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A viscoplastic model to simulate settlements inside innovative asphalt concrete railway structures

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Abstract

A French project named REVES started in 2015. The goal of this project is to design ballastless railway tracks without sleepers in order to reduce track thickness and increase gauge in tunnels. Older tunnels would benefit particularly from such a track since it would allow for modern freight trains to circulate inside them while providing a cost-effective and time-saving construction process.
A PhD thesis has begun within this project. It aims at modelling the viscoplastic behaviour of asphalt concretes in order to predict the long-term mechanical response of a railway infrastructure such as those considered in project REVES.
A viscoplastic model using the Perzyna formulation was developed to describe the irreversible creep behaviour of asphalt concretes. Model parameters were identified by means of triaxial tests. An efficient yield surface was developed as well as a hardening law with a single parameter. A sequential method for determining model parameters was established. The model was implemented in FEM software Cast3M in order to perform numerical railway track simulation. Some simulations of ballastless railway structures were performed. Firstly, it can be observed than predicted settlements stabilizes and do not reach the limits recommended by the French railway board. It can also be seen that viscoplastic strains concentrates in the Asphalt concrete, just under the rail. Then, it can be seen that stresses redistribute inside the structure over time, leading to eliminate tensile and shear stresses.

Keywords: Continuum mechanics, bituminous mixtures, railways, transient numerical modelling, viscoplasticity.

Nomenclature

AC	Asphalt Concrete
SNCF Réseau	The French national railway board
IFSTTAR	French institute of science and technology for transport, development and networks
VP	viscoplastic

1. Introduction

SNCF Réseau, the French railway board, and IFSTTAR, The French institute of science and technology for transport development and networks, started a collaboration aiming at studying innovative ballastless railway infrastructures, ensuring the safety of rail traffic while reducing financial jobsite costs. Rehabilitating tunnels and increasing tunnel gauges is one of the current challenges of SNCF Réseau. The collaboration consists in a PhD thesis proposed as part of the national project named REVES (translated "Reducing operated railways thickness in tunnels"). Innovation consists in designing a very thin track, by replacing the granular sub-layer, the ballast and the sleepers by an asphalt concrete (AC) layer. This concept of AC track is not new, but its specific use in freight traffic must be assessed and validated.

Such materials are well known to be adapted to roadway traffic, but freight railway traffic is heavier, slower and more concentrated (under the rail) than truck traffic. The standard French method for designing road materials is not adapted to this case, so new specific tools need to be developed.
In this paper, the viscoplastic behaviour of asphalt concretes under static loads, is presented. It is based on previous works aiming at studying permanent strains in bituminous mixtures, by means of experimental tests [Soh11]. An initial VP constitutive model was developed and fitted by means of triaxial tests performed on a typical AC10 French asphalt concrete at different confining pressures and deviatoric stresses, at 20°C. Part of the experimental results are presented here; they were also used to fit the parameters of the new viscoplastic model presented in the next sections. Then, the implementation of the new Perzyna model in Cast3m was set up, for achieving transient viscoplastic structural calculations. Displacements, stress and strain fields' evolution were assessed at the heart of railway structures in asphalt mixes. Results highlight that the initial experimental domain was well defined. Results also highlights that the asphalt concrete tends to behave like an unbound material after a while, eliminating the tensile stresses usually responsible for cracks inside the asphalt layer.

2. Viscoplastic model

2.1. Conventions, hypotheses, stress and strain invariants

The following hypotheses and conventions have been considered:
- Elastic and viscoplastic behaviours are decoupled : only the VP evolution is considered for the hardening
- Small strains hypothesis
- Strains are expressed in percentage (%) and stresses are expressed in MPa

Hydrostatic stress p and von Mises equivalent q stress can be written as follows :

$$p = \frac{1}{3} tr\, \underline{\underline{\sigma}} \quad , q = \sqrt{\frac{3}{2}\left(\underline{\underline{s}} : \underline{\underline{s}}\right)} \qquad (1), (2)$$

We define volumetric strain ε_v and build a deviatoric strain invariant ε_d as follows :

$$\varepsilon_v = tr\, \underline{\underline{\varepsilon}} \quad , \varepsilon_d = \sqrt{\frac{2}{3}\left(\underline{\underline{e}} : \underline{\underline{e}}\right)} \qquad (3), (4)$$

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 $\underline{\underline{\varepsilon}}$. The deviatoric strain was build so as to verify the following condition :

$$\underline{\underline{\sigma}} : \underline{\underline{\varepsilon}} = p.\, \varepsilon_v + q.\, \varepsilon_d \qquad (5)$$

2.2. Perzyna Viscoplastic model

A standard associated Perzyna flow rule is used. The viscoplastic strain rate $\dot{\underline{\underline{\varepsilon}}}^{vp}$ is calculated as shown below. $\langle f \rangle$ is the positive part of the *f* yield function (eq.(5)). η is a viscosity parameter and N is an experimentally-determined exponent.

$$\underline{\underline{\dot{\varepsilon}}}^{vp} = \frac{1}{\eta} \langle f \rangle^N \frac{\partial f}{\partial \underline{\underline{\sigma}}} \quad (5)$$

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

$$f_1 = cos(\alpha)\, q - sin(\alpha) \quad , \quad f_2 = \sqrt{(p - p_c)^2 + q^2} - p_c sin(\alpha) \quad (6), (7)$$

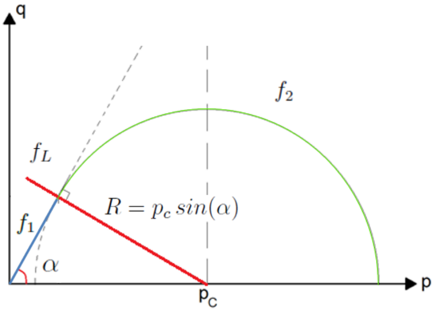


Fig 1. Yield surface associated to the VP flow: A Drucker-Prager straight line closed by a circular cap model.

A “limit” function is also considered :

$$f_L = q - \frac{1}{\tan(\alpha)}\,(p_c - p)$$

The line defined by $f_L = 0$ passes through the center of the circle and the tangent point between f_1 and f_2. This function allows us to choose the value of f . 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
- Setting η the hardening parameter to fit with the kinetic of the strain curves

Table 1. A first set of parameters.

Parameter	Parameter value
N	2
a	2.4
pc0	0.16
b	1.4
η	12

In Fig 2, we can see the comparison between experimental results from one of the previously mentioned triaxial creep tests and theoretical results obtained with this model using these parameters. We can see that the model fits very well the experimentally-obtained data.

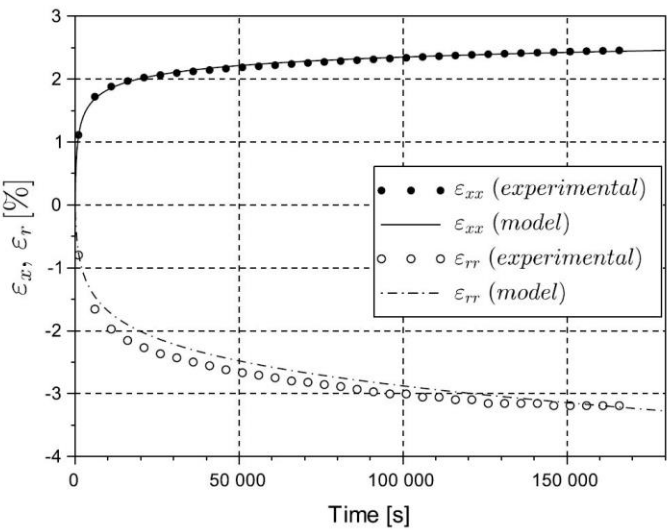


Fig 2. Comparison between experimental and theoretical results

2.3. Implementing Perzyna in the FEM code Cast3m

2.3.1. Validation on a Gauss point

The presented simulation is a homogeneous creep test on a single finite element. Loads similar to those applied during the triaxial creep tests were used. The evolution of strain components is presented in Fig 3. Results show that the strains calculated by Cast3m correspond to the expected strain.

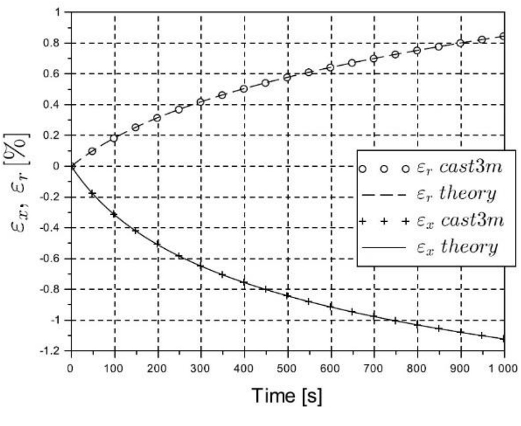


Fig 3. Strains calculated by Cast3m vs VP law.

2.3.2. Validation by a 2D plane strain calculation

A structural simulation was carried out in order to simulate a punching test of an asphalt concrete slab under a heavy static load, see figure 4.

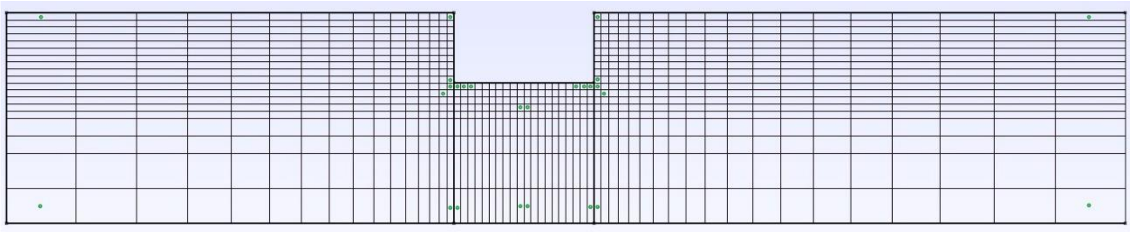


Fig 4. Validation of the numerical implementation

Strains and stresses were analysed at on the points represented by green dots. The theoretical behaviour law was respected with an error lower than 1% on every point.
We can thus conclude that the model was correctly implemented into Cast3M.

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 our study, Gmsh was used as pre-processor. Firstly, it was used for designing the railway structure, in a parameterized manner, so that most of the dimensions can easily be modified for further optimizations.

Once the geometry is defined (‘file.geo’), it can be converted to a mesh and saved in ‘universal’ format (‘file.unv’) usable by Cast3m for further FEM calculations. Meshing can also be parameterized, for example to densify meshing close to the point of load application or to choose the kind of element (tetrahedron, cube…). 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 (figure 5a), and a numerical simulation has been performed with our viscoplastic model 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 (figures 5b and 6).

3.2.1. Studied design

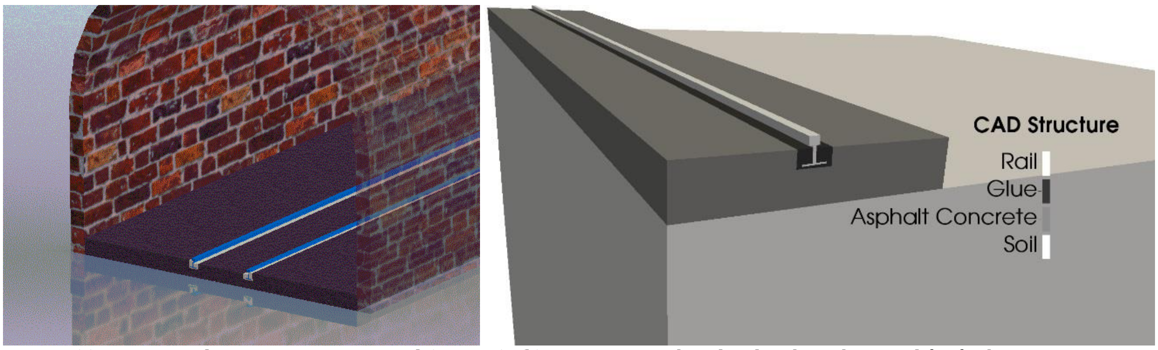


Fig 5. (a) REVES Railway structure in a tunnel (concept) (b) ¼ structure with soil and without the tunnel for further computations.

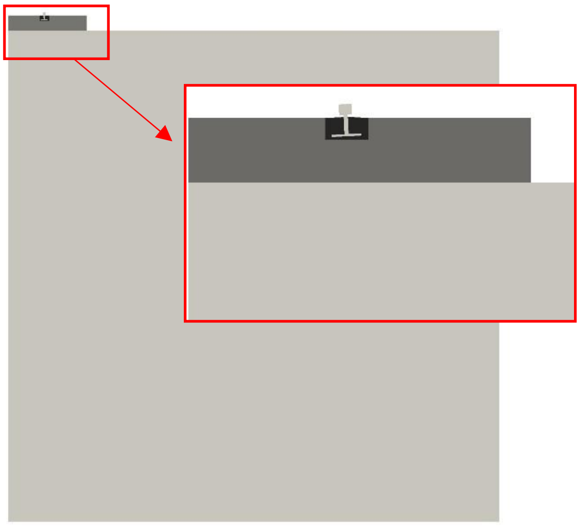


Fig 6: Vertical section used for numerical simulations.

3.3. Boundary conditions, symmetries

In order to limit computation times, only one rail has been modelled. This may be a very strong hypothesis, but at this level we aim to obtain an order of magnitude of the displacements and stresses, for an acceptable computation time. The model has also been reduced by exploiting the symmetries present in the system. The two vertical planes are symmetry planes (visible in figure 7a). Due to these symmetries, the applied force of 62.5 kN is one half of the total force exerted by the wheel on the rail. A 62.5 kN force is distributed on the edge of the rail as shown in Fig 7(b). In this model, interfaces are assumed to be perfectly glued.

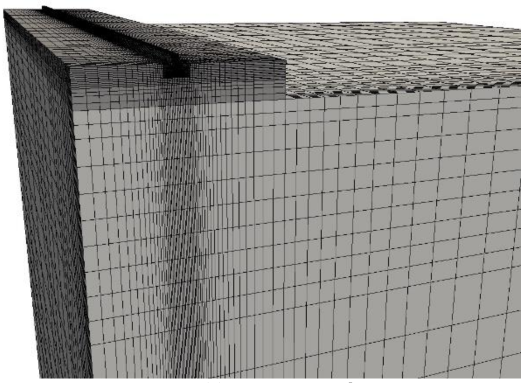
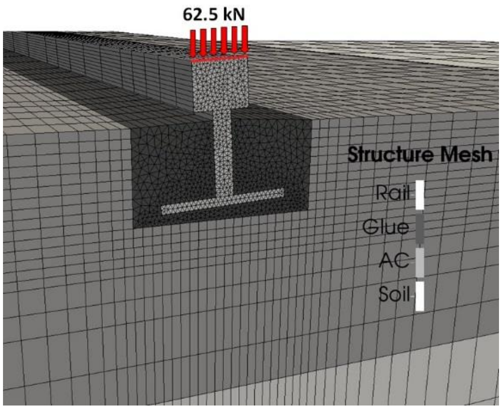


Fig 7. (a) Structure mesh



(b) Zoom on the AC layer and rail.
The vertical force is distributed on the edge of the rail.

4. Creep simulations Results

For practical reasons due to computation times and memory, only 10 seconds of real time have been simulated, thus, we cannot affirm that the results at final time represent the response at an infinite time. However the first trends are given thanks to these simulations. Problems of computation and memory are being solved at the time of writing.

4.1. Displacements, strains, vertical settlement

4.1.1. Local settlement of the structure

Results of the creep 3D simulation on the railway structure are partially presented in Fig 8, where the deformed structure is shown, with an amplification factor of 100. This figure shows, under the rail, a settlement of the soil under the asphalt concrete, a strong 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 (figure 8). The maximum acceptable irreversible displacement of 3.0 mm given by SNCF standards.

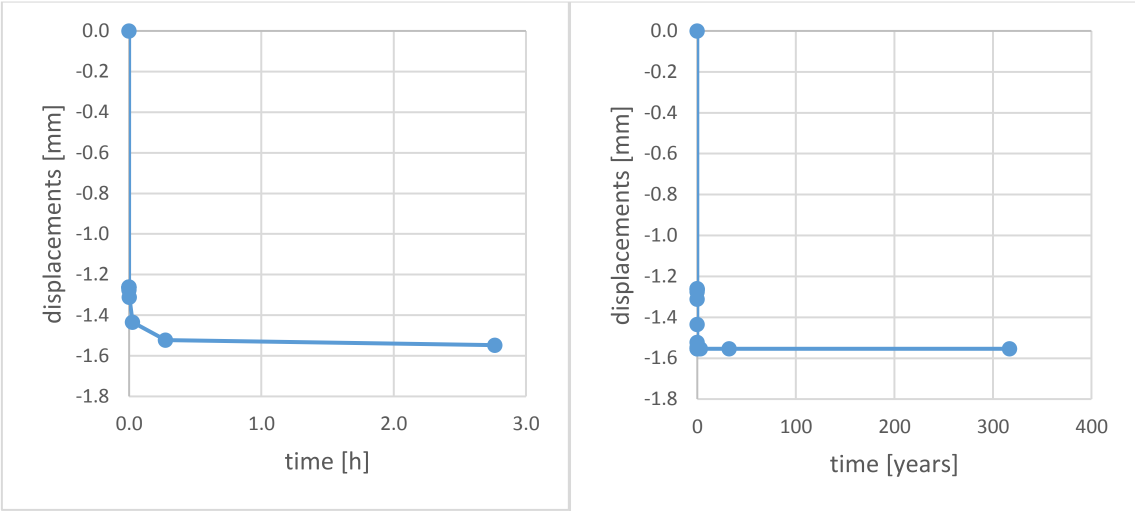


Fig 8. Displacements versus time at the top of the rail.

A view of the deformed asphalt concrete section at initial time step, just after loading and at final time step is presented in Fig 9. The complete structure is also presented at final step. The figure shows two kinds of response. The immediate response is the elastic response, it corresponds to a global settlement of the soil under the asphalt concrete, leading to a global displacement of the asphalt concrete section. The left part of the AC section, which corresponds to the centre of the structure due to symmetry, presents more settlement than the right part, which is close to the tunnel wall. The viscoplastic response leads to a settlement more localized under the groove, under the load and the rail. It is clearly highlighted by the gap between the final state and the elastic response.

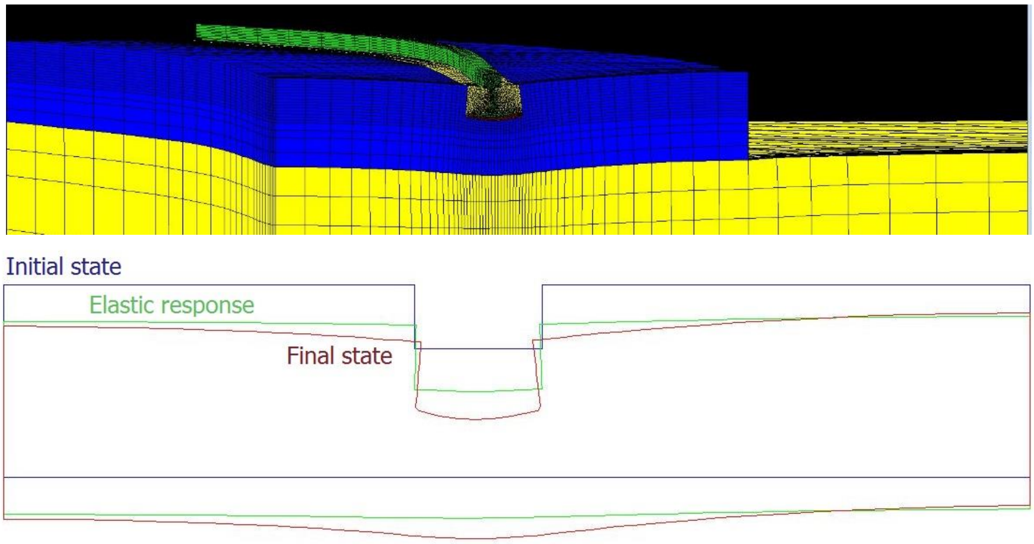


Fig 9. Evolution of the asphalt concrete section with time.

4.1.2. Vertical stresses

The evolution of the vertical stress between the initial and the final time step is presented Fig 10. Firstly it can be observed that positive stresses corresponding to tensile stress are very low in the vertical direction, and tends to completely disappear with time. The compressive stress, strongly concentrated under the middle of the groove, tends to spreads under the groove and beyond, tending to show that settlement are stabilizing with time. The stress state obtained at the end of the simulation is already close to those observed in typical unbound granular materials.

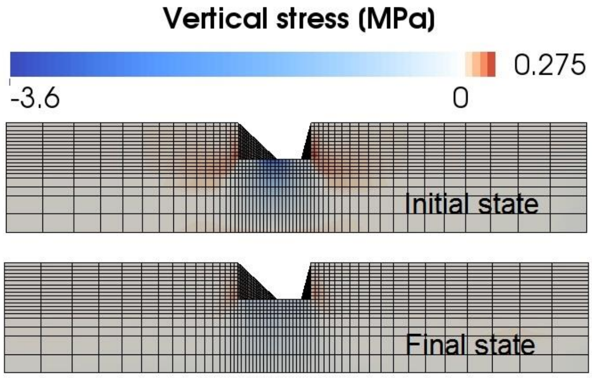


Fig 10. Vertical stress inside the AC layer at initial and final time steps.

4.2. Horizontal tensile strains and stresses

AC layers usually cannot withstand tensile stresses over a long period of time, which leads to cracking. Horizontal stresses and strains are presented in figure 11, time steps are defined here for the analysis: step 0 (reference step or initial unloaded state), step one, which mostly corresponds to the immediate elastic response and the final step (about 300 years). The horizontal stresses, presented on the right part of the figure, show compression at the bottom of the groove and traction at the bottom of the AC layer as the instantaneous elastic response. This response is typical of a beam in flexion. At the final timestep, all horizontal tensile stresses have disappeared. The horizontal strains are presented in the left part of the figure. At step 1, the elastic response is also that of a beam in flexion. On the final step, tensile strains are very high under the groove, while compression is concentrated at the corners of the groove, spreading at 45°. These strains may be higher than 0.01% (100 µstrains), but this can be considered as acceptable for long term strains.

The viscoplastic horizontal strains allow the horizontal tensile stresses, usually responsible for fatigue cracking, to disappear. This positive effect of viscoplasticity must be considered for designing railway AC structures.

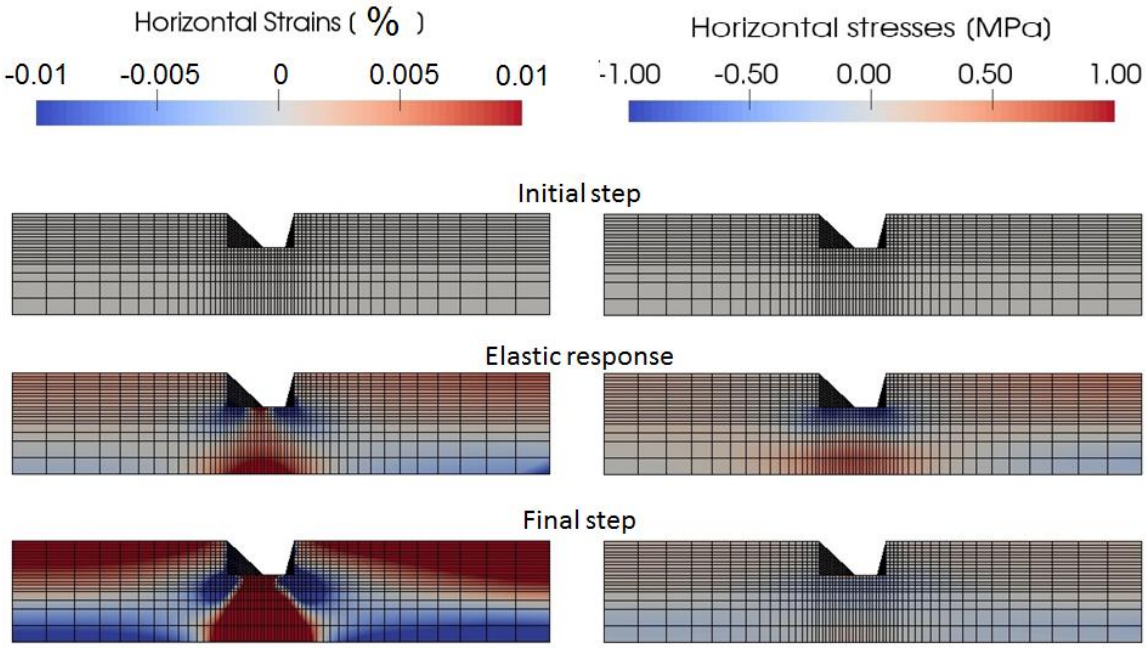


Fig 11. Horizontal strain (a) and stress (b) states during the creep test.

4.3. Shear Stresses in the AC layer

Shear stress, like tensile stress can lead to cracking, especially at long term. Shear stress inside the AC layer are represented here by the Von Mises stresses, in figure 12, at step 1 and final step time. The figure shows that shear stresses vanish over time, certainly thanks to the viscoplastic strains. This phenomenon is good to prevent fatigue cracking.

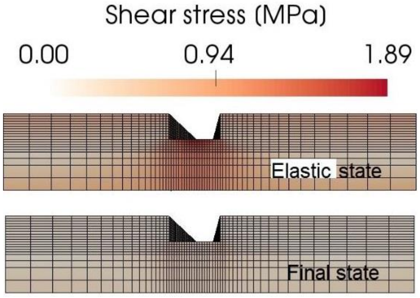


Fig 12. Shear stress in the asphalt concrete layer

5. Conclusions and Outlook

5.1. Conclusions

A new viscoplastic model of Perzyna type was developed and implemented into the FEM code Cast3m, based on a Drucker-Prager yield surface closed by a circular cap model. Gmsh was used as pre-processor to design the structure, enabling an efficient handling of the CAD structure and a parameterization of this structure for further analysis and developments. Gmsh was also used to perform a controlled meshing for FEM computation.

Then, 3D FEM simulations of a ballastless railway structure under viscoplastic creep were done, with the aim of predicting settlement of such a structure under heavy loads (freight). 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 and shear stresses tend to disappear. The final stress states inside the asphalt concrete look like those found in unbound granular soils.
Stabilization in creep is due to the evolution of stresses from a state resembling a bending beam 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.

5.2. Outlook

After this work, further experimental tests will have 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, we will need to perform simple structural experimental creep tests 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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