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DYNAMICS OF A PRECAST SYSTEM FOR HIGH-SPEED RAILWAY TRACKS

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Abstract. *As far as slab tracks are concerned, UIC [1] considers seven different families of structures, regarding the type of slab supporting (punctual or continuous), the construction method (in situ or precast), the number of resilient levels and also the type of the foundation material (plain concrete or bituminous material).*

This paper begins with a brief description of precast slab systems currently available for high-speed railway lines. A research work on the dynamic behavior of precast slab tracks is being undertaken in order to identify the dynamic effects of high-speed traffic in this type of systems. In this paper some of the results attained so far in the numerical calculations are presented and discussed. Calculations are performed in 2D with the finite element program Ansys, considering several vehicle speeds and also different types of vehicle models. The dynamic response of the track is evaluated in terms of track displacement, force at the fastening systems, bending moment on the slab and also on the support concrete layer. Also the influence of the track foundation and the track geometrical quality on its response is studied.

1 INTRODUCTION

According to the Technical Specification for Interoperability (TSI) relating to the infrastructure [2], there are three types of high speed railways: new lines for speed higher than 250 km/h; specially upgrade lines for speed higher around 200 km/h; new or upgrades lines with technical constraints.

In general, railway tracks can be categorized in ballasted systems and ballastless or slab systems. Nowadays, there are two currents of opinion on the track concept for high speed railway lines. The first one defends the ballasted track -the traditional permanent-way. The second current considers that slab tracks can meet the exigent demands of a modern railway track for high speed lines with reduced maintenance actions.

As far as slab tracks are concerned, UIC [1] considers seven different families of structures, regarding the type of slab supporting (punctual or continuous), the construction method (in situ or precast), the number of resilient levels and also the type of the foundation material (plain concrete or bituminous material), which are:

1. systems without punctual fixing of the rail;
2. systems with punctual fastening of the rail and independent stretches of rail;
3. systems with punctual fastening of the rail on sleepers incorporated in structure by infill concrete;
4. systems with punctual fastening of the rail on sleepers incorporated in structure by vibration;
5. systems with punctual fastening of the rail on sleepers laid and anchored on a supporting structure;
6. systems with punctual fastening of the rail on sleepers separated from supporting structure by a resilient level;
7. systems with punctual fastening of the rail on prefabricated slabs.

Currently commercial prefabricated slabs present a wide variety of dimensions, materials and configurations. These prefabricated slabs may be reinforced or prestressed into which fastening systems and rails are incorporated.

Figures 1 to 3 present the most known precast slabs used in high speed railways lines: the Bogl, the OBB-Porr and the Shinkansen systems.

Figure 1: Bogl system

Figure 2: OBB-Porr system

Figure 3: Shinkansen system

The Bogl system (Figure 1) consists in prestressed slabs in the transversal direction fixed with spindles on a stabilised layer in the earthworks case, on a tunnel base or on a bridge deck [3]. The OBB-Porr system (Figure 2) is a conventionally-reinforced precast concrete slab with two rectangular openings from where concrete is introduced during construction in the site. This concrete block ensures the transfer of forces in the horizontal direction. The joints between adjacent slabs are no filled. The Shinkansen system (Figure 3) is used by the Japanese National Railways and it has provided excellent performance by maintaining track geometry and reducing maintenance costs of the track. The geometrical configuration of this system is more complex than the two previous ones, because of the slab geometry and also because of the existence of stoppers between adjacent slabs. Complete descriptions of these precast systems and others (in situ) slab systems may be found in [1, 3, 4, 5].

2 VEHICLE TRACK INTERACTION MODEL

In general, the simulation of train-track interaction implies that the whole system is divided into two subsystems, the vehicle and the track, and between them a physical wheel-rail contact. Until recently the behavior of these dynamic subsystems were investigated separately but the increase of train speed demands a better understanding of the dynamic phenomena, considering the vehicle and the track together as an unique system. In the present study a time domain methodology is adopted to calculate the interaction forces between the wheel and the rail and the track vibrations, in the vertical direction.

2.1 Vehicle model

Assuming loading to be symmetrically distributed on the two rails, 2D models can be adopted to represent the vehicle, such as the models presented in Figures 4 to 6.

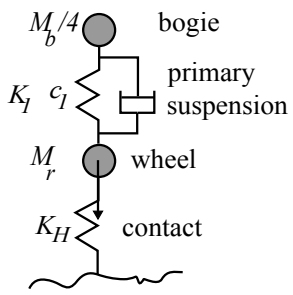

Figure 4: Quarter bogie model

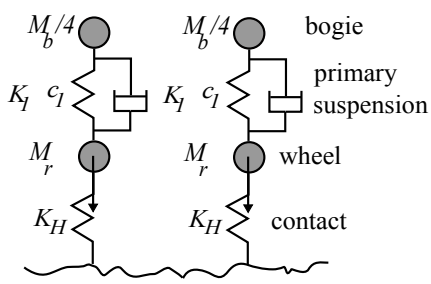

Figure 5: Two independent quarter bogie model

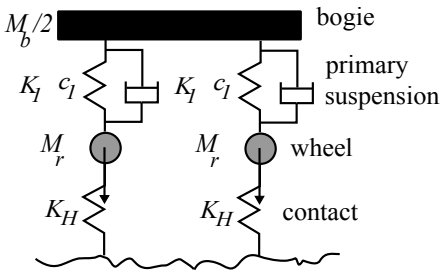

Figure 6: Half bogie model

In all these models, the vehicle is characterized by the wheel and the bogie masses and by the primary suspension represented by a linear spring in parallel to a dashpot. The two independent quarter bogie model (Figure 5) and the half bogie model (Figure 6) allow to consider the superposition of the action of the two bogie axles in the track response. In the half bogie model, the two axles are connected by the bogie, which is more realistic than the two independent quarter bogie model.

2.2 Track model

A rail track is a complex structure and in the case of slab track it is composed by rails, pads, sleepers, slab, concrete support layer and foundation.

To represent the precast slab track in study the model indicated in Figure 7 may be used. The rail is modeled as a continuous beam discretely supported on sleepers. The fastening systems and the pads are represented by springs in parallel with dashpots; theirs masses are disregarded. The slab and the concrete support layer are modeled by plain stress finite elements. The foundation is modeled by distributed springs in parallel to dashpots with no interaction between them (Winker foundation with damping). The joint between adjacent slabs are filled with an elastic material with the same mechanical characteristics of the interface layer between the slab and the concrete support layer.

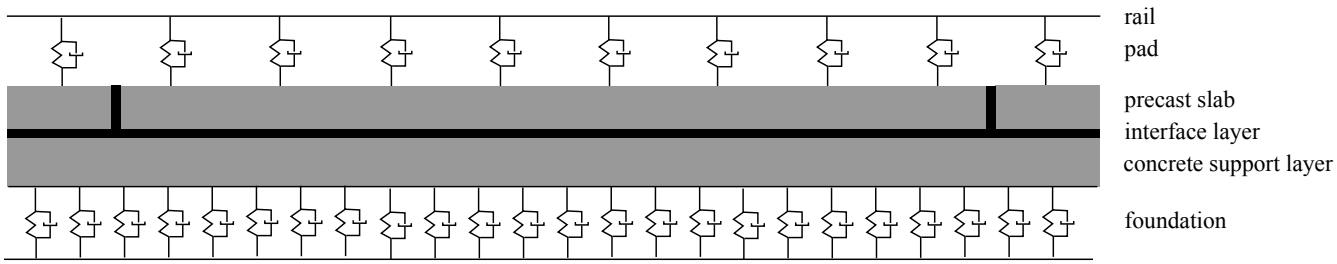

Figure 7: Track model

2.3 Contact model

The contact interaction force between the wheel and the rail is determined by the contact theory. For normal contact between two bodies with no tangential forces and at the contact area, the nonlinear Hertzian model is usually adopted. According to the Hertz model, the interaction

(contact) load is given by Equation (1):

$$F = \begin{cases} C_H(x - y - \overline{r})^{3/2} & \text{if } x - y - \overline{r} \geq 0 \\ 0 & \text{if } x - y - \overline{r} \leq 0 \end{cases} \tag{1}$$

where x is the wheel vertical displacement; y is the rail displacement; $\overline{r}$, the rail profile; C_H, the Hertzian stiffness.

However a linearized model can be adopted when the variation of the dynamic load is not considerable. In this situation, the linearized stiffness can be evaluated by Equation (2):

$$k_H = \frac{dF}{d\delta} = \frac{3}{2} C_H \delta^{1/2} = \frac{3}{2} C_H (F/C_H)^{1/3} = \frac{3}{2} C_H^{2/3} F^{1/3} \tag{2}$$

where: $\delta = x - y - \overline{r}$ is the relative displacement between the wheel and the rail; F is the load adopted for the linearization.

3 NUMERICAL ANALYSIS

In this section of the paper, the dynamic response of a precast tracks is evaluated in order to study:

- the influence of the vehicle model and the train speed;
- the influence of the mechanical characteristics of the interface layer between the slab and the concrete support layer;
- the influence of the track foundation;
- the influence of the slab dimension;
- the influence of the geometrical quality of the track.

The numerical assumptions considered for calculations are:

- 2D track model;
- track composed by 20 slabs;
- segment track in a straight alignment;
- ICE 2 train;
- train speed varying from 200 to 420 km/h in steps of 20 km/h.

In all calculations, except for the analysis of the influence of slab dimension on the track response, the total length of the model is 20×5.15 m = 104.0 m .

3.1 Track and train characteristics

In Table 1, the characteristics of the track are presented. Usually the foundation is characterized by the elastic modulus and the Poisson coefficient. To define the foundation stiffness and damping parameters to include in the track model the methodology proposed by Vale et al. [6] is used.

Component	Type of element	Parameter
Rail UIC 60	Euler Bernoulli beam	$E = 210$ GPa; $I = 3055$ cm^4 ; $\nu = 0.3$; $A_t = 76.84$ cm^2 ; $\rho = 60.34$ kg/m
Pad + fastening system	spring and dashpot in parallel	$k_p = 40$ kN/mm; $c_p = 8$ kNs/m
Prefabricated slab	plain stress finite elements	$E = 34$ GPa; $\nu = 0.2$; $H_s = 0.24$ m; $L_s = 5.15$ m; $W_s = 2.8$ m; $\rho = 2500$ kg/m^3
Interface layer	plain stress finite elements	$E = 300$ MPa; $\nu = 0.3$; $H_i = 0.06$ m; $L_i = 104$ m;
Joint	plain stress finite elements	$E = 300$ MPa; $\nu = 0.3$; $w = 0.05$ m;
Concrete support layer	plain stress finite elements	$E = 10$ GPa; $\nu = 0.3$; $H_c = 0.30$ m; $L_c = 104$ m; $W_c = 3.4$ m; $\rho = 2500$ kg/m^3
Foundation	Winkler foundation	$k_f = 50$ kN/mm; $c_f = 492$ kNs/m

Table 1: Mechanical and geometrical properties of the track elements

In this Table, E is the elasticity modulus; I, the moment of inertia; ν, the Poisson coefficient; A_t, the area of the transversal section of the rail; ρ, the density; k_p, the stiffness of the pad; c_p, the damping of the pad; H_s, the thickness of the precast slab; L_s, the longitudinal length of the slab; W_s, the width of the slab; H_i, the thickness of the interface layer; L_i, the longitudinal length of the interface layer; w, the width of the joint; H_c, the thickness of the concrete support layer; L_c, the longitudinal length of the concrete support layer; W_c, the width of the concrete support layer; k_p, the stiffness of the foundation; c_f, the damping of the foundation.

The vehicle characteristics are indicated in Table 2.

Bogie	Mass - M_b [kg]	5600
Primary suspension	Stiffness - k_1 [N/m]	2.40×10^6
	Damping - c_1 [Ns/m]	5.4×10^4
Wheel	Mass - M_r [kg]	1001.5
	Axle load - P [N]	0.981×10^5
Contact	Stiffness - k_H [N/m]	1.588×10^9

Table 2: Mechanical and geometrical parameters of ICE2 - 2D model ([7])

In Figure 8, the complete load model of the ICE2 train is presented.

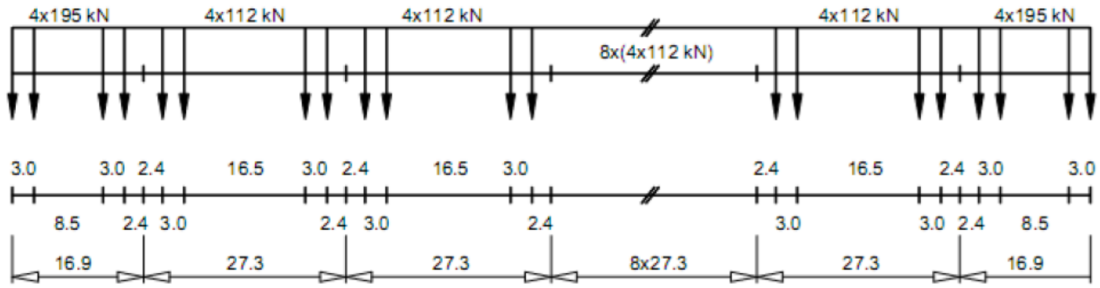

Figure 8: Load model of the ICE2 train [7]

3.2 Results and discussion

3.2.1 Influence of the vehicle model and the train speed

For studying the influence of the vehicle model and the train speed, the response of a perfect track is evaluated for train speeds varying from 220 to 420 km/h in steps of 20 km/h and considering the three vehicle models indicated in Section 2.1.

In Figures 9 and 10, the maximum vertical displacement in the rail and in the slab are presented for the three models together with the results attained with the complete load model of the ICE2 train (Figure 8).

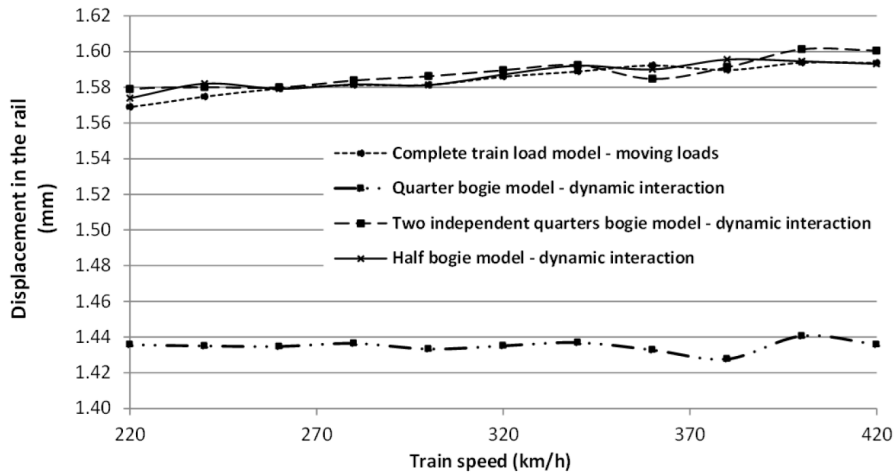

Figure 9: Maximum vertical displacement in the rail for different vehicle model and train speed

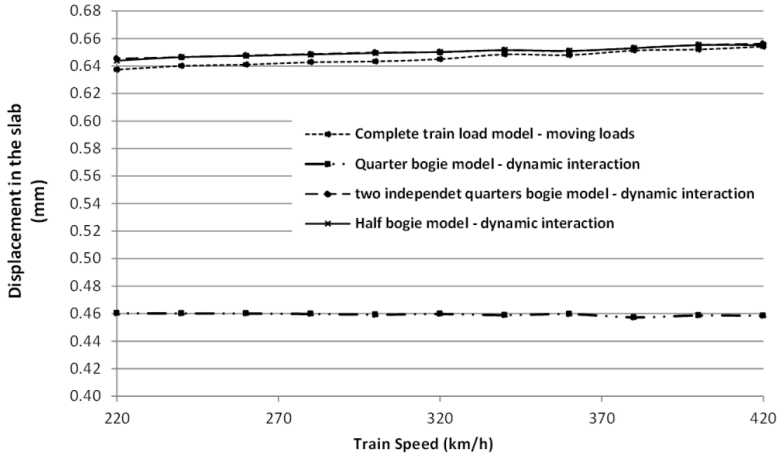

Figure 10: Maximum vertical displacement in the slab for different vehicle model and train speed

The maximum moments in the slab is presented in Figure 11, for the same scenarios.

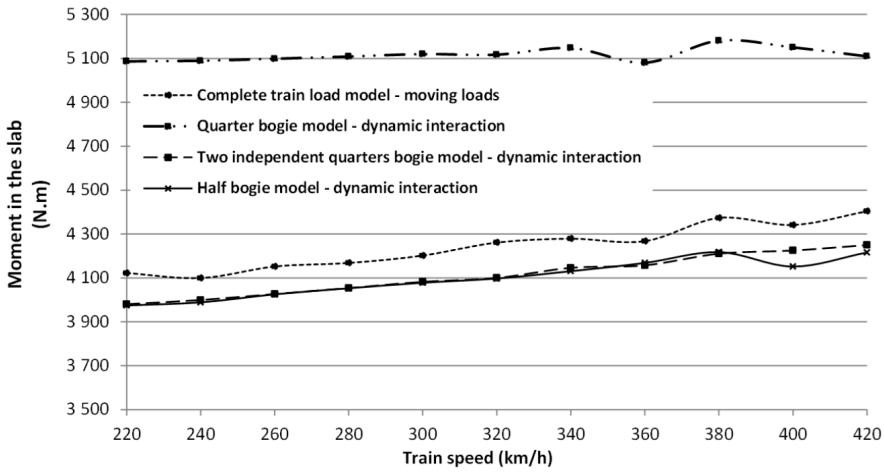

Figure 11: Maximum moments in the slab for different vehicle model and the train speed

The results presented in Figures 9 to 11 show that the quarter bogie is insufficient to represent the correct response of the track due to the passage of the bogie, because the load of the quarter bogie model is $1/2$ to the load of the half bogie model and also because the influence of the wheel spacing of the same bogie is relevant in this type of track models. Although the moving load model gives similar response to the ones attained with the two quarter bogie and the half bogie models, the moving load model is no suitable in the case of track with irregularities. In this analysis the results are similar for these three vehicle models, because the track has no irregularity.

Based on these results the following calculations are performed considering the half bogie model.

3.2.2 Influence of the interface characteristics between the slab and the concrete support layer

For the analysis of the influence of the characteristics of the interface layer between the slab and the concrete layer, elastic modulus varying from 0 to 10000 MPa with $\nu = 0.5$. The simulation of a sliding interface between the slab and the underlying concrete layer corresponds to an elastic modulus equal to zero with a Poisson coefficient equal to 0.5. In this study, a vehicle speed of 360 km/h is adopted. Although the value of the Poisson coefficient ($\nu = 0.5$) is different from $\nu = 0.3$, the value indicated in Table 1 and used for the other parametric analysis, this fact does not influence the system elasticity for the numerical application presented here, as Figures 12 and 13 show.

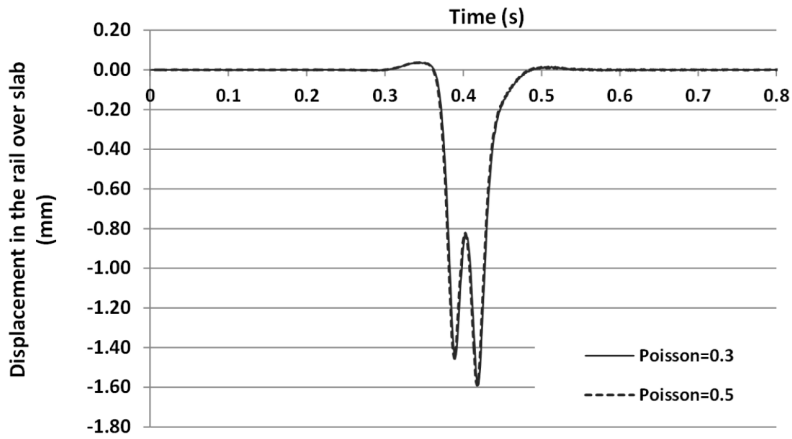

Figure 12: Rail displacement over the slab

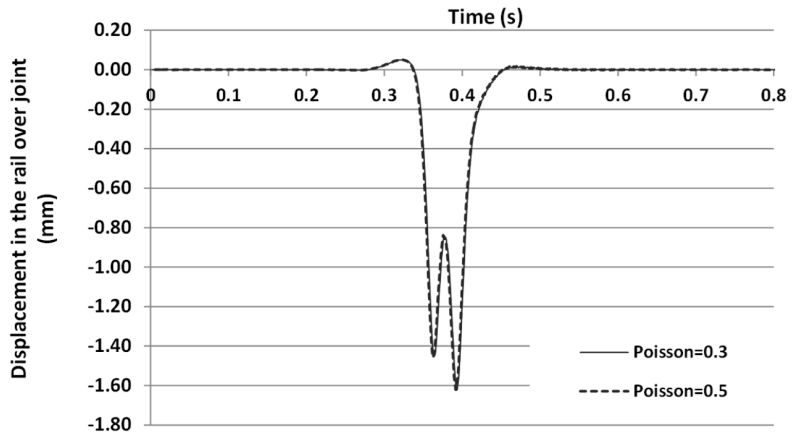

Figure 13: Rail displacement over the joint

In Figures 14 and 15, the maximum dynamic loads at the front and at the rear vehicle axles are presented for different elastic modulus of the interface layer.

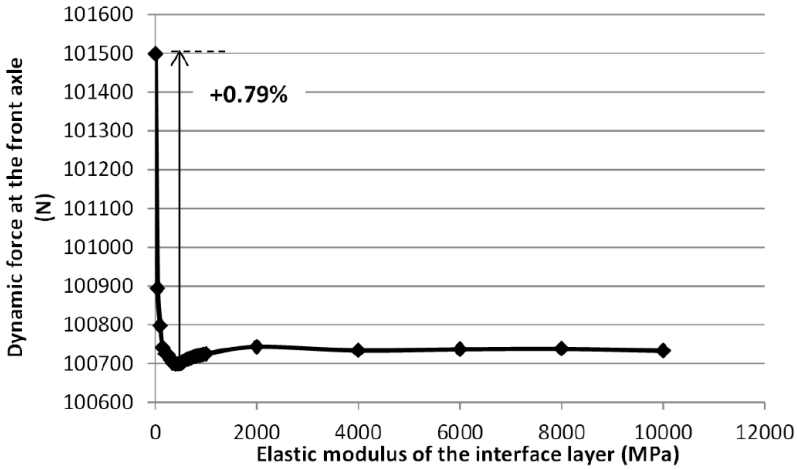

Figure 14: Maximum dynamic load at the front axle

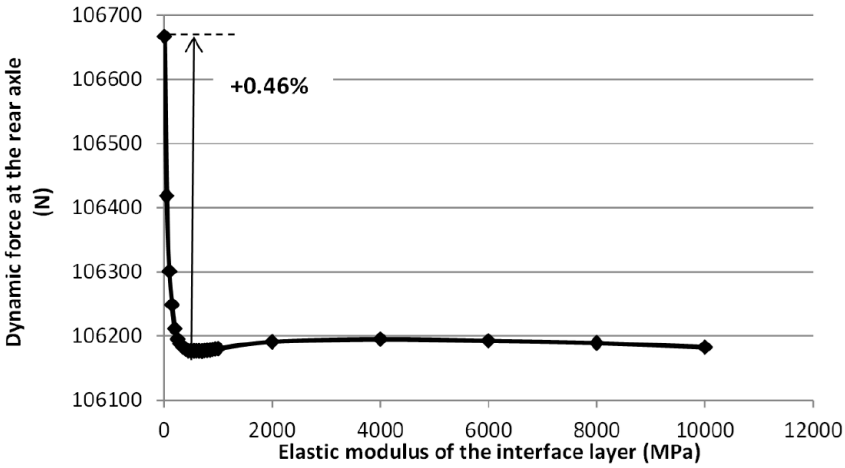

Figure 15: Maximum dynamic load at the rear axle

These figures show that the maximum dynamic load is independent of the interface elastic modulus. However, the elastic properties of the interface layer between the slab and the concrete layer may influence the track dynamic behavior.

In Figures 16 to 21, the maximum track response in terms of vertical displacement in the rail, in the slab and in the concrete sub-base are presented for an increasing interface elastic modulus.

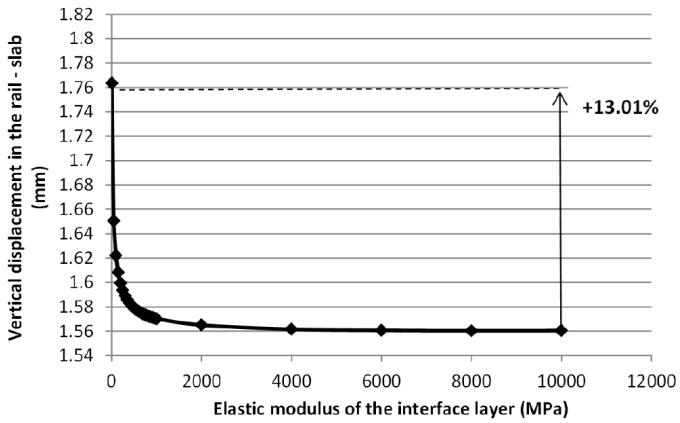

Figure 16: Maximum vertical displacement in the rail over the middle point of the slab

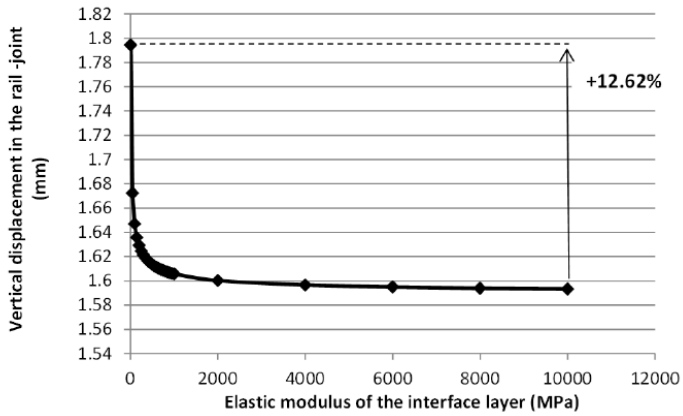

Figure 17: Maximum vertical displacement in the rail over the joint between slabs

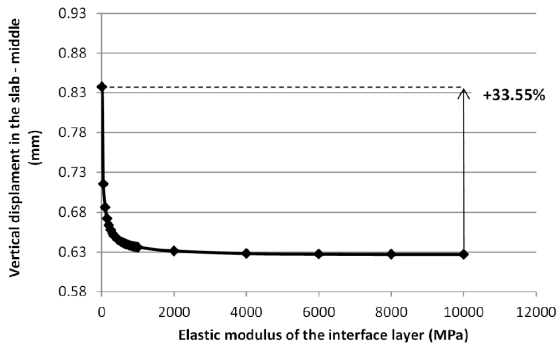

Figure 18: Maximum vertical displacement in the middle point of the slab

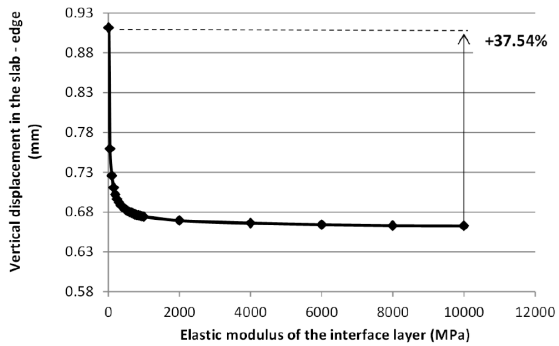

Figure 19: Maximum vertical displacement in the edge of the slab

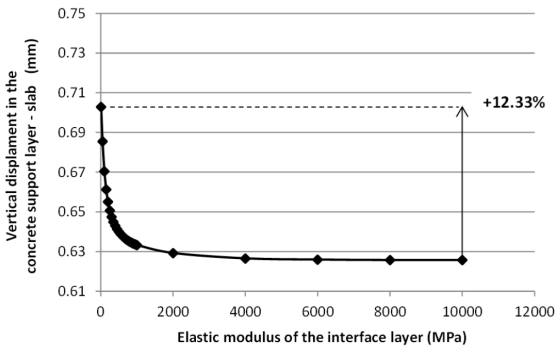

Figure 20: Maximum vertical displacement in the concrete support layer under the middle point of the slab

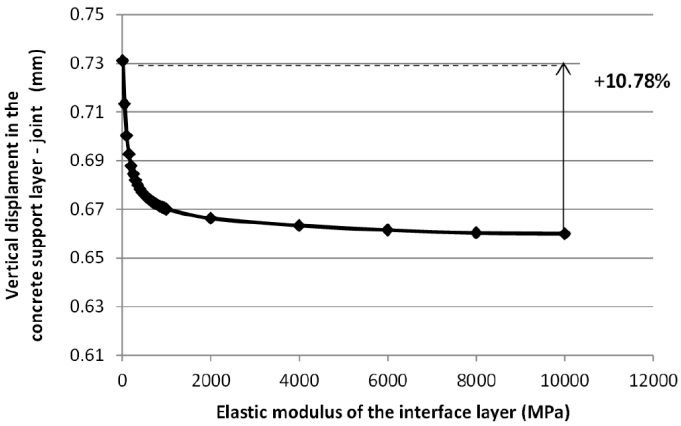

Figure 21: Maximum vertical displacement in the concrete support layer under the joint between slabs

The results evidence that the vertical displacement of the rail decreases with the increase of the elastic modulus of the interface layer. Varying this elastic modulus from zero to 10000 MPa, the decrease of the slab vertical displacement is around 33-37% and the vertical displacement of the concrete support layer is slighty lower, around 10-12% (Figures 18 to 21). For elastic modulus of the interface higher than 1000 MPa, the displacements of the track elements tend to a constant value.

Figure 22 shows that increasing the interface elastic modulus also the maximum dynamic force in the fastening increases with a decreasing rate.

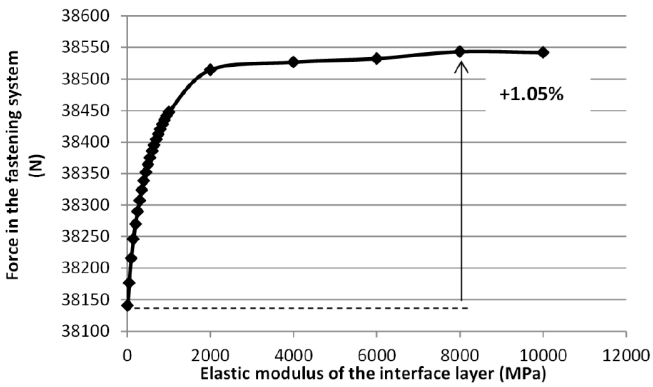

Figure 22: Maximum dynamic force in the fastening systems

Figure 23 and 24 present the maximum bending moments in the rail and in the slab for different characteristics of the interface material.

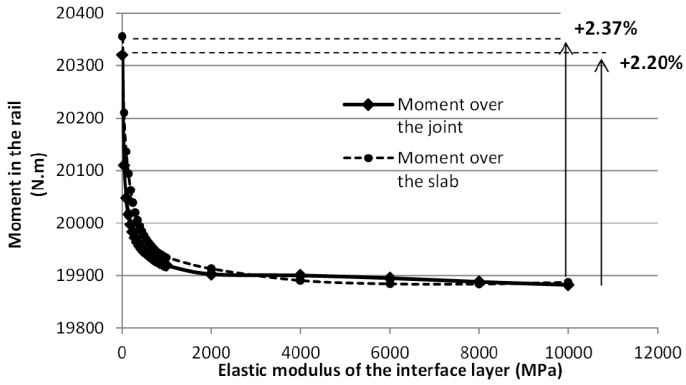

Figure 23: Maximum moment in the rail

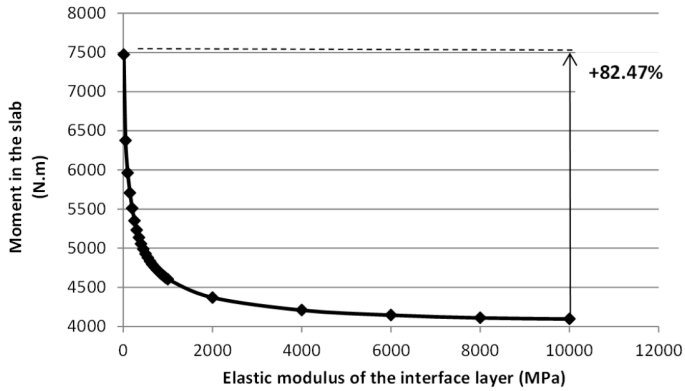

Figure 24: Maximum moment in the slab

The moments in the rail and in the slab decrease with the increase of the elastic modulus of the interface layer. In the rail the reduction is insignificant ($\approx 2\%$); in the slab the reduction of the moments is considerable (around 82%).

3.2.3 Influence of the track foundation

Figures 25 and 26 present, respectively, the maximum vertical displacements in the rail and in the slab, for a vehicle speed of 360 km/h and for four elastic modulus of foundation: 50, 80, 130 and 200 MPa.

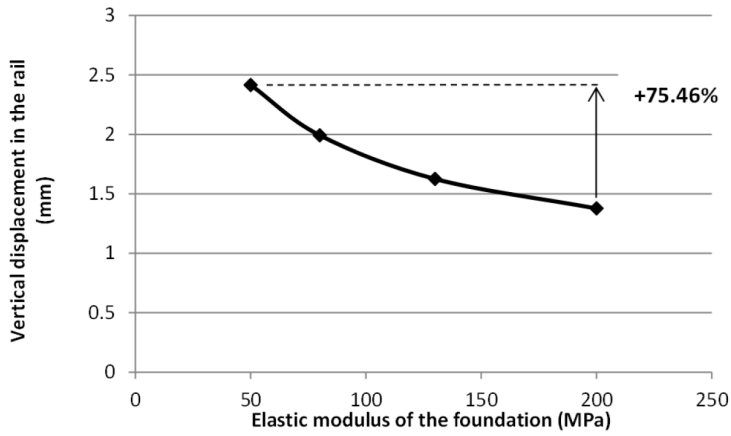

Figure 25: Maximum vertical displacement in the rail

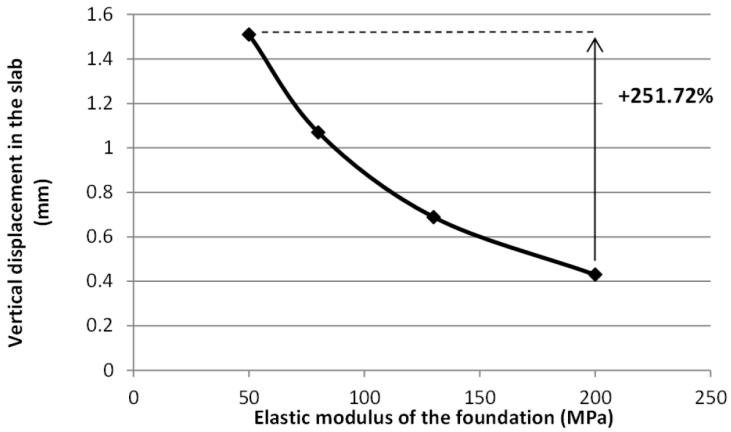

Figure 26: Maximum vertical displacement in the slab

The maximum moments in the rail and in the slab for the same traffic and foundation scenarios are shown in Figures 27 and 28.

From the Figures, the increase of the elastic modulus of the foundation causes a reduction of the maximum values of displacements and bending moments on both the rail and the slab. The influence of the foundation characteristics is more pronounced in the slab than in the rail.

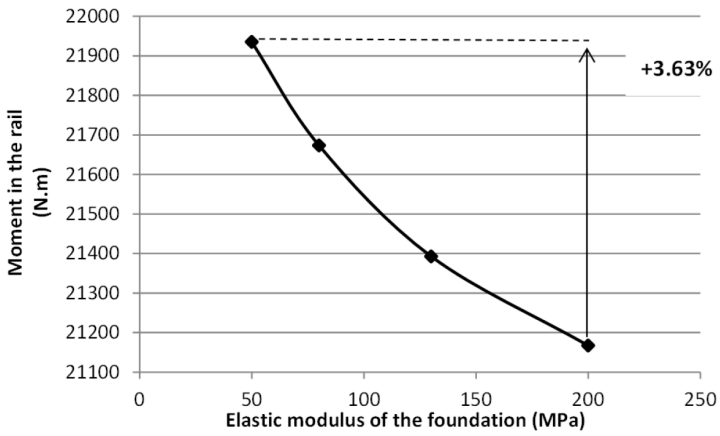

Figure 27: Maximum moments in the rail

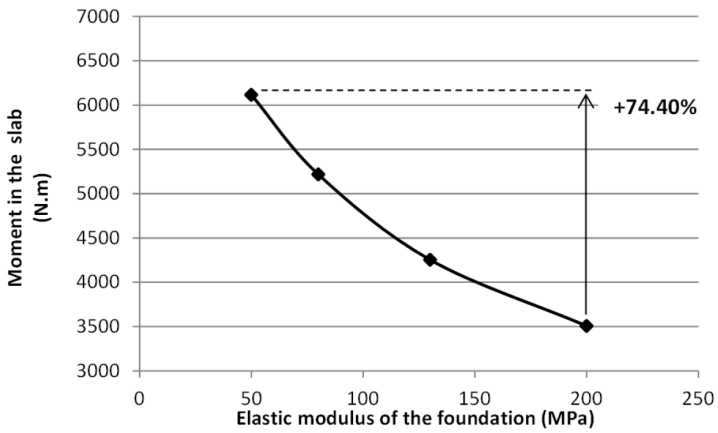

Figure 28: Maximum moments in the slab

In Figure 29, the percentage of the global displacement in each one of the track elements is presented for different elastic modulus of the foundation. As it can be seen, the displacement of the concrete support layer decreases with the increase of the elastic modulus of the foundation.

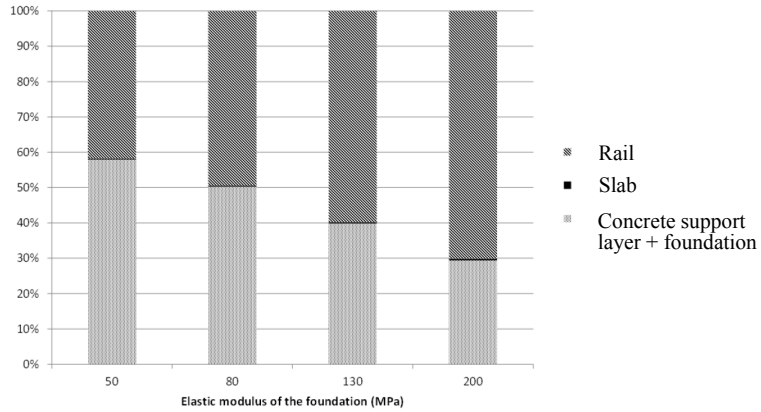

Figure 29: Percentage of displacement in the track elements for different elastic modulus foundation

3.2.4 Influence of the slab dimension

In this paper, the influence of the slab dimension is analyzed for a vehicle speed of 360 km/h. In calculations the width of the slab is considered to be constant (2.4 m). The length of the slab varies between 3.2 and 7.75 m in steps of 0.65 m.

Figures 30 and 31 illustrate that the length of the slab do not influence significantly the maximum vertical displacement of the rail and the slab.

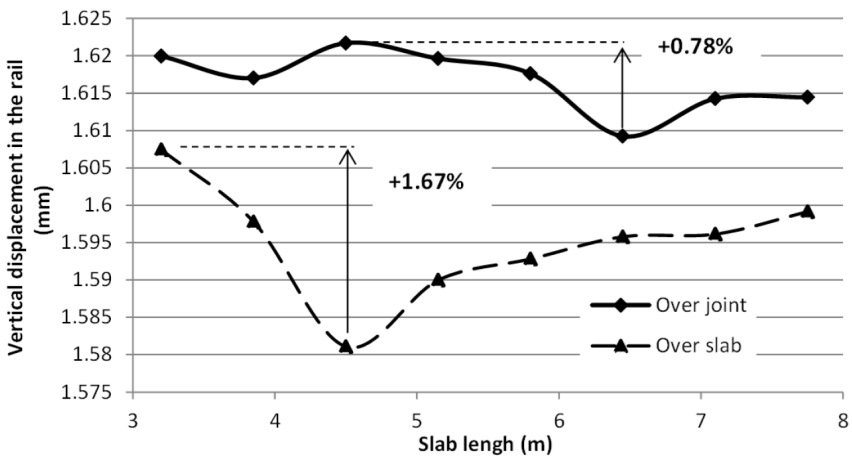

Figure 30: Maximum vertical displacement in the rail

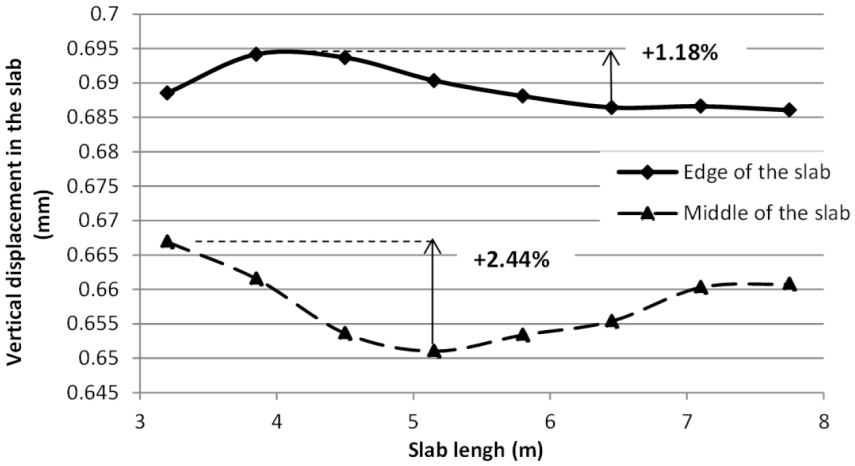

Figure 31: Maximum vertical displacement in the slab

From figure 32, increasing the length of the slab, the moments in this track element also increase, which shows that bigger slabs behave almost as continuous elements.

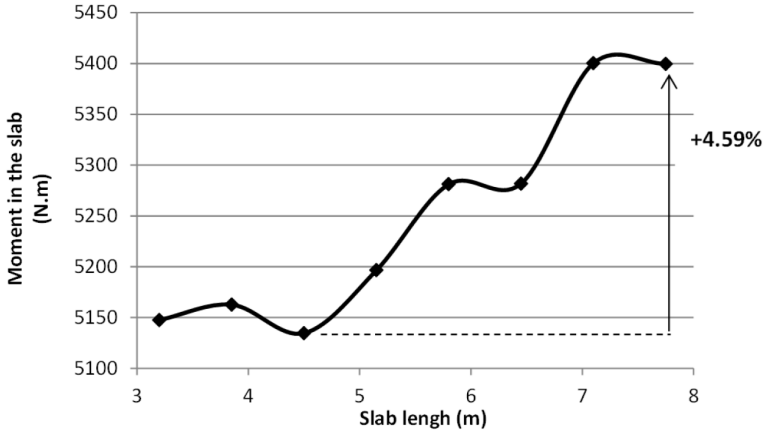

Figure 32: Maximum moments in the slab

3.2.5 Influence of the geometrical quality of the track

Although slab tracks may present a low level of irregularities, in this research the influence of the geometrical quality of the track on its response is also evaluated for train speeds from 220 to 420 km/h.

In Figure 33, the longitudinal level adopted in calculations is indicated. This track profile presents a standard deviation of 1.25 mm, which is near the alert limit for preventive maintenance according to the European Standard EN 13848-5 [8] for wavelengths between 3 and 25 m.

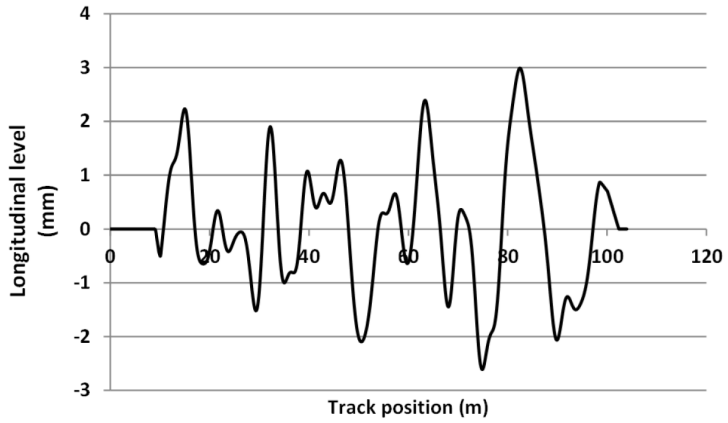

Figure 33: Longitudinal level of the track

The dynamic load for perfect and rough track is presented in Figure 34 together with the static load.

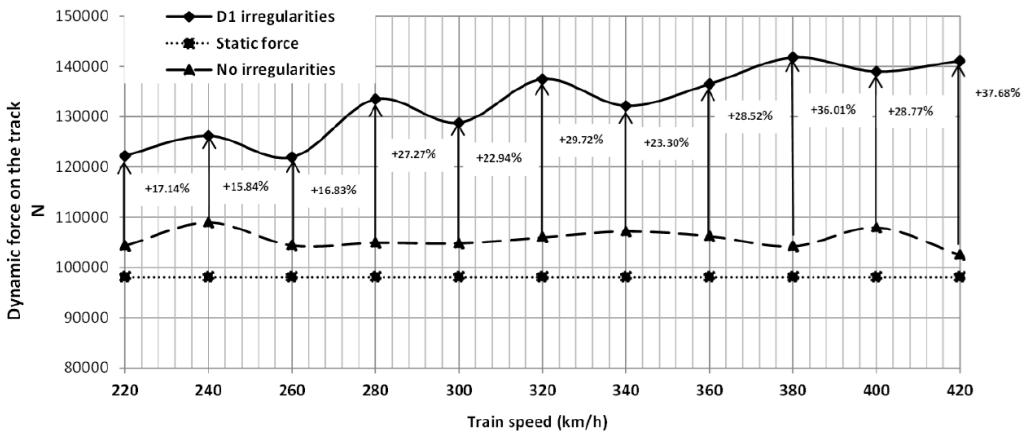

Figure 34: Static load and dynamic load for perfect and rough track

The results reveal that dynamic load in the track is higher in a rough track than in a perfect one and the ratio between these two dynamic loads increase with the increase of the train speed.

4 CONCLUSIONS

A numerical study on the dynamics of a precast track for high speed railways is presented in order to evaluate in the track response the influence of the vehicle model and the train speed, the influence of the interface characteristic between the slab and the concrete support layer, the influence of the track foundation elastic properties, the influence of the slab dimension and also the influence of the track geometrical quality. Calculations are performed in 2D, with Ansys software, in the time domain, considering no dynamic interaction between the wheel of the ICE 2 and the rail (load model) and dynamic interaction between these two elements. For second case, three vehicle models are used: the quarter bogie model, two independent quarter bogie model and half bogie model.

The results show that:

- the half bogie model is the most suitable simplified vehicle model to be used when assessing numerically in 2D the dynamic behavior of slabs tracks composed by precast elements;
- the characteristics of the interface layer between the precast slab and the concrete support layer mainly influence the slab response;
- the rail displacements and bending moments are higher over the slab joint than in the middle point of this element;
- the vertical displacement of the concrete support layer decreases with the increase of the elastic properties of the foundation;
- the elastic properties of the foundation strongly influence the slab response in terms of displacements and bending moments;
- the influence of the slab length in the track response seems to be insignificant;
- the track irregularity induces higher dynamic loads on the track, that increase with the vehicle speed.

In the authors' opinion, more numerical and experimental research is needed on this topic for a better understanding of precast systems for high speed railway lines.

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