ENHANCED FINITE ELEMENT MODELING OF THE THERMO-MECHANICAL RESPONSES OF JOINTED PCC PAVEMENTS UNDER ENVIRONMENTAL AND TRAFFIC LOADS

MOHAMMAD ALI ZOKAEI ASHTIANI

Department of Civil Engineering

APPROVED:

Cesar J. Carrasco, Ph.D., Chair

Soheil Nazarian, Ph.D.

Carlos Martin Chang-Albitres, Ph.D.

Pavana Prabhakar, Ph.D.

Lev Khazanovich, Ph.D.

Bess Sirmon-Taylor, Ph.D.
Interim Dean of the Graduate School

Dedication

To my love, Hoda

To my wonderful parents, Behnaz and Hedayat

ENHANCED FINITE ELEMENT MODELING OF THE THERMO-MECHANICAL RESPONSES OF JOINTED PCC PAVEMENTS UNDER ENVIRONMENTAL AND TRAFFIC LOADS

by

MOHAMMAD ALI ZOKAEI ASHTIANI, MSCE

DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

Department of Civil Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2014

Acknowledgements

I owe my deepest gratitude to the kind people that writing and completion of this doctoral dissertation would not have been possible without their help and support.

I would like to sincerely express my gratitude to my advisor, Dr. Cesar Carrasco, for his excellent guidance, support and encouragement. I would also like to thank Dr. Soheil Nazarian for his support and for giving me the opportunity to work on this research work at the Center for Transportation Infrastructure Systems (CTIS). I highly appreciate their great ideas in developing this research and providing me with invaluable feedbacks and comments.

My gratitude extends to my committee members, Dr. Carlos Chang, Dr. Pavana Prabhakar and Dr. Lev Khazanovich. Their feedback gave me a better insight into the quality of this work and future developing it.

I want to acknowledge the funders of my research project (NYPAS), Federal Highway Administration and New York Department of Transportation, especially Dr. Julian Bendaña.

I would like to thank all the staff at CTIS, especially Dr. Cesar Tirado who helped me in developing this project, and Dr. Imad Abdallah the coordinator of CTIS. I also would like to thank all of the graduate and undergraduate students who helped me in completion my research work.

I want to thank my father, Dr. Hedayat Zokaei Ashtiani, for his eternal encouragement and support through my life, my mother, Behnaz Gouya, for her continuous understanding and endless kindness and patience and my lovely brothers, Amin and Milad, for always having my back. I am especially thankful to my wonderful wife, Dr. Hoda Azari, for her love, encouragement, support and understanding.

Abstract

Jointed plain concrete pavements (JPCP) are the most commonly used type of rigid pavement systems and the accurate modeling of their thermo-mechanical responses is of primary importance in a mechanistic-empirical pavement design procedure. In JPCP, the temperature gradient and resulting slab shape play a crucial role in the magnitude of stresses and deflections caused by the superimposed traffic loads. Temperature gradients through the slab depth can produce thermal curling in slabs and can also produce slab expansion and contraction, which leads to the generation of frictional tractions between slabs and foundation. The prediction of these frictional tractions is complicated by the curling of the slabs that causes some portions of the slabs to lose contact with the foundation. From the initial development of pavement analysis software in the early 1970's, it was recognized that the finite element (FE) method was the most appropriate modeling tool, due to its potential ability to capture all the pavement response features. A series of software development efforts have culminated in the production of NYSLAB, a jointed pavement analysis tool that has the capability to predict the complete thermo-mechanical responses, due to the combined effect of environmental and vehicular loads. This dissertation presents a series of studies conducted toward developing an improved FE-based model to be used in the source code of NYSLAB. A complete review of characteristics and mechanistic behavior of components of JPCP is provided. Detailed mathematical models of pavement slabs, load transfer devices and foundation layers developed in NYSLAB are presented. In addition, the implementation of "interface elements" used to model the contact between pavement layers is included. These elements have the ability to capture the separation and sliding between pavement layers, due to thermal loads, and calculate the frictional traction at their interface. Finally, a series of parametric studies was carried out to determine that the governing equations that were used to idealize the behavior of JPCP in NYSLAB have been accurately selected and implemented in the FE model. The results presented in these studies highlight the capabilities of NYSLAB in modeling and considering the most important factors that affect the prediction of the stresses and strains produced in concrete slabs.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Scope of Study

This study is mainly involved with the development of analytical and numerical procedures to evaluate rigid pavement responses subjected to vehicular loads and environmental conditions. The principle effort to be used for this analytical model development will focus on (1) the reliability of employed theories (2) feasibility of numerical methods and (3) applicability of the model consistent with the actual behavior of rigid pavements in the field.

The structural model of a rigid pavement system can be represented as a slab placed over an elastic foundation. An analysis of this type of structural system brings to light several applications of structural and geotechnical theories. The primary concern of pavement engineers is to detect and evaluate pavement behavior under different possible conditions. The goal of this evaluation is to explore and utilize the best possible options for simulating the pavement structure to predict their performances. This study is concerned with a comprehensive review of literature about the characteristics and mechanistic behavior of rigid pavements, the level and type of applied loads and analytical or experimental pavement analysis methods. The literature examines the identification and incorporation of structural theories (e.g. Theory of elasticity, plate theory), geotechnical theories (soil models) and soil-structure contact problems in the modeling of rigid pavements.

1.2 Problem Statement

Jointed plain concrete pavements (JPCP) are the most commonly used type of rigid pavement systems and the accurate prediction of their thermo-mechanical responses, due to the combined effect of environmental and traffic loads, are of primary importance for rigid pavement designers in a mechanistic-empirical pavement design procedure. Surface Portland cement concrete (PCC) slabs in JPCP often curl due to the effect of seasonal and daily temperature variations throughout the slab depth, which plays a critical role in the magnitude of stresses imposed by traffic loads. Field measurements reveal that the actual temperature gradient through the PCC slab depth is nonlinear (Ioannides *et al*., 1998; Choubane *et al*., 1992, Ashraf *et al*., 1996). This nonlinear thermal gradient can not only produce curling and expansion or contraction in slabs but actually leads to stresses that are higher than those

produced by a linear gradient with the same top to bottom temperature difference. While thermal curling tends to produce bending stresses in the slabs, because of slab-foundation interaction and slab self weight, the uniform thermal expansion or contraction tends to produce additional compressive or tensile stresses within the slabs, due to friction in slab-foundation interface. Therefore, in addition to the stiffness of PCC slabs and the level of applied loads, the stiffness of the underlying foundation layers and the contact conditions along the slab-foundation interface significantly impact the mechanical behavior of PCC pavements. Interface friction introduces nonlinearity and complicates the analysis of PCC pavements. A sophisticated modeling method, such as finite element (FE) modeling, is required to accurately idealize the slab-foundation contact conditions, which is impacted by temperature induced curling (separation) and expansion or contraction (sliding) in the PCC slabs (Zokaei Ashtiani *et al.*, 2013).

Since the development of ILLI-SLAB in 1979, significant amount of research and development have been conducted to improve the capabilities of jointed pavement analysis tools. These accomplishments have culminated in some software packages such as JSLAB, ISLAB, and EverFE with the capability to analyze jointed pavements under self-weight, traffic and thermal loads. JSLAB and ISLAB incorporate two-dimensional (2D) FE models based on the plate-on-grade idealization. Even though the 2D tools have undergone several improvements, the underlying core of the software still maintains the formulation of the initial ILLI-SLAB source code, which was created when computer resources were limited. The limitations affected the maximum number of pavement layers and jointed PCC slabs that can be modeled, because their software developers had to implement algorithms with the minimum need of computer memory. The limitations also affected the number of elements that can be considered in the model generation and analysis. Even further restrictions appeared in the type of applied loads and the contact conditions, which in turn reduced the applicability of those tools in realistic analysis of rigid pavement systems. Modeling the contact between slab and foundation was limited to the vertical contact (separation), and modeling the horizontal or frictional contact (sliding) was not achievable in those tools. Moreover, thermal analysis of jointed slabs was unattainable in case of continuous foundation models. Three-dimensional (3D) FE analysis tools, such as EverFE, models

the slab more accurately and allows for the interpretation of detailed responses throughout the slab thickness. However, the number of elements, and consequently the number of degrees of freedom, which is needed to accurately model plates (slabs) in 3D analysis are substantially larger than those used in 2D plate analysis. For this reason modeling multi-slab pavement sections in EverFE is computationally intensive. A thorough review of existing rigid pavement analysis tools revealed that it would be beneficial to redesign these software completely by taking advantage of modern computer resources and the finite element modeling techniques available today. Identifying and understanding the potentials, limitations and applicability of current analysis tools, a new analysis tool is required to significantly enhance the efficiency and capabilities of FE-based jointed concrete pavement models.

1.3 Objectives of Research

The primary purpose of this research is to evaluate and improve existing rigid pavement analysis tools and develop a new tool that is able to analyze complete thermo-mechanical responses of jointed concrete pavements. The analytical tool must be able to realistically predict the stresses, strains, and displacements of the concrete slab and its supporting layers due to possible traffic and environmental loads, and make use of them in the design of the pavement system. For this reason, a new analysis tool, named NYSLAB, was developed at the University of Texas at El Paso. The NYSLAB source code was built up in MATLAB®, which has an interactive environment for numerical computation and programming. Matrix creation and calculation, which are necessary in the FE analysis, is quite feasible in MATLAB®. The specific objectives of this study and the corresponding approaches are described as follows:

1. *Finite element modeling of concrete slabs*. NYSLAB incorporates 2D FE modeling by considering the pavement section as a thin to medium-thick plate (slab) resting on an elastic foundation system. The first step in developing NYSLAB will be toward getting familiar with the plate and shell theories to model concrete slabs. To model multi-layer pavement slabs with different material property and thickness, which are bonded at their interface, the theory of laminated plates will be utilized. It is imperative that the finite element model accounts for all degrees of freedom needed to idealize the actual behavior of PCC slabs. The major variables that characterize the slab deformation

are the vertical deflection, the rotations about the slab longitudinal and transverse axes and the in-plane or horizontal displacements in the longitudinal and transverse directions. Appropriate slab modeling can be attained by employing such a structural theory that is able to estimate the responses that have significant impacts on rigid pavements performance. For instance, if the design of slab is intended to estimate the fatigue cracking, bending stresses are the main parameters. In this case, the incorporated plate or laminated plate theories should be able to calculate bending stresses and strains accurately throughout the slab thickness. An appropriate plate element with five degrees of freedom per node will be introduced to model the PCC slabs.

2. *Finite element modeling of load transfer devices*. The process of modeling the load transfer elements (dowels, ties, key and aggregate interlock) in NYSLAB, that are used to connect adjacent slabs in a JPCP system, will be examined. Moreover, the impact of horizontal interaction between the jointed slabs, due to thermal expansion and contraction, will be investigated. "Linkage elements" will be developed to capture this impact.
3. *Implementation of thermal and traffic loads in NYSLAB*. The major loads that rigid pavements are subjected to during their life are examined in this study. The procedure of implementation of nonlinear temperature gradient, built-in temperature gradient and tire loads to the FE model in NYSLAB will be explained.
4. *Finite element modeling of foundation*. The next step in modeling rigid pavements is the simulation of foundation or slab supports. In this manuscript all the existing foundation models (solid elastic, dense liquid and two or three parameter foundation) and their mathematical model will be reviewed. Moreover, a new procedure for determining the Vlasov foundation (Vlasov et al. 1966) parameters for one and two-layered foundation systems will be introduced and an iterative process for that purpose will be implemented in the source code of NYSLAB.
5. *Finite element modeling of contact between pavement layers*. One of the principal contributions of this research study is devoted to the modeling of contact between pavement layers (e.g. between concrete slabs and foundation or among unbonded concrete slabs). Separation and sliding of concrete slabs at the slab-foundation interface, due to thermal loads, are significant occurrences that

have great impacts on the slab responses in the analysis of rigid pavements. The first step in modeling contact is to identify the contact condition and frictional characterization of the interface and propose an appropriate constitutive friction law. The second step is to develop a finite element procedure and propose an interface element to simulate the contact at the pavement layer's interface.

6. *Parametric study*. A series of parametric studies will be carried out using NYSLAB to determine whether the governing equations that were used to idealize the behavior of jointed concrete pavements in NYSLAB have been accurately selected and implemented in the FE model. The parametric studies in this manuscript also attempts to provide better understanding of the interaction between the most relevant parameters that govern the performance of JPCP. The studies include the "Effect of nonlinear temperature gradient on responses of JPCP", "Effect of slab-foundation friction on responses of JPCP", "Impact of different approaches to modeling rigid pavement base layers on slab curling stresses", and "Effect of loss of support due to built-in curling on PCC slab stresses".

1.4 Significance of Study

The contribution of this research study to the field of pavement engineering is a thorough investigation of the potentials and limitations of rigid pavement analysis methods, in order to develop an improved finite element model for the analysis and design of jointed concrete pavements. Developing an advanced procedure to capture the separation and sliding of concrete slabs at their interface with the foundation (during daily temperature variations) and calculating the frictional stresses are the first known instances in modeling thermo-mechanical behavior of JPCP. Even though the mathematical model of foundations developed in NYSLAB is not the first attempt in this manner, the improved Vlasov foundation model in this tool allows for analyzing a pavement system with multiple jointed PCC slabs subjected to thermal loads, which was a missing link in other existing analysis tools. In addition, determining the Vlasov parameters is feasible through an iterative procedure in NYSLAB. Using laminated plate theory to model bonded slabs and developing interface elements between unbounded pavement layers, the developed model has the potential to analyze rigid pavement systems with any bonding or contact conditions. The parametric studies in this manuscript are the first known studies that employ finite element analysis and use real pavement properties (e.g., the dimensions and the stiffness

of pavement layers, slab-foundation friction and thermal and truck loads) to investigate the effect of friction between pavement layers, the effect of base layer rigidity, and the effect of loss of support due to built-in curling in estimating the PCC slab stresses. Accurate estimation of stresses produced in PCC slabs will be beneficial for pavement designers to predict the location and the time of generation of fatigue cracking. The completed analysis tool developed in this study will be a state-of-the-art tool that can be used by transportation agencies and engineers around the United States and the world to more realistically design and analyze pavements. Researchers can also use this tool to better understand the mechanistic behavior of rigid pavements to apply in the AASHTO Mechanistic-Empirical Pavement Design Guide.

1.5 Structure of the Dissertation

Chapter 2 provides a thorough review on the structures of rigid pavement systems and the available methods and tools for their design and analysis. The Laminated plate theories and their application in modeling pavement slabs are introduced. The functionalities of load transfer elements for connecting jointed slabs and the available modeling methods for simulating them are included. Different foundation models for idealizing the soil domain are reviewed. Lastly, an overview of the attempts on modeling contact between dissimilar bodies is presented. Chapter 3 explains the detail of the laminated plate theory and the plate element that used in NYSLAB to model the PCC slabs. The elements used for modeling the load transfer devices are introduced. Moreover, the procedure of applying the tire and thermal loads in the finite element model is presented. Chapter 4 provides the mathematical model of different foundation idealization used in NYSLAB. The process of calculation of foundation parameters is also included. Chapter 5 discusses the modeling of contact between pavement layers. A constitutive model and interface elements are introduced to demonstrate the frictional characteristics of pavement layers interface. The algorithm for the calculation of frictional stresses in the finite element analysis of rigid pavement systems in NYSLAB is described. Chapter 6 demonstrates a summary of the mathematical model of rigid pavement systems in NYSLAB. Chapter 7 presents the results of several parametric studies on the effect of different factors on the PCC slab stresses. Chapter 8 presents a

summary and conclusions of this research study. It also states the limitations of the developed tool and provides recommendations for future studies.

Chapter 2: Theoretical Background

This chapter contains the review on the structural elements of rigid pavement systems and an evaluation of the existing methods for modeling and analyzing jointed concrete pavements.

2.1 Rigid Pavement Analysis

This section is devoted to identifying the functionalities of rigid pavement systems and evaluating the available concepts for their design and analysis. Moreover, the applicability of available rigid pavement analysis tools will be examined and a new analysis tool, named NYSLAB, will be introduced.

2.1.1 Rigid Pavement System

Rigid pavement systems consist of a number of Portland cement concrete (PCC) slabs placed over one or more foundation layer(s) (base, sub-base, and subgrade). In a rigid pavement system, the PCC slab is the stiffest structural element that provides major bearing capacity against the applied loads. Pavement slabs can be composed of layers with different material property and thickness, with the interface between them considered either bonded or unbonded. The slab layers are usually placed over an unstabilized or stabilized base course. Unstabilized or unbound base courses may be composed of densely graded or open-graded granular materials. Stabilized bases are usually composed of granular materials bounded with Portland cement, asphalt, lime or fly ash blend, or other agents. Base layers can also contribute to the load resistance system. However, their main roles (as defined in some design guides) are to provide a uniform support for pavement slabs, contribute to the subgrade drainage and frost protection, improve the foundation strength, and prevent subgrade pumping (Hammons and Ioannides, 1997). One or more sub-base layer may also be used in the pavement foundation system. Sub-bases are usually made with lesser quality granular materials to replace soft and compressible soils. In addition, they can provide strength to the pavement system and offer frost and swelling protection. The last layer in a rigid pavement system is subgrade, which is either natural or compacted soil. The subgrade strength property is represented by resilient modulus, which is a function of soil classification, compaction and moisture content.