JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2017; 4 (2): 206–214

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jtte

Original Research Paper

# Application of semi-analytical finite element method to analyze asphalt pavement response under heavy traffic loads

*Pengfei Liu* [a], *Dawei Wang* [a,b,*], *Markus Oeser* [a]

[a] *Faculty of Civil Engineering, RWTH Aachen University, Aachen 52074, Germany*
[b] *Faculty of Civil Engineering, University of Siegen, Siegen 57076, Germany*

## HIGHLIGHTS

- SAFEM is able to fast and accurately predict asphalt pavement structural responses.
- The responses of asphalt pavement under heavy traffic loads are analyzed.
- The surface deflection is sensitive to the change of axle load.
- The compressive stress in asphalt binder course increases more significantly.

## ARTICLE INFO

*Article history:*
Available online 7 March 2017

*Keywords:*
Asphalt pavement response
Heavy traffic loads
SAFEM
Deflection
Stress
Fatigue

## ABSTRACT

Accurate assessment of the impact of heavy traffic loads on asphalt pavements requires a computational model which is able to calculate the response of the pavement fast and precisely. Currently the most finite element analysis programs based on traditional methods have various limitations. A specific program SAFEM was developed based on a semi-analytical finite element method to overcome the problems. It is a three-dimensional FE program that requires only a two-dimensional mesh by incorporating the semi-analytical method using Fourier series in the third dimension. The computational accuracy and efficiency of the program was verified by analytical verification previously. The experimental verification is carried out in this paper and the results show that the SAFEM is able to predict the mechanical responses of the asphalt pavement. Using the program SAFEM, the impact of heavy traffic loads was analyzed in terms of stress and strain distribution, surface deflection and fatigue life. The results indicate that if the asphalt pavement is subjected to the heavy traffic load more, the thicknesses and stiffness of the pavement structural layers should be increased adequately in order to support the surface deflection. The compressive stress in asphalt binder course is relatively large and increases more significantly compared with that in the other asphalt layers when the axle load

* *Corresponding author*. Faculty of Civil Engineering, RWTH Aachen University, Aachen 52074, Germany. Tel.: +49 241 80 26742; fax: +49 241 80 22141.
E-mail addresses: liu@isac.rwth-aachen.de (P. Liu), wang@isac.rwth-aachen.de (D. Wang), oeser@isac.rwth-aachen.de (M. Oeser).
Peer review under responsibility of Periodical Offices of Chang'an University.
http://dx.doi.org/10.1016/j.jtte.2017.03.003

becomes larger. With comparison of the predicted fatigue life, the increase of the axle load will lead to the destruction of the asphalt pavement extremely easily.



## 1. Introduction

In the past decades the finite element (FE) method has been developed rapidly and increasingly used in many industrial fields as well as in the routine pavement design and assessment process (Zienkiewicz and Taylor, 2000). But several limitations exist in the conventional FE packages such as ABAQUS (ABAQUS, 2011), e.g., the complexity and hence the time-consuming user training process often renders it impractical to be used by a road engineer. The specifically developed FE tools for pavement analysis usually offer the results quickly, such as GAPPS7 (Zeevaert, 1980), ILLI-PAVE (Raad and Figueroa, 1980), MICH-PAVE (Harichandran et al., 1989), FENLAP (Brunton and De Almeida, 1992), and APADS 2D (Gonzalez and Oeser, 2012), but it is difficult to simulate a pavement model with a determined scale and the complex loading condition due to oversimplifications of the modeling, e.g., from a three-dimensional (3D) condition to a two-dimensional (2D) plane strain or axisymmetric one. Therefore, it is necessary to find means that both improve the computational speed without increasing the resource requirement and offer the computational accuracy.

The semi-analytical finite element method (SAFEM) is one of the methods which can meet the requirements. For a typical pavement structure problem, the geometry and material properties usually do not vary in one of the coordinate direction, but the boundary conditions, e.g., the load terms, exhibit a significant variation in that direction. As a result, the pavement structure problem could not be simplified as a 2D plane strain case. By assuming that the displacements in the geometrical direction with the variation can be represented using a Fourier series and exploiting its orthogonal properties, the problem of such a class can be numerically solved by a series of 2D FE-meshes (Zienkiewicz and Taylor, 2005). This method is so-called SAFEM and was first developed in linear analysis by Wilson (1965). Meissner (1976) extended Wilson's work to an elasto-plastic body. Winnicki and Zienkiewicz (1979) used a visco-plastic formulation to tackle material non-linearity. Carter and Booker (1983) provided an efficient analysis of the consolidation of elastic bodies subjected to non-symmetric loading by using the continuous Fourier series. Lai and Booker (1991) successfully applied a discrete Fourier technique to analyze the non-linear behavior of solids under three-dimensional loading conditions. Further development was taken by Fritz (2002) and Hu et al. (2008), who programed specific FE codes to apply this method in problem analysis of asphalt pavements. However, their FE codes are relatively simple, e.g., only static analysis with linear elastic material properties and a total bond between pavement layers can be performed. Recently, an FE code named SAFEM with more features was developed by the authors (Liu et al., 2013, 2014, 2015, 2016). The partial bond condition between pavement layers was considered and infinite elements were applied to reduce the influence of the boundary on the computational results.

In the following sections, the mathematical basis of the SAFEM will be shortly introduced first, followed by the verification using the results derived from field measurement. With the verified program, the impact of heavy traffic loads on the asphalt pavement is analyzed in terms of surface deflection, stress and strain distribution, and fatigue life. Finally, a brief summary and conclusions are provided at the end of this paper.

## 2. Description of semi-analytical finite element method

By using SAFEM, the general form of the shape functions $N$ defining the variation of displacements $U$ can be written as a Fourier series in which $z$ ranges between 0 and $a$, as shown in Fig. 1. The pavement is assumed to be held at $z = 0$ and $z = a$ in a manner preventing all displacements in the $xy$ plane but permitting unrestricted motion in the $z$-direction (Fritz, 2002; Hu et al., 2008; Liu et al., 2013, 2014; Zienkiewicz and Taylor, 2005).

$$U = \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \sum_{l=1}^{L} \sum_{k=1}^{6} N_k \begin{bmatrix} \sin\left(\frac{l\pi z}{a}\right) & 0 & 0 \\ 0 & \sin\left(\frac{l\pi z}{a}\right) & 0 \\ 0 & 0 & \cos\left(\frac{l\pi z}{a}\right) \end{bmatrix} \begin{bmatrix} u_k^l \\ v_k^l \\ w_k^l \end{bmatrix} = \sum_{l=1}^{L} N^l U^l \tag{1}$$

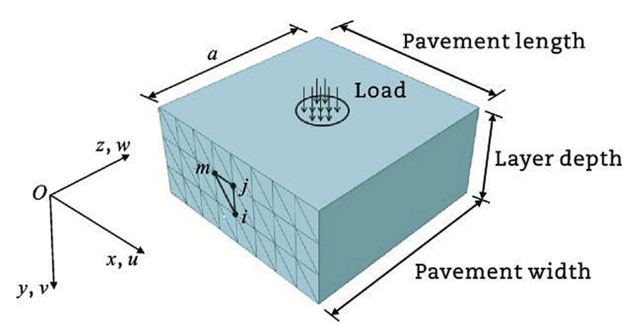


**Fig. 1 – Schematic representation of a SAFEM situation (Liu et al., 2014).**