# Settlement under creep loading of an asphalt concrete in a railway structure. Triaxial tests and viscoplastic modelling

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## ABSTRACT

SNCF Réseau and IFSTTAR are performing research to set up, in tunnels, new railway structures using an asphalt concrete (AC) instead of ballast and sleepers. A PhD thesis started in 2016 on this topic, taking into account loading conditions of a railway for freight. The thesis is linked to the French national project REVES.

The PhD thesis focuses on the creep triaxial behaviour of AC. A viscoplastic model of Perzyna type is developed, made of a Drucker-Prager yield function closed with a cap model, associated with a hardening function at one parameter. A procedure is developed to identify the model parameters. Some structural simulations are then performed. They highlight some characteristics of AC structures under heavy constant loadings. Amongst them, it is showed that stresses redistribute in the structure over time leading to delete any tensile stress, like granular materials. The first results seem to confirm that settlements of such a structure remain under the maximum standard values imposed by SNCF.

**Keywords**: railways, Continuum mechanics, asphalt concretes, transient numerical modelling, viscoplasticity.

## 1. INTRODUCTION

SNCF Réseau, the French railway board, and IFSTTAR, the French institute of science and technology for transport development and networks, started a PhD thesis for studying innovative ballastless railway infrastructures in tunnels. Tunnels rehabilitation is one current challenge of SNCF Réseau. The collaboration consists in a PhD thesis proposed as part of the national project “REVES” (translated "Reducing operated railways thickness in tunnels”). Innovation consists in designing a very thin track, replacing the blanket layer, the ballast and the sleepers by an asphalt concrete layer (AC). Despite this concept of AC track not being new, the settlement of AC due to concentrated loads such as freight traffic is assessed here.

AC are well adapted to roadways, but freight railway traffic is heavier, slower and more concentrated than truck traffic. Since the French method for designing road materials is well stablished and standardized, new tools to consider this specific application in railway infrastructure are needed.

The viscoplastic behaviour of AC under creep loads is studied and presented here. Based on previous works and experimental tests [Soh11], a constitutive model is developed and fitted by means of triaxial tests on a typical AC10 French asphalt concrete at different confining pressures and deviatoric stresses, at 20°C. The protocol for fitting the parameters of the new viscoplastic model is also presented in the next sections. Then, as the implementation of this Perzyna model in Cast3m was set up, some transient viscoplastic structural calculations are achieved. Displacements, stress and strain fields’ evolution is assessed at the heart of railway structures in asphalt mixes. Results highlights that the asphalt concrete tends to dissipate tensile and shear stresses and then to behave like an unbound material after a certain amount of loading time. This behaviour prevents from cracking, but leads to settlement in the structure. The first results show that calculated settlements of our virtual structure are less important than those authorized in the standard.

# 2. VISCOPLASTIC MODELLING

## 2.1 Conventions, Hypotheses, stress and strain invariants

The following hypotheses and conventions have been considered: small strains hypothesis elastic and viscoplastic strains are decoupled, only the VP evolution is considered for the hardening, strains can be expressed in percentage (%) and stresses are expressed in MPa.

Hydrostatic stress p and von Mises equivalent q stress, as well as volumetric strain $\varepsilon_v$ and built deviatoric strain invariant $\varepsilon_d$ can be written as follows, where $\underline{\underline{s}}$ is the deviatoric part of the stress tensor $\underline{\underline{\sigma}}$ and $\underline{\underline{e}}$ is the deviatoric part of the strain tensor $\underline{\underline{\varepsilon}}$ :

$$p = \frac{1}{3} tr\, \underline{\underline{\sigma}} \quad , \quad q = \sqrt{\frac{3}{2}\left(\underline{\underline{s}} : \underline{\underline{s}}\right)}, \quad \varepsilon_v = tr\, \underline{\underline{\varepsilon}} \ \text{ et } \ \varepsilon_d = \sqrt{\frac{2}{3}\left(\underline{\underline{e}} : \underline{\underline{e}}\right)}$$

The deviatoric strain was built so as to verify the following condition: $\underline{\underline{\sigma}} : \underline{\underline{\varepsilon}} = \mathrm{p}.\, \varepsilon_v + q.\, \varepsilon_d$

## 2.2 Perzyna Viscoplastic model

A standard associated Perzyna flow rule is used. The viscoplastic strain rate $\dot{\varepsilon}^{vp}$ is calculated as shown below. $\langle f \rangle$ is the positive part of the yield function *f*. $\eta$ is a viscosity parameter and $N$ is an experimentally-determined exponent.

$$\dot{\underline{\underline{\varepsilon}}}^{vp} = \frac{1}{\eta} \langle f \rangle^N \frac{\partial f}{\partial \underline{\underline{\sigma}}}$$

The chosen yield is a Drucker-Prager cone associated to a spherical cap:

$$f_1 = cos(\alpha)\, q - sin(\alpha) \quad , \quad f_2 = \sqrt{(p - p_c)^2 + q^2} - p_c sin(\alpha)$$

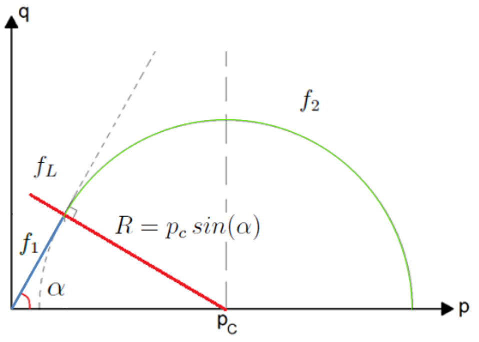

FIGURE 1.Yield surface associated to the VP flow.
A Drucker-Prager straight line closed by a circular cap model.

A “limit” function $f_L$ is also considered: $f_L = q - \frac{1}{\tan(\alpha)}\,(p_c - p)$. The line $f_L = 0$ passes through the center of the circle and the tangent point between $f_1$ and $f_2$ . If $f_L \leq 0$, then $f = f_1$. If $f_L > 0$, then $f = f_2$.

A set of parameters was identified by means of the triaxial tests carried out in a previous study [Soh11]. The identification is made in several steps described here: setting N, the power of the function (imposed to 1 or 2 at the moment), setting $p_{c0}$, to start the test at constant volume, setting a $= tan(\alpha)$, the DP slope, corresponding to the tests able to stabilize, setting b, maximum strain reached for any test and Setting $\eta$ the hardening parameter to fit with the kinetic of the strain curves

TABLE 1. A first set of parameters.

| Parameter | Value |
|---|---|
| N | 2 |
| a | 2.4 |
| pc0 | 0.16 |
| b | 1.4 |
| $\eta$ | 12 |

## 2.3 Implementing Perzyna in the FEM code Cast3m

The Perzyna law was implemented in Cast3m as a user law. Simulations on a single finite element were performed to validate the implementation. A basic 2D structural simulation was also carried out in order to simulate a punching test of an asphalt concrete slab under a heavy static load. Strains and stresses were analysed on elements located in critical zones of the AC. The theoretical behaviour law was respected with an error lower than 1% on every element analysed, which are represented by green dots on FIGURE 2. It can thus be concluded that the model was correctly implemented into Cast3M.

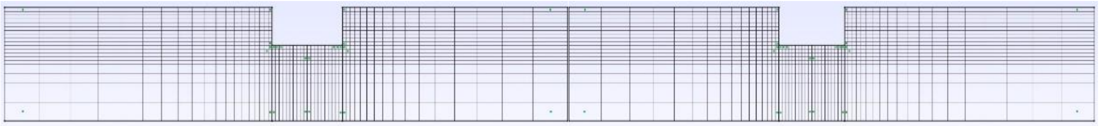

FIGURE 2. Validation of the numerical implementation on a 2D structural simulation

# 3. CREEP SIMULATIONS ON AN INNOVATIVE RAILWAY STRUCTURE

## 3.1 Using Gmsh to Parameterize the design

Gmsh [GR09] is a 3D finite element mesh generator with built-in pre- and post-processing facilities, distributed under the terms of the GNU General Public License (GPL). In this study, only Gmsh pre-processor tools were used. Firstly, the railway structure geometry was designed in a parameterized manner, so that most of the dimensions can easily be modified for further optimizations. Once the geometry was defined and saved (‘file.geo’), the mesh was generated and saved in ‘universal’ format (‘file.unv’), which allowed it to be readable by Cast3m for further FEM calculations. Meshing can also be parameterized to densify elements’ sizes close to the point of load application as well to choose the type of element (tetrahedron, cube, etc). Any kind of geometric entity can be saved as a physical group, simplifying the application of boundary conditions, loads, and further analysis.

### 3.2 Structural design of the Railway structure

Considering the specifications of the REVES project, a first ballastless railway structure has been designed. First numerical simulations were performed with previous viscoplastic models during B. Mazaheri's internship at IFSTTAR [Maz16]. The structure has been subjected to a heavy static load representing a freight train stopped on the track for a long time (300 years).

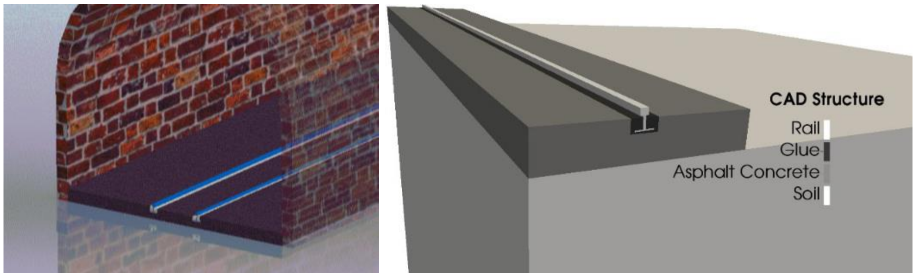

FIGURE 3. (a) REVES Railway structure in a tunnel (concept).
(b) ¼ structure with soil and without the tunnel for further computations.

In order to limit computation times, only one rail has been modelled. The two vertical symmetry plans have been used as shown in FIGURE 3(b). Due to these symmetries, the applied force is one fourth of the total force exerted by the wheel on the rail, 32.5 kN. A line force is applied on the edge of the rail as shown in FIGURE 4(b).

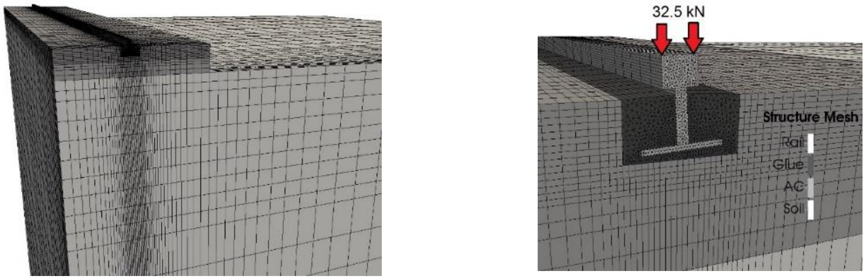

FIGURE 4. (a) Meshing (b) Zoom on the AC layer and rail.

## 4. CREEP SIMULATIONS RESULTS

### 4.1 Displacements, strains, vertical settlement

Results of the creep 3D simulation on the railway structure are partially presented in **Erreur ! Source du renvoi introuvable.**(a), where the deformed structure is shown, with an amplification factor of 100. This first figure shows, under the rail, a settlement of the soil under the asphalt concrete, a deformation of the bottom of the groove in the vertical section, and also a deformation of the rail.

The maximum vertical displacement of the rail after 300 years of simulation is 1.56 mm. The maximum acceptable irreversible displacement of 3.0 mm is given by SNCF levelling standards.

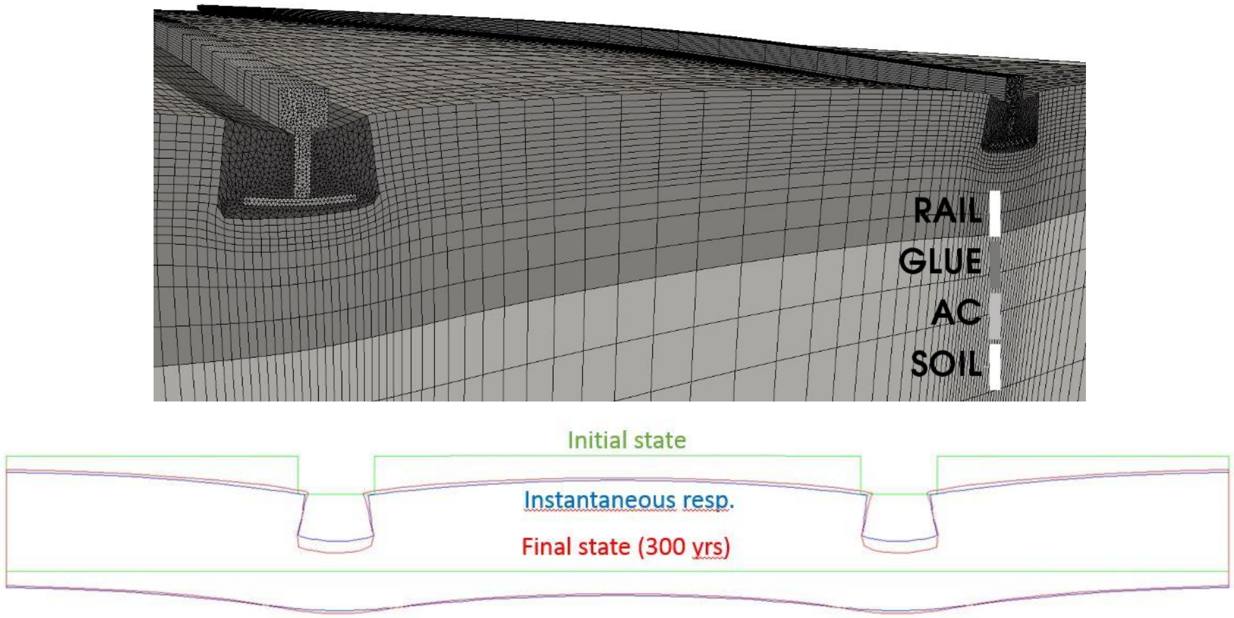

FIGURE 5. (a) Deformed structure at the end of the simulation (amplified 50 times).
(b) Evolution of the asphalt concrete section with time.

A view of the deformed Asphalt concrete section at initial time step, just after loading and at final time step is presented in FIGURE 5(b). The immediate response is the elastic response, it corresponds to a global settlement of the soil. The viscoplastic response at final step leads to a settlement more localized under the groove, under the load and the rail.

## 4.2 Vertical stresses in the vertical section under the load

The evolution of the vertical stress between the initial and the final time step is presented in FIGURE 6. Initial tensile stress is very low in the vertical direction, and tends to completely disappear with time. The compressive stress, strongly concentrated under the middle of the groove, finally spreads under the groove and beyond.

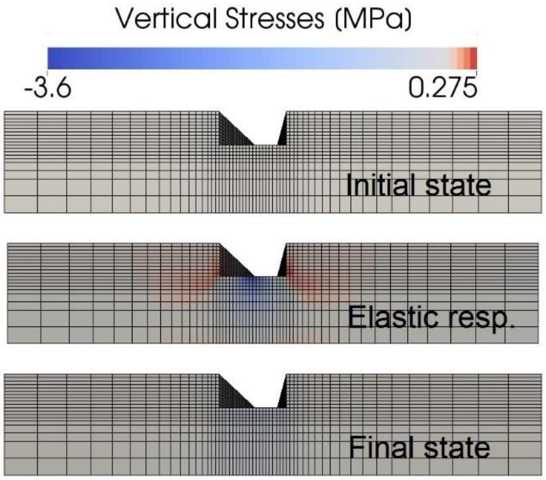

FIGURE 6. Vertical stress inside the AC layer at initial and final time steps.

### 4.3 Horizontal tensile strains and stresses

Horizontal stresses and strains are presented in **Erreur ! Source du renvoi introuvable.**. Three different time steps are selected for the analysis: the initial step "0", the step one, which mostly corresponds to the immediate response of the structure and the final step (300 years). The horizontal stress shows initial compression at the bottom of the groove and traction at the bottom of the AC layer. At the final time step, all horizontal tensile stress disappears. The horizontal strains at step 1 shows a kind of beam in flexion. At the final step, tensile strains reach 100µdef under the groove, while compression is concentrated at the corners of the groove. These strains can be considered as acceptable for long term strains.

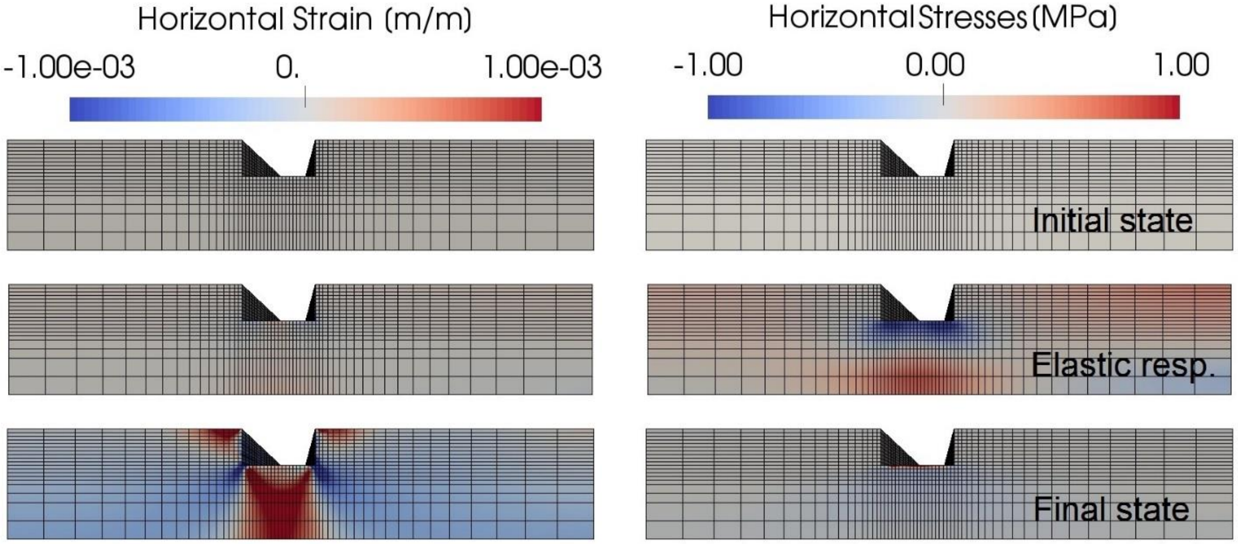

FIGURE 7. Horizontal strain (a) and stress (b) states during the creep test.

## 5. CONCLUSIONS AND OUTLOOK

The first results obtained showed a coherent response of our viscoplastic model. The deformed structure presents a correct shape. The order of magnitude of displacements, the stabilizing creep and the “bump" near the loaded region all are representative of real asphalt concrete behaviour. Stress states in the bituminous mixture evolve in such a way that tensile stresses tend to disappear. Stabilization in creep is due to the evolution of stresses from a bending beam state to that of an unbound soil without any tensile stresses. Further studies will be needed to determine how representative this is and whether this interesting result comes from the constitutive model's construction or from the numerical computation. The results obtained from the first 3D railway structure simulations show acceptable displacements in the case of a creep loading, such as a train stopped on the track for a long period of time could generate. Once again, tensile and shear stresses tend to disappear over time. These first results also need to be confirmed.

The next steps of this work include experimental tests, to be performed in order to determine model parameters for a bituminous mixture that would be used in the REVES project. This will allow us to verify the viability of the various ballastless track concepts that will be developed. Furthermore, simple structural experimental creep tests will be performed in order to assess the accuracy of the model outside of a homogeneous triaxial test. Afterwards, rutting and fatigue resistance will be taken into account to improve structural design.

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