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# A numerical study on the fatigue life design of concrete slabs for railway tracks

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ABSTRACT

With the growing use of high-speed trains, non-ballasted tracks have become more popular compared to ballasted ones. However, the study on fatigue evaluation in concrete slabs under train load has been rather limited. This work presents a numerical study on the fatigue life design of concrete slabs for railway tracks. A finite element model for a three-slab track system is established for extracting the principal vibration modes and transient analysis under time-dependent loads. The fatigue evaluation procedure is first validated against full-scale experiments on slabs carried out in a three-point-bend load configuration under fatigue. Next, techniques in the context of digital signal processing, i.e., random phases combined with each constituent frequency amplitude to generate new load pulses, are employed to obtain the most unfavourable load scenario from numerous measured real-time train loads. A novel fatigue criterion which singles out the significance of stress amplitude (proper to concrete-like materials) is implemented to obtain the critical load direction. Fatigue damage under compression is evaluated under this most unfavourable load situation. Meanwhile, parametric analyses on material strength and slab geometry are carried out, recommendations for improved designs towards fatigue life are given accordingly. Even though the established procedure is demonstrated for fatigue under compression, damage evaluation based on the Model Code, extension to tension or mixed tension–compressive stress evaluations, as well as damage calculations with alternative criterions can be easily implemented.



## 1. Introduction

Slab track, also called ballastless track, is a modern form of track construction which has been successfully used around the world for high speed lines, heavy rail, light rail and tram systems [1–14]. Such a trend is mainly attributed to the fact that slab track systems have numerous structural and operational advantages compared with the traditional ballasted track. For instance, the maintenance cost can be reduced up to 70–90% according to Esveld [2], the possibility of rail buckling is diminished due to the fixed track alignment, higher running speeds are achievable due to the greater lateral and longitudinal track stability [14]. An additional advantage of slab track systems in comparison with the ballasted ones, shown by Sheng et al. [9], is the reduced level of vibration in the presence of vertical track irregularities.

Depending on the spectrum of the train load as well as the running velocity, the dynamic response of a railway track can be significantly larger than its static counterpart. Furthermore, effects such as vertical track irregularities [9,15,16], temperature variations [17,18], or wheel-rail interaction, can all aggravate such a situation. Under such circumstances, a complete dynamic analysis of the slab structure is necessary in order to predict the service life of the constructed track. The dynamic response is, on the one hand, related to the vibration of the entire system (thus noise control and passenger comfort); on the other hand, the fatigue damage within the slab resulted from repeated train load.

Studies on the former are concentrated on the vehicle-track-subgrade coupling [19,20,13,7,18]. For example, Tanabe et al. [19] analysed the dynamic interaction between the Shinkansen train (through multi-body dynamics employing non-linear springs and dampers) and the railway structure (consisting of truss, beam, shell and solid elements). Steenbergen et al. [13] focused on the dynamic response of a slab track system to a running train axle in order to reduce the amplitudes of the slab vibration. By employing a beam on viscoelastic half-space subjected to a moving load, they determined the influence of slab stiffness, slab mass and soil improvement to reduce track deterioration.

As regards the fatigue evaluation in concrete slab tracks, the studies have been rather scant. Even though the interest in the fatigue of concrete began with the development of highway systems in the 1920s [21], fatigue evaluation and constitutive relations in

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concrete have been mainly focused on bridge deck slabs [22–24]. For instance, recently, Sousa et al. [23] carried out fatigue analysis in concrete girder webs subjected to loads induced by railway traffic. However, they concentrated on the particularities of the stress states in reinforced concrete girder webs, where a specific algorithm was designed to consider the combined effects of in-plane shear and transverse bending. Considerably less attention has been paid to the fatigue behaviour under random train loads in the design of the relatively new concrete slab tracks [25,26]. Indeed, after reviewing the different calculation methods, parameters and design theories of the ballastless tracks in the world in comparison with the Chinese slab tracks, Liu et al. [17] singled out fatigue as one of the main fields which need to be further explored.

In this current work, we study the fatigue behaviour of concrete slabs for high-speed railway tracks. These slabs are similar in geometry to the ones employed in the Japanese Shinkansen system, the initiator of high-speed technology. This slab track system is composed of the concrete roadbed (often cast in situ), cylindrical bollards or dowels to prevent lateral and longitudinal movement, precast concrete slabs and a thin layer of cement asphalt mortar (CAM), which is injected afterwards between the in situ roadbed and the precast slabs [2]. Such a system has been selected by a Spanish construction company as the starting point to develop new types of high-speed railway tracks. On the one hand, materials of different characteristics are going to be employed, for instance, the concrete matrix is of higher or lower strength, the steel reinforcement amounts or types are necessarily adjusted, the CAM layer also needs to be correctly engineered; on the other hand, geometric design calls for a systematic procedure to assess the feasibility of the proposed track system. Consequently, both experimental validation and a numerical procedure for fatigue life evaluation are indispensable. Experimental campaign for both material level characterisation and full-scale fatigue tests were carried out as described in [27] for validation. In this current work, we concentrate on the numerical procedure to evaluate the fatigue life of concrete under compression. This is due to the fact that sufficient steel reinforcements in both longitudinal and transversal directions were included in the actual concrete slab to carry all the tensile stresses; furthermore, these tensile stresses in steel only reach a moderate level and would not cause fracture of steel rebars. In addition, we rely on the experimental results for the purpose of validation.

Taking into account what has been mentioned above, we model a three-slab track system, together with its cement-asphalt mortar base, the concrete roadbed and the supporting soil. Then we proceed to extract its modal response and carry out the transient analysis applying a real time train load.

It needs to be pointed out that real train loads can vary significantly depending on factors such as the speed, track or wheel irregularities. We were provided with numerous measured train signals at specific sections of a Spanish high-speed railway. In order to take advantage of this information, detailed signal analysis was carried out to obtain the worst scenario of the possible train loads. First, these signals were scaled in amplitude and time to take into consideration of the real train weight and a constant train speed (300 km/h in this case). Next, the average spectrum is computed to smooth out possible biased information in each measurement. Finally, random phases were incorporated into this average spectrum to obtain a set of random signals in the time domain through the inverse Fourier transform. For the desired reliability of 95%, a minimum of 20 calculations for 20 different signals were performed. The signal that resulted the maximum damage for the most unfavourable node was selected for the global damage evaluation.

It needs to be emphasised, even though this way of processing signals is rather common in the community of digital media [28], but application to the measured train loads is not preceded by any, at least to our knowledge.

Fatigue analysis is performed as the post-processing of the transient response. Since the concrete slab is heavily reinforced, we consider fatigue damage at compressive range is more relevant. Cycle counting is based on the rain-flow algorithm [29].

The rest of the paper is structured as follows: the finite element methodology, which includes the mode and transient dynamic analysis as well as fatigue calculations, is presented in Section 2. Validation against full-scale three-point bending experimental tests, applications to real train loads and geometric design of a real slab based on fatigue damage are unfolded in Section 3. Finally, relevant conclusions are drawn in Section 4.

## 2. Finite element methodology

In this section, we set out to model the slab track superstructure using the ANSYS Parametric Design Language (APDL), a script language to automate common tasks and build complicated finite element models in terms of variables [30]. First, the geometry and boundary conditions of the three-slab system as well as the material characterisation are explained. Then, the procedure for dynamic analysis, in particular, damage accumulation and generation of the most unfavourable train signal are illustrated in detail.

### 2.1. Geometry and boundary conditions

The concrete slab shown in Fig. 1a, is of similar design to that of the Japanese Shinkansen slab track, though the specific dimensions are quite different. Taking advantage of the track line symmetry ($x$-axis), half of the track geometry is actually modelled. In order to reduce the boundary effects, numerical calculations were carried out for three slabs, but only data from the central one were extracted for the posterior fatigue analysis. Neighbouring slabs are separated by a cylindrical bollard to prevent lateral and longitudinal movements. However, the bollards are neglected in the numerical model, since they would induce only small longitudinal stresses in their neighbourhoods within the slab. The slab, the cement asphalt mortar (CAM) layer, the concrete roadbed and the soil sub-base are all discretised as 8-node volumetric elements, see Fig. 1b. The vertical and transversal dimensions for each constituent layer are given in Table 1.

It needs to be pointed out that the Vossloh rail-fastening device [31] has been simplified as a fastening cushion, whose elastic modulus is calibrated with the experimentally measured stiffness. This fastening cushion, made of rubber, 0.35 m in width and 0.45 m in length, is represented as deformable solids, while the fastening mechanism is modelled through connecting the rail inferior nodes to the slab surface below the rubber pad. Meanwhile, no-sliding constraint is imposed between the rubber pad and the slab surface.

The UIC 60 rail cross-section profile, see Fig. 2, is modelled as beam elements (BEAM188) with its proper section. Its dimension and section properties are the known properties for this kind of profile [2]. The cited beam element in ANSYS is well suited for linear, large rotation, it includes shear-deformation effects and provides options for unrestrained and restrained warping of cross-sections (unconstrained warping is used in the current work). Above all, it allows us to input the exact cross-section profile for UIC 60. A rail length of 15.53 m which covers the three-slab track system is modelled and symmetry boundary conditions are imposed on both ends. Such symmetry conditions are equally imposed for the concrete roadbed, CA mortar layer and the soil subgrade. In addition, out-of-plane movements in the soil subgrade are also restricted at the bottom and the two side surfaces parallel to the track line.