USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No. 041IY02

Thermal Cracking Performance Prediction and Asset Management Integration

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USDOT Region V Regional University Transportation Center Final Report

TECHNICAL SUMMARY

NEXTRANS Project No. 041IY02 Final Report, March 2011

Thermal Cracking Performance Prediction and Asset Management Integration

Introduction

With shrinking maintenance budgets and the need to 'do more with less,' accurate, robust asset management tools are greatly needed for the transportation engineering community. In addition, the increased use of recycled materials and low energy production techniques such as warm-mix asphalt are leading to increased needs for preventive and rehabilitative maintenance activities. The timing of such activities will greatly affect the total discounted life-cycle cost of the pavement system. Low-temperature cracking of hot-mix asphalt (HMA) pavements continues to be a leading cause of premature pavement deterioration in regions of cold climate and/or where significant thermal cycling occurs. Recent advances in fracture testing and modeling of hot-mix asphalt (HMA) materials have greatly aided in the understanding of the key mechanisms behind this important pavement distress, which can greatly reduce pavement lifespan and the lifespan of subsequent rehabilitation cycles. However, there is a need for implementation of new models into a standalone program which can be readily utilized by researchers and practitioners. Moreover, the complete integration of material selection, material design, pavement design and pavement performance into a more holistic asset management system has been hampered by the lack of accurate, user-friendly performance prediction models for pavements.

The objective of this project was to complete the development of a user-friendly interface that provides simplified access to sophisticated low-temperature cracking prediction models. This stand-alone program will greatly accelerate the transfer of this technology to practitioners and other interested scientists and engineers (pavement designers, analysts, and researchers). The program is designed to be compatible with the existing thermal cracking model used in the Mechanistic Empirical Pavement Design Guide (MEPDG), and with the new thermal cracking model being developed under the National Pooled Fund Study on Low Temperature Cracking. As part of this report, the key developments associated with the new mechanics-based thermal cracking model are presented. The funding provided by this NexTrans supplement allowed the development of the thermal cracking software to include aspects which will facilitate its seamless integration into an overarching pavement management software program.

Findings

A stand-alone low temperature cracking analysis program developed under this project and the National Pooled Fund Study on Low Temperature Cracking is presented in this report. Details on various components of the analysis modules were presented, including: mesh generation, viscoelastic pavement response calculation and finite element implementation of the numerical time-integration scheme, and pavement distress (thermal cracking) simulation via cohesive zone finite element modeling. The theoretical background for the finite element analysis program are also briefly presented in Chapter 2. The major components of this model were found to match reference solutions in the verification studies conducted. In order to make this comprehensive simulation model accessible to practitioners and other researchers, a user-friendly graphical user interface was developed, called 'Visual LTC.' Visual LTC, presented in Chapter 3, was written with the object-oriented programming language C# under Microsoft's .NET framework. The key programming steps required to produce Visual LTC were also documented in this report. Finally, Chapter 4 presents a recently developed framework for the integration of mechanics-based pavement distress prediction into a comprehensive asset management system, which will be continued in the upcoming phase III research activities of this project.

Recommendations

The next step in this research will involve the integration of the mechanics-based pavement distress prediction into a comprehensive asset management system. The first step will be to develop an integrated framework that links the new TCMODEL program with actual pavement cracking, distress and roughness, and to develop a framework that links the pavement roughness and distress information with vehicle maintenance and driver comfort. The proposed framework will also undertake the goal of extending fundamental predictions of pavement cracking distress to the prediction of pavement roughness and other forms of deterioration (crack spalling, potholes) as a function of pavement maintenance, traffic, and climate. This will lead to the development of an integrated model linking infrastructure condition to vehicle wear-and-tear and to driver safety.

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CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

With shrinking maintenance budgets and the need to 'do more with less,' the need for accurate, robust asset management tools are greatly needed for the transportation engineering community. Furthermore, increases in traffic intensity, vehicular loads, and truck tire stiffness are placing additional 'pressure' on pavements across the United States. Finally, modern practices in crude petroleum refining, such as 'coking', are squeezing more high energy products out of each barrel of crude, and the increased use of recycled materials and low energy production techniques such as warm-mix asphalt are leading to increased needs for preventive and rehabilitative maintenance activities. The timing of such activities will greatly affect the total discounted life-cycle cost of the pavement system.

Low-temperature cracking of hot-mix asphalt (HMA) pavements continues to be a leading cause of premature pavement deterioration in regions of cold climate and/or where significant thermal cycling occurs. Recent advances in fracture testing and modeling of hot-mix asphalt (HMA) materials have greatly aided in the understanding of the key mechanisms behind this important pavement distress, which can greatly reduce pavement lifespan and the lifespan of subsequent rehabilitation cycles. While new tests and models represent powerful tools for the design of more reliable, more sustainable flexible pavement systems, there is a need for implementation of the models into a standalone program which can be readily utilized by researchers and practitioners. Moreover, the complete integration of material selection, material design, pavement design and pavement performance into a more holistic asset management system has been hampered by the lack of accurate, user-friendly performance prediction models for pavements. This research provides two of the critical links needed to move this integrated approach to the state of practice (development of mechanics-based thermal cracking model and development of user-friendly graphical-user interface), and presents a framework for the next phase of research needed in the development of this comprehensive, mechanics- and performance-based asset management model.

1.2 Relation to NexTrans Objectives

The scope of this work is within the vehicle-infrastructure research pillar of the NexTrans center. This research is geared towards development of an integrated solution scheme that incorporates short-term and long-term pavement performance solutions through advanced research. The overall objective is to deliver a stand-alone user-friendly tool to highway designers for design of thermal cracking resistant asphalt pavements. This tool will greatly facilitate the design of economical pavement systems and the utilization of modern material formulations and construction techniques that are environmentally friendly and sustainable, such as the use of very high amounts of recycled materials and the use of low energy/low emission warm mix technologies. In addition, mechanics- and performance-based asset management model framework can be readily extended to include other critical pavement distress types, such as rutting, fatigue cracking, reflective cracking, and moisture damage.

1.3 Objectives

The objective of this work was to complete the development of a user-friendly interface that provides simplified access to sophisticated low-temperature cracking prediction models. This stand-alone program will greatly accelerate the transfer of this technology to practitioners and other interested scientists and engineers (pavement designers, analysts, and researchers). The program is designed to be compatible with the existing thermal cracking model used in the Mechanistic Empirical Pavement Design Guide (MEPDG), and with the new thermal cracking model being developed under the National Pooled Fund Study on Low Temperature Cracking. As part of this report, the key developments associated with the new mechanics-based thermal cracking model are presented. The funding provided by this NexTrans supplement allowed the development of the thermal cracking software to include aspects which will facilitate its seamless integration into an overarching pavement management software program.

1.4 Organization of this Report

The remainder of this report is organized as follows:

- Chapter 2: Low Temperature Cracking Model for Asphalt Pavements – This chapter summarizes the key elements of the new, mechanics-based thermal cracking model, including the automated mesh generator, viscoelastic pavement response model, and cohesive zone fracture model.
- Chapter 3: Visual LTC: A Graphical User Interface for Low-Temperature Cracking Analysis – This chapter provides an in-depth summary of the newly developed GUI for the mechanics-based thermal cracking model, along with illustrative examples to provide a sense of the GUI's 'look and feel'
- Chapter 4: Development of Framework for Asset Management Integration – This chapter presents the results of a series of collaborative meetings between pavements and systems faculty at the University of Illinois, leading to the development of a framework for the integration of the newly developed thermal cracking software into a comprehensive asset management system. In addition, details pertaining to the next proposed phase of research are presented, which will focus on the extension of the thermal cracking amount prediction to include severity and its effect on pavement roughness, vehicle wear and tear, and safety.
- Chapter 5: Summary – A summary of the completed research in Phase II and upcoming research tasks in Phase III are presented.

CHAPTER 2. LOW TEMPERATURE CRACKING MODEL FOR ASPHALT PAVEMENTS

This chapter introduces a new stand-alone low temperature cracking analysis program developed around a cohesive zone fracture model. Section 2.1 introduces the analysis program along with the major components as well as the overall flow of information and data. Section 2.2 describes the input file generator for the finite element analysis code. Section 2.3 discusses the details on the formulation of viscoelastic and cohesive zone finite elements. Section 2.4 summarizes the low temperature cracking model.

2.1 Introduction

In order to tackle thermal cracking distress from a design perspective, the most widely accepted pavement design guide in United States, the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG), utilizes a one-dimensional viscoelastic analysis program with a Paris law cracking criteria based on linear elastic fracture mechanics (LEFM). The aforementioned thermal cracking analysis program (commonly referred to as, TCModel) was developed in early 1990’s (Lytton et al, 1993) and relies on use of material tensile strength as the key input for linking the material behavior with low-temperature cracking performance (Roque et al, 1995a, 1995b) using Linear-elastic Fracture Mechanics (LEFM). A number of studies in recent years have demonstrated that fracture in asphalt concrete is a highly non-linear phenomenon, typically characterized as quasi-brittle behavior. This has been demonstrated through modeling (Song et al. 2006), and through laboratory experiments (Wagoner et al. 2005; Li et al. 2006) amongst others. TCModel does not capture these type of material failure behaviors. Furthermore, the crack propagation model in TCModel is based on Paris law (Paris et al., 1961), which is a phenomenological model for linking structural response to pavement failure.

An accurate model is necessary to design asphalt concrete pavements that are resistant to thermal cracking. The model must represent the time and temperature dependent viscoelastic material behavior and capture the nonlinear fracture behavior of quasi-brittle materials. Cohesive zone fracture models allow for accurate and efficient representation of the quasi-brittle fracture in asphalt concrete (Song et al. 2006), while a viscoelastic finite element analysis procedure, such as recursive-incremental scheme (Yi and Hilton 1994; Zocher et al. 1997; Dave et al. 2010) captures the rate- and temperature-dependent material behavior. Thus, a cohesive zone fracture model with a viscoelastic finite element analysis engine is a suitable analysis procedure for thermal cracking simulation in asphalt pavements. This type of procedure has been successfully utilized to model thermal cracking in various pavement test sections (Marasteanu et al. 2007; Dave et al. 2008). Previous studies have utilized commercial finite element software with user-defined cohesive zone fracture models viscoelastic material models. However, use of commercial software is a major hindrance in wide-spread deployment of such analysis procedures to public and private agencies.

The present study dealt with development of a stand-alone analysis and design software to predict thermal cracking performance of asphalt concrete pavements. The software program provides an intuitive and user-friendly graphical user interface (GUI) as a means to perform rigorous viscoelastic finite element analysis with cohesive zone modeling. The program can be divided into GUI and analysis modules. The GUI collects and compiles the input conditions provided by the user and executes various analysis modules to conduct finite element analysis as well as interpret the results. In-depth description of GUI along with details on its implementation is presented in the next chapter. The analysis modules are briefly described in this chapter.

The overall flow of program along with various inputs and outputs is graphically illustrated in Figure 2.1. As seen from the figure, the code consists of three major analysis modules, namely, the integrated climatic model, the input file generator and the finite element analysis engine. The integrated climatic model (ICM) used in the analysis program is same as that available in the AASHTO MEPDG. The ICM modulus from MEPDG is being presently utilized to generate the pavement temperature profiles. In the next phase of the project, a series of ICM simulations will be conducted to have a library of pavement temperature profiles available to the user. At last three sets of temperature profiles will be generated for each State participating in the Pooled Fund Study (sister project to this NexTrans project) for various pavement configurations. The Input File Generator module generates all necessary files for the finite element analysis engine. Finally, the Finite Element module is executed, it simulates the pavement for evaluation of thermal cracking potential. The results are read by the GUI and interpreted into user-friendly plots and tables. Subsequent sections provide descriptions of Input File Generator and Finite Element Analysis modules.

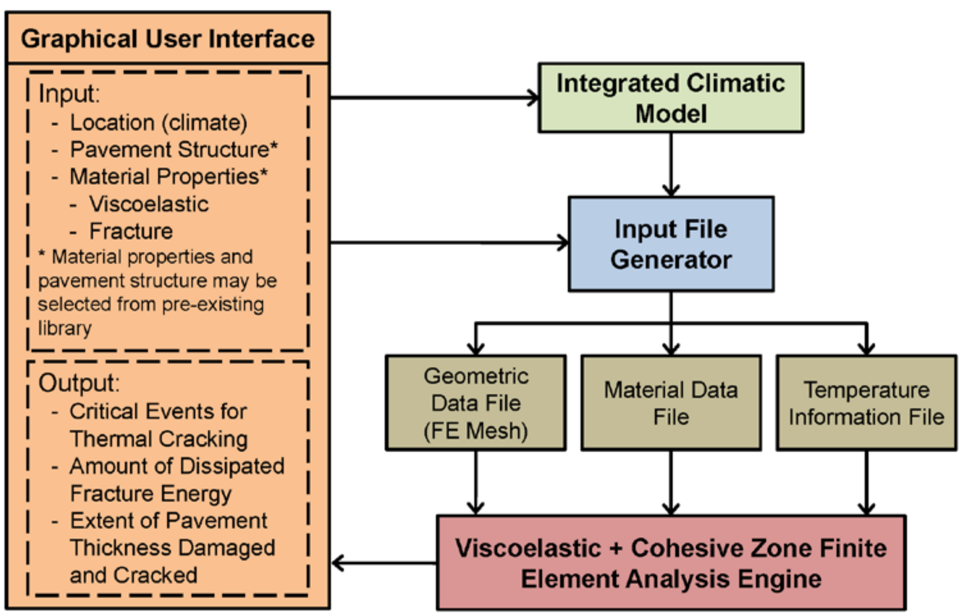
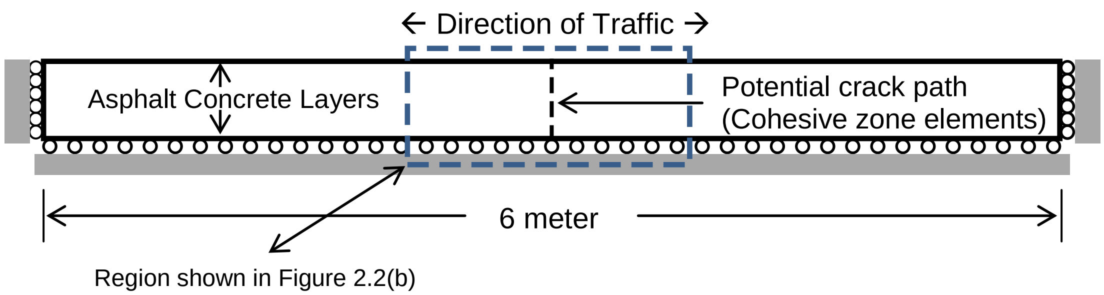


Figure 2.1. Flowchart of stand-alone low temperature cracking model.

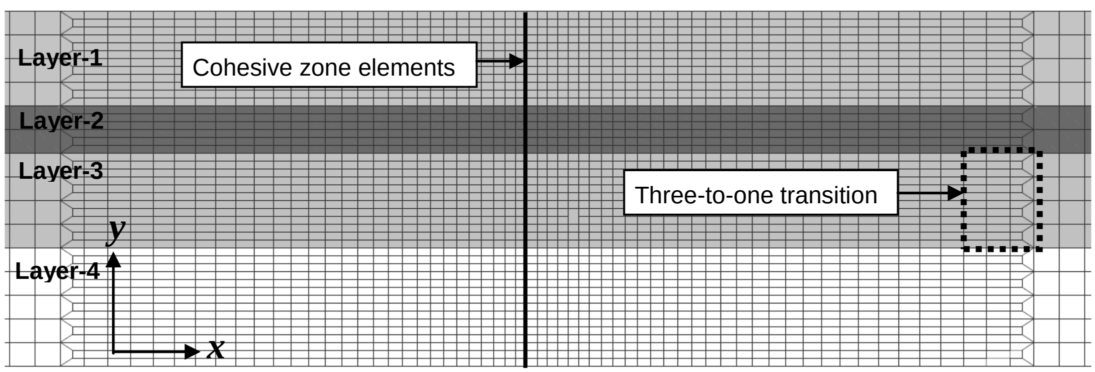
2.2 *Input File Generator*

The first task of the Input File Generator is to develop a finite element mesh for the pavement geometry selected by user. The finite element mesh consists of coordinates of the nodal points, and an element connectivity table that links node numbers to their respective elements. During the first phase of low temperature pooled fund study preliminary version of mesh generator was developed (Marasteanu et al., 2007). In the present work, this mesh generation code was significantly revised and extended to develop full pavement models, perform checks for inconsistencies in the mesh, and automatically insert interfacial cohesive elements. Based on the recommendations and findings from previous studies (Paulino et al. 2006; Dave et al. 2007), the finite element domain size 6 m is selected. The mesh generation code creates smaller elements near the potential crack path and gradually transitions them to larger size to reduce the computational costs. The finite elements near the potential crack path are generated with 4 mm edge lengths, this is also based on the recommendations from previous studies (Paulino et al. 2006; Dave et al. 2007). The code generates a finite element mesh using four node quadrilateral elements (Q4) and it automatically increases the element side lengths in the longitudinal direction of pavement (x-direction) until the relative difference be the element side lengths reach 30%. At this point the mesh generator combines the smaller elements into one larger element using a three-to-one transition scheme.

Figure 2.2 shows a typical pavement mesh with four asphalt concrete layers, including the three-to-one transition, generated using the software. The code supports multiple lifts of asphalt concrete, each with distinct material properties and thicknesses. To insert cohesive interface elements, the code traverses the mesh and generates duplicate nodes along the potential crack path. Next, cohesive zone elements are inserted and attached to the duplicate nodes. The location of cohesive elements is also illustrated in Figure 2.2.



(a) Model geometry and boundary conditions (domain size: 0.18 m by 6 m, four asphalt layers)



(b) Close-up of the mesh in vicinity of potential crack path.

Figure 2.2. Finite element model from input file generator

The second task of the Input File Generator is to create the material data file, which is primarily based on the information provided by the user. This file consists of viscoelastic (bulk) properties, the thermal expansion and contraction coefficient, and fracture properties. The list of properties utilized by the analysis code is shown in Figure 2.3.

Material Properties Required for Analysis Engine
1. Parameters for generalized Maxwell model (spring and dashpot coefficients) and reference temperature
2. Time-temperature shift factors for two temperatures other than reference temperature
3. Coefficient of thermal expansion and contraction
4. Fracture energy
5. Tensile strength

Figure 2.3. Material properties required by the analysis model

The user can either directly input the coefficient of thermal expansion and contraction (CTEC) or provide asphalt mixture volumetric properties. If volumetric properties are provided, the CTEC is estimated using the approximation equation utilized by the AASHTO MEPDG software.

In the present version of software, the user is required to provide the thermo-viscoelastic material properties in form of Prony series parameters (Generalized Maxwell model) and time temperature shift factors. The viscoelastic model coefficients can be determined by using creep testing of asphalt concrete following the AASHTO T-322 test procedure. In the next phase of this project, modifications will be made such that users can directly enter laboratory measured 1000 second creep test data from three temperatures. Tensile strength can also be determined using the AASHTO T-322 test procedure.

The fracture energy of asphalt concrete can be determined using a variety of test geometries, such as disk-shaped compact tension (DC[T]), semi-circular bend (SC[B]) and single-edge notched beam (SEN[B]) test. Currently, the model is anticipated to be calibrated and validated for the fracture energy obtained from the ASTM D7313 test procedure that utilizes DC[T] test geometry. Furthermore, the test is expected to be performed at crack mouth opening displacement (CMOD) rate of 0.0167 mm/s and at temperature of 10°C above the 98% reliability Superpave PG low temperature grade, as dictated by the project location.

Finally, the Input File Generator also provides the analysis engine with temperature loading conditions. The finite element framework requires that temperature conditions be applied at each node. Input generator uses the ICM output to generate nodal temperatures at the necessary locations and times, which are then passed to the finite element analysis engine.

2.3 Finite Element Analysis Engine

Finite element analysis is becoming increasingly popular in the design and analysis of pavements, for example, the current AASHTO design guide (MEPDG) utilizes finite element analysis for determination of critical pavement responses. The ability to model complex geometries and boundary conditions make finite element analysis well-suited for simulation of asphalt pavements. Material behavior of asphalt concrete is time and temperature dependent with hereditary response requiring the use of thermo-viscoelastic analysis.

In order to simulate the complex mechanisms underlying the thermal cracking phenomenon, a standard "strength of materials" type analysis is insufficient, due to: 1) the highly non-linear behavior in the vicinity of the crack tip, and 2) the importance of the crack in the overall structural response (i.e., the need to model thermal crack as a moving boundary value problem). The cohesive zone model provides a computationally efficient way to predict the damage occurring in a process zone located ahead of a crack tip in a material. In the present project a finite-element analysis program is being created that utilizes both, (1) bulk viscoelastic behavior and, (2) cohesive zone model. Description and formulations for each of these components are described in subsequent sub-sections.

2.3.1 **Viscoelastic Finite Element Analysis**

General viscoelastic theory can be found in several textbooks and articles, for example, Christensen (1982). A generalized Maxwell model is utilized in this study due to its flexibility in representing a wide variety of viscoelastic materials as well as the availability of established formulations in the literature. The constitutive relationship for generalized Maxwell model can be given as,

$$\boldsymbol{\sigma}(\xi) = \mathbf{E}_{\infty}\boldsymbol{\varepsilon}(\xi) + \int_0^t \mathbf{E_t}\left(\xi - \xi^{'}\right)\frac{d\boldsymbol{\varepsilon}\left(\xi^{'}\right)}{d\xi^{'}}d\xi^{'} \tag{1}$$

where $\boldsymbol{\sigma}$ is stress, $\boldsymbol{\varepsilon}$ is strain, ξ is reduced time and $\mathbf{E}_{\infty}$ is fully relaxed modulus and $\mathbf{E_t}$ is relaxation modulus for the Maxwell chains. The relaxation modulus for Maxwell units is given by,

$$\mathbf{E}_t = \sum_{m=1}^{M}\mathbf{E}_m e^{-\left(\xi-\xi^{'}\right)/\boldsymbol{\tau}_m}; \quad \boldsymbol{\tau}_m = \frac{\boldsymbol{\eta}_m}{\mathbf{E}_m} \tag{2}$$

The material parameters $\mathbf{E}_m, \boldsymbol{\eta}_m$ are spring coefficients and viscosities for the m^{th} Maxwell unit. The spring coefficients and viscosities are related through relaxation times $\boldsymbol{\tau}_m$ and the total number of Maxwell units in the model is given by M. The effect of temperature on the material properties is accounted for through use of time-temperature superposition principle. The superposition is governed time-temperature shift factor a_T which is a material property. The real time t is related to the reduced time ξ and temperature T as,

$$\xi = \int_0^t \frac{dt^{'}}{a_T\left(T, t^{'}\right)} \tag{3}$$

For isotropic conditions the above shown constitutive relationships can be re-written in form of deviatoric and volumetric stress-strain relationships as,

$$\begin{aligned} \sigma_{kk}(\xi) &= 3K_{\infty}\varepsilon_{kk}(\xi) + \int_0^{\xi} 3K_t\left(\xi - \xi^{'}\right)\frac{d\varepsilon_{kk}\left(\xi^{'}\right)}{d\xi^{'}}d\xi^{'} \\ s_{ij}(\xi) &= 2G_{\infty}\varepsilon_{ij}^{s}(\xi) + \int_0^{\xi} 2G_t\left(\xi - \xi^{'}\right)\frac{d\varepsilon_{ij}^{s}}{d\xi^{'}}d\xi^{'} \end{aligned} \tag{4}$$

where, $K_{\infty}, K_t, G_{\infty}, G_t$ are shear and bulk relaxation modulus components following the similar descriptions as shown before. The deviatoric strain components are shown by ε_{ij}^{s} and the corresponding stress components by s_{ij}, these are evaluated as,

$$s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}; \ \varepsilon_{ij}^{s} = \varepsilon_{ij} - \frac{1}{3}\varepsilon_{kk}\delta_{ij} \tag{5}$$

where, δ_{ij} is Kronecker's delta.

The time-integration approach used in this study is based on the recursive-incremental scheme developed by Yi and Hilton (1994). Similar schemes have been utilized for solving viscoelastic finite element problems by several researchers (for example, Muliana and Khan 2008). In field of asphalt concrete an incremental-recursive scheme has been utilized by Dai and You (2009) for analysis of asphalt mixtures undergoing damage in lab sized specimens.

The incremental-recursive formulations (Zocher et al. 1997) rely on determination of incremental stress components $(d\boldsymbol{\sigma})$ in response to the strain increment $(d\boldsymbol{\varepsilon})$ given by,

$$d\boldsymbol{\sigma}(\xi) = \mathbf{K}(\mathbf{x},\xi) \times d\boldsymbol{\varepsilon}(\xi) + d\boldsymbol{\sigma}^R(\xi) \tag{6}$$

where, the stiffness is given by $\mathbf{K}$ and the viscoelastic history effect is accounted through residual stress term $d\boldsymbol{\sigma}^R$. Using the constitutive relationships shown in equation (4) and recursive-incremental formulation in equation (6), the volumetric and deviatoric stress increments can be evaluated as,

$$\begin{aligned} ds_{ij}(\xi) &= 2\left[G_\infty + \sum_{m=1}^{M} \frac{G_m \tau_m}{d\xi}\left(1 - e^{-d\xi/\tau_m}\right)\right] d\varepsilon_{ij}^s(\xi) + ds_{ij}^R(\xi) \\ d\sigma_{kk}(\xi) &= 3\left[K_\infty + \sum_{m=1}^{M} \frac{K_m \tau_m}{d\xi}\left(1 - e^{-d\xi/\tau_m}\right)\right] d\varepsilon_{kk}(\xi) + d\sigma_{kk}^R(\xi) \end{aligned} \tag{7}$$

At any reduced time ξ_n the increment in reduced time $(d\xi)$ and the corresponding strain rates $(\mathbf{R})$ can be approximated as,

$$d\xi \approx \Delta\xi = \xi_n - \xi_{n-1};\ \mathbf{R} = \frac{d\boldsymbol{\varepsilon}}{d\xi} \approx \frac{\Delta\boldsymbol{\varepsilon}}{\Delta\xi}. \tag{8}$$

The residual stress can be evaluated for deviatoric and volumetric components using the approximations shown in equation (8) as,

$$ds_{ij}^R(\xi_n) = \sum_{m=1}^{M} -(1 - e^{-\Delta\xi/\tau_m}) S_m(\xi_n);\ d\sigma_{kk}^R(\xi_n) = \sum_{m=1}^{M} -(1 - e^{-\Delta\xi/\tau_m}) V_m(\xi_n) \tag{9}$$

where, symbols S_m and V_m represent viscoelastic (history) stress contributions at any given reduced time. These effects account for hereditary contributions should be tracked for each stress component throughout the entire range of time-steps used in a given simulation. Also notice that these terms are independent for each Maxwell unit in the material constitutive properties. The viscoelastic stress contributions are updated for each time increment. Using the approximate strain rate (equation (8)) and the expansion of equations (4) and (7) the viscoelastic stress contributions can be evaluated as,

$$
\begin{aligned}
S_m(\xi_n) &= 2G_m\tau_m\left(1-e^{-\Delta\xi/\tau_m}\right)R_{ij}^s + S_m(\xi_{n-1})e^{-\Delta\xi/\tau_m} \\
V_m(\xi_n) &= 3K_m\tau_m\left(1-e^{-\Delta\xi/\tau_m}\right)R_{kk} + V_m(\xi_{n-1})e^{-\Delta\xi/\tau_m}
\end{aligned}
\tag{10}
$$

Dave et al. (2010) conducted thermo-viscoelastic verifications to verify the accuracy of the recursive-incremental viscoelastic finite element formulations in the context of time dependent temperature conditions and temperature dependent viscoelastic properties. The boundary value problem simulated in this case is similar to the thermal stress restrained specimen test (TSRST), which is sometimes used for the evaluation of thermal cracking performance of asphalt concrete (AASHTO TP-10). In order to ensure good accuracy for thermal cooling and warming conditions, the temperature boundary conditions were chosen to impose both warming and cooling events. The results from the finite element formulations used in this study were compared with the results obtained from the commercial software ABAQUS. Figure 2.4 shows the variation of temperature with time as well as the corresponding thermal stresses generated in the restrained viscoelastic body. The stress response is shown for the formulations and implementation from the present study as well as those obtained using ABAQUS, showing excellent agreement.

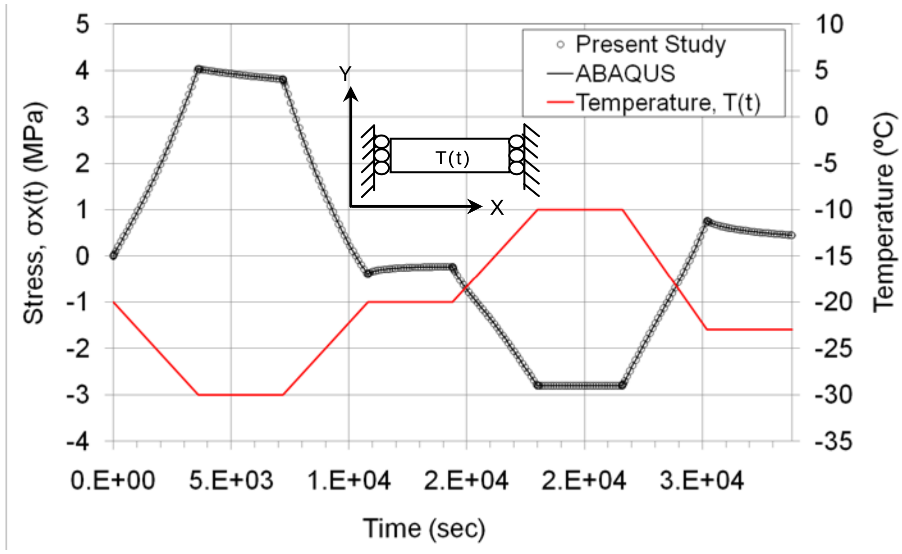


Figure 2.4. Comparisons for thermo-viscoelastic analysis conducted using recursive-incremental viscoelastic finite element formulations and commercial software ABAQUS (from Dave et al., 2010)

2.3.2 Fracture Modeling of Asphalt Concrete

Asphalt concrete is classified as a quasi-brittle material because of the large nonlinear fracture process zone resulting from crack overlapping and branching, and from the weak interface between aggregates and asphalt binder. Such nonlinear fracture process zone is approximated by the cohesive zone model (Baranblatt 1959; Dugdale 1960). The cohesive zone model has been widely utilized to investigate a range of civil engineering materials such as Portland cement concrete (Hillerborg et al. 1976), reinforced concrete (Ingraffea et al. 1984), asphalt concrete (Song et al. 2006), and fiber reinforced concrete (Park et al. 2010), etc.

In the cohesive zone model, nonlinear cohesive traction is defined as a function of separation (or crack opening width) ahead of a macroscopic crack tip. A crack is initiated when the cohesive traction reaches the cohesive strength of the material. Note that further investigation is needed for crack initiation criteria. Then, as the separation increases the cohesive traction decreases. Finally, when the separation is greater than a critical value, the material no longer has bearing capacity and the cohesive traction is zero. In this study, the bi-linear CZM described by Song et al. (2006) is being employed. This model has been successfully employed for simulation of thermal and reflective cracking in asphalt pavements and overlays, for example by Dave et al. (2007, 2008). Additionally, an intrinsic cohesive zone modeling approach is used; hence a penalty stiffness (i.e. initial ascending slope) is introduced in the computational implementation. The initial penalty stiffness is determined on the basis of the numerical stability associated with the finite element implementation (Roesler et al. 2007).

The material parameters used in the cohesive fracture model are: material strength (σ_t) and fracture energy (G_f). Figure 2.5 shows schematically illustration of the bi-linear cohesive model. The horizontal axis represents the displacement-jump across the cohesive zone and vertical axis represents the traction. The area under the plot is the fracture energy (G_f) and the peak traction is limited to material strength (σ_t). The unloading and loading during the course of softening are also shown in the model. The displacement jump at the complete separation is indicated by critical displacement jump (δ_C). The bi-linear cohesive zone model was implemented in the program using a modified Newton-Raphson solution scheme.

The implementation of the cohesive zone model with recursive incremental viscoelastic finite element formulations is verified by comparing the results of the finite element analysis engine with the results of the commercial software ABAQUS. Figure 2.6 illustrates the stress variation with respect to time and shows excellent agreement. The stress reaches a given cohesive strength (e.g. 2MPa), and decrease to zero while temperature decreases from 0ºC to -10ºC during 600 sec.

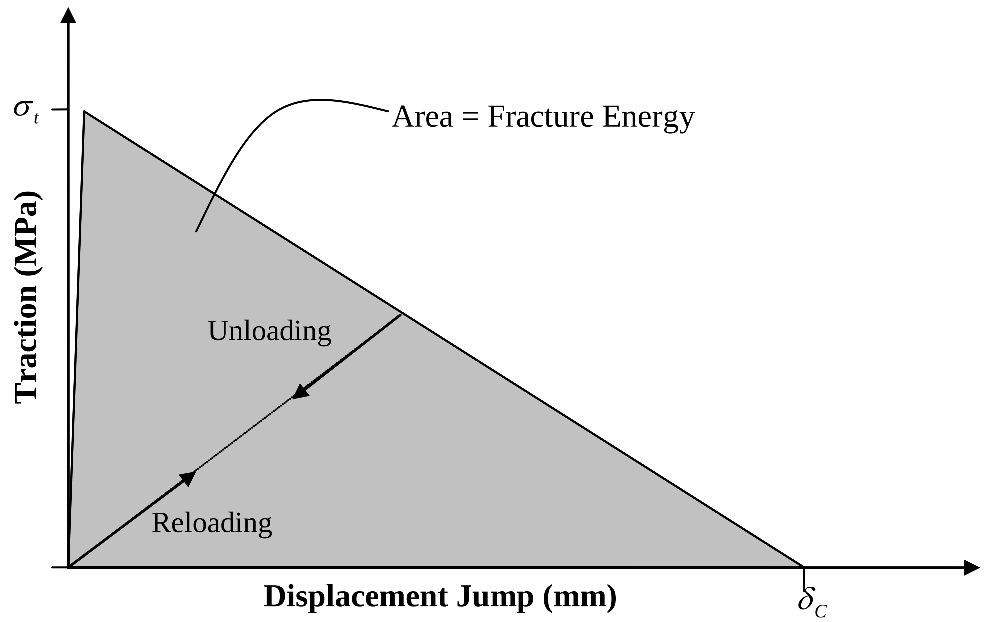


Figure 2.5. Bi-linear cohesive zone model

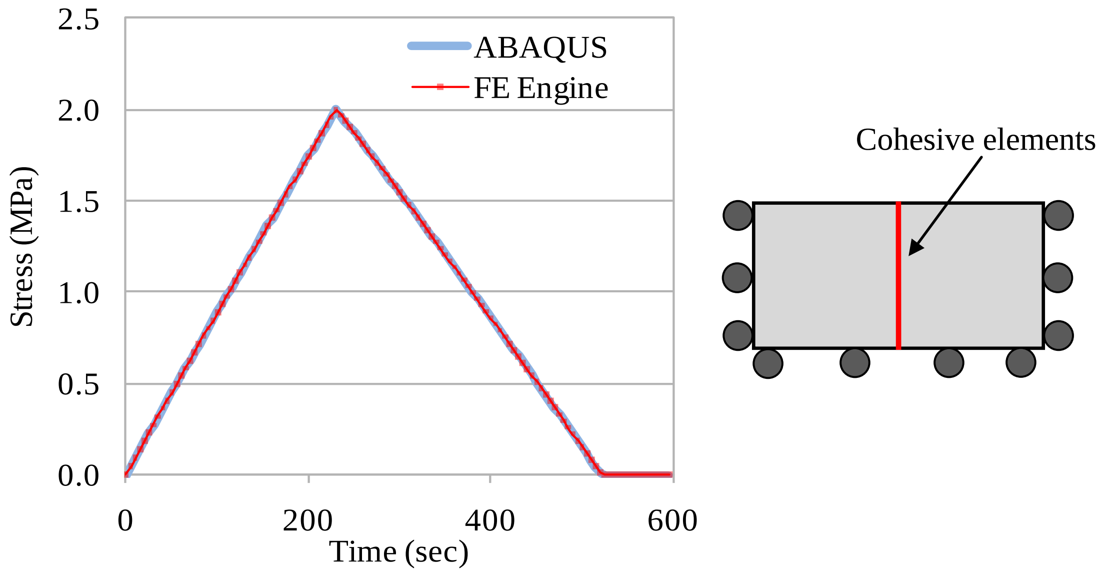


Figure 2.6. Finite element (FE) engine results of the cohesive zone model with recursive incremental viscoelastic finite element formulations. Temperature linearly decreases from 0ºC to -10ºC during 600 sec.

2.4 Summary

The stand-alone low temperature cracking analysis program developed through this project was introduced in this chapter. Details on various components of the analysis modules were presented. The theoretical background for the finite element analysis program was briefly discussed in this chapter. The graphical user interface (GUI) for the stand-alone program is described in the following chapter.

CHAPTER 3. VISUAL LTC: A GRAPHICAL USER INTERFACE FOR LOW-TEMPERATURE CRACKING ANALYSIS

3.1 Introduction

A standalone graphical user interface (GUI), called “Visual LTC”, was developed for conducting low-temperature cracking analysis and design of asphalt concrete pavements. A GUI plays an important role in the process of design through use of sophisticated simulation models which involve complex computations and allows integration of various design components such as, climatic modeling, determination of material viscoelastic parameters, non-linear fracture modeling, pavement structure data handling, etc. Visual LTC unifies several analysis modules in an intuitive, accessible manner, thereby improving efficiency and productivity of the pavement analysis and design processes.

This chapter provides an overview of the development of and usage of Visual LTC in sections 3.2 and 3.3, respectively. Future work related to the GUI is discussed in Section 3.4.

3.2 Development of Visual LTC

Visual LTC was written with the object-oriented programming language C# (pronounced “see-sharp”) under Microsoft’s .NET framework. Upon completion, Visual LTC will be distributed via the internet, as programs written in C# under the .NET framework are intended for use as deployable software.

A simple and intuitive class structure is employed to (1) store material properties and climatic data, (2) maintain the pavement structure as the user adds and/or modifies layers (i.e. asphalt concrete, base, and subgrade layers), (3) run analysis modules and display results to the user, and (4) save data and results to a library which can be recalled during the analysis/design process. The key programming steps of Visual LTC are shown in Figure 3.1. The following subsections describe the functionality of Visual LTC:

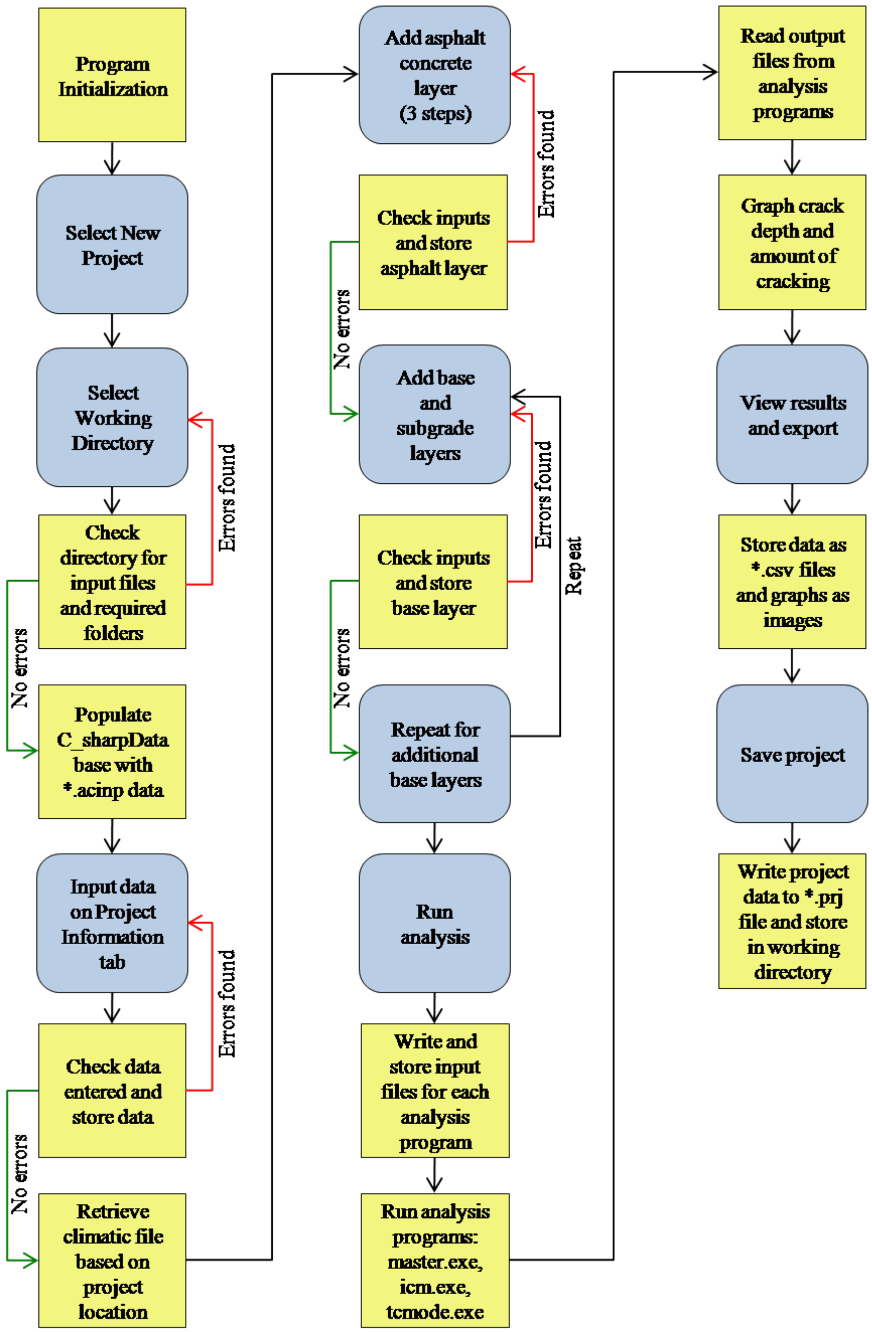


Figure 3.1. Key programming steps of Visual LTC

3.2.1 **Data storage**

Visual LTC stores and maintains material properties, climatic data, pavement structure, and project information. The data should be easily accessible by the user and should not require installation of additional software. A working directory containing input files stores all of the data necessary for Visual LTC to conduct analysis. Furthermore, the user is not required to directly access the files, as Visual LTC creates and modifies files automatically. The project input file stores general information (i.e. project name, description, date, etc), climatic information, and the pavement structure. Asphalt concrete input files store all material properties associated with the mix. A working directory can contain many project files, thus giving the user the option of creating a new project by modifying an existing one. Similarly, the working directory can contain as many asphalt concrete input files as necessary, which creates a library of mix designs for the analyst or designer to investigate.

3.2.2 **Analysis modules**

Visual LTC currently executes the following analysis modules: Master.exe and TCMomdel.exe. Master.exe collects creep compliance test data and constructs the master creep compliance curve. This output is then passed to TCModel.exe, which computes the amount of cracking versus time. Master.exe and TCModel.exe will be replaced by the new finite element analysis engine. Details of this change are discussed in Section 3.4. Additionally, climatic data is required for low temperature cracking analysis. Rather than executing another module to compute pavement temperatures at various depths with time, a library of climatic data files will be compiled and preloaded into Visual LTC.

3.2.3 **Results**

Results are automatically displayed in graphical form upon completion of the analysis modules, and the user has the option to save the raw data files for further post processing. The yearly crack depth and yearly amount of cracking are currently presented, however this output will be replaced when the finite element analysis engine is integrated into Visual LTC, see Section 3.4.

3.3 Use of Visual LTC

This section briefly demonstrates the use of Visual LTC, which is organized into five sections:

Section 1 - Start: The user either opens an existing project or starts a new project. When an existing project is opened all the inputs are pre-loaded into Visual LTC, but the user still has capability to alter or change any of the inputs. In case of new project, the user is required to provide all inputs.

Section 2 – Project Information: The user inputs general information about the project including project name, location, length of analysis, etc., as shown in Figure 3.2. The location of analysis corresponds to the locations where climatic data is available.

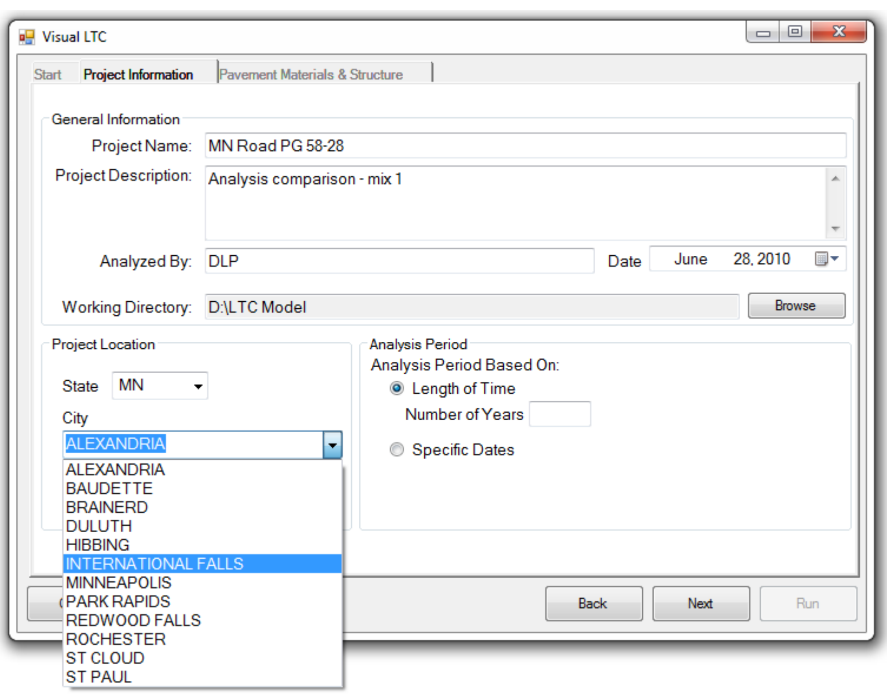


Figure 3.2. Project information

Section 3 - Pavement Materials and Structure: The user builds the pavement structure by adding layers (i.e. asphalt layer, base layers, subgrade layer). Pavement structural characteristics and material properties can either be provided by the user or selected from a preexisting library. Figure 3.3 shows the third of the three steps required to add an asphalt layer.

Section 4 - Run: Visual LTC executes the necessary analysis modules for pre-processing, analysis and post-processing the results. As the analysis runs, the Visual LTC informs the user of the runtime progress by indicating which stages of the analysis are complete and which are in queue to be executed.

Section 5 - Results: Results are displayed to the in graphical form. The user has options of saving graphical output as image files and of exporting raw data files for further post processing.

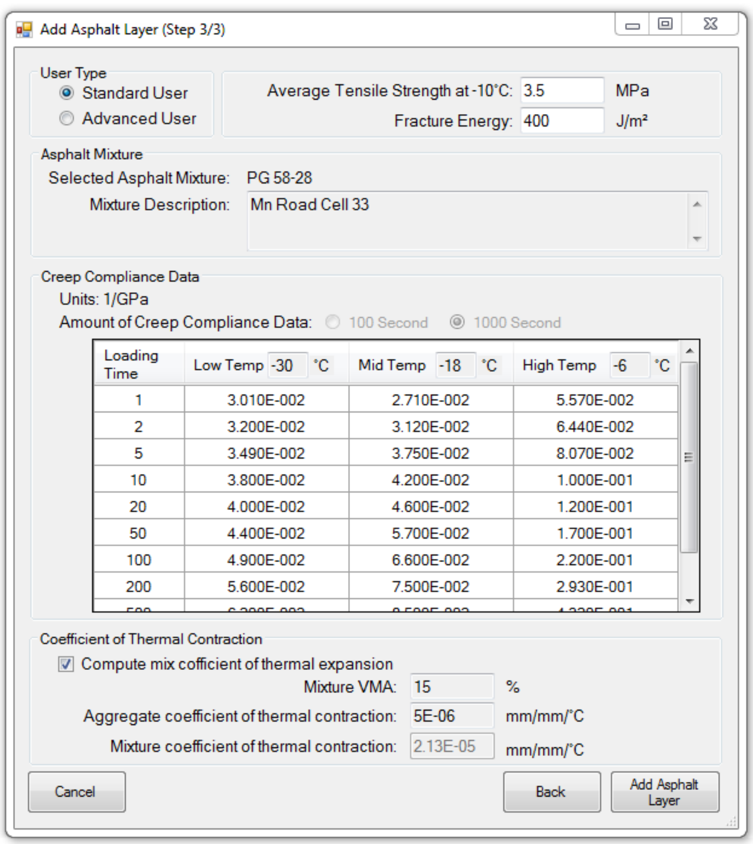


Figure 3.3. Step three of three to add an asphalt layer to the pavement structure

3.4 *Future work and improvements to Visual LTC*

Visual LTC currently conducts low temperature cracking analysis through TCModel, however this will be replaced by a more accurate and sophisticated viscoelastic and cohesive zone finite element analysis engine (described in Chapter-2). Integration of the new model into Visual LTC will require minor modifications to the data file structures, for instance fracture parameters will be needed as inputs. Additionally, communication between Visual LTC and the various analysis modules will be updated. Note that these changes will not affect the appearance or usage of Visual LTC from the perspective of the user.

Once the new analysis engine is integrated with Visual LTC, the output displayed to the user will be different. The new output will be percent of fracture energy dissipated, extent of pavement thickness damaged and extent of pavement thickness cracked. The format of the results will still be graphical with the option to save raw data; therefore this update will be very minor as Visual LTC already has these capabilities.

In addition to the improvements associated with the new analysis engine, the outputs of the model (i.e. physical damage to the pavement) can be directly used in a pavement management or asset management system. For instance, cracking amount can be used to compute maintenance costs, time to the next major rehabilitation, performance of subsequent overlay cycles, and to future pavement salvage values. To this end, a series of new graphical user interface pages may be created for asset management inputs and parameters.

CHAPTER 4. DEVELOPMENT OF FRAMEWORK FOR ASSET MANAGEMENT INTEGRATION

4.1 Introduction

The long-term objectives of this research is to truly integrate the 'hard-side,' e.g., physical pavement modeling and distress prediction software elements, with the 'soft side,' e.g., asset management system software, to create a comprehensive, performance-based asset management tool for pavement engineers. To this end, a sub-task of this project was formed, which involved collaboration between the pavements- and mechanics-oriented research team under the supervision of Professor William Buttlar and Professor Glaucio Paulino and the systems-oriented research team of Professor Yanfeng Ouyang of the University of Illinois at Urbana-Champaign. Due to funding constraints, the major elements of this task were predominantly moved into the third year work plan for this project. However, initial collaborative brainstorming meetings were conducted, and a framework for the collaboration was firmly established. A short summary of this collaborative framework is now presented.

4.2 Background

With shrinking maintenance budgets, the need for accurate, robust asset management tools are greatly needed for the transportation engineering community. Furthermore, increases in traffic intensity, vehicular loads, and truck tire stiffness and changes in the asphalt refining and construction have led led to increased needs for preventive and rehabilitative maintenance activities. The timing of such activities will greatly affect the total discounted life-cycle cost of the pavement system.

The proposed integrated approach will build upon the work of Ouyang and colleagues (Ouyang and Madanat, 2004; Ouyang and Madanat, 2006; Ouyang, 2007, and; Peng and Ouyang, 2010) . In Ouyang and Madanat (2004), a mathematical programming model providing exact and approximate solutions for optimizing pavement rehabilitation planning with respect to life-cycle cost was developed. The solution addressed the ability to model multiple rehabilitation activities across a network of pavement facilities, based upon a discrete control theory approach. In their work, an approximate greedy heuristic solution, which has a pseudo-polynomial computational time, was found to provide efficient, approximate results as compared to the more rigorous branch-and-bound algorithm approach used. In Ouyang and Madanat (2006), an analytical solution was provided for the planning problem involving finite-horizon pavement resurfacing. The optimal resurfacing strategy was proven to have a "threshold structure," and it was consistent with the results obtained using the aforementioned infinite-horizon approach. In this study, pavement roughness[1], and its effect on user costs was directly considered, which is an important aspect to be considered in the proposed integrative software program (which is discussed in the following section).

In Ouyang (2007), a modeling framework was presented for the planning of pavement resurfacing activities across a highway network based on a continuous pavement state, discrete time, and infinite horizon approach. In this approach, life-cycle costs were minimized by solving a multidimensional dynamic programming problem, which simultaneously considered travelers' route choices and agency resource allocation decisions. This and the previously presented models were considered and applied in a recently completed study with the Illinois Center for Transportation, as part of project ICT-R27-34 (Peng and Ouyang, 2010). Although these models can directly consider mechanics-based pavement distress predictions, to date, the models have been developed with existing, empirically-based distress prediction models.

[1] Other types of pavement distresses (e.g., those with discrete measurement values) can also be modeled in a similar manner.

4.3 *Proposed Integration Framework*

Considering the available software modeling tools available for: (1) mechanics-based prediction of thermal cracking based upon asphalt properties (particularly asphalt grade selection), e.g., as described in chapters 2 and 3, and; (2) comprehensive pavement management systems modeling, the stage is set for the integration of these two emerging modeling paradigms in a holistic, performance-based asset management system for pavement infrastructure.

In the aforementioned studies by Ouyang and collaborators, pavement roughness, and its effect on user costs were directly considered. This is an important feature, since the next phase of this study will involve the integration of a mechanics-based thermal cracking prediction system into a numerical pavement management software program. Thermal cracking, if fully developed and left untreated, will create an expensive and recurring maintenance liability. Thermal cracking is a recurring distress in the sense that it creates an uncontrolled, full-width, full-depth fissure in the pavement structure that will almost always reflect upwards into subsequently placed asphalt overlays. As the thermal crack widens, spalls, and permits moisture ingress, pavement roughness and the rate of pothole development significantly increases. This in turn has a significant effect on user costs associated with vehicle wear and tear. Thus, the first step in the proposed integration will be to develop an integrated framework that allows for linking of the new TCMODEL program with actual pavement cracking, distress and roughness, and to develop a framework that links the pavement roughness and distress information with vehicle maintenance and driver comfort.

The proposed work in phase III of this project will also undertake the goal of extending fundamental predictions of pavement cracking distress to the prediction of pavement roughness and other forms of deterioration (crack spalling, potholes) as a function of pavement maintenance, traffic, and climate. This will lead to the development of an integrated model linking infrastructure condition to vehicle wear-and-tear and to driver safety. Once complete, this comprehensive model will allow the designer to base his/her design and maintenance decisions on a life-cycle analysis that will include not only traditional pavement condition considerations, but also the effects of pavement condition on vehicle operating costs and accident rates. This presents a holistic approach to pavement design and maintenance, with the ultimate goal of providing the USDOT with a tool to decrease life cycle costs of a pavement system in a much broader sense, and moreover, to enhance safety through scientifically informed design and maintenance decisions.

In order to accomplish these objectives, a series of collaborative meetings were held between pavement and systems faculty and students at the University of Illinois, which led to the development of the following future research tasks:

• Development of pavement distress databases for use in model calibration. Most State DOTs already maintain pavement performance and roughness database; these databases will be utilized to identify sections for utilization in this study.

• Thermal cracking predictions should be made using the pavement cracking simulation software (described earlier) for the pavement sections identified in the previous step.

• Statistical and numerical tools should be utilized to develop a probabilistic predictive tool that links the cracking information from the simulation software to the actual pavement cracking and roughness data.

• The probabilistic model should be used to calibrate and validate the pavement cracking simulation software.

• Calibrated and validated pavement cracking simulation software should be integrated with the probabilistic model for development of a tool that can be deployed for prediction of pavement distress (amount of cracking and roughness) caused by thermally induced cracking.

• Effects of pavement cracking distress on driver comfort and vehicle maintenance should be studied to create a framework for linking pavement roughness information with vehicle distress and driver comfort levels.

Figure 4.1 outlines the critical steps needed in the next phase of the research as well as the general research approach. The flow of the project along with various critical steps and research approaches are discussed next.

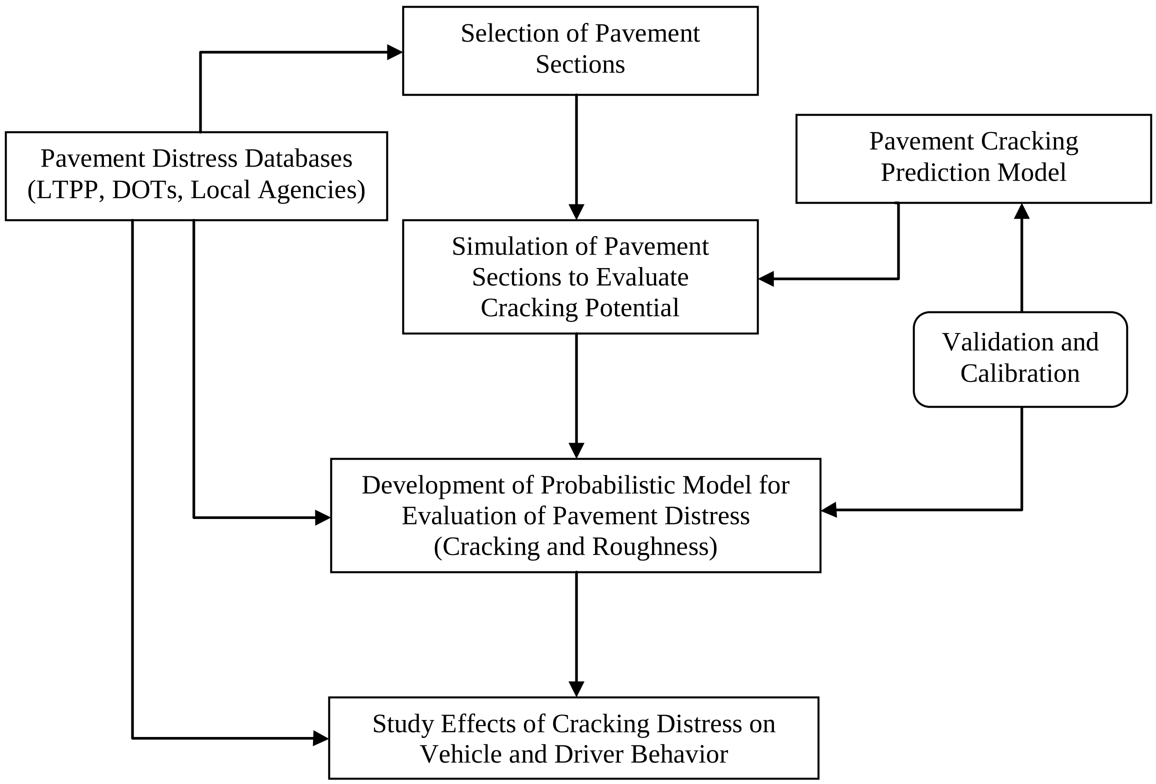


Figure 4.1. Project Outline and Major Research Steps

The first step in the proposed phase III study will entail selection of various pavement sections for which distress data (roughness and cracking) is available along with other information such as location (for climatic evaluation), traffic, pavement structural details (layer types, thicknesses etc.), material type etc. Various existing test sections from the FHWA Pooled Fund Study on Low Temperature Cracking, the LTPP (Long Term Pavement Performance) Database, IDOT's Condition Rating System (CRS), and Mn/ROAD will be utilized along with additional ones from DOTs and local agencies. Some basic statistics associated with some of the aforementioned pavement performance databases are: LTPP - Initiated in 1989, over the last 20 year period a total of 2,512 LTPP test sections located throughout the United States and Canada have been included in the database, and at the end of 2009, a total of 950 test sections were currently active. The database includes various distresses including transverse cracking and international roughness index (IRI). MnROAD: Data collection started in 1996; a total of 48 (25 mainline and 23 low-volume) asphalt pavement test cells are present. A total of 75 asphalt pavement test sections have been constructed and tested. Various forms of distress data are available including surface profile, roughness, crack counts, severity of cracking, etc. IDOT CRS: Digital video images, IRI, and rut depths are collected on the entire highway network on a biennial basis, and converted and categorized by type, extent, and severity of distress. Data is collected using a “Data Collection Vehicle (DCV)”. This information is utilized to evaluate the condition rating using the CRS.

The next step in the project will include performing the cracking predictions using the pavement cracking prediction model which is developed jointly through a previous NEXTRANS project and the FHWA Pooled Fund Study. The cracking prediction model utilizes a finite element based analysis engine and accounts for asphalt materials bulk viscoelastic and quasi-brittle cracking behavior. The prediction model integrates the climatic and structural information to predict the extent of damage and cracking that is anticipated for a given asphalt pavement system. The output from the prediction model is in the form of a variety of engineering quantities such as, dissipated fracture energy, extent of damage and fracture, etc. The next step in the project is a critical one; the utilization of field performance data (in the form of pavement distress, cracking and roughness) and correlation with the engineering quantities obtained from the simulation model. This step is also critical for calibration and validation of the simulation model. This procedure is illustrated in graphical form in Figure 4.2. The correlation between the simulation model and the pavement distress and roughness information will be developed in the form of a probabilistic prediction model that will rely heavily on the use of statistical tools such as artificial neural networks.

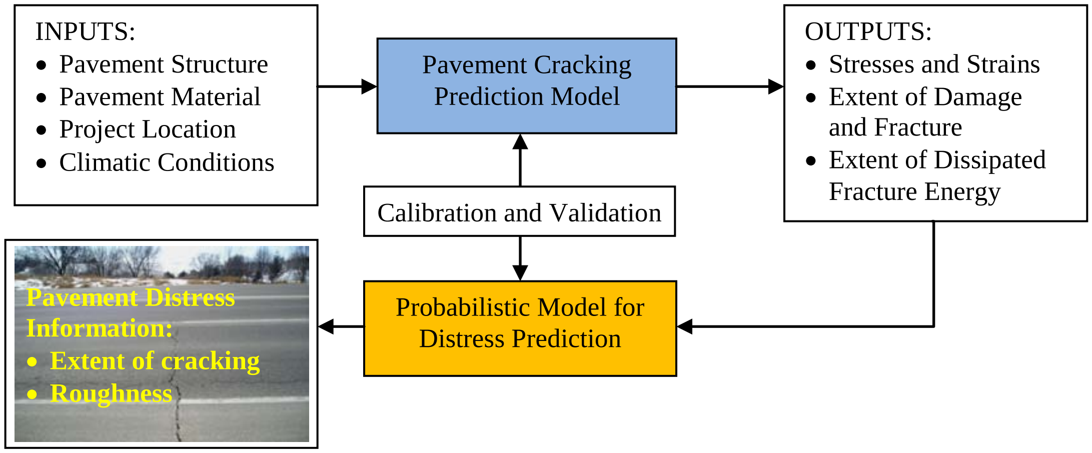


Figure 4.2. Development of Probabilistic Model for Distress Prediction

The second critical aspect of this project involves developing a framework for relating the pavement distress and roughness information with the vehicular distress and driver comfort and behavior. This type of framework is critical for evaluation of vehicle-infrastructure and driver-infrastructure interactions. At present, very limited research has been conducted on this topic, whereby there is gap between researchers working on topics related to distress of highway infrastructure and interaction between infrastructure and vehicles and infrastructure and drivers. This framework will allow for future research to develop a multi-faceted integrated system that links infrastructure renewal, infrastructure-driver interaction, infrastructure-vehicle interaction, and asset management. The proposed project will be conducted in a parallel track approach whereby, the study interaction between pavement distress and drivers and vehicles will be conducted in parallel with the development of probabilistic model for relating simulation results with pavement distress predictions.

CHAPTER 5. SUMMARY

This chapter summarizes the research, highlights its contributions, and proposes directions for future research. The stand-alone low temperature cracking analysis program developed under this project and the National Pooled Fund Study on Low Temperature Cracking was introduced in Chapter 2. Details on various components of the analysis modules were presented, including: mesh generation, viscoelastic pavement response calculation and finite element implementation of the numerical time-integration scheme, and pavement distress (thermal cracking) simulation via cohesive zone finite element modeling. The theoretical background for the finite element analysis program was also briefly presented in Chapter 2. In order to make this comprehensive simulation model accessible to practitioners and other researchers, a user-friendly graphical user interface was developed, called 'Visual LTC.' Visual LTC, presented in Chapter 3, was written with the object-oriented programming language C# (pronounced "see-sharp") under Microsoft's .NET framework. A simple and intuitive class structure was employed to: (1) store material properties and climatic data; (2) maintain the pavement structure as the user adds and/or modifies layers (i.e. asphalt concrete, base, and subgrade layers); (3) run analysis modules and display results to the user, and; (4) save data and results to a library which can be recalled during the analysis/design process. The key programming steps of Visual LTC were also documented in this report.

Finally, Chapter 4 presented a recently developed framework for the integration of mechanics-based pavement distress prediction into a comprehensive asset management system, which will be continued in the upcoming phase III research activities of this project. The first step in the proposed integration will be to develop an integrated framework that allows for linking of the new TCMODEL program with actual pavement cracking, distress and roughness, and to develop a framework that links the pavement roughness and distress information with vehicle maintenance and driver comfort. The proposed framework will also undertake the goal of extending fundamental predictions of pavement cracking distress to the prediction of pavement roughness and other forms of deterioration (crack spalling, potholes) as a function of pavement maintenance, traffic, and climate. This will lead to the development of an integrated model linking infrastructure condition to vehicle wear-and-tear and to driver safety. Once complete, this comprehensive model will allow the designer to base his/her design and maintenance decisions on a life-cycle analysis that will include not only traditional pavement condition considerations, but also the effects of pavement condition on vehicle operating costs and accident rates. This presents a holistic approach to pavement design and maintenance, with the ultimate goal of providing the USDOT with a tool to decrease life cycle costs of a pavement system in a much broader sense, and moreover, to enhance safety through scientifically informed design and maintenance decisions.

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