Thermal Cracking Prediction Model and Software for Asphalt Pavements

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Abstract

Thermally induced cracking in asphalt pavements remains to be one of the prominent distress mechanisms in regions with cooler climates. At present, the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) is the most widely deployed pavement analysis and design procedure. For thermal cracking predictions, MEPDG utilizes a simplified one-dimensional stress evaluation model with a simple Paris-law (i.e. linear elastic fracture mechanics) based crack propagation procedure. The user-friendly graphical interface for MEPDG makes it an attractive design procedure of choice, however, the over simplicity of the model and lack of a physics-based representation to accurately capture the nonlinear fracture behavior of rate-dependent asphalt concrete reduce(s) the reliability of predictions. This study presents an interactive thermal cracking prediction model that utilizes a nonlinear finite element based thermal cracking analysis engine which can be easily employed using a user-friendly graphical interface. The analysis engine is comprised of (1) the cohesive zone fracture model for accurate simulation of crack initiation and propagation due to thermal loading and (2) the viscoelastic material model for time and temperature dependent bulk material behavior. The graphical user interface (GUI) is designed to be highly interactive and user-friendly in nature, and features screen layouts similar to those used in the AASHTO MEPDG, thus minimizing transition time for the user. This paper describes the individual components of the low temperature cracking prediction software (called LTC Model) including details on the graphical user interface, viscoelastic finite element analysis, cohesive zone fracture model, and integration of various software components for thermal cracking predictions.

Introduction and Background

Asphalt pavements are usually constructed in a continuous manner without presence of periodic joints resulting in smooth driving characteristics. During the periods of severe low temperature climatic events, caused by low absolute temperatures or high cooling rates, thermal stresses build up in the continuous asphalt concrete layer. Damage accumulates as thermally induced stresses approach the material strength, and eventually cracks are formed. This type of cracking is commonly referred to as thermal cracking. Thermal cracking in asphalt pavements is often formed in periodic manner and is a prevalent form of pavement distress and damage mechanism in areas with cold climates. Figure 1 shows a typical thermal crack in asphalt pavement. The cracks in the figure have been sealed and hence more clearly visible in the picture.

Figure 1. Thermal cracking in asphalt concrete pavements.

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 analysis program in the MEPDG was developed by Roque et al. (1996). 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.

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 1993; 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 cohesive zone fracture models and user-defined 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. In the current study, a stand-alone analysis and design software to predict thermal cracking performance of asphalt concrete pavements is presented. It provides an intuitive and user-friendly graphical user interface (GUI) as a means to perform rigorous viscoelastic finite element analysis with cohesive zone modeling. Description of various components of the analysis model is presented in the next section.

Low Temperature Cracking Prediction Software

This section describes various components of the thermal cracking prediction software. The GUI and input file generator are described first, followed by the viscoelastic finite element analysis engine and the cohesive zone fracture model.

Graphical User Interface (GUI)

The standalone low-temperature cracking prediction software unifies several analysis modules into a user-friendly GUI. A graphical representation of the interaction between the GUI and the analysis modules is shown in Figure 2. The GUI collects and compiles the input conditions provided by the user and calls the Input File Generator to generate all necessary files for the finite element analysis engine. As described in Figure 2, the three main outcomes of the Input File Generator are the geometric data file, material data file and temperature boundary condition file. Finally, the GUI executes the finite element simulation to evaluate the potential of thermal cracking. The details of the codes listed in Figure 2 are discussed in the remainder of this section.

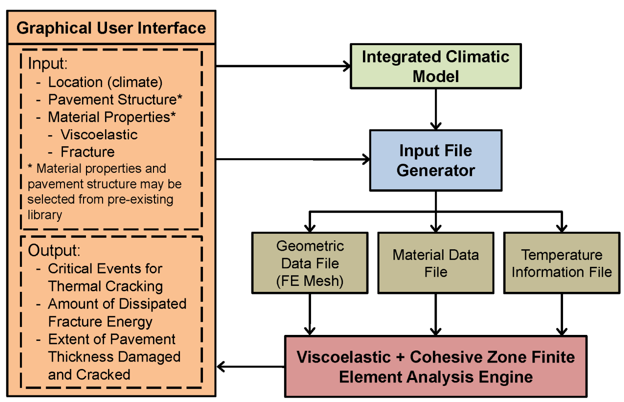
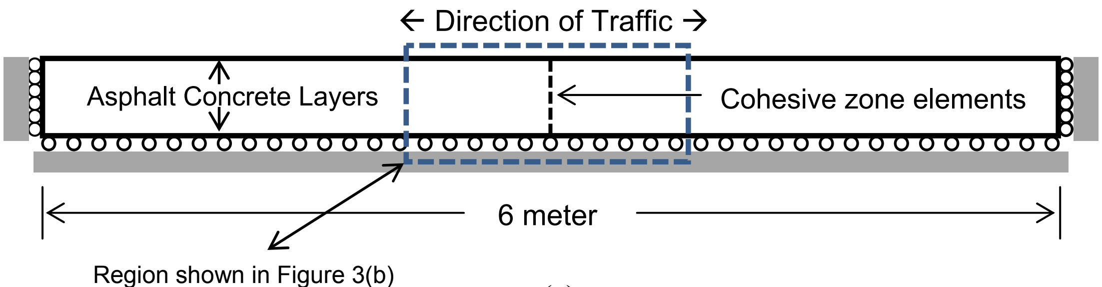
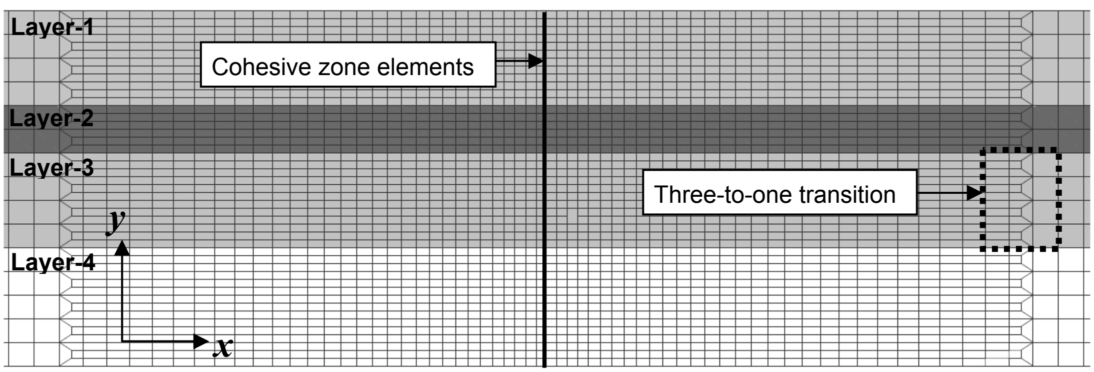


Figure 2. Flowchart of interaction between GUI and analysis modules

The first task of the Input File Generator is to develop a finite element mesh for the selected pavement geometry. 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 an initial version of mesh generator was developed (Marasteanu et al., 2007). In the present work, this mesh generation code was significantly 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 domain size and minimum element sizes were selected as 6 m and 4 mm respectively. The mesh generator utilizes an automatic transition scheme to reduce the computational cost of the problem. 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 in 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 3 shows a typical pavement mesh, 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 3.



(a)



(b)

Figure 3. Finite element mesh from input file generator: (a) Illustration of a model geometry and boundary conditions (domain size: 0.18 m by 6 m), and (b) Close-up of the mesh in vicinity of cohesive zone elements

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 4.

At the current stage of the software, the user must 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. Prior to full-scale deployment of the software, 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 95% reliability Superpave PG low temperature grade, as dictated by the project location.

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 4. Material properties required by the LTC 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 by using the same approximation equation that is utilized by the AASHTO MEPDG software.

Finally, the Input File Generator also provides the analysis engine with temperature loading conditions. The temperature profiles within the asphalt pavement are determined using the Integrated Climatic Model (ICM) developed by Larson and Dempsey (1997). ICM is also used in MEPDG for determining pavement temperature profiles. The ICM utilizes climatic information such as air temperature, wind velocity, cloud cover, precipitation, etc. to predict the pavement temperature through a finite difference heat flow analysis. Prediction of transient temperatures through the pavement thickness makes the ICM optimal for determining temperature boundary conditions, which are applied in the thermal cracking analysis. The finite element framework requires that temperature conditions be applied at each node, however the ICM outputs one-dimensional pavement temperatures with depths that do not necessarily correspond to those nodal locations. To overcome this challenge, the ICM is executed prior to the finite element analysis. A pre-processor uses the ICM output to generate nodal temperatures at the necessary locations and times, which are then passed to the finite element analysis engine.

Viscoelastic Finite Element Analysis

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. A typical response of asphalt concrete at low and intermediate temperatures is viscoelastic in nature. Figure 5 shows the creep compliance master-curve of asphalt concrete at two temperatures; a

Prony series model is fitted to the laboratory data. The change of loading time and temperature provides significant effect on the material behavior. In order to accurately capture the hereditary and temperature dependent behavior of asphalt concrete, a thermo-viscoelastic analysis procedure is needed. A variety of formulations have been proposed for thermo-viscoelastic finite element analysis (Yi and Hilton 1993; Zocher et al. 1997; Muliana and Khan 2008). In the present work, an incremental-recursive finite element formulation is utilized for thermo-viscoelastic finite elements (Yi and Hilton 1993; Zocher et al. 1997). This type of formulation has also been used for simulation of cracking in aged asphalt pavements (Dave et al. 2010). The analysis engine with thermo-viscoelastic finite elements is currently in the verification stage.

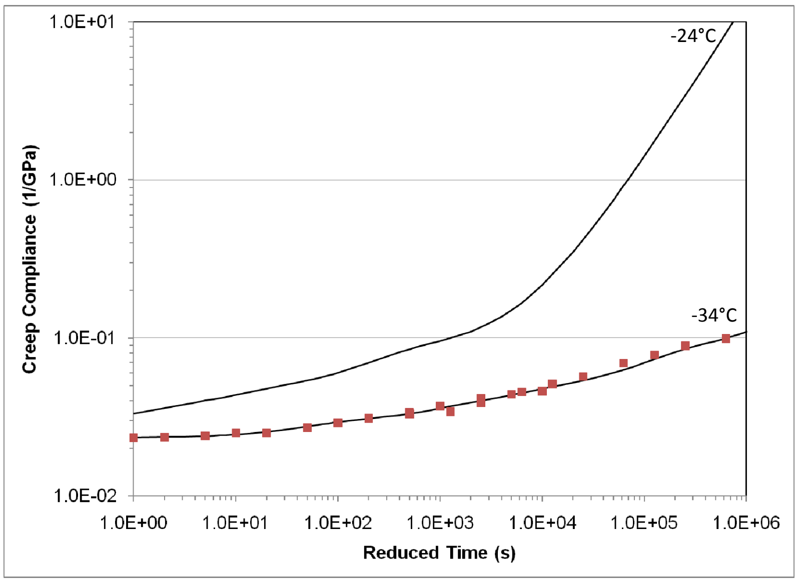


Figure 5. Creep compliance mastercurves for a asphalt concrete mixture at temperatures of -34 (Superpave PG low temperature grade, PG-LT) and -24°C (PG-LT+10°C)

Cohesive Zone Fracture Model

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, a linear softening model is employed, which is defined by the fracture energy (G_F) and the cohesive strength (σ_{max}). 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).

Use of LTC Model through GUI

This section briefly demonstrates the use of LTC Model through the GUI. Upon execution of the software, the user is greeted by the GUI that is organized into five sections: (1) Start, (2) Project Information, (3) Pavement Materials and Structure, (4) Run, (5) Results. For each section there are number of inputs required from the user. The flow of the program is described below in context of each of the five sections.

(1) Start: The user either opens an existing project or starts a new project. When existing project is opened all the inputs are pre-loaded into the GUI, 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.

(2) Project Information: The user inputs general information about the project including project name, location, length of analysis, etc., as shown in Figure 6. The location of analysis is necessary to select the pavement temperature profiles.

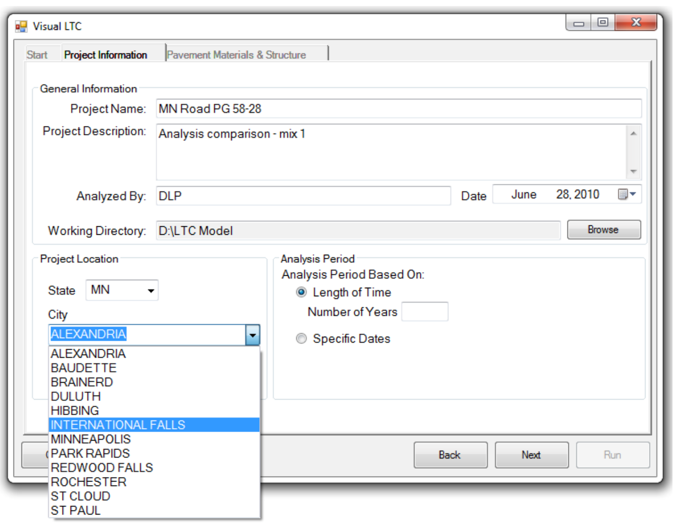


Figure 6. Project information

(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 7 shows the third of the three steps required to add an asphalt layer.

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

(5) Results: The results from finite element analysis is converted to a user-friendly format and presented to user. Three sets of outputs are provided, namely: percent of fracture energy dissipated, extent of pavement thickness damaged and extent of pavement thickness cracked (shown in Figure 8). The outputs are available to users in both graphical and tabular formats with capability to export data in convenient comma separated value (CSV) format.

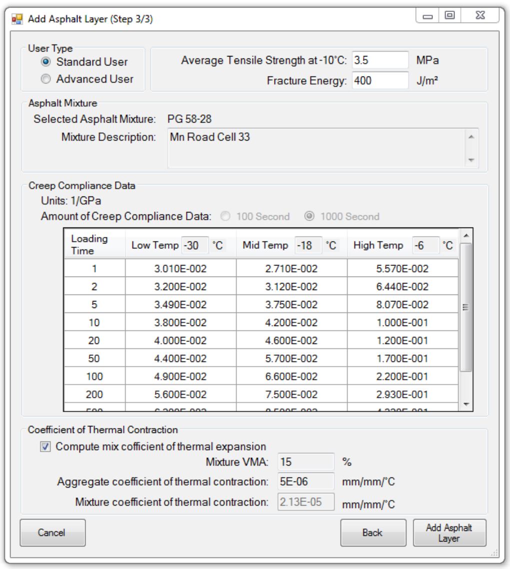


Figure 7. Step three of three to add an asphalt layer to the pavement structure

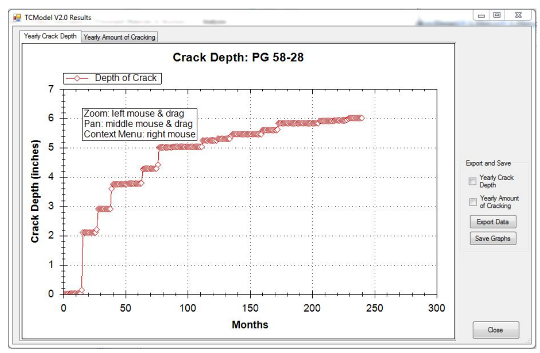


Figure 8: Depth of cracking in asphalt layer as graphical output from GUI

Summary and Future Extensions

This paper describes the framework and organization of a low temperature cracking prediction model called "LTC Model". An overview of the various components of the model are presented along with in-depth details on the graphical user interface that acts as the pre- and post-processor to the finite element based analysis engine. The preprocessing step involves generation of finite element mesh, material properties and temperature boundary conditions. The finite element analysis is developed using a thermo-viscoelastic formulation for the bulk material response and a cohesive zone model for initiation and propagation of cracks. A brief demonstration is presented by showing use of the GUI for thermal cracking analysis. The development of LTC Model is presently in the final stages. Verification and calibration is currently being conducted on the finite element based analysis engine.

The thermal cracking prediction model is anticipated to be deployed to public and private transportation agencies in form of freely distributed software. Agencies participating in the low temperature cracking pooled fund study will form the first set of users to help fine tune the software and, if present, identify and resolve any software bugs. There are several aspects of the model and the analysis procedure that can be extended to improve the capabilities and applicability of the model described in this paper, these includes:

- Critical climatic events that are likely to induce progressive damage to asphalt pavement should be identified. With critical climatic events identified only pavement in-service durations with such events will be simulated, thus reducing the computation costs.
- Tire loading conditions may be added to the analysis engine to include effects of traffic on the pavement cracking performance.
- Effects of loading rate and temperature on the cracking should be included to further increase the efficiency and reduce reliance on calibration. This could be achieved through extending the cohesive zone model to include aforementioned effects.
- Aging has significant effect on the bulk viscoelastic and fracture behavior of asphalt concrete. Aging models could be incorporated in the analysis engine such that, the mechanical properties are dependent on age, climate, thickness, volumetric properties, etc.

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