Extended abstract

Contributing to the study of ballastless railway tracks

Behaviour of the concrete slab due to traffic and temperature loads

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ABSTRACT

The present dissertation seeks to make a contribution towards research into railway transport on ballastless tracks. This correspondingly develops a finite element tool to study the Rheda 2000 system in terms of the cracking of its concrete slabs under the combination of actions stipulated by the Eurocode as limit states. This seeks to reach conclusions about the effects of temperature, combined with the actions of trains, on the structural behaviour of the concrete slab. This analysis also covers the influence of the expansion joints, the application of transversal prestressing and the number of load cycles prior to reaching fatigue failure.

1. INTRODUCTION

Even though “Slab Track” research has been ongoing now for several decades, the structural behaviour of this type of infrastructure is still clearly under development (Matias, 2014). This thesis pays particular attention to the actions of temperature given that authors in the literature consulted make frequent reference to the need for more detailed research findings (Song, Zhao and Zhu, 2014; Zhu and Cai, 2014).

The study of concrete slab behaviour in ballastless systems was proposed by Instituto Superior Técnico Civil Engineering Master’s Degree as the subject for student’s dissertation. This correspondingly aims to evaluate the responses of these slabs to the effects of temperature while acting and train loads simultaneously. Hence, a numerical tool was developed in order to enable analysis of how such concrete slabs respond to the impacts of various combinations of actions so as to reach conclusions on the behaviour of concrete slabs and their deterioration over the long term.

2. THE “SLAB TRACK” BASED RAILWAY TRACK SYSTEM

In what regards the “Slab Track” system, there are various alternatives currently in operation (Gautier, 2015). Initially, the construction process was bottom up on placing the sleepers directly over a continuous concrete slab. However, following progress in research, in technology and the accumulated experience, there was the increased incorporation of structural components, with the sleepers then embedded in the slab itself with the geometric quality of the track guaranteed by the fixation systems, i.e. a top down approach (Gautier, 2015).

2.1. Benefits and drawbacks

Throughout various decades of research and data gathered on sections of track already applying this technology, various benefits and drawbacks have been identified in comparison with classic ballasted tracks. However, some of these points constitute no more than predictions or expectations due to the limited number of systems operating for any extended periods of time. Thus, the characteristics were divided into two categories in accordance with their level of recognition by the scientific community.

Table 1 – "Slab Track" system advantages and disadvantages.

Scientific recognition	**Advantages**	**Disadvantages**
Cited by the majority of authors consulted – greater relevance and reliability	Without the need for frequent geometric correction	Troublesome in case of the need for geometric correction
	Reduced frequency of maintenance requirements	High level of initial investment
	Greater track stability, which leads to greater passenger comfort (especially at high speeds)	Vibro-acoustic problems
	Reduction in the cost of tunnels and bridges	Problems related to the “Slab Track” transition to a ballasted track
	Enables the circulation of emergency vehicles – of particular relevance in tunnels	--
Cited by some authors – lesser relevance and/or reliability	Fewer periods of track closure – better operational performance	Reduced capacity for geometric correction
	Greater lateral resistance, enabling higher speeds on curves	Drainage problems
	Longer life cycles	Need for additional components to ensure the elasticity required
	Reduced sensitivity to small settlements	Requires high quality ground surfaces (or additional work to obtain them)

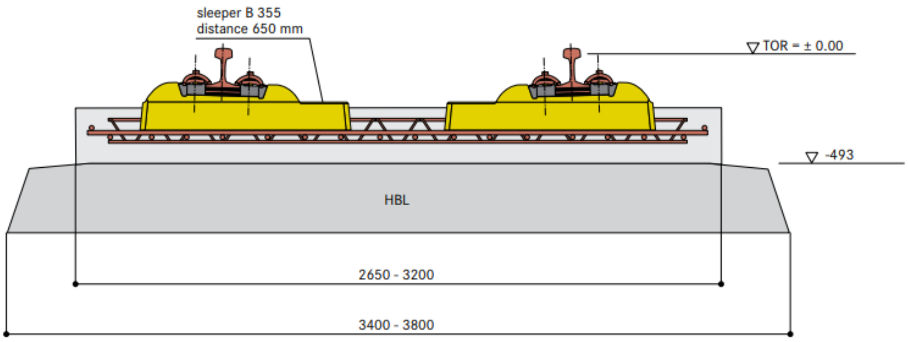
Adapted from (Steenbergen, Metrikine and Esveld, 2007; Giannakos and Tsoukantas, 2009; Shengyang and Chengbiao, 2011; Michas, 2012; Ižvolt and Šmalo, 2014; Matias, 2014; Poveda *et al.*, 2015; Giannakos, 2016; Ren *et al.*, 2016)

2.2. *Rheda* System

Concerning the behaviour of concrete slabs subject to different actions (instantaneous and long term), especially to temperatures (uniform and differentiated) and loads applied to the rails, it was decided to study the Rheda 2000 system. This system, even while one of those most commonly deployed worldwide, needs continuous research in order to deal with increasingly demanding challenges, especially in terms of climate change for temperature loads.

Right from the building of the first stretch in 1972, this system has undergone successive alterations in order to adapt to the specific constraints of respective different projects. Through its most recent version, Rheda 2000, this system has maintained the original principles for which it was first developed. This applies a uniform but highly adaptable architecture to various types of substructure. This is a commonly adopted system given its appropriate performance standards that themselves reflect the vast knowledge and experience built up about Rheda (Michas, 2012).

Figure 1 - *Rheda 2000 system*,



(Rail.One, 2000)

3. MODELLING SLAB TRACK

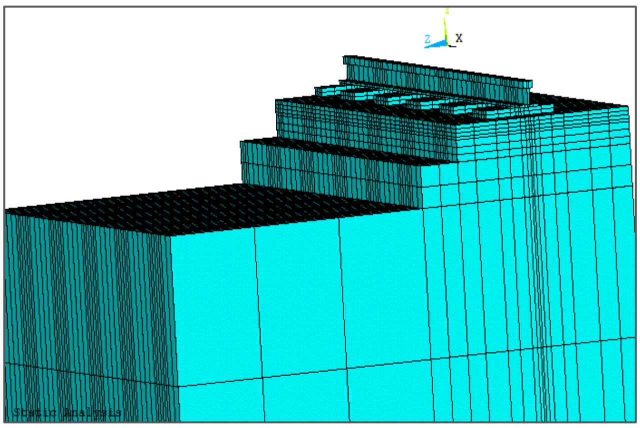
Finite element models enable approaches to complex structures through the provision of basic analytical methods for resolving problems of various natures, including the effects of temperatures or structural fatigue caused by cyclic actions (Shengyang and Chengbiao, 2011).

The finite element software adopted for this study was *ANSYS™* [1], which enables the undertaking of static and dynamic structural analysis whether in linear or nonlinear approaches. Furthermore, the APDL[2] function of this software provide for a step wise approach in the error correction process while it also eases changes to the model properties.

The model simulates the behaviour of the following elements (from the top downwards the foundations):

1. Track;
2. Shock absorption layer;
3. Concrete sleeper;
4. Concrete slab (including longitudinal and transversal reinforcement);
5. Hydraulic binder layer;
6. Foundation.

Figure 2 - ANSYS™ representation of the modelled elements



[1] The ANSYS™ software is recognized as the world's leading fully integrated computer-aided engineering tools, with advanced technology in the structural area.

[2] APDL stands for ANSYS Parametric Design Language and consists of a scripting language able to automate tasks (https://www.sharcnet.ca/Software/Ansys/16.2.3/en-us/help/ans_apdl/Hlp_P_APDL1.html).

3.1. Sensitivity analysis and validation

Sensitivity analysis seeks to study the ways in which some parameters influence the number of the model's degrees of freedom and, consequently, the time associated with the convergence of any solution. This reduction impacts on both the time taken for computation and the results obtained, requiring careful analysis of the errors generated.

For this study, two variations were analysed as regards two different parameters:

- Refining the foundation mesh (vertical dimension);
- Foundation depth.

We may conclude that the height of the foundation bears a significant influence on the results obtained and generating a considerably greater influence than the mesh. Hence, and in relation to the computational efforts with the errors generated, it was decided to adoption of a mesh of elements measuring 0.3x1.0 for modelling the foundation with a 4-metre depth.

In order to validate the model developed, the results obtained were compared with those of another study model (Matias, 2014). We may correctly validate the model in question given that, for the same action, the tension and displacement values are both extremely proximate (in the majority of cases, the error is below 1%).

4. DEVELOPING THE SCENARIOS

We developed the scenarios through applying the combination of actions stipulated by Eurocode 0 (CEN, 2005) for building design within the scope of the objective of studying just which slab zones develop the higher levels of stress and the circumstances under which cracking takes place. We also sought to grasp the influence in terms of the positioning of the expansion joints as regards the load point of application, the effects of carrying out prestressing on postponing cracking and the acceptable number of cycles prior to entering into fatigue failure.

4.1. Final and service limit states

Taking into account the aforementioned goal, there is every relevance in establishing the actions, requiring consideration in order to define the scenarios for studying. To this end, authors may take as their design reference the German design code for "Slab Track" design (Liu, Zhao and Dai, 2011) as well as combining the actions stipulated by Eurocode 0.

According to the author (Pingrui, Xueyi and Guan, 2014), in ballastless track systems, in which the slab is not continuous, as happens in the Rheda 2000 case due to the presence of joints, the thermal gradient provides the most unfavourable action. Thus, in the definition of scenarios for studying the service limit state, the main variable considered was only the temperature gradient (TG), thus enabling more expedite analysis.

Table 2 – Scenarios for the combining of actions forecast for final and service limit states

Scenarios	Core variable	LS	Train action (KN)	Action: uniform temperature (ºC)	Action: differential temperature (ºC/m)	Relative joint-load position
1	LM71	ULS	1.5*(LM71)*1	1.5*(+35)*0.6	1.5*(+50)*0.6	Non applicable
2	LM71	ULS	1.5*(LM71)*1	1.5*(-35)*0.6	1.5*(-25)*0.6	Non applicable
3	LMSW/2	ULS	1.5*(LMSW/2)*1	1.5*(+35)*0.6	1.5*(+50)*0.6	Non applicable
4	LMSW/2	ULS	1.5*(LMSW/2)*1	1.5*(-35)*0.6	1.5*(-25)*0.6	Non applicable
5	TU[3]	ULS	1.5*(150)*1	1.5*(+35)*1	1.5*(+50)*0.6	Distant
6	TU	ULS	1.5*(150)*1	1.5*(+35)*1	1.5*(+50)*0.6	Proximate
7	TU	ULS	1.5*(150)*1	1.5*(-35)*1	1.5*(-25)*0.6	Distant
8	TU	ULS	1.5*(150)*1	1.5*(-35)*1	1.5*(-25)*0.6	Proximate
9	TG	ULS	1.5*(150)*1	1.5*(+35)*0.6	1.5*(+50)*1	Distant
10	TG	ULS	1.5*(150)*1	1.5*(+35)*0.6	1.5*(+50)*1	Proximate
11	TG	ULS	1.5*(150)*1	1.5*(-35)*0.6	1.5*(-25)*1	Distant
12	TG	ULS	1.5*(150)*1	1.5*(-35)*0.6	1.5*(-25)*1	Proximate
13	TG	SLS	1*(150)*0.8	0	1*(+50)*0.5	Distant
14	TG	SLS	1*(150)*0.8	0	1*(+50)*0.5	Proximate
15	TG	SLS	1*(150)*0.8	0	1*(-25)*0.5	Distant
16	TG	SLS	1*(150)*0.8	0	1*(-25)*0.5	Proximate

4.2. Influence of the expansion joints

For a continuous “Slab Track” system, without the inclusion of any joints, uniform temperature loads features as the determinant action for structure design. However, whenever opting for ballastless track with modular slab pieces or a continuous system but with the incorporation of expansion joints, as is the case with Rheda 2000, the stresses deriving from bending deformations caused by temperature gradients take on additional importance for design the “Slab Track” (Pingrui, Xueyi and Guan, 2014).

Hence, in order to grasp the effects of the possible occlusion[4] of these expansion joints, a scenario able to take this situation into account was established. It is to be noted that, in occurrences of the occlusion, this only ends up influencing cases in which the temperature variations are positive.

In order to analyse the effects of poor expansion joint performance, as detailed in the paragraph above, was decided to use combinations of actions studied in chapter 4.1 relative to positive temperature variations but now on a slab without modelling the joint.

[3] The term TU stands for uniform temperature.
[4] The term occlusion refers to situations in which the space of the expansion joint fills with some undesirable material that thereby prevents the free volumetric expansion of the slab.

Table 3 – Expansion joint scenarios

Scenarios	Core variable	LS	Train action (KN)	Action: uniform temperature (ºC)	Action: differential temperature (ºC/m)
17	TG	ULS	1.5*(150)*1	1.5*(+35)*0.6	1.5*(+50)*1
18	TU	ULS	1.5*(150)*1	1.5*(+35)*1	1.5*(+50)*0.6
19	TG	SLS	1.5*(150)*0.8	0	1*(+50)*0.5
20	TU	SLS	1.5*(150)*0.8	1*(+35)*0.5	0

4.3. Influence of prestressing

Prestressed cables are used to control concrete cracking in order to ensure a state of compression in the slab that reduces the positive stresses that leads to cracking.

In order to apply this pressure, the analyse was bottom up the methodology applied to the FF Bögl system (Bögl, 2015), which foresees the introduction of 6 prestressed cables in the Z direction (perpendicular to the train movement) with a strength equivalent to approximately 21.5KN each.

However, assuming the correct distribution of cables incorporated into this model, in which the tension is thus distributed uniformly across the elements making up the slab face and thus controlling the development of cracks in the anchorage points, was decided to make recourse to the simplification off assuming a distributed 6-cable strength equivalent to 21.5 KN apiece, per module (each module registers a lateral area, on the X-Y level, of 0.1476m), and hence 875KN/m2.

Table 4 – Study scenario for the influence of prestressed cables

Scenarios	Core variable	LS	Train action (KN)	Action: uniform temperature (ºC)	Action: differential temperature (ºC/m)	Relative joint-load position
24 (C5)	TU	ULS	1.5*(150)*1	1.5*(+35)*1	1.5*(+50)*0.6	Distant
25 (C6)	TU	ULS	1.5*(150)*1	1.5*(+35)*1	1.5*(+50)*0.6	Proximate
26 (C9)	TG	ULS	1.5*(150)*1	1.5*(+35)*0.6	1.5*(+50)*1	Distant
27 (C10)	TG	ULS	1.5*(150)*1	1.5*(+35)*0.6	1.5*(+50)*1	Proximate
28 (C12)	TG	ULS	1.5*(150)*1	1.5*(-35)*0.6	1.5*(-25)*1	Proximate
29 (C17)	TG	ULS	1.5*(150)*1	1.5*(+35)*0.6	1.5*(+50)*1	Without joint
30 (C18)	TU	ULS	1.5*(150)*1	1.5*(+35)*1	1.5*(+50)*0.6	Without joint

4.4. Influence of the fatigue phenomenon on slab cracking

Taking into account how the model representing the Rheda 2000 system includes almost permanent combinations of service limit states, certain conclusions were reached as regards the number of cycles the slab undergoes before entering into fatigue failure. In order to classify as fatigue failure, 50% of the slab needs to display evidence of cracking (Matias, 2016).

Table 5 – Scenarios for studying fatigue

Scenarios	Train action (KN)	Action: uniform temperature (ºC)	Action: differential temperature (ºC/m)
31	150*0.8	0	0
32	0	+35*0.5	0
33	0	-35*0.5	0
34	0	0	+50*0.5
35	0	0	-25*0.5

5. RESULTS OBTAINED

In accordance with the scenarios proposed, the behaviour of slabs in terms of the occurrence of cracking were analysed. In the cases where cracking took place, the load percentage corresponding to the formation of the first crack was registered. The maximum levels of positive tension and the core zone (bottom or top of the slab) of cracking occurrence were listed. The conclusions for the results obtained are set out in chapter 6.

5.1. Cracking for limit states

In accordance with the scenarios proposed, we undertook analysis of the behaviour of slabs in terms of the occurrence of cracking. In the cases where cracking took place, we registered the load percentage corresponding to the formation of the first crack. We also recorded the maximum levels of positive tension and the core zone (bottom or top of the slab) of cracking occurrence.

Table 6 - Results returned by the limit state scenarios

Temperature scenario (+ or -)	Cracking - Load %	SX max (MPa) Top or bottom of slab	SZ max (MPa) Top or bottom of slab
1: ULS (+)	Yes – 57	1.37 – Bottom	2.26 – Bottom
2: ULS (-)	No	1.45 – Top	2.02 – Bottom
3: ULS (+)	Yes – 57	1.37 – Bottom	2.26 – Bottom
4: ULS (-)	No	1.50 – Bottom	2.01 – Bottom
5: ULS (+)	Yes – 70	1.64 – Bottom	2.31 – Bottom
6: ULS (+)	Yes – 67	1.90 – Bottom	2.30 – Bottom
7: ULS (-)	No	1.50 – Top	1.70 – Bottom
8: ULS (-)	No	2.15 – Top	1.80 – Bottom
9: ULS (+)	Yes – 51	2.02 – Bottom	2.35 – Bottom
10: ULS (+)	Yes – 51	1.94 – Bottom	2.28 – Bottom
11: ULS (-)	No	2.18 – Top	1.68 – Bottom
12: ULS (-)	Yes – 70	2.18 – Top	0.95 – Bottom
13: SLS (+)	No	1.50 – Bottom	2.25 – Bottom
14: SLS (+)	No	1.66 – Bottom	2.22 - Bottom
15: SLS (-)	No	0.63 – Top	1.30 – Bottom
16: SLS (-)	No	1.18 – Top	1.05 - Bottom

5.2. Influence of the expansion joint

In order to analyse the influence of the expansion joint on “Slab Track”, specifically in the Rheda 2000 system, the load percentage applied to the model that returned the first crack in the scenarios simulated was extracted. Was also registered the maximum tension verified in the X and Z directions and detailing whether the crack occurs in the bottom or the top of the slab in each situation.

Table 7 - Results on the influence of the expansion joint

Scenario	Cracking – Load % (With joint)	Cracking – Load % (Without joint)	SX max (MPa) Top or bottom of slab (Without joint)	SZ max (MPa) Top or bottom of slab (Without joint)
17 (ULS)	Yes – 0.51	Yes – 41	Compression	2.3 – Bottom
18 (ULS)	Yes – 0.67	Yes – 40	Compression	2.3 – Bottom
19 (SLS)	No	No	Compression	2.2 – Bottom
20 (SLS)	No	No	Compression	1.4 – Bottom
21	-	No	1.3 – Bottom	1.9 – Bottom
22	-	No	1.8 – Bottom	1.9 – Bottom
23	-	Yes – 82	2.3 – Bottom and top	1.64 – Bottom

5.3. Influence of prestressing

In order to study the influence of applying prestressing in the scenarios detailed in chapter 5.1, the increase in the load percentage that leads to the formation of the first crack was removed and the direction in which this takes place so as to conclude what is the conditioning one. This result enables the understanding about whether a possible increase in the prestressed cables would feasibly generate a greater capacity for slab resistance.

Table 8 - Results on the influence of prestressing

Scenario	Cracking – Load % (Without prestressing)	Cracking – Load % (With prestressing)	Increase in load prior to cracking (%)	Conditioning direction (X or Z)
24 (C5)	Yes – 70	Yes – 90	29	Z
25 (C6)	Yes – 67	Yes – 84	25	X
26 (C9)	Yes – 51	Yes – 61	20	Both
27 (C10)	Yes – 51	Yes – 61	20	Both
28 (C12)	Yes – 70	Yes – 68	-	X
29 (C17)	Yes – 41	Yes – 50	22	Z
30 (C18)	Yes – 40	Yes – 50	25	Z

5.4. Influence of fatigue on slab cracking

Through the scenarios developed taking into consideration the almost permanent service limit state, this seeks to register the stresses that the slab is subjected to, through to a maximum value, calculating the number of cycles prior to cracking (according to the criteria explained in chapter 4.4).

Table 9 – Influence of the fatigue phenomenon on slab cracking

Scenario	Action	Cracking – Load %	SX max (MPa)	SZ max (MPa)	No. of cycles before fatigue failure (*10^3)
31	F	No	0.6 - Bottom	1.4 – Bottom	-
32	TU+	No	0.8 – Bottom	1.7 – Bottom	2000
33	TU-	No	1.1 – Bottom	1.5 – Bottom	-
34	TG+	No	1.3 – Bottom	2.2 – Bottom	50
35	TG-	No	1.3 – Top	0.5 - Bottom	-

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

6.1. Conclusions

The core objective of this current dissertation involved studying the behaviour of the concrete slab subject to different actions, especially the trains loads and variations in uniform and differentiated temperatures. Hence, in addition to setting out the state-of-the-art in the literature on this theme, a numerical tool through *ANSYS^{TM}* software was developed, duly validated for subsequent analysis of the effects of the aforementioned actions.

As a result of the analysis carried out, can be conclude that a relationship between raising or lowering the temperature and the direction of the cracking exists**.** In the scenarios simulating an increase in temperature, was found that there are greater levels of stress developing in the Z direction, transversal to the movements of trains while reductions in temperature mean the X direction emerges as a conditioning factor.

As regards the study of the influence of the expansion joints, the results obtained enabled the conclusion that for the cases in which there is joint occlusion, thereby preventing the free volumetric expansion of the slab in the X direction, the first crack is formed at positive temperatures at a 20% to 30% lower level. This also underpinned the confirmation that the larger the continuous span of the beam, the lower the negative module temperature needed to drive the formation of the first crack, with the slab revealing cracking at lengths of 18m and negative temperatures of -43ºC.

This also studied the influence of introducing transversal prestressed cables into the loading necessary to cause the first crack. Following analysis of the results obtained, was able possible to conclude that a prestressed strength equivalent to 875 KN/m^2 enabled increases of between 10ºC and 8ºC/m in the variations in the uniform and differentiated temperatures respectively. Thus, the inclusion of prestressing stands up as a relevant alternative for taking into consideration when scaling ballastless tracks in high temperature climates with the respective study still requiring further analysis.

As regards the long term behaviour of slabs, was concluded that temperature gradient actions trigger serious effects in slabs, thus reflecting an important factor for taking into account when planning ballastless track systems, especially as regards their long term behaviour.

6.2. Future developments

The production of this dissertation rendered very clear the need to further advance studies on the effects of temperature on the structural behaviour of concrete slabs in ballastless track systems, in particular their long term behaviour. With the progress in computational capacities, applying numerical tools holds increasing pertinence, such as finite element programs, in order to study the responses of components as regards the various situations. Taking into consideration the work done, some suggestions regarding future developments are presented:

- Studying the concrete slab response after reaching the point of cracking with the objective of understanding the effects of extreme events on structural cracking. Hence, there is the need to grasp the influence of new reinforcement configurations for the Rheda 2000 system able to control the opening of cracks.
- Making use of dynamic models able to more closely simulate reality, the effect of passing trains, especially in the case of infrastructures carrying high speed trains;
- Analysis of the consequences of the deformations in terms of the substructure, especially the vertical settlements, on the geometric alterations in the superstructure;
- Making use of similar numerical tools in order to analyse other common ballastless track systems.

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