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Effect of uncertain material property on system reliability in mechanistic-empirical pavement design

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HIGHLIGHTS

- A system reliability-based approach for flexible pavement design is developed.
- The effect of uncertain material property can be quantified using this reliability approach.
- The design considering only the dominant failure mode can underestimate the failure potential.

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ABSTRACT

This study is devoted to developing an efficient system reliability-based mechanistic-empirical pavement design procedure to address the uncertain material property. This procedure consists of the following four components: 1) mechanics-based layered elastic analysis for computing the tensile strain and the compressive strain, 2) empirical models for predicting fatigue life and rutting life, 3) first-order reliability method (FORM) for estimating the probability of pavement failure, and 4) an updated spreadsheet tool for estimating the system probability of pavement failure. The proposed procedure can efficiently estimate the probability of pavement failure without requiring the engineers to have a detailed knowledge of theoretical mechanics and reliability simulations.

1. Introduction

The mechanistic-empirical pavement design guide (MEPDG) has recently been adopted by many highway transportation agencies for the design of pavement structures [1]. Pavements are subjected to daily vehicle load repetitions and will exhibit one or more types of distresses during service, including but not limited to rutting, fatigue cracking, longitudinal cracking, and transverse cracking [2]. This study focuses on two major pavement failure modes: rutting (i.e., permanent deformation) and fatigue cracking. The rutting failure is evaluated using the rutting life, defined as the cumulative standard axles to produce 0.25-inch rut depth (i.e., the specified rut depth limit) in the hot mix asphalt (HMA) layer. The fatigue failure is assessed using the fatigue life, defined as the allowable cumulative standard axles that yield a certain percentage of cracked surface area (e.g., 20%) for the flexible pavement. Over the years, several generations of empirical models for estimating the rutting life and fatigue life have been developed. This study adopts the most widely accepted recommendations by the American Association of State Highway and Transportation Officials (AASHTO) [3].

In pavement design using the MEPDG, it is known that the input parameters for structure, material, traffic, and environmental conditions are associated with uncertainty, which will lead to uncertainty in the predicted fatigue life and rutting life. For example, the design thickness of a pavement may not be accurately achieved due to construction error. There is also uncertainty involved in traffic and material moduli. In this regard, numerous efforts have been dedicated to transforming the deterministic pavement design to the reliability-based design [4–10]. Reliability-based approaches, such as Monte Carlo simulation and point estimate method, have been applied in the pavement assessment to estimate the effect of uncertainty in parameters of asphalt and granular layers, and in parameters of subgrade strength variability, interface condition, reinforcement, design traffic, and/or environmental actions [7–13]. It is noted that the current MEPDG overstates pavement reliability and some researchers have proposed using the load and resistance factor method in the selection of pavement design parameters for

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the MEPDG [14]. The reliability-based pavement design is generally realized through meeting a target reliability level or an equivalent probability of failure. It is known that the common method adopted in MEPDG for predicting various distresses at a required reliability level is expressed as: $Distress_R = Distress_M + SE \times ZR$ [3], in which $Distress_R$ is predicted distress at required reliability level, $Distress_M$ is predicted distress at 50% reliability level by using the prediction equations provided in MEPDG, SE is the standard error, and ZR is the standard normal deviate. For example, the values of ZR are 1.2816, 1.6449 and 2.3264 to achieve 90%, 95% and 99% reliability, respectively.

Most engineers are not familiar with the reliability-based design procedure. The current MEPDG is not a single closed-form solution and thus the implementation of sophisticated reliability-based approaches is challenging, especially when the designed pavement system is complex, e.g., multiple asphalt concrete layers. Monte Carlo simulation (MCS), a robust tool for reliability analysis, can produce accurate reliability estimates [12]. However, a large amount of computational time and effort is required if MCS is adopted in pavement design for reliability analysis [15,16]. On the other hand, it is shown that the simplified approaches such as first-order reliability method (FORM) can yield reasonably accurate solutions in comparison to MCS [7,8,10,11,17]. Thus, it is desirable to adopt the simplified approaches to reduce the computational effort in the reliability-based mechanistic-empirical pavement design [18]. As aforementioned, pavement deterioration involves several failure modes, but there is still a lack of understanding the effect of correlation between failure modes in the reliability-based pavement design. It is more rational to conduct system reliability-based design through quantitatively considering the correlated pavement failure modes.

In this paper, a spreadsheet-based approach for reliability-based pavement design using the state-of-the-practice MEPDG guidelines is presented. The layered elastic analysis is conducted using a computer code – MultiSmart3D [19], for calculating the axle load-induced tensile strain and compressive strain in a three-layer flexible pavement system. The second-order response surface method (RSM) is employed to establish a mechanics-based model for estimating the tensile strain and compressive strain. To reduce the computational effort for practitioners, the first-order reliability method (FORM) is implemented in a spreadsheet to efficiently calculate the reliability and the equivalent probability of failure. The correlation coefficients between rutting failure and fatigue failure are quantitatively evaluated based on FORM results. Further, the system reliability considering the correlated failure modes is explicitly estimated, in addition to the reliability for a single failure mode. It is shown that although one failure mode may dominate the pavement design, it is more critical to properly address the system effect. The developed approach is demonstrated through a case study of the three-layer pavement system. Using the design charts generated by the FORM solution, it is shown that the design pavement thickness can be readily determined based on the required reliability level. MCS was also performed to evaluate the effectiveness of the spreadsheet-based FORM approach.

2. Empirical models for pavement design

The rutting life (N_R) and fatigue life ($N_{f\text{-}HMA}$) of the HMA layer in the AASHTO design guide [3] are quantified as follows. The rutting life of the pavement is calculated with

$$\Delta_{p(HMA)} = \varepsilon_{p(HMA)} h_{HMA} = \beta_{1r} k_z \varepsilon_{r(HMA)} 10^{k_{1r}} n^{k_{2r}\beta_{2r}} T^{k_{3r}\beta_{3r}} \tag{1}$$

$$N_R = \left(\frac{\Delta_{p(HMA)}}{\beta_{1r} k_z \varepsilon_{r(HMA)} 10^{k_{1r}} T^{k_{3r}\beta_{3r}}} \right)^{\frac{1}{k_{2r}\beta_{2r}}} \tag{2}$$

where

$\Delta_{p(HMA)}$ = accumulated permanent distortion in HMA layer (in),
$\varepsilon_{p(HMA)}$ = accumulated permanent or plastic axial strain in HMA layer,
$\varepsilon_{r(HMA)}$ = elastic strain calculated by the structural response model at mid-depth of HMA layer (in/in),
$h_{(HMA)}$ = depth of HMA layer (in),
n = number of repetitions of axle-load,
T = pavement or mix temperature (°F),
$k_{1r,\ 2r,\ 3r}$ = global field calibration parameters,
$\beta_{1r,\ 2r,\ 3r}$ = local or mixture field calibration constants, and
k_z = depth confinement factor

Following AASHTO [3], the fatigue life of the pavement is calculated as follows:

$$N_{f-HMA} = k_{f1}(C)(C_H)\beta_{f1}(\varepsilon_t)^{k_{f2}\beta_{f2}}(E_{HMA})^{k_{f3}\beta_{f3}} \tag{3}$$

where

$N_{f\text{-}HMA}$ = allowable number of axle-load applications for flexible pavement and HMA overlays,
ε_t = tensile strain at critical locations calculated by the structural response model (in/in),
E_{HMA} = dynamic modulus of HMA measured in compression (psi),
$K_{f1,\ f2,\ f3}$ = global field calibration parameters,
$\beta_{f1,\ f2,\ f3}$ = local or mixture filed calibration constants, and
C_H = thickness correction term, dependent on the type of cracking.

3. Mechanistic models for pavement design

3.1. Multi-layer elastic analysis

In this study, multi-layer elastic analysis is performed to estimate the compressive strains and tensile strains in flexible pavement layers. We choose to use MultiSmart3D [19], an efficient computer program that allows users to carry out multi-layer elastic analysis of flexible pavements. This user-friendly program can model various user-defined features such as multiple pavement layers, e.g., sublayers of HMA layer, anisotropic materials, multiple loads, three-dimensional (3D) effect, etc [20–25]. The analysis procedure involves defining parameters such as type of analysis (pure elastic or thermo-elastic), boundary condition (elastic half-space or rigid foundation), and layer characteristics (number of layers, thickness, Poisson's ratio and resilient modulus), loading condition (position, magnitude and area) and response points (number and location). It should be noted that under the proposed reliability-based framework in this paper, other programs for evaluating the strains in pavements can also be implemented instead of MultiSmart3D.

In this study, the three layers of the pavement structure are modelled as purely elastic materials with the third layer being a homogeneous half-space. Tire inflation pressure of 0.6895 MPa is assumed, and the contact area is circular with a radius of 13.6 cm. The corresponding responses directly below the point of tire application are calculated with the linear elastic analysis. The three layers in the pavement system are the hot mix asphalt (HMA) layer, granular base layer, and subgrade, as shown in Fig. 1. The thickness and moduli for each sublayer are summarized in Table 1. The Poisson's ratios for HMA layer, base layer and subgrade layer are 0.45, 0.35 and 0.35, respectively.

The input parameters (Table 1) can be entered in this layered elastic analysis program, and the displacements, strain, and stress at the desired response points can be efficiently calculated. In this study, the maximum tensile strain (ε_t) at the bottom of the HMA