2D Multilayer Analysis of Electrified Roads with Charging Box Discontinuities

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ABSTRACT

To inductively charge the electric vehicle acting as an embedded power source, one of the solutions proposed is a charging box placed in one of the top layers of the electrified Roads. Box inclusions generate huge points of singularities indicating failure under the loading that cannot be analysed by usual pavement design tools. To take into account such a material discontinuity due to the box inclusion in asphalt overlays, a new development is done in a 2D specific tool. This tool, based on an advanced modelling, the M4-5nW, is dedicated more generally to the calculation of 3D multi-layered pavement structures with cracks. Separating the problem into multiple zones as per different materials in a layer, the problem is solved numerically. It provides then all the mechanical fields including interface stresses between layers. A parametric study is performed for different layer thicknesses and equivalent elastic material layers. This mechanical analysis, which includes a possible vertical crack between the box and the material layer, helps to predict failures such as the debonding between layers. An available choice of the material parameters for the first layers is finally proposed in that paper.

Keywords: eRoads, Discontinuities, Cracks, Modelling, M4-5nW

1. INTRODUCTION

In order to attain the reduction of CO2 emissions under the objectives of the European Energy Agency for 2050, one of the solutions being proposed is the electrified Roads (eRoad) [1-2]. To inductively charge the moving Electric Vehicle (EV), one idea is to insert a Charging Unit (CU), in one of the top asphalt layers of existing traditional Roads (tRoads) [3], then to covert the all pavement structure with another thin layer also made with an asphalt material (Figure 1).

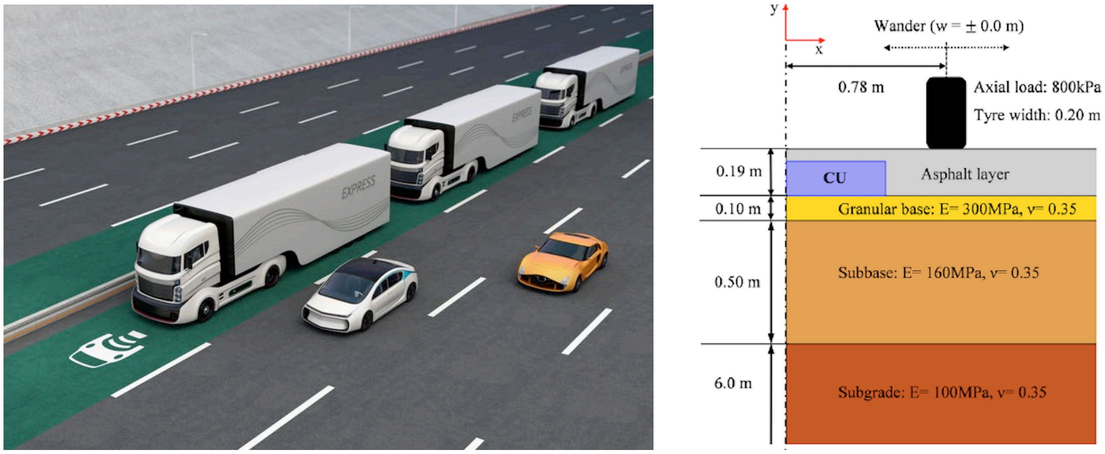


FIGURE 1 eRoads examples (Left) Wired-up roads (from [2]); (Right) Half cross-sectional geometry of an asphalt eRoad with a Charging Unit – CU (from [3])

The adaptation of eRoads is being looked upon as one of the innovative solution. Nevertheless, the material and pavement structures allowing acceptable charging solutions needs to be analysed in detail. Box inclusions generate points of singularities close to the CU-asphalt intersections indicating failure under the moving load [3]. In particular, the proposed CU being made of cement concrete material introduces a huge material discontinuity that may lead to a poor bond between the box and the asphalt material layers. Indeed, the ratio of modulus between these two materials causes a huge singularity that depends on environmental conditions, on the speed of the vehicle (specially when the vehicle is accelerating or is decelerating [4]) and on the lateral wandering (noted w) of vehicles when moving from a lane to another one. Such a vertical discontinuity along with interface discontinuity between the box and the materials has not been yet fully modelled. To take into account the material discontinuity due to the box inclusion in asphalt overlays, a new development is done in a 2D specific tool, called M4-5nW [5]. The M4-5nW is based on an advanced modelling, the Multi-Particle Model of Multilayer Materials (M4) with 5n of equilibrium equations (n: total number of layers), and Winkler's springs. This paper presents the main results of this new M4-5nW development for analysing such discontinuities in eRoads. It aims to propose to engineers an alternative pavement structure that could be tested further by means of full-scale accelerated experiments.

2. THE M4-5NW APPROACH FOR MODELING PAVEMENT WITH CRACKS

The simplified approach, chosen to study discontinuities in pavements, uses the M4-5n that is specially designed to analyse the delamination in multilayered systems under bending loadings [6]. Its construction is based on a polynomial approximation per layer in z for the in-plane stress fields (x and y represent the coordinates of the plane of the layers and z represents the vertical coordinate, see Figure 2). The coefficients of these polynomial approximations are expressed via Reissner's classical stress generalized fields per layer i. The shear and normal stresses, noted respectively $\tau_{\alpha}^{i,i+1}(x,y)$ and $\nu^{i,i+1}(x,y)$ Eq. (1) at the interface between layers i and i+1 (similarly i-1 and i, i ϵ{1,n-1}, α ϵ {1,2}), are ensuring the continuity between these two consecutive layers.

$$\begin{cases} \tau_{\alpha}^{i,i+1}(x,y) = \sigma_{\alpha 3}\left(x,y,h_i^+\right) = \sigma_{\alpha 3}\left(x,y,h_{i+1}^-\right) \\ \nu^{i,i+1}(x,y) = \sigma_{33}\left(x,y,h_i^+\right) = \sigma_{33}\left(x,y,h_{i+1}^-\right) \end{cases} \tag{1}$$

where h_i^+ and h_i^- are the coordinates of the upper and lower face of layer i respectively

Each i layer has then their own behaviour laws, equilibrium equations and lateral boundary conditions. A vertical crack is easy to introduce in each layer separately. This model can be viewed as a superimposition of n Reissner plates linked by interfacial forces. It reduces the real 3D problem to the determination of plane fields (x, y) per each layer i and at the interface i, i+1, (and i-1, i). Thus the real 3D (2D) object is transforming into a 2D (1D) geometry. This approach leads to the development of delamination criteria and semi-analytical calculations without encountering singularity problems of interface stresses [6-7].

For pavement applications, the M4-5n layer numbering starts at the surface layer. In the so-called M4-5nW tool developed for 2D problems [5], the pavement is chosen equivalent to 3 material layers (surface course, base course and sub-base course) resting on a soil. The soil is assumed equivalent to a combination of a fictitious layer (shear soil layer N°4) ensuring the transfer of shear stresses between the sub-base course and Winkler's springs (Figure 2). The stiffness of springs uses Odemark's formula. In 2D plane strain case, the problem is solved semi-analytically with M4-5nW and depends only on the variable x. More details can be found in [5].

3 NUMERICAL DEVELOPMENT IN THE M4-5NW TOOL FOR EROADS ANALYSIS

In order to test if the M4-5nW would be a convenient tool for the parametrical study of material inclusions in eRoads with possible macro cracks between materials, it is proposed here to analyse the elastic stress distribution around the charging box of the 2D example of Chen's PhD works [3]. Elastic modelling is assumed being acceptable with equivalent modelling assumptions [8]. The M4-5nW problem is divided so into four zones (Figure 1) [9]. As the CU is covered with a thin layer of asphalt material, the first additional zone introduced in the M4-5nW tool concerns the CU location, where $x \in [0, l_b]$, and the layer N°2 of the multi-layered structure (Figure 2). The loading conditions are written in the third zone, where $x \in [l_b + l_w, l_b + l_w + l_F]$.

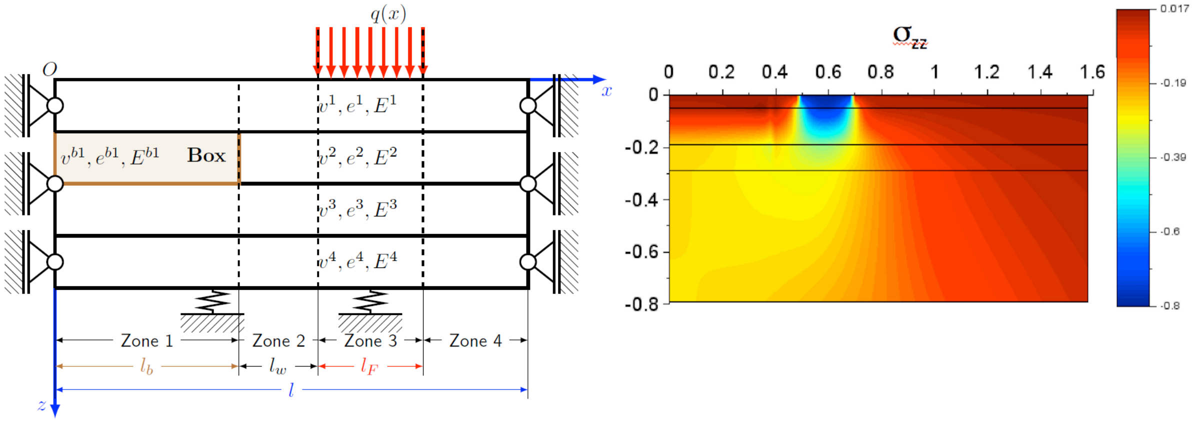


FIGURE 2 M4-5nW equivalent eRoad modelling (from [9]) : (Left) The half cross sectional geometry; (Right) Example of the σ_{zz} M4-5nW pavement distribution (w=-0,2)

A series of M4-5nW equation manipulations leads to write a 12×12 second-order differential system of analytical equations [5]. To solve this system numerically by means of the Finite Difference Method (FDM), the multi-layered equivalent medium is discretized into N points in the x direction (Figure 3). At each point, there are all the M4-5n mechanical fields of each layer i. The introduction of change of material in one (or several) layer equations of the M4-5nW tool leads to modify initial equations of the differential system and the FDM scheme with approximations around the change of zone 1 and 2, that is to say at point j_b $(x = l_b)$.

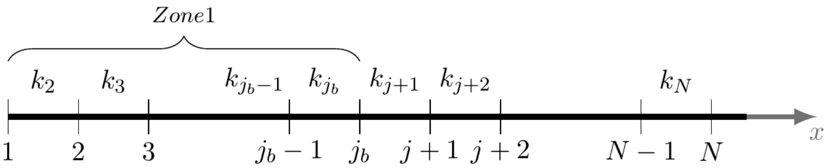


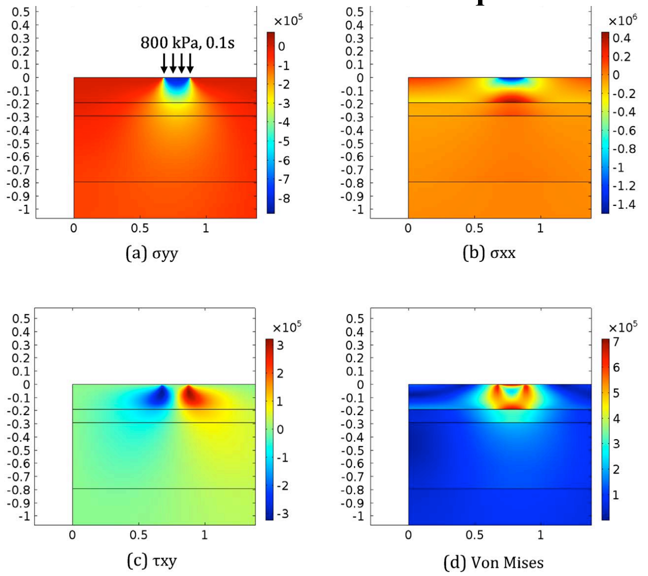
FIGURE 3 M4-5nW discretization of the eRoad half cross section (from [9])

Thus, having the primary displacement field unknowns after solving this primary system, it is necessary to calculate the secondary unknowns linked to stress fields. The functions calculating derivatives are also modified to take care of the material discontinuity. To calculate interface unknowns the functions are used separately for zone 1 and zone 2 and then combined selectively for zone 1 and zone 2. In addition, depending on the case of bond chosen, as illustrated in section 4, the M4-5nW lateral boundary conditions need to use a system of continuity (or not) equations written in terms of the generalized stresses and generalized displacements of layer 2 at point j_b of the CU edge $(x = l_b)$.

4. RESULTS AND ALTERNATIVE EROAD STRUCTURE PROPOSITION

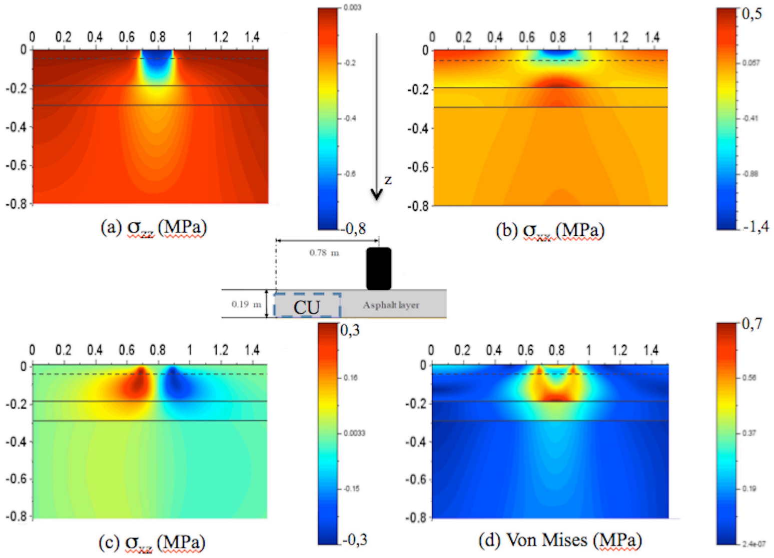
For the study of rutting effect in such eRoad, an all viscoplastic behaviour law with damage coupled for asphalt layers can be used [3]. This leads to determine and use lot of parameters in a structural tool. The present analysis focuses more on the effects of possible existing macro-crack in the eRoads. The geometry and the elastic material characteristics of the eRoad studied in this paper are those given in Figure 1 by Chen et al. [3] except for the asphalt layers 1 $\left(e^1 = 0.05m\right)$ and 2 that have a Poisson's ratio of 0.35. The stiffness of the prefabricated CU (height $e^2 = 0.14m$, width $2l_b = 0.8m$) is supposed to be 30 GPa with a Poisson's ratio of 0.2.

4.1 Validation of the new tool and determination of the equivalent elastic material of layer1



(a) σyy (b) σxx (c) τxy (d) Von Mises

FIGURE 4 tRoad viscoplastic Finite Element Modelling results (from [3] with Figure 1)



(a) σ_{zz} (MPa) (b) σ_{xx} (MPa) (c) σ_{xz} (MPa) (d) Von Mises (MPa)

FIGURE 5 tRoad M4-5nW elastic equivalent results (after [9] with Figure 2)

Aiming to validate the new M4-5nW numerical scheme that takes into account of a CU inclusion (with or not macro cracks), this first parametric study leads to determine the equivalent elastic asphalt Young modulus of the layer in which the CU is placed for the initial tRoad. Figure 4 and 5 illustrate the successful validation of the new numerical implementation by comparison between Chen's viscoelastic results (Figure 4) and those of the M4-5nW obtained in the case of a tRoad (with for M4-5nW a virtual CU inclusion having the same Young modulus than the layer 2) with a very low equivalent Young Modulus value $E^1 = E^2 = 1000MPa$ (Figure 5).

4.2 Material and pavement eRoad structure proposition

In the case of a perfect bond between the CU and asphalt layers, as illustrated with VonMises curves in [3] and with M4-5nW σ_{zz} distribution on Figure 2, the bond between the CU and the asphalt material may be affected due to the change of materials in the layer 2. With help of the present new M4-5nW tool, considering a scenario where the bonding conditions have failed completely between the CU and the asphalt, a vertical macro crack in the all thickness of layer 2 is easily introduced. According to the M4-5n theory, only zero stress conditions of layer 2 are used at the j_b point (Figure 3). Figure 6 illustrates the huge variation of interface normal stress (Eq. 1) between layer 1 and layer 2 obtained in that case (called BBSG BBSG – crack).

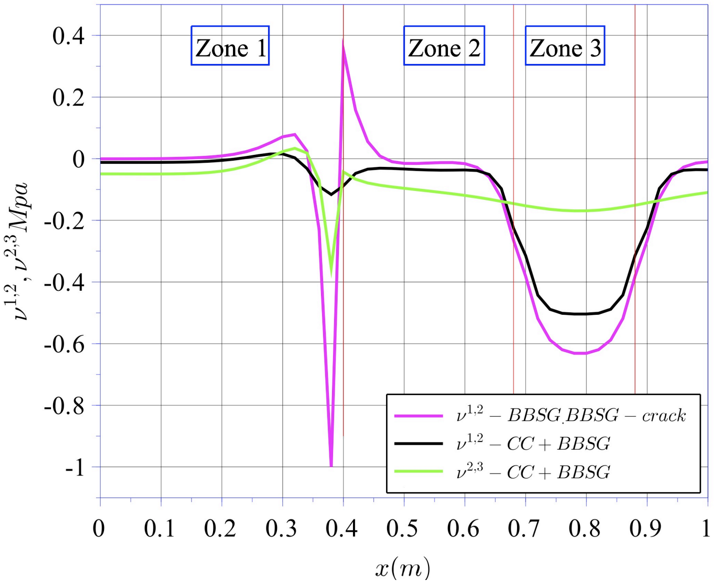


FIGURE 6 Dimensionless interface normal stresses comparison between different cases (w=0.0)

A regular mesh is used (with 20 meshes for zone 1) and for the comparisons with the other following cases, the values are normalized by its minimum.

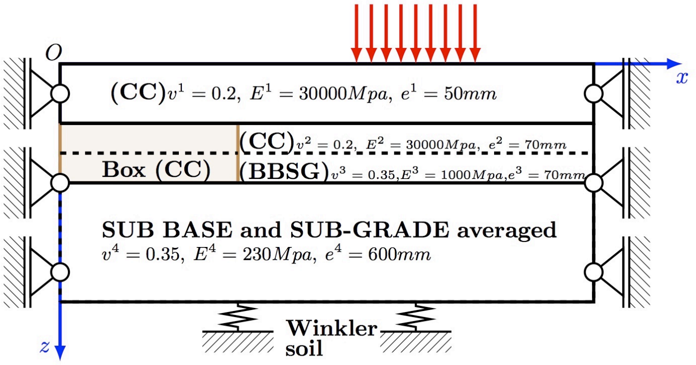


FIGURE 7 An alternative eRoad pavement structure proposition

Then, considering that the thick layer 2 of the tRoad (Figure 2) originally built with two asphalt sub-layers that do not have anymore a perfect bond between them, an alternative eRoad structure is studied finally (Figure 7). It is proposed to engineers to test the option to first remove half of the existing layer 2 before placed the CU in the remaining half-layer. Then it should be possible to cast and cover the all with a cement concrete such as commonly used for Ultra-Thin White Topping pavement. These inverse composite pavements that mixes a cement concrete overlay casted directly on asphalt existing pavement, have shown their efficiency in term of bond between layers even if thermal gradients and water may affect them [10-12]. For this new pavement structure, the M4-5nW tool leads to consider the proposed multi-layered system on the Figure 7 where the cement concrete (CC) layer is virtually divided into layer 1 and 2 for all zones except zone 1. In that case, the CU is located both in the existing sub-asphalt layer N°3 and the new sub CC-layer N°2. The CC layers are supposed to have the same cement material characteristics than the CU. Of course, if needed, this is a parameter easy to change in the M4-5nW tool. As summarized in that paper and illustrated on Figure 6 with M4-5nW results (CC+BBSG curves at the interfaces between layers 1 and 2 and between layers 2 and 3 of Figure 7), the new structure proposition, reduces the interface normal stress intensity between layers 1 and 2 around the CU edge (Figure 6). Even if, in that case, a small concentration of interface normal stress exists at CU edge between layer 2 and 3 (Figures 6&7), this alternative structure offers an interesting solution for adapting the tRoads into eRoads.

5. CONCLUSION & PROSPECTS

In order to adapt existing pavement structures into eRoads, among all the behaviour material problems to solve, some structural solutions need to be found to avoid possible debonding phenomenon between the CU inclusion and the other pavement materials. This failure may occur quickly and, in such condition, it is one of the major distress parameter to take into account for the durability of such new road concepts. In that case, the use of M4-5nW simulations is interesting for making several parametric studies. To consider such a material discontinuity due to a box inclusion in asphalt overlays as studied in Chen's PhD works [3], a new development is done in the 2D specific M4-5nW tool of [5]. The introduction of change of material in one (or several) layer leads to modification of the 12×12 second-order differential system of M4-5nW analytical equations as well as the FDM numerical scheme with approximations around the CU edges in these layers. Considering that in this paper, the use of a CU made with cement concrete material and vertical cracks around it, it is shown that a mix between cement concrete materials casted directly on an asphalt material layer could be a good option for avoiding failures between the different material overlays. In order to participate to this energetic transition period, this modelling aims to quickly highlight, from a pavement point of view, if some particular mix of materials between layers could be an interesting option to be studied with more detail.

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