Fourier-finite element analysis of pavements incorporating high precision tire footprint measurements

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ABSTRACT: This paper presents a numerical model, the Fourier-Assisted Finite Element Method (FSAFEM), for the efficient calculation of pavement responses under traffic loads. The model was employed to determine the in-pavement stresses and strains of a mill-and-overlay pavement, focusing on the asphalt surface overlay layer. High-precision tire footprint measurements of a truck tire at different tire inflation pressures were incorporated into the simulations, along with variations in the interlayer bond conditions. The results showed the significance of precise numerical models capable of integrating such detailed inputs, particularly for analyzing pavement distresses that originate near the surface.

1 INTRODUCTION

In recent years, the concept of digital twins has emerged in pavement engineering, emphasizing the need for precise modeling of pavement responses to realistic loading conditions. This precision is particularly critical near the pavement surface, where stresses are highest and the upper asphalt layer houses valuable sensor equipment. Traditional modeling techniques, such as three-dimensional finite element modeling (3D FEM), have been widely used to simulate tire-pavement interactions. However, these methods often require very fine meshing to capture the details of the tire pressure distributions in the tire contact patch (further referred to as tire footprints), leading to substantial computational time and resource constraints. The limitations of conventional 3D FEM in this context highlight the need for alternative modeling approaches that can speed up the delivery of results without compromising their quality.

This paper uses the Fourier Series Assisted Finite Element Method (FSAFEM). With FSAFEM, it is feasible to utilize high-precision measurements of the tire footprint to determine pavement responses. By effectively accounting for the detailed geometry and pressure distribution within the tire-pavement contact area, FSAFEM achieves pavement response predictions comparable to those of 3D FEM methods while requiring only a fraction of the computational time.

The paper begins with an overview of the mathematical background of FSAFEM and its implementation into an in-house developed software, Dromos. Next, an application case is presented where Dromos is employed to simulate the responses in the surface layer of an hypothetical mill-and-overlay asphalt pavement. The simulations were conducted using tire footprint measurements of a truck tire at three different inflation pressures. The interlayer bond between the surface and the underlying asphalt layer was also varied (considering both full bond and no bond conditions). Finally, the key findings are discussed, along with potential applications into a digital twin of the road.

2 FOURIER SERIES ASSISTED FINITE ELEMENT METHOD (FSAFEM)

The FSAFEM (Potts 2001) is a numerical approach that combines the computational efficiency of analytical methods with the geometrical modeling versatility of FEM. This method is particularly well-suited for pavements, as it approximates the calculation domain as straight and infinite in the longitudinal (traffic) direction. Such an approximation is valid for most pavements geometries, where the length and radius of curvature greatly exceed their thickness and width.

The core concept of FSAFEM is to perform Fourier analysis in the longitudinal direction while using finite elements to model the cross-section of the pavement. The cross-section plane (x-y plane) is discretized with a 2D finite element mesh, where field variations within this plane are represented using nodal values and shape functions. Assuming that (1) the material properties remain constant in the traffic direction and (2) the materials exhibit linear behavior, a Fourier transform can be applied to all special dependent variables (i.e. displacement, stress and strain) in the traffic direction (z-coordinate). Additionally, if it is further assumed that the load is periodic, the Fourier transform can be replaced by a Fourier series.

By applying this transformation, the analysis reduces to the solution of a 2D boundary value finite element problem for each wavenumber in the Fourier series. The results, obtained in the wavenumber domain, must then be inverse Fourier transformed to retrieve the solution in the spatial domain. A detailed description of the mathematical background of FSAFEM is provided in Canon (2021).

In a nutshell, the pavement responses under measured tire contact pressures using FSAFEM are determined as follows:

1. Compute the Fourier transform (Fourier series) of the tire footprint measurements in the traffic direction.
2. Create a 2D finite element mesh of the pavement cross-section. The finite element discretization within the loading region shall match the spatial dimensions of the tire footprint measurements.
3. Solve the 2D finite element boundary value problem in the wavenumber domain for each Fourier term representing the tire footprint measurements.
4. Apply the inverse Fourier transform to obtain displacements, stresses, and strains in the spatial domain.

The FSAFEM was programmed in Fortran 90 into an in-house developed software, *Dromos*, by the Institute of Pavement Engineering at TU Dresden. The software was designed in a modular manner, comprising three main modules: The Preprocessing Module defines the data structures for the problem. It includes a mesh generator and a load generator. The mesh generator creates the 2D finite element mesh of the pavement cross-section using 4-node isoparametric finite elements. The interfacial deformation at the interlayer zone is modeled using the zero-thickness element proposed by Goodman (1977). Figure 1 shows a schematic representation of the 2D finite element mesh and both types of elements. The load generator computes the Fourier coefficients of the load, representing the tire footprint pressure. The Processing Module is responsible for computational tasks such as assembling stiffness matrices and force vectors for each Fourier harmonic. It solves the finite element boundary value problem in the wavenumber domain. The Post processing Module handles the transformation from the wavenumber domain back to the spatial domain. The postprocessor also generates output files compatible with the open-source visualization tool *ParaView* for easy analysis and visualization.

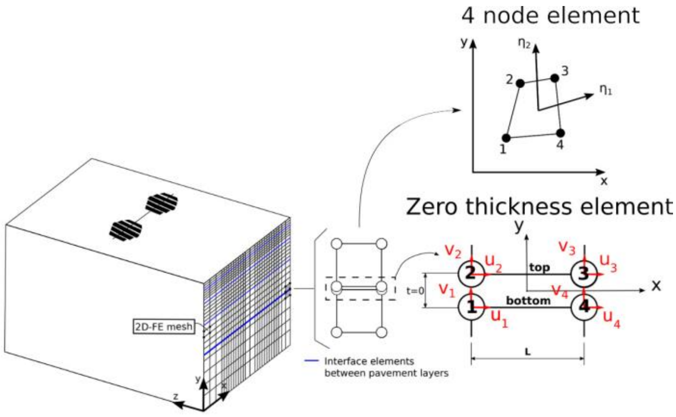

Figure 1. Schematic representation of the 2D finite element mesh.

The implementation and accuracy of *Dromos* were verified by comparing its results with those obtained from commercial 3D finite element software, such as Abaqus, across several benchmark cases (Canon (2021)). The validation demonstrated the potential of *Dromos* to significantly reduce computation time compared to Abaqus, particularly when simulating pavement structures with non-fully bonded layers. *Dromos* employs the Goodman element to account for such scenarios directly. In contrast, Abaqus requires the use of a contact formulation with slave and master surfaces, which substantially increases computation time.

3 TIRE FOOTPRINT MEASUREMENTS

In this paper, the tire footprints were measured utilizing the tire stiffness test rig (SteiReP) developed at the Institute for Automotive Engineering (ika), RWTH Aachen University (Fig. 2). The test rig offers the flexibility to use various surfaces for the assessment of stiffness characteristics as well as a dedicated truck tire pressure-mapping sensor surface for collecting contact pressures. The truck tire used in this study, is Pirelli - ST:01T with dimensions 385/55R22.5 and carcass construction 160K.

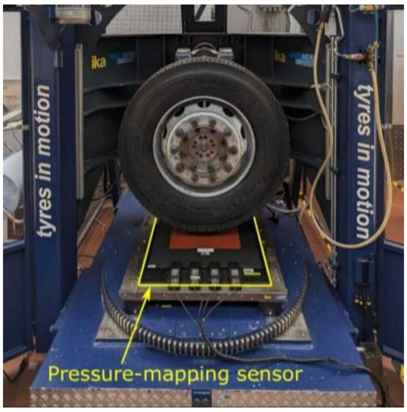

Figure 2. Tire Stiffness Test Rig (SteiReP).

Utilizing load control operation mode of the test rig, footprints of the tire, shown in Figure 3, were measured at a constant vertical load of 35.3 kN and three inflation pressures: 6 bar, 8 bar and 10 bar. The measurements show that the loaded area is slightly decreasing with increase of the inflation pressure. On the other hand, the maximum and average local contact pressures are significantly increasing with increase of the inflation pressure. This highlights the concentration of the load towards the centre of the contact patch and thus potentially increase the local stresses transferred to the road surface.

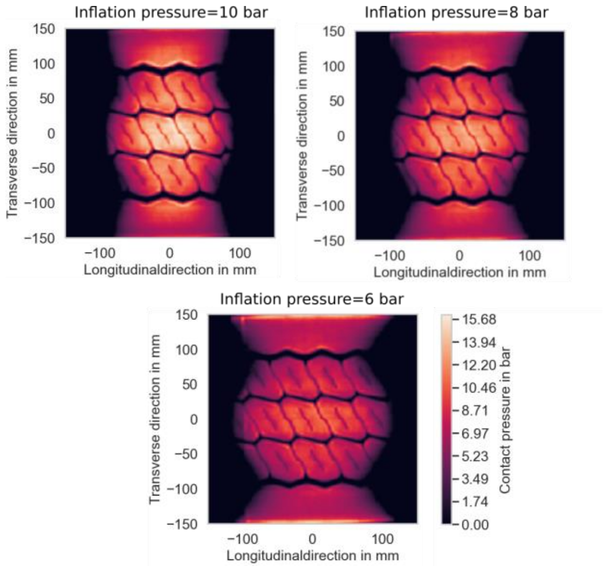

Figure 3. Measured tire footprints for three different inflation pressures.

4 APPLICATION AND SIMULATION RESULTS: EFFECTS OF INFLATION PRESSURE AND INTERLAYER BOND

Simulations were performed on a hypothetical mill-and-overlay pavement where the top surface layer was replaced with an asphalt overlay. Within the context of digital twin road, this asphalt overlay is a smart asphalt layer that interact with the digital twin. Accurately determining the in-pavement stresses of this smart layer is crucial, as it hosts valuable sensors whose functionality supports the operation of the digital twin system. Furthermore, the service life of this layer largely dictates the overall lifespan of the digital twin. Consequently, it is essential to accurately predict key pavement responses associated with common distresses to estimate the layer's durability.

The pavement structure consists of a 40 mm asphalt overlay (Elasticity modulus, E=3000 MPa, Poisson's ratio, ν=0.35) placed over a 240 mm asphalt concrete layer (E=5000 MPa, ν =0.35), underlain by a 320 mm unbound base course (E=400 MPa, ν =0.4) and 400 mm unbound subbase (E=120 MPa, ν =0.4). The subgrade (E=45 MPa, ν =0.2) was modeled with a thickness of 2000 mm. At its current stage of development, *Dromos* models all materials as linear elastic. However, future enhancements are planned to account for the viscoelastic behavior of asphalt materials.

Figure 4 illustrates the calculation domain, which comprises a 2D finite element mesh representing the transverse cross-section of the pavement. A width of 6 m is assumed to eliminate the influence of boundary conditions. The results along the longitudinal direction are obtained by evaluating the nodal variables of the mesh at various positions along the z-coordinate. Within the loading area, a fine mesh discretization of 1.56 mm is employed, matching the resolution of the tire footprint measurements.

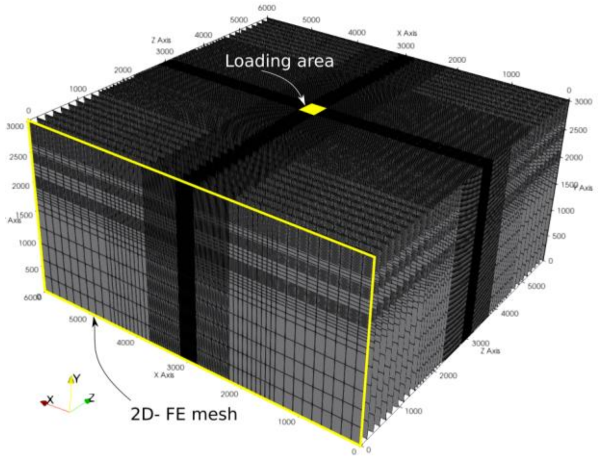

Figure 4. *Dromos* calculation domain.

The tire footprint measurements were transformed in the longitudinal direction using a Fourier series with 400 harmonics and a period of 6 m. Figure 5 presents the histogram of the goodness-of-fit (R-square) values from the Fourier transformation compared to the original measurements. The histogram shows that the majority of R-square values are concentrated near 1, indicating an excellent fit between the Fourier-based regression and the measured data. However, a small number of lower R-square values highlight cases where the regression may not perform as well. An example of such a case is detailed in the figure, which occurs when the measurements exhibit high variability with sharp peaks.

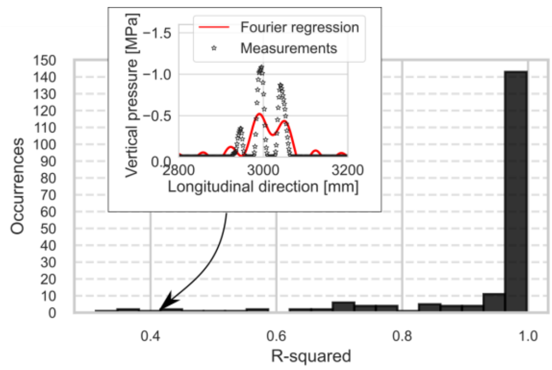

Figure 5. *Histogram of goodness-of-fit (R-square)*

Figure 6 shows the simulation results in terms of stress distribution within the pavement at the cross-section beneath the tire footprint. The results clearly indicate that the asphalt overlay is subjected to high localized stresses, which increase with the magnitude of the inflation pressure. The stress concentration is particularly critical at the center of the tire footprint under the 10 bar inflation pressure. In contrast at the 6 bar inflation pressure, the stresses are more evenly distributed throughout the entire contact patch area.

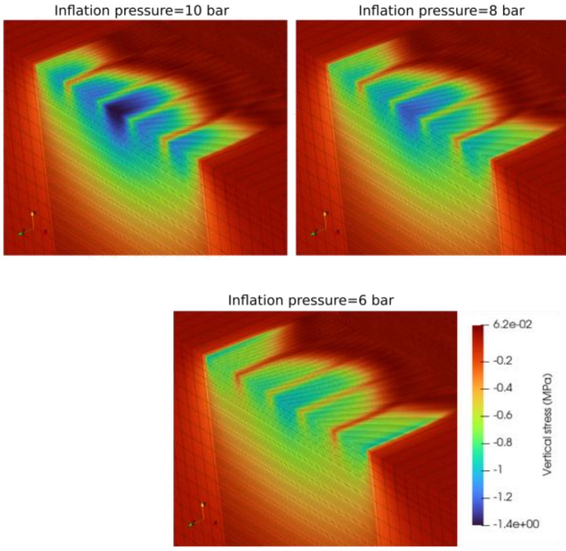

Figure 6. *In pavement vertical stresses*

The interlayer bond between asphalt layers significantly influences the service life of the pavement. When the bond breaks, the asphalt structure behaves as a laminated composite, leading to tensile strains emerging at the bottom of the layers where the bond failure occurs. Under repeated traffic loads, these strains can initiate cracking that propagates and result in fatigue damage. This phenomenon is evidenced in Figure 7, which illustrates the longitudinal strains at the pavement cross-section for both interlayer conditions: full bond and no bond. Under the full bond condition, the bottom of the asphalt overlay experiences compressive strains. However, when the bond fails (no-bond condition), significant tensile strains develop at the bottom of the overlay.

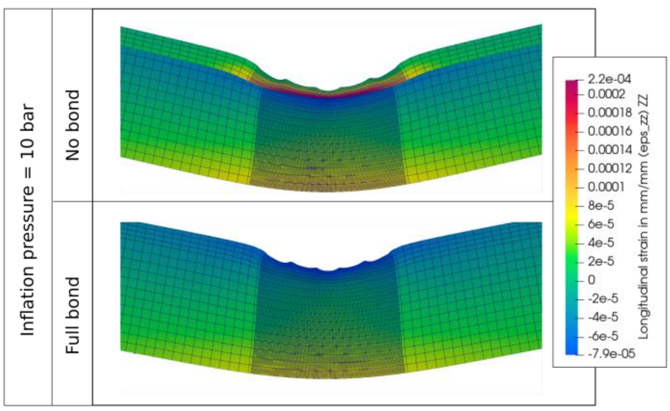

Figure 7. *In-pavement Longitudinal strains.*

Figure 8 presents the magnitude of the longitudinal strains at the bottom of the overlay and at the bottom of the asphalt. The magnitude of the tensile strains is an indicator used in empirical formulas to determine the fatigue resistance of the layer. Thus, it is evident that both the inflation pressure and the interlayer bond significantly affect the service life of the overlay. High-performance asphalt materials are crucial to accommodate off-design scenarios where the interlayer bond fails, leading to substantial tensile strains near the load.

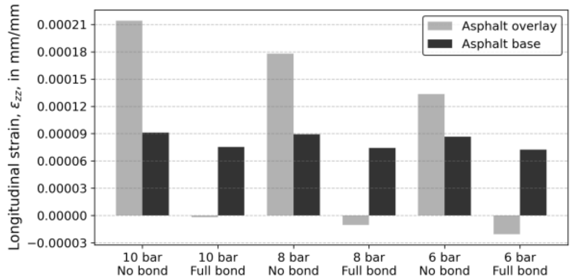

Figure 8. Longitudinal strains at the bottom of the asphalt layers.

5 CONCLUSIONS

This paper presents an efficient numerical alternative to 3D-FEM, the FSAFEM, for accurately determining pavement responses to realistic traffic loads. The following conclusions can be drawn:

- FSAFEM efficiently incorporates high-precision tire footprint measurements and varying interlayer bond conditions, offering significant computational advantages over traditional 3D-FEM methods.
- Tire inflation pressure strongly affects stress and strain magnitudes at the surface layer. For digital twin roads, which host expensive sensors near the loads, it is crucial to use high-performance asphalt materials to handle such stress/strain conditions.

6 ACKNOWLEDGEMENTS

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