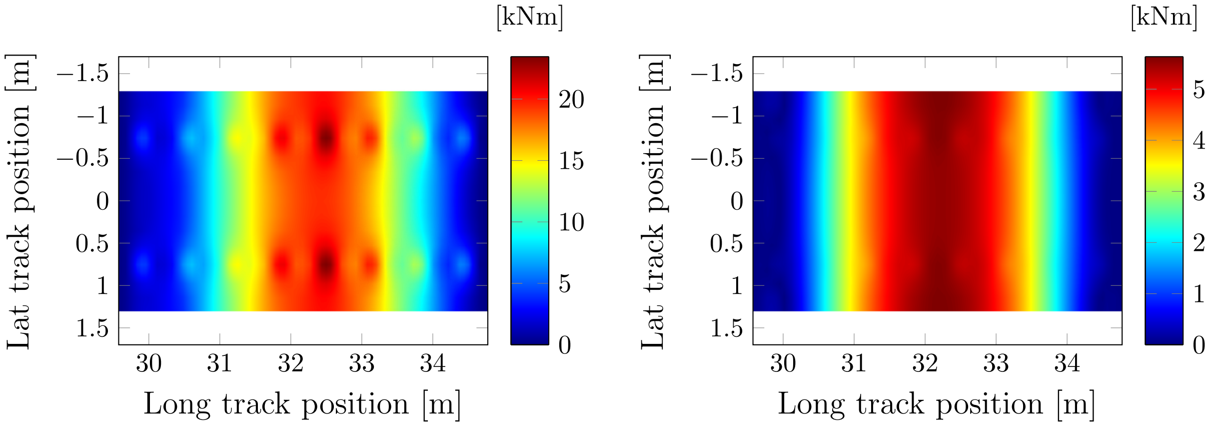


Fig. 3: Principle sketch of track and vehicle models. The considered irregularities, i.e. wheel flat, foundation washout and rail irregularities, are highlighted in the figure.

As an example of the output from the simulation of dynamic vehicle–track interaction, Fig. 4(a) shows the distribution of the maximum bending moment that causes stresses in the longitudinal direction of the prefabricated element when there are no cracks in the pavement. The response was calculated using $k_{\text{min}} = 0$ MN/m^3 and $l_{\text{wash}} = 5.2$ m. The illustrated distribution of maximum bending moment corresponds to the maximum value in each spatial position evaluated over all time instants. From the figure, it is noted that concentrations of the bending moment are found at the locations of the rail seats, where the load is transferred from the rail to the prefabricated element. Also, note that even though the washout is symmetric in relation to the prefabricated element, the response is slightly skewed to the right due to the dynamic vehicle–track interaction (the vehicle travels from left to right in the figure).

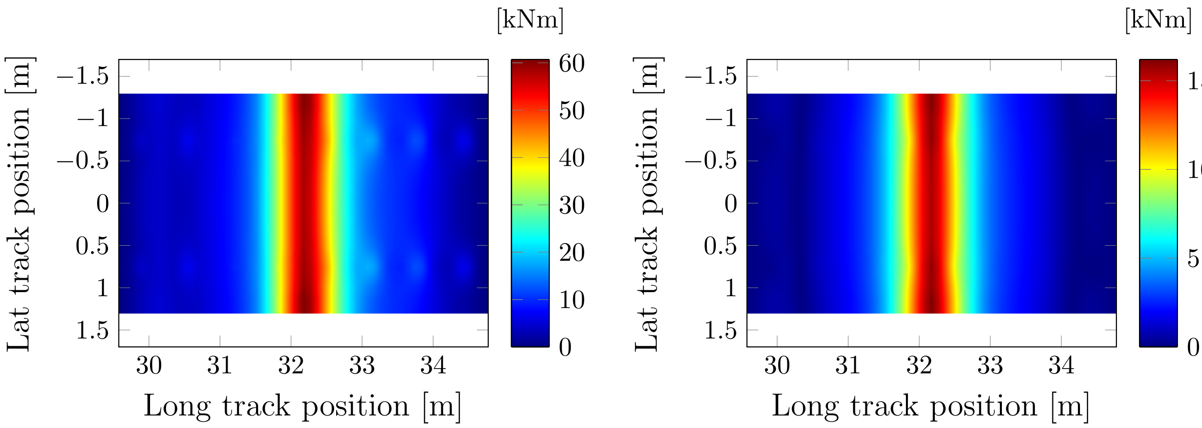
In addition to the dynamic vehicle load, the contribution of the dead weight of the superstructure on the distribution of the maximum bending moment in the prefabricated element has been calculated, see Fig. 4(b). As expected, the response is symmetric with respect to the slab. As long as the track model (including the substructure) can be taken as linear, the contributions from the dynamic vehicle load and the dead weight of the track superstructure can be added using superposition.

In Fig. 5, the corresponding distributions of maximum bending moments when there is a crack in the pavement are shown. Note the different scales in Figs. 4 and 5. As expected, the magnitudes are significantly increased since the cracked pavement cannot carry the load to the same extent as an uncracked pavement.



(a) (b)

Fig. 4: Distribution of maximum bending moment in the prefabricated element (concrete panel) that causes stress in the longitudinal direction from (a) dynamic vehicle load and (b) dead weight of the track superstructure. Response calculated for a foundation washout with $k_{\text{min}} = 0$ MN/m^3 and $l_{\text{wash}} = 5.2$ m. Uncracked pavement.



(a) (b)

Fig. 5: Distribution of maximum bending moment in the prefabricated element (concrete panel) that causes stress in the longitudinal direction from (a) dynamic vehicle load and (b) dead weight of the track superstructure. Response calculated for a foundation washout with $k_{\text{min}} = 0$ MN/m^3 and $l_{\text{wash}} = 5.2$ m. One through-thickness crack in the pavement is located at the centre of the washout ($X = 32.175$ m).

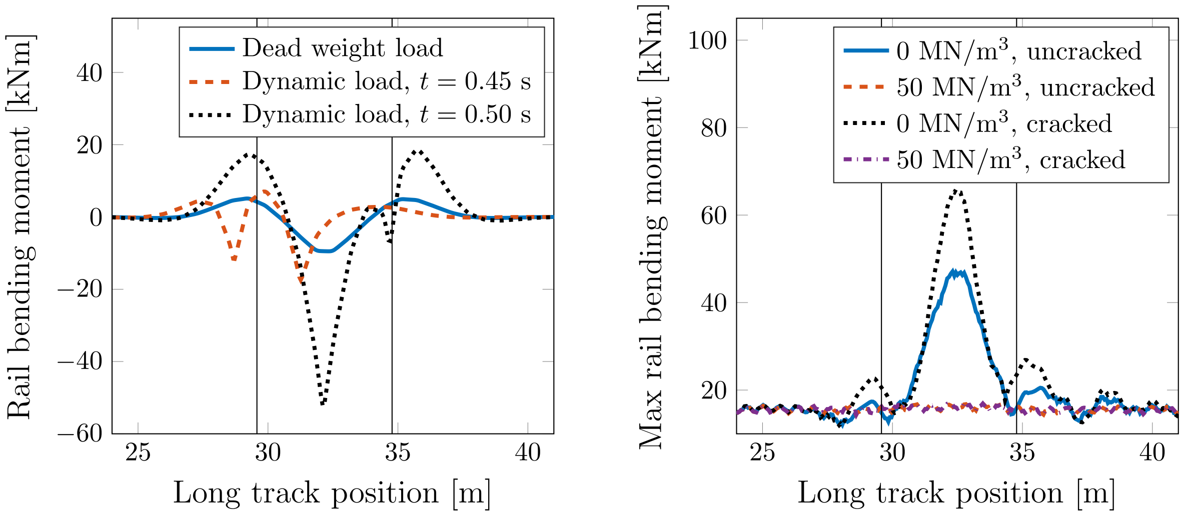
Table 1: Maximum crack width for different lengths and minimum bed moduli of the washout. The pavement is either uncracked or contains one through-thickness crack located at the centre of the washout.

	$l_{\text{wash}} = 2.6$ m	$l_{\text{wash}} = 5.2$ m	$l_{\text{wash}} = 10.4$ m
Uncracked pavement Crack width [mm] $k_{\text{min}} = 0$ MN/m^3	0.012	0.035	0.082
Uncracked pavement Crack width [mm] $k_{\text{min}} = 50$ MN/m^3	0.006	0.006	0.006
Pavement crack Crack width [mm] $k_{\text{min}} = 0$ MN/m^3	0.025	0.12	0.32
Pavement crack Crack width [mm] $k_{\text{min}} = 50$ MN/m^3	0.006	0.006	0.006

The total maximum bending moment in the prefabricated element has been used as input to the model of reinforced concrete. In Table 1, the predicted maximum crack width is shown for all considered washout configurations. When $k_{\text{min}} = 0$ MN/m^3, predicted crack widths are increased significantly when the length of the washout is increased. This effect is not seen when $k_{\text{min}} = 50$ MN/m^3 since the maximum bending moment for this bed modulus converges to a similar value for all considered washout lengths. By comparing the calculated crack widths with the limit of 0.3 mm according to Refs. [21, 30], it is concluded that only the longest washout with a cracked pavement generated a critical crack width in the prefabricated element.

Since only the extreme event of a 10.4 m washout with $k_{\text{min}} = 0$ MN/m^3 in combination with a cracked pavement resulted in a critical crack width, there seems to be potential for design improvements that would reduce the LCC and LCA of the track design, see Secs 4 and 5. One of the parameters that affect the crack width the most is the design of reinforcement. In this paper, a reinforcement bar diameter of 20 mm and a reinforcement spacing of 14 cm were considered since these values are used in the calculation example in the European standard 16432-2 [21]. However, from the calculations above, it is concluded that there is a potential to use fewer and/or thinner bars without compromising track performance.

In addition to the crack widths in the prefabricated element, also the bending moment in the rail has been assessed. In Fig. 6(a), the bending moment is shown for one washout configuration ($k_{\text{min}} = 0$ MN/m^3, $l_{\text{wash}} = 5.2$ m and through-thickness crack present in the pavement). In the figure, the bending moment from the dead weight of the superstructure and the dynamic vehicle load at two different time instances are compared. In the second time instance illustrated in the figure, $t = 0.50$ s, the trailing wheelset is directly above the centre of the washout. This was the time step that generated the largest bending moments in the rail. By considering all time steps in the dynamic simulation and superposing the influence of the dead



(a) (b)

Fig. 6: (a) Distribution of bending moment in the rail from the dead weight of the superstructure and from two time instances during the vehicle passage ($k_{\text{min}} = 0$ MN/m^3, $l_{\text{wash}} = 5.2$ m and through-thickness crack present in the pavement). When $t = 0.50$ s, the trailing wheelset is above the centre of the washout, where also the pavement crack is located. (b) Distribution of maximum bending moment when the influence of the dynamic vehicle load and the dead weight load are added using superposition ($l_{\text{wash}} = 5.2$ m). The vertical lines indicate the start and end positions of the considered foundation washout.

weight of the superstructure, the distribution of the maximum bending moment in the rail was calculated, see Fig. 6(b). It is seen that the magnitude of the bending moment in the rail is not affected much when the bed modulus in the washout is halved (from 100 MN/m^3 to 50 MN/m^3). However, when assuming that no foundation support is provided in the washout region ($k_{\text{min}} = 0$ MN/m^3), a significant increase in the bending moment is noted. Similar to the crack widths in the prefabricated element, higher bending moments in the rail are observed when a through-thickness crack is present in the pavement.

From the distributions of the maximum bending moment, the maximum tensile stress in the rail has been calculated using Navier's formula. In Table 2, the maximum tensile stress in the rail has been calculated for all washout configurations. By comparing the values with the proposed limit value of 220 MPa [26], it is noted that only the longest washout generated critical stresses in the rails.

The second demonstration example investigated in this paper is the impact excitation due to a wheel flat. The wheel trajectory was determined by accounting for the curvature of the wheel as described by Wu and Thompson [11]. The relation between initial length, l_{wf}, and depth, d_{wf}, of the new wheel flat was found from the intersecting chords theorem. However, due to the rounding of edges around the wheel flat that develops due to plastic deformation and wear, the length of the wheel flat used in the simulations was increased by 50% compared to the initial length. In Table 3, the predicted maximum crack widths in the prefabricated element are shown for two different wheel flat depths and three different rail pad stiffnesses, k_{rp}. The longer wheel flat led to a momentary loss of wheel–rail contact, whereas the shorter flat remained

Table 2: Maximum rail stress for different lengths and bed moduli of the foundation washout. The pavement is either uncracked or contains one through-thickness crack located at the centre of the washout.

	$l_{\text{wash}} = 2.6$ m	$l_{\text{wash}} = 5.2$ m	$l_{\text{wash}} = 10.4$ m
Uncracked pavement Rail maximum tensile stress [MPa] $k_{\text{min}} = 0$ MN/m^3	58	125	243
Uncracked pavement Rail maximum tensile stress [MPa] $k_{\text{min}} = 50$ MN/m^3	45	45	45
Pavement crack Rail maximum tensile stress [MPa] $k_{\text{min}} = 0$ MN/m^3	69	175	277
Pavement crack Rail maximum tensile stress [MPa] $k_{\text{min}} = 50$ MN/m^3	46	45	45

Table 3: Maximum crack width in the prefabricated element for different combinations of rail pad stiffness and wheel flat depth.

	$k_{\text{rp}} = 34$ kN/mm	$k_{\text{rp}} = 100$ kN/mm	$k_{\text{rp}} = 200$ kN/mm
Crack width [mm] $d_{\text{wf}} = 0.1$ mm	0.006	0.008	0.010
Crack width [mm] $d_{\text{wf}} = 0.3$ mm	0.006	0.009	0.011

in continuous contact with the rail. Note that the lowest considered rail pad stiffness ($k_{\text{rp}} = 34$ kN/mm) corresponds to the value obtained from a previous calibration of the employed slab track model versus measurements [25]. The main reasons for the small crack widths generated by the wheel flat are the short duration of the dynamic impact load and the dynamic decoupling between rail and prefabricated element which occurs because the rail pad acts as a dynamic filter blocking high-frequency excitations. The effect of the dynamic decoupling is smaller with stiffer rail pads. Therefore, maximum crack widths for (in slab track uncommon) stiffer rail pads have also been investigated. From Table 3, it is found that crack width increases as rail pad stiffness is increased. All crack widths are, however, well below the crack width limit of 0.3 mm.

As a complement to the crack width analysis, the maximum tensile stress in the rails has been determined, see Table 4. When using the softer rail pad, the rail stress is increased. Nevertheless, none of the considered combinations of wheel flat depth and rail pad stiffness generated stress levels above the 220 MPa limit.

Table 4: Maximum rail tensile stress for different combinations of rail pad stiffness and wheel flat depth.

	$k_{\rm rp} = 34$ kN/mm	$k_{\rm rp} = 100$ kN/mm	$k_{\rm rp} = 200$ kN/mm
Rail maximum tensile stress [MPa] $d_{\rm wf} = 0.1$ mm	51	42	37
Rail maximum tensile stress [MPa] $d_{\rm wf} = 0.3$ mm	78	67	59

4. Life cycle cost

The life cycle cost (LCC) of a slab track structure is key if it is to be considered a competitive track design.

4.1. Demands

In an LCC analysis, all major costs should be included. However, the initial investment cost, maintenance costs, and discount rates are typically those that are the most important. The initial cost for building a slab track varies significantly depending on the type of slab track design considered. The ratio in cost compared to ballasted track has been reported to range from 1.0 to 3.0 [1]. For prefabricated slab track systems, which is the most widespread slab track solution, the initial cost ratio compared to ballasted track ranges from 1.3 to 2.0. In terms of maintenance costs, Shiau et al. [31] state that the maintenance cost of slab track is approximately 10% of the maintenance cost of a ballasted track. However, the maintenance cost varies significantly between different sites, and Ando and Sunaga [32] concluded that the maintenance cost of the Sanyo Shinkansen slab track line was 25% of the maintenance cost for a ballasted track.

Today, the consensus is that slab tracks are (compared to ballasted tracks) more expensive to build, but cheaper to maintain. For next-generation slab track designs, well-defined LCC models should be defined. This is missing in current standards [20, 21]. In these models, all costs for building and maintaining the track should be included. Further, if less material is used to reduce the environmental footprint, see Sec. 5, the corresponding risks of increased maintenance and resulting costs need to be assessed.

4.2. Evaluation

Although the decision of whether building slab track or ballasted track has major economic (as well as other) consequences, published studies describing all the decisions made including assessments of the costs are limited [12, 33]. Furthermore, LCC analysis comparisons between ballasted track and slab track (if such would exist) are not transferable in general terms since the outcome of such analyses would vary with topography, climate, operational conditions, discount rate, etc. [33, 34].

Today, the number of LCC models related to slab track seems to be limited, cf. [35–37]. In order to be able to compare different slab track solutions, it is recommended that the same LCC model is applied, similar to the application of the same analytical calculation method for structural integrity as suggested in the European standard [21]. Even though there are uncertainties in all LCC analyses, at least a qualitative comparison between the different systems would then be possible.

Three key issues that strongly affect the result of an LCC calculation are (i) the selection of discount rate, (ii) the definition of time horizon of the infrastructure project, and (iii) the evaluation of the residual value of the investment [34, 38]. Based on the concluding technical report from the European project Innotrack [34], it is suggested that discount rates from $3-5\%$ should be considered. Regarding the definition of the time horizon of the project, $30-40$ years is typically used for ballasted track. For slab track structures, longer times should most likely be used. In the employed LCC model, it should be clear which time horizon has been adopted. Finally, the residual value is considered as a liquidation value of the project and should include the discounted value of all expected net revenues and costs after the planned time horizon.

It is inevitable that an LCC analysis includes a lot of uncertainties and unknown parameters. The impact of such uncertainties can, however, be assessed with a probabilistic approach [34, 38]. This approach is initiated by identifying the technical and economical uncertainties. The impact of the unknown parameters on the net present value (NPV) is then analysed using a simple sensitivity analysis. Based on the results of this analysis, the most important parameters are selected. For these parameters, the associated probability density functions are defined, and a more detailed analysis can be conducted for example using Monte-Carlo simulations.

In future evaluations of slab track structures, detailed LCC analyses need to be carried out. In particular, clear and standardised documentation of all assumptions and parameters is required to obtain a transparent analysis and achieve comparable results. This can preferably be obtained using a so-called In/Out frame, where it can be identified which cost elements a certain innovation and/or modification affects [34].

The classic LCC phases contain: (i) concept and definition, (ii) design and development, (iii) production, (iv) installation, (v) operation and maintenance, and (vi) disposal [39]. In this paper, the selected slab track design to be assessed is assumed to be ready for production/installation meaning that the costs related to concept, definition, design and development can be neglected. Hence, the cost function used to minimise the LCC from a slab track structure can be formulated as

$$f_{\mathrm{LCC}}(\boldsymbol{x}) = x_{\mathrm{s}}C_{\mathrm{s}} + x_{\mathrm{c}}C_{\mathrm{c}} + x_{\mathrm{r}}C_{\mathrm{r}} + y_{\mathrm{m}}C_{\mathrm{m}} + z_{\mathrm{d}}C_{\mathrm{d}}, \tag{1}$$

where x_{s}, x_{c} and x_{r} are the total amounts of rail steel, concrete and steel reinforcement (in kg), C_{s}, C_{c} and C_{r} are the corresponding costs per kg, y_{m} is the total amount of hours for maintenance, C_{m} is the cost per hour, z_{d} is the track length that shall be disposed at the end of its life, while C_{d} is the cost of track disposal per metre. When the data for the cost function is determined, it is important to take the discount rate into account, e.g. using the NPV [40].

In the cost function defined above, it should be noted that installation costs, e.g. costs related to substructure treatment (soil strengthening), are not included. The main reason for this is that such properties – and in particular how they differ between different track configurations – are difficult to estimate. However, for an optimised slab track design, which would most likely be lighter than most designs used today, it is assumed that installation costs would not be higher than costs used today.

Based on the cost function in Eq. (1), an optimisation problem can be formulated as

$$\begin{aligned} \min\ & f_{\text{LCC}}(\boldsymbol{x}), \\ \text{subject to } & \boldsymbol{x} \in S,\ \boldsymbol{g}_{\text{LCC}}(\boldsymbol{x}) \leq \mathbf{0}, \end{aligned} \tag{2}$$

where $\boldsymbol{x}$ are the design variables and S is the design space. The design variables consist of selected parameters that are assumed to significantly increase the performance of the track. The multivariable constraint function $\boldsymbol{g}_{\text{LCC}}(\boldsymbol{x})$ consists of constraints that need to be fulfilled for the design to pass the demands related to the structural integrity, structural robustness and LCA, see Secs. 2, 3 and 5.

5. Environmental footprint

Based on one of the most recent reports from the Intergovernmental Panel on Climate Change [41], it is concluded that climate change in the world is widespread, rapid and intensifying. To change this ominous trend, strong and sustained reductions in emissions from CO_2 are required. For this reason, and due to the fact that both concrete and steel are commonly related to large CO_2 emissions, the environmental assessment presented here is limited to an analysis of CO_2 emissions. Other environmental challenges related to slab track include noise [42] and ground vibrations [10].

5.1. Demands

Based on the sustainability section in the European standard [20], CO_2 emissions are indicated as one of the most important parameters. However, no emission limits are defined. Instead, it is stated that an assessment of the sustainability performance should be undertaken when required. In which situations such an assessment is required is, unfortunately, not specified in the standard.

In this paper, stricter requirements for the environmental footprint of slab tracks are proposed. All designs should report estimated values for the CO_2 emissions per metre track and year. Today, most designs use similar rails, but there is a significant potential for reduced CO_2 emissions in terms of the dimensions of the (reinforced) concrete parts, the type of concrete and the amount of reinforcement. In particular, some designs employ two layers of reinforced concrete. This type of design induces significantly larger emissions compared to a design that uses one layer of reinforced concrete in combination with an HBL [43].

From an environmental point of view, the traditional design of using rectangular concrete parts (prefabricated elements and pavement) is most likely not optimal. As an alternative, structural optimisation can be used to minimise the environmental footprint of slab tracks by only using reinforced concrete where it is structurally most effective [3]. However, when introducing alternative designs with less environmental impact, it needs to be verified that these designs pass the requirements in terms of LCC, structural integrity and robustness. In particular, if there is a risk of additional maintenance activities for a design, the (environmental) impact of such activities should also be reported and considered.

5.2. Evaluation

To evaluate and/or measure the environmental impact, all main stages of the track life need to be considered, i.e. construction, maintenance and end-of-life [44]. Thus, a life cycle analysis (LCA) perspective is typically employed. From several previous works, cf. [43–45], it has been concluded that end-of-life activities, i.e. track dismantling, transport and disposal, and maintenance activities, i.e. rail grinding, are only a small part of the overall emissions for slab tracks. Hence, in order to significantly reduce the environmental footprint, the main focus should be on the design and construction of new tracks and track renewal.

If the scope is limited to CO_2 emissions, it can be concluded that the production of rail steel, concrete and reinforcement is responsible for the major part of the emissions [43]. Since the production of rail steel is one of the dominating emission sources, a significant CO_2 saving would be obtained if the service life of the rails could be extended or if rail designs with less environmental impact could be used. However, rails have already been optimised for several decades, which implies that the possibilities for further improvements in the geometrical design are limited.

On the other hand, it is argued that the concrete parts (including reinforcement) have great potential for further optimisation [3]. The environmental footprint from these parts can be reduced in different ways, where the most promising methods include different kinds of structural optimisation. These optimisations include (i) using material where it is structurally most effective, (ii) prestressing, and (iii) employing steel-fibre reinforcements.

Optimisation with the objective to minimise the environmental footprint from slab track is a research area with very few publications up to now. In one of the few published papers, the CO_2 emissions from the concrete parts of the slab track were minimised with the constraint that the design must pass the European standard [2, 21]. In the optimisation problem presented in Ref. [2], the type (and quality) of concrete in the prefabricated element and the height and width of each rectangular concrete part were included as design variables. By extending the presented optimisation procedure to include non-rectangular cross-sections in combination with prestressing and steel-fibre reinforcement, there is a great potential to reduce the environmental footprint of next-generation slab track structures even further.

The optimisation problem used in the evaluation process related to the environmental footprint can be written as

$$\begin{aligned} &\min \ f_{\mathrm{LCA}}(\boldsymbol{x}), \\ &\text{subject to } \boldsymbol{x} \in S, \ \boldsymbol{g}_{\mathrm{LCA}}(\boldsymbol{x}) \leq \mathbf{0}, \end{aligned} \tag{3}$$

where the design variables, $\boldsymbol{x}$, and the design space, S, were defined adjacent to Eq. (2), while $f_{\mathrm{LCA}}(\boldsymbol{x})$ is a function used to calculate the CO_2 emissions. The multivariable constraint function $\boldsymbol{g}_{\mathrm{LCA}}(\boldsymbol{x})$ consists of constraints that need to be fulfilled for the design to pass the demands related to the structural integrity, robustness and LCC, see Secs. 2–4.

Based on the general optimisation problem presented in Eq. (3), limitations need to be established in terms of which variables should be included as design variables and what track responses are included as constraint functions. For different slab track designs, different design variables may need to be investigated to achieve maximum effect. Thus, it is suggested that manufacturers of slab tracks should be free to choose which variables to include. However, simplifications regarding how the amount of CO_2 emissions, f_{LCA}, is calculated should be reported. Similar to the cost function related to LCC, f_{LCA} can be written as

$$f_{\mathrm{LCA}}(\boldsymbol{x}) = x_{\mathrm{s}}E_{\mathrm{s}} + x_{\mathrm{c}}E_{\mathrm{c}} + x_{\mathrm{r}}E_{\mathrm{r}} + y_{\mathrm{m}}E_{\mathrm{m}} + z_{\mathrm{d}}E_{\mathrm{d}}, \tag{4}$$

where E_{s}, E_{c} and E_{r} are the emissions per kg rail steel, concrete and reinforcement, E_{m} is the emissions due to maintenance activities per hour and E_{d} is the emissions of disposal per metre. In agreement with previous studies, cf. [44], all major contributions are taken into account in this simplified cost function.

Based on previous research, it has been shown that the cost function defined in Eq. (4) is dominated by the first three terms [43]. As discussed above, it is probably difficult to use less rail steel. However, for the concrete parts, there is great potential to reduce the environmental footprint. As an example, in a comparison between an (in theory) environmentally optimised slab track design and a commercially used design, it was shown that the emissions from the concrete parts could be reduced by 44% [43].

Since there may be a conflict of interest between the optimisation problems formulated in Eqs. (2) and (3), it is possible to construct a multiobjective optimisation problem where both objective functions are included and minimised simultaneously. From the solution of such an optimisation problem, the trade-off between the functions can be illustrated using non-dominated fronts [46, 47].

Finally, it can be noted that this methodology can be employed to compare different slab track solutions, e.g. for tender evaluations. In this case, the cost functions are evaluated for the different designs, but no optimisation is carried out. Note that such an evaluation needs to quantify environmental footprint in economical terms. In other words, a relation between f_{LCA} and f_{LCC} needs to be established.

6. Conclusions

In this paper, refined requirements and evaluation procedures for slab track structures have been presented, demonstrated and discussed. The requirements covered structural integrity and robustness of the track design, life cycle costs (LCC), and environmental footprint (here limited to CO_2 emission analyses). The analyses have been demonstrated by the application of relevant state-of-the-art models. As an example, it was shown that the evaluation of the structural integrity and robustness of the track design can be improved by applying representative wheel–rail contact loads from simulations of dynamic vehicle–track interaction and calculating the dynamic response of the track using validated models (instead of applying a traditional static calculation procedure with a dynamic amplification factor).

The evaluation process of structural robustness of slab tracks has been extended by calculating critical track responses for load cases previously not considered. In particular, a methodology to study dynamic–vehicle track interaction was combined with a model of reinforced concrete to assess the influences of a washout (loss of foundation material supporting the superstructure over an extended track length) and a wheel flat. From the analyses, it was found that crack widths generated in the reinforced, prefabricated element due to a wheel flat impact were small due to the short duration of the impact and the dynamic decoupling of rail and prefabricated element by the soft rail pads. In contrast, larger crack widths in the prefabricated element were obtained for a washout irregularity. For the investigated slab track structures, the maximum crack widths were well below the threshold value of 0.3 mm [21, 30] for most of the studied washout configurations. However, in the extreme scenario of a long washout (10.4 m) with no foundation support over the washout length and a cracked pavement, a crack width above the limit value was found. The maximum tensile stress in the rail was below the limit value of 220 MPa [26] for most studied load cases. Also in this case, the exception was a long washout in combination with no support from the foundation over the washout length. Since only the most extreme scenarios generated critical track responses, there seems to be a strong potential to use less material in designs to further reduce LCC and the environmental footprint of a well maintained slab track.

How to optimise the structure with respect to LCC and environmental footprint while ensuring structural integrity and robustness has been outlined in the paper. When LCC and environmental impact are evaluated before the construction of a new track section, there is often a limited number of track designs that need to be considered. By using the methodologies presented in this paper in a comparative fashion, the best solution can then be determined.

In the formulation of requirements for structural integrity, structural robustness, LCC and environmental footprint, there is a conflict of interest that needs to be addressed: From an environmental point of view, as little material as possible should be used. However, using less material might be non-beneficial considering the structural performance and possibly also the LCC. Thus, for the design of next-generation slab track solutions, it is argued that multi-objective optimisation procedures should be applied where the environmental footprint and LCC are minimised while requirements for structural integrity and robustness are used as constraints.

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