Numerical modeling of multilayer asphalt-concrete roads based on the finite element method

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Abstract. The task of creating progressive technologies for the construction of highways and high-speed railways require the development of new methods of computational and design analysis based on computer technologies and modern methods of mechanics, considering the complex, physically and geometrically nonlinear nature of the problems being solved, the peculiarities of the operation of multilayer structures and the cyclical nature of transport loads. Studies on the application of the finite element method (FEM), carried out at the Department Construction material technology, MADI, have shown the effectiveness of this method for calculating road surfaces and high-speed railways, considering the real work of bases, structural features of longitudinal and transverse seams, etc. These studies made it possible to identify such features of the behavior of road structures that could not be described by existing engineering techniques. The presented finite element models for solving various problems of analyzing the behavior of pavement structures have shown the prospects of using the developed approaches for digital modeling of multilayer roads with asphalt concrete pavement.

1. Introduction

During the operation of road and airfield pavements, cracks form in them, which, spreading both in the horizontal direction and deep into the pavement, over time can lead to fragmentation of the pavement and the impossibility of its further use. Considering the annually increasing intensity of traffic flows and an increase in the weight of vehicles, the process of destruction of coatings can be significantly accelerated, and the real terms of durability of coatings will significantly differ from those laid down in the project. In this regard, it becomes necessary to develop modern methods for calculating and designing road and airfield pavements, considering the latest advances in computer technologies and methods of fracture mechanics. The analysis is based on the development of finite element adequate spatial models for analysis. Our works on the application of numerical methods of nonlinear spatial mechanics to solving the problem of modeling the behavior of multilayer road surfaces are presented in [1–4]. In this paper, we consider some new approaches to the construction and verification of the adequacy of some digital models of road structures, which make it possible to take a certain step in the development of methods for virtual digital analysis of the work of multilayer road pavements.
2. Finite-element model of a laboratory installation of a 4-point bend of a beam

In Russian Federation and abroad, laboratory installations of 4-point bending of rectangular beams are most often used to study the fatigue life of asphalt concrete (Fig. 1).

Tests for 4-point bending are most consistent with the operating conditions of asphalt concrete in the structures of real road surfaces and therefore allow you to evaluate the fatigue life of various asphalt concrete mixtures in the road surface.

![Figure 1. Design diagram of the installation for fatigue testing of a girder asphalt concrete sample for 4-point bending](image)

Fatigue life testing of asphalt concrete mixtures requires the use of complex expensive equipment and a significant investment of time. Therefore, replacing at least some of these tests with virtual tests using finite element models is an urgent task for a researcher.

In our work, to assess the durability of an asphalt concrete beam specimen at 4-point bending, we used methods of fracture mechanics. The finite element model (FE model) of the experimental setup is shown in Figure 2.

Figure 3 shows the simulated vertical displacement distribution in a finite element model of an asphalt concrete specimen at a load frequency of 10 hertz and a crack length of 31.5 mm.

The effect of load frequency on the durability of an asphalt concrete specimen is illustrated by the graph in Figure 4.

In [5], based on the results of field experiments, it was shown that there is a relationship between the speed of a heavy vehicle (with an axle load of 100 kN) and the vibration frequency of the asphalt concrete pavement

\[ f = 0.277v^{0.944} \]  

where \( f \) is the vibration frequency of the asphalt concrete pavement; 
\( v \) is vehicle speed.

In the same work, based on the results of laboratory tests of asphalt concrete samples for 4-point bending, a relationship was proposed between the frequency of application of a load to an asphalt concrete sample and the speed of a heavy vehicle in the form

\[ f \text{ [Hz]} \sim 0.5v \left[ \frac{\text{km}}{\text{h}} \right] \]  

where \( f \) is the frequency of the load applied to the asphalt concrete sample; 
\( v \) is vehicle speed.

It follows that, using formulas (1 - 2), and the results of calculations using a finite element model of an experimental setup for testing on a 4-point bend, it is possible to judge the influence of the speeds of a heavy vehicle on the durability of the asphalt concrete road surface.
Figure 2. Finite element model of the experimental setup: 1 - longitudinal plane of symmetry of the experimental setup; 2 - transverse plane of symmetry of the experimental setup; 3 - asphalt concrete sample; 4 - stationary steel cylindrical supports; 5 - steel cylinders transmitting a cyclic load to an asphalt concrete sample

Figure 3. Distribution of displacements in the finite element model at a load frequency of 10 Hz and a crack length of 31.5 mm
It follows from the graph in Figure 4 that an increase in the speed of heavy vehicles above 42 km/h should lead to an increase in the fatigue life of asphalt concrete pavements.

3. FE model of temperature interaction of AC coating with the environment

To create a FE model of the thermal interaction of the road surface with the environment, the results published in [6] were used. In this work, a one-dimensional heat exchange of an asphalt concrete pavement with the environment was investigated for three days. The solution obtained by the finite difference method was compared with the experimental results.

In our work, the same problem was solved by the finite element method. A finite element model of the road surface in a one-dimensional setting is shown in Figure 5.

The coating, in accordance with Figure 6, is exposed to solar and atmospheric radiation. The heated coating radiates heat to the atmosphere, is cooled by wind currents and exchanges heat with the underlying coating layers and the substrate. All of these effects are modeled using appropriate initial and boundary conditions.

The results are illustrated by the graphs shown in Figure 7. As can be seen from the comparison of these graphs, the results obtained in this work by the finite element method (FEM) are in good agreement with both the experimental results and the results obtained by the finite difference method (FDM).
Figure 5. One-dimensional finite element model of asphalt concrete pavement for calculating heat transfer between the pavement and the environment

Figure 6. Diagram of the components of the thermal balance of the road surface with the environment
The proposed finite element model can be used to study the thermal interaction of the road surface with the environment in a flat and spatial setting.

4. Influence of the thickness of the asphalt concrete layer on the fatigue life of the road surface and the study of rut formation

The axisymmetric finite element model of the AC coverage gives the results of calculating stresses and strains close to the results obtained using the spatial finite element model, but, at the same time, requires significantly fewer computing resources. Therefore, to assess the effect of the thickness of the layer of asphalt concrete on the fatigue life of the road surface, it was the axisymmetric finite element model that was chosen (Figure 8). It is used to analyze the durability of AC coatings using fracture mechanics methods.

The load from a car wheel in this model was transferred to the coating through a circular contact area with an area of 0.02 m$^2$. The contact pressure was taken to be 0.83 MPa. The calculated scheme of the load on the asphalt concrete pavement from the vehicle (trailer) is shown in Figure 9a.

At a trailer speed of 80 km/h, the load versus time can be represented as shown in Figure 9b. It was assumed that the repeated passage of the trailer took place 30 seconds after the previous one. Base layers were considered as linearly elastic bodies. The material of the AC layer was assumed to be viscoelastic. To determine the fatigue life of the AC coating, a crack propagation calculation method was used, known as the Virtual Crack Closure Technique.
Figure 8. Axisymmetric finite element model of asphalt concrete pavement created in the Marc® and Mentat® finite element package

Figure 9. Design diagram of the load on the asphalt concrete pavement from the vehicle (trailer): a) - load diagram; b) - for a trailer speed of 80 km / h
As a result of the numerical experiment, it was found that for relatively thin AC coatings 5 and 10 cm thick, fatigue cracks appear on the lower edge of the AC layer and develop from bottom to top. At the same time, for relatively thick AC coatings with a thickness of 15 and 20 cm, fatigue cracks appear on the upper edge of the AC layer and develop from top to bottom.

![Figure 10. Crack position corresponding to 1.10491×10^7 loading cycle of AC coating](image)

These results are consistent with the results of studies by other authors. As an example, illustrating the results of calculations of the fatigue life of AC pavements under the action of a transport load, the results obtained for a road surface with an AC layer thickness of 10 cm are presented.

Figure 10 shows the crack position corresponding to the 11.10491×10^7 loading cycle of the AC coating. Deformations for clarity of figures are increased by 1000 times. The results of studying the dependence of the durability of the AC coating on the thickness of the AC layer are presented in the form of a graph shown in Figure 11.

![Figure 11. Graph of the dependence of the durability of the AC coating on the thickness of the AC layer](image)

It follows from this graph that the durability of the AC coating increases with an increase in the thickness of the AC layer, and the relationship between the thickness of the AC layer and the durability of the coating can be approximated by a polynomial of the 2nd degree (red curve): 

\[
 y = 1E+07x^2 - 2E+07x + 1E+07
\]

\[R^2 = 1\]
with an approximation reliability $R^2 = 1$.

Within the framework of the axisymmetric task (Figure 8), the issue of the appearance of a rut in the asphalt concrete pavement under the action of a cyclic load that changes over time was also considered in accordance with Figure 9.

**Figure 12.** Fragment of the FE model, reflecting the distribution of the residual vertical displacements of the surface of the asphalt concrete pavement after 1000 load cycles (the displacements are increased by 10000 times for the clarity of experiment)

**Figure 13.** Comparison of service life up to the formation of the maximum track depth of 6.35 mm, obtained by the mechanical-empirical method (MEPDG) (green curve) and using the FE package MARC-MENTAT (red curve)
Figure 12 shows a fragment of the FE model showing the distribution of the residual vertical displacements of the surface of the asphalt concrete pavement after 1000 load cycles.

The results reflecting the increase in the track depth in the asphalt pavement depending on its service life are shown in Figure 13.

The maximum track depth is considered to be 6.35 mm (horizontal blue line).

The red curve practically coincides with a similar curve constructed in [6] based on the results of calculations in the ABAQUS finite element package. A significant discrepancy between the results found by the mechanical empirical method (MEPDG) and the finite element method, in [7], is explained by the lack of consideration in the finite element model of the viscous plastic properties of asphalt concrete and the mechanisms of structural destruction of the material.

5. A model for studying the effect of the asphalt concrete bearing layer on the deformations of the ballastless topside of the railway track

In modern operating conditions of railway tracks with an increase in the speed of rolling stock, axle load, an increase in the mass and length of trains, one of the main problems is the deformability of the track. The use of a ballastless structure - a ballastless track superstructure (BTSP) - is one of the options for increasing track stability.

The results of long-term monitoring show that the load-bearing layer of asphalt concrete in the BVSP structure reduces deformation of the subgrade, which has a beneficial effect on reducing the cost of the life cycle of railway equipment.

The Moscow-Kazan-Yekaterinburg high-speed rail structure was taken as the basis for creating a FE model of the high-speed rail with BTSP and a carrier layer of asphalt concrete, which, in turn, is based on the ballast-free structure of the superstructure of the CRTS III (China Railway Track System III) track, developed in China.

The task of creating a digital model for studying the operation of the asphalt concrete layer of BTSP was proposed by N.V. Bystrov.

The spatial model of the ballastless rail track structure created in the licensed FE complex Ls-Dyna is shown in Figure 14.

![Figure 14. Spatial image of the FE model of a ballastless railway track](image)

The calculation results are presented in Figures 15 and 16.

The vertical displacements of the base of the BTSP with an asphalt concrete layer thickness of 30 cm at a time instant of 0.071999 seconds are shown in Figure 15. Graphs showing how the maximum
deflections of the foundation slab varied over time depending on the asphalt concrete layer thickness are shown in Figure 16.

Figure 15. Vertical displacements of the BTSP base with a layer of asphalt concrete of 30 cm at a time of 0.071999 sec. The movements are enlarged 5000 times for the clarity of experiment.

Figure 16. Graphs of the vertical displacements of the foundation slab versus time for the thickness of the asphalt concrete slab: A-0 cm; B-10 cm, C-20 cm, D-30 cm.

In accordance with work [8], it is assumed that the maximum displacement for the lower edge of the foundation slab is 0.5 mm, then the maximum displacement equal to 0.576 mm (Figure 16), obtained for the construction of a railway track without a layer of asphalt concrete, exceeds the permissible by 15.2%.
However, even with a 10 cm thick layer of asphalt concrete in the railway track structure, the maximum displacement of the bottom edge of the foundation slab becomes 0.458 mm, which is 8.4% less than the permissible displacement. With the thickness of the asphalt concrete layer equal to 30 cm, the maximum displacement of the lower edge of the foundation slab becomes 0.321 mm, which is 35.8% less than the permissible displacement.

6. Conclusion
The task of creating progressive technologies for road construction requires the development of new methods of computational and design analysis based on computer technologies and modern methods of mechanics, considering the complex, physically and geometrically nonlinear nature of the problems being solved, the peculiarities of the operation of multilayer road structures and the cyclical nature of transport loads. At present, the methods of fracture mechanics are widely used abroad in the study of the stress-strain state of road structures. In this case, any impacts, both transport and climatic, are considered.

The results obtained by various researchers have not yet been reflected in foreign regulatory documents, but judging by the intensity of the development of this direction in recent years, the norms for the calculation and design of road structures based on the use of fracture mechanics methods may appear within the next five years.

Previous studies and the latest results presented in this work on the application of the finite element method (FEM) for modeling the loading and destruction of structures of multilayer pavements, performed at the Department of Construction Mechanics, MADI, have shown the effectiveness of this method, including for digital modeling of roads with asphalt concrete pavement.

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