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# PROBABILISTIC PREDICTIVE STRAIN CALCULATION IN ASPHALT PAVEMENTS

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## ABSTRACT

*Structural failure of an asphalt pavement is primarily caused due to fatigue and rutting. To measure fatigue and rutting performances, the critical horizontal tensile strain (* $\varepsilon_t$ *) at the bottom of asphalt layer and critical vertical compressive strain (* $\varepsilon_z$ *) at the top of subgrade layer are popularly used in mechanistic-empirical (M-E) pavement design process. However, the prediction of* $\varepsilon_t$ *and* $\varepsilon_z$ *in asphalt pavement structure is very much probabilistic in nature, due to significant uncertainties associated with the input parameters, empiricisms in evaluation process etc. This paper focuses on the probabilistic strains (* $\varepsilon_t$ *and* $\varepsilon_z$ *) calculation based on predictive models used in mechanistic-empirical pavement design and using Monte Carlo simulation.*

***Keywords: Asphalt Pavement, Strain, Fatigue, Rutting, Probability***.

## I. INTRODUCTION

Mechanistic-empirical (M-E) design method is being popularly used for structural design of asphalt pavements [1-7]. Traditionally, the mechanistic parameters viz. critical horizontal tensile strain ($\varepsilon_t$) at the bottom of asphalt layer is correlated empirically with fatigue performance and the critical vertical compressive strain ($\varepsilon_z$) at the top of subgrade layer is correlated with rutting performance in asphalt pavements. However, the accurate estimation of $\varepsilon_t$ and $\varepsilon_z$ in pavement structures is complex and uncertain as well. To avoid difficulties in structural analysis, certain simplifications and approximations are made and the solutions are obtained through numerical analysis. Software such as ABAQUS, ANSYS, KENPAVE, FPAV etc are used by various researchers [8-14] for pavement analysis. However, it requires high technical skill, expertise manpower and good computational facility. Therefore, various predictive strain models are also developed by various researchers based on principles of regression analysis, which can be used in deterministic strain prediction. Moreover, such deterministic strain calculation may not be adequate enough due to uncertainties involved with various input parameters like, layers modulii, layer thickness, loads etc. This paper aims to present a simple methodology for probabilistic strain calculation based on predictive strains models in multilayered asphalt pavements.

## II. BACKGROUND

Current practice of asphalt pavements design, popularly known as mechanistic-empirical (M-E) design method is followed in various guidelines [1-7]. Fatigue and rutting are considered as two primary modes of structural failures. In general, 20% of surface cracks area in case of fatigue and 20mm of rut depth in case of rutting failure are adopted as failure criteria. The numbers of load repetitions till failure is noted as pavement life. Fatigue life ( $N_f$ ) and rutting life ( $N_r$ ) of the pavement are empirically correlated with the critical strain parameters of the section. A general form of fatigue and rutting equations may be expressed as given in Eqs.(1) and (2) respectively.

$$N_f = k_1 \times \left(\frac{1}{\varepsilon_t}\right)^{k_2} \times \left(\frac{1}{E_1}\right)^{k_3} \tag{1}$$

$$N_r = c_1 \times \left(\frac{1}{\varepsilon_z}\right)^{c_2} \tag{2}$$

where, $N_f$ is the fatigue life; $N_r$ is the rutting life; $\varepsilon_t$ is the initial critical horizontal tensile strain at the bottom of asphalt layer; $\varepsilon_z$ is the initial critical vertical compressive strain at the top of subgrade layer; $E_1$ is the initial stiffness of asphalt material; and, $k_1$, $k_2$, $k_3$, $c_1$ and $c_2$ are regression constants. Different literatures suggest different values for these parameters [1, 4-7, 15-19].

Based on the total number of traffic repetitions to be sustained during the design life, the maximum allowable $\varepsilon_t$ and $\varepsilon_z$ values can be determined from Eqs.(1) and (2) respectively. Accordingly, comparing these strains values with the computed $\varepsilon_t$ and $\varepsilon_z$ as obtained from the structural analysis program, the thicknesses of the design layer(s) can be obtained iteratively. However, computing the values of $\varepsilon_t$ and $\varepsilon_z$ is in continuously supported multilayered pavement structures is complex task. Otherwise also, for a 3 layered asphalt pavement the predictive strain functions may be used as given in Eqs.(3) and (4) [20] .

$$\varepsilon_t = f_1 + f_2 \ln(E_1) + f_3 \ln(E_2) + f_4 \ln(E_3) + f_5 \ln(h_1) + f_6 \ln(h_2) \tag{3}$$

$$\varepsilon_z = r_1 + r_2 \ln(E_1) + r_3 \ln(E_2) + r_4 \ln(E_3) + r_5 \ln(h_1) + r_6 \ln(h_2) \tag{4}$$

where, $E_1$, $E_2$ and $E_3$ are the modulii (MPa) of asphalt, granular and subgrade layer respectively; $h_1$ and $h_2$ are the thicknesses (cm) of asphalt and granular layer respectively, and $f_i$, $r_i$ are the model parameters. The $f_i$, and $r_i$ parameters are tabulated in Table 1 [20].

**TABLE 1. Parameters of strains ($\varepsilon_t$ and $\varepsilon_z$) functions.**

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $f_1$ | $1.453\times10^{-03}$ | $r_1$ | $-2.441\times10^{-03}$ |
| $f_2$ | $-7.998\times10^{-05}$ | $r_2$ | $3.20\times x10^{-05}$ |
| $f_3$ | $-6.595\times10^{-05}$ | $r_3$ | $7.299\times10^{-05}$ |
| $f_4$ | $-1.421\times10^{-07}$ | $r_4$ | $9.529\times10^{-05}$ |
| $f_5$ | $-1.060\times10^{-04}$ | $r_5$ | $1.07\times10^{-04}$ |
| $f_6$ | $-6.913\times10^{-06}$ | $r_6$ | $2.236\times10^{-04}$ |

Eqs.(3) and (4) are statistical equation and therefore, the strains ($\varepsilon_t$ and $\varepsilon_z$) prediction would posses significant viabilities due to variability in $E_i$ and $h_i$ input parameters. Thus, the estimation of $\varepsilon_t$ and $\varepsilon_z$ need to consider the probability aspects and is discussed in the next section.

## III. PROBABILISTIC STRAINS CALCULATION

It is well known fact that pavement lives prediction in asphalt pavements is very uncertain due to many reasons like, various assumptions, approximations and empiricisms associated with structural analysis program, loading conditions and environmental factors, uncertainties in materials properties and layers thicknesses etc. The uncertainties in materials property and layers thickness ultimately lead to an uncertain estimation of strains ($\varepsilon_t$ and $\varepsilon_z$) parameter. Such variability can be reduced through proper quality control during constructions. Also, these uncertainties can be accommodated using probabilistic method.

For probabilistic strain calculation, one needs to know the distribution of strain parameter and its distribution's parameter(s). This can be obtained for known distributions of various input parameters, say modulii ($E_i$) and thickness ($h_i$) values of different pavement layers. Different literatures had reported different distributions and their coefficient of variations. Details can be seen elsewhere [21-25]. In case of lognormal distributions of layers modulus ($E_i$) and thickness ($h_i$) parameters, the strain parameters ($\varepsilon_t$ and $\varepsilon_z$) as given in Eqs.(3)-(4) would follow normal distributions with certain mean and variance. Mean of $\varepsilon_t$ or $\varepsilon_z$ ($mean_\varepsilon$) can be obtained using Eqs.(3)-(4) and considering mean of all the input parameters. The variance of $\varepsilon_t$ or $\varepsilon_z$ ($\sigma_\varepsilon^2$) can be estimated as given in Eqs.(5) and (6).

$$\left.\begin{aligned}\sigma_{\varepsilon_t}^2 &= \sum_{i=1}^{3} f_{i+1}^2\times\sigma_{E_i}^2+\sum_{i=1}^{2} f_{i+4}^2\times\sigma_{h_i}^2\\ \sigma_{\varepsilon_z}^2 &= \sum_{i=1}^{3} r_{i+1}^2\times\sigma_{E_i}^2+\sum_{i=1}^{2} r_{i+4}^2\times\sigma_{h_i}^2\end{aligned}\right\}\text{; for 3-layred structure.}\qquad(5)$$

$$\left.\begin{aligned}\sigma^2_{\varepsilon_t} &= \sum_{i=1}^{4} f^2_{i+1}\times\sigma^2_{E_i} + \sum_{i=1}^{3} f^2_{i+5}\times\sigma^2_{h_i}\\ \sigma^2_{\varepsilon_z} &= \sum_{i=1}^{4} r^2_{i+1}\times\sigma^2_{E_i} + \sum_{i=1}^{3} r^2_{i+5}\times\sigma^2_{h_i}\end{aligned}\right\} \text{; for 4-layred structure.} \qquad (6)$$

where, $\sigma_x^2$ represents the variance of random variable $x$; and $f_i$ and $r_i$ are given in Table 1. Thus, the probability of strain ($\varepsilon$) parameter less than to any allowable strain ($\varepsilon_{allow}$) value can estimated using a normal density function and is given in Eq.(7).

$$\text{Prob.}(\varepsilon < \varepsilon_{allow}) = \int_0^{\varepsilon_{allow}} f_\varepsilon(x)dx = \frac{1}{\sqrt{2\pi\sigma_\varepsilon^2}} \int_0^{\varepsilon_{allow}} e^{-\frac{1}{2}\left(\frac{x - mean_\varepsilon}{\sigma_\varepsilon^2}\right)^2} dx \qquad (7)$$

In Eq.(7), $\varepsilon$ may be $\varepsilon_t$ or $\varepsilon_z$ and $\varepsilon_{allow}$ may be allowable strain from fatigue or rutting consideration, based on traffic repetitions to be sustained during the design period. In other words also, for any given probability level the strain value can be obtained using normal table. However, if the input parameters (i.e. $E_i$ and $h_i$) in Eqs.(3) – (4) follow other than lognormal distributions, the distributions of $\varepsilon_t$ and $\varepsilon_z$ need to be derived analytically or through simulation. For this purpose, a Monte Carlo simulation (MCS) has been performed considering 10000 data points for each normally distributed random input. Data used in MCS is given in Table 2 [21].

**TABLE 2. Data used for MCS of strain parameters.**

| Parameter | Mean | Coefficient of variation | Standard deviation |
|---|---|---|---|
| $E_1$ | 1500MPa | 15% | 225MPa |
| $E_2$ | 400MPa | 20% | 80MPa |
| $E_3$ | 50MPa | 25% | 12.5MPa |
| $h_1$ | 15cm | 10% | 1.5cm |
| $h_2$ | 30cm | 20% | 6cm |

Fig.1 shows the distributions of $\varepsilon_t$ and $\varepsilon_z$ derived from simulation study. As observed, both $\varepsilon_t$ and $\varepsilon_z$ parameters seem to follow normal. This case, the mean and standard deviation are obtained as 0.000165 and $2.14\times10^{-5}$ respectively for $\varepsilon_t$ and, -0.000353 and $5.8\times10^{-5}$ respectively for $\varepsilon_z$ parameters.

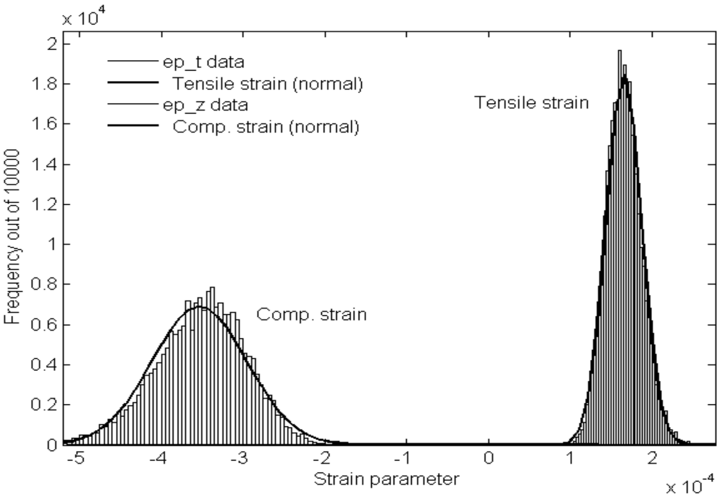

**Figure 1. Probability distributions of tensile strain and compressive strain.**

## IV. CONCLUSIONS

The present paper illustrates a procedure for probabilistic strains calculation based on predictive strain models and using MCS. It may be concluded that the $\varepsilon_t$ and $\varepsilon_z$ parameters may be considered to follow normal distribution for given all input parameters of $E_i$ and $h_i$ as lognormal and normal distributions as well. Such information would be useful while using M-E fatigue and rutting equations for probabilistic pavement design, where the $\varepsilon_t$ and $\varepsilon_z$ are the primary factors for fatigue and rutting failures respectively.

## REFERENCES

[1]. Asphalt Institute (AI). (1999). *Thickness design - asphalt pavements for highways and streets.* Manual Series No.1, 9th Edition, The Asphalt Institute, Lexington, Ky, USA.

[2]. Austroads. (2004). *Pavement design*. Austroads, Sydney, Australia.

[3]. French. (1997). *French design manual for pavements structures*. Guide Technique, LCPC and SETRA, Francaise.

[4]. Indian Roads Congress (IRC). (2012). *Guidelines for the design of flexible pavements*. IRC: 37-2012, 3rd Revision, The Indian Roads Congress, New Delhi, India.

[5]. National Cooperative Highway Research Program (NCHRP). (2004). *Mechanistic-empirical design of new & rehabilitated pavement structures*. NCHRP Project 1-37A, Transportation Research Board, Washington, D.C.

[6]. Shell. (1978). *Shell pavement design manual – asphalt pavement and overlays for road traffic*. Shell International Petroleum Company Limited, London, UK.

[7]. Transport Research Laboratory (TRL). (1993). *A guide to the structural design of bitumen-surfaced roads in tropical and sub-tropical countries*. Overseas Road Note 31, 4th Edition, Overseas Center, TRL, London.

[8]. Chandra, S., Viladkar, M.N., and Nagrale, P.P. (2008). Mechanistic approach for fiber-reinforced flexible pavements. *Jr. of Transportation Engineering*, ASCE, 134(1), pp.15-23.

[9]. Das, A., and Pandey, B.B. (1999). Mechanistic-empirical design of bituminous roads: an Indian perspective. *Jr. of Transportation Engineering*, ASCE, 125(5), pp.463-471.

[10]. Hadi, M.N.S., and Bodhinayake, B.C. (2003). Non-linear finite element analysis of flexible pavements. *Advances in Engineering Software* , Elsevier, Vol.34, pp.657-662.

[11]. Helwany, S., Dyer, J., and Leidy, J. (1998). Finite-element analyses of flexible pavements. *Journal of Transportation Engineering*, ASCE, 124(5), pp.491–499.

[12]. Kuo, C.M., and Chou, F.J. (2004). Development of 3-D finite element model for flexible pavements. *Journal of the Chinese Institute of Engineers*, 27(5), pp.707-717.

[13]. Lacey, G., Thenoux, G., and Rodríguez-Roa, F. (2007), Three-dimensional finite element model for flexible pavement analysis based on field modulus measurements. *The Arabian Journal for Science and Engineering*, Vol. 33, No. 1B, pp.65.

[14]. Rahman, M.T., Mahmud, K., and Ahsan, S. (2011). Stress-strain characteristics of flexible pavement using finite element analysis. *Int. Jr. of Civil and Structural Engineering*, 2(1), pp.233-240.

[15]. Huang, Y.H. (2004). *Pavement analysis and design*. Second Edition, Pearson Prentice Hall, New Jersey.

[16]. Behiry, A.E.A.M. (2012). Fatigue and rutting lives in flexible pavement. *Ain Shams Engineering Journal*, Ain Shams University, Vol.3, pp.367–374.

[17]. Hajj, E.Y., Sebaaly, P.E., and Weitzel, D. (2005). Fatigue characteristics of superpave and Hveem mixtures. *Jr. of Transportation Engineering*, ASCE, 131(4), pp.302–310.

[18]. Priest, A.L. (2005). Calibration of fatigue transfer functions for mechanistic-empirical flexible pavement design. *M.Sc Thesis*, Civil Engineering Dept., Auburn University, Auburn, USA.

[19]. Thompson, M.R. (1987). ILLI-PAVE based full-depth asphalt concrete pavement design procedure. *6th Int. Conf. of Structure Design of Asphalt Pavements*, Vol.1, University of Michigan, Ann Arbor, pp.13–24.

[20]. Engleng, G. (2015). “Development of strains transfer functions and asphalt stiffness reduction models in asphalt pavements”, *PhD thesis*, Civil Engg. Dept., NIT Silchar.

[21]. Kalita, K., and Rajbongshi, P. (2015). Variability characterization of input parameters in pavement performance evaluation. *Jr. of Road Materials and Pavement Design*, 16(1), pp.172-185.

[22]. Maji, A., and Das, A. (2008). Reliability considerations of bituminous pavement design by mechanistic-empirical approach. *Int. Jr. of Pavement Engineering*, 9(1), pp.19-31.

[23]. Rajbongshi, P., and Das, A. (2008). Optimal asphalt pavement design considering cost and reliability. *Jr. of Transportation Engineering*, ASCE, 134(6), pp.255-261.

[24]. Retherford, J., and McDonald, M. (2010). Reliability methods applicable to mechanistic-empirical pavement design method. *Jr. of Transportation Research Board*, Transportation Research Record, No.3476, pp.130-137.

[25]. Wojtkiewicz, S.F., Khazanovich, L., Gaurav, G., and Velasquez, R. (2010). Probabilistic numerical simulation of pavement performance using MEPDG. *Road Materials and Pavement Design*, 11(2), pp.291–306.