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STRAIN TRANSFER FUNCTION IN FLEXIBLE PAVEMENTS

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ABSTRACT

Structural failure of anflexible pavement is primarily caused due to fatigue and rutting failures. To measure fatigue performances, the critical horizontal tensile strain (ε_t) at the bottom of flexible layer is popularly used in the mechanistic-empirical (M-E) pavement design process. However, the computation of ε_t in a 3-D multilayered pavement structure with distributed loading is a complex phenomenon. This paper attempts to present simple strain transfer functions for estimation of ε_t, considering 3-D nonlinear analysis of flexible pavements. The transfer function is validated and found adequate in prediction of ε_t. Degree of accuracy has also beenjustified statistically. ABAQUS software is used for analysis of pavement structures.

Keywords: Flexible Pavement, Strain, Fatigue,3-D, Nonlinear

I INTRODUCTION

Mechanistic-Empirical (M-E) design method is being popularly used for structural design of flexible pavements [1-7]. Traditionally, the mechanistic parameters like critical horizontal tensile strain (ε_t) at the bottom of flexible layer is correlated empirically with fatigue performance in flexiblepavements. However, the accurate estimation of ε_t in pavement structure is a complex issue. Primary reasons of such complexities are multilayered and its interaction between the layers, visco-elastic behavior of flexible material, structural boundary conditions, axle and wheel configurations, environmental factors etc. To avoid these, certain simplifications and approximations are made and the solutions are obtained through numerical analysis. Softwaresuch as ABAQUS, ANSIS, KENPAVE, FPAV etc areused by various researchers [8-14] for pavement analysis. It requires high technical skill, expertise manpower and computing facility as well. However, a designer or a state department may not be comfortable for such infrastructures and efforts. This paper attempts to present simple expressions for strains calculation inmultilayered flexiblepavements, including its acceptability and validation. Finite element method (FEM) based software 'ABAQUS' is adopted for analysis of multilayered pavement sections.

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II BACKGROUND

Current practice of flexiblepavements design, popularlyknown as Mechanistic-Empirical (M-E) designmethod is followed in various guidelines[1-7]. Fatigue and rutting are considered as two primary modes of structural failures. Normally, the failure criteria adopted as 20% of surface cracks area in case of fatigue and 20mm of rut depth in case of rutting failure.The numbers of load repetitions till failure is recorded as pavement life. Fatigue life (N_f) isempirically correlated with the critical strain parameter of the section. A general form of fatigue equation may be expressed as given in Eq.(1).

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

where, N_f is the fatigue life; ε_t is the initial critical horizontal tensile strain at the bottom of flexible layer; E_1 is the initial stiffness of flexible material; and, k_1, k_2, and k_3 are regression constants.Different literatures suggest different values forthese parameters. Some of them are listed in Table 1.

Table 1. Parameters of fatigue equation adopted in M-E pavement design.

Organization	k_1	k_2	k_3	References
Indian Roads Congress	2.21×10^{-4}	3.89	0.854	[3]
Flexible Institute	0.0795	3.291	0.854	[1, 16]
Shell Research	0.0685	5.671	2.363	[4, 15]
US Army Corps of Engineers	497.156	5	2.66	[15, 16]
Belgian Road Research Center	4.92×10^{-14}	4.76	0	[16]
Transport and Road Research Laboratory	1.66×10^{-10}	4.32	0	[5, 16]

It may be mentioned that N_f and ε_t shall be in respect of same loading conditions (say, standard axle load of 80kN). Replacing N_f by the total number of traffic repetitions to be sustained during the design life, the maximum allowable ε_t value can be determined from Eq.(1). Accordingly, comparing these strains values with the computed ε_t as obtained from structural analysis, the thicknesses of the design layer(s) can be decided iteratively.

To calculate ε_t value, it needs to solve 3-D equilibrium and compatibility equations, along withadequate boundary conditions.Approximate solution can be obtained through numerical analysis.FEM is one of the most powerful numerical techniques, which is widely used for such solutions. FEM based software ‘ABAQUS’ has

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been adopted by various researchers [8-12] for numerical analysis of pavement structures. In the present work also, ABAQUS is used to model and analyze the flexible pavements,and it is discussed in the next section.

III MODELING OF PAVEMENT STRUCTURE

Normally, anflexible pavement structure contains 3 to 4 number of load bearing layers. In this study, a 3-layred and a 4-layred pavement has been modeled as 3-D nonlinear elastic structure with finite boundaries. A 3-layred pavement section is shown in Figure 1. FEM based analysis of the pavement is carried out in the ABAQUS environment. Eight noded linear brick elements with reduce integration (C3D8R) is used in analysis, which considers only one integration point at the middle. This element has ability to reduce the computational effort without significant affect on the accuracy.Each element is considered with three degrees of freedom (i.e. displacement in X,Y and Z-directions). Pavement section of 3.5m×10m with end conditions of zero displacement in transverse (-X) and longitudinal (-Y) directions, and fixed end at the bottom of subgrade are used, including rough interface between two layers.A fine mesh of 4.9cm x 7.2cm for flexible layer, and coarse mesh of 9.8cm × 14.24cm for granular and subgrade layers are chosen. This is depicted in Figure 1. The analysis of pavement structureshas been discussed in the next section.

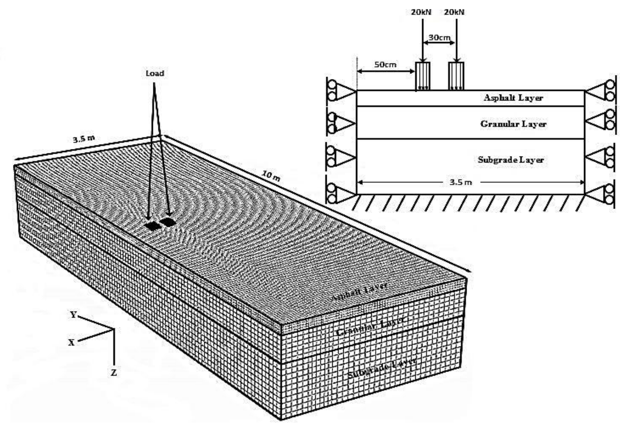

Figure 1. 3-layred flexible pavement structure.

IV PAVEMENT ANALYSIS AND MODEL DEVELOPMENT:

In M-E pavement design process, the fatigue performance is predicted based on initial critical horizontal tensile strain (ε_t) at the bottom of flexible layer. Table 2 shows the layers information for a 3-layred pavement section. To represent the different cases, possible ranges of each parameter has been considered as shown in the table. Poisson's ratio is taken as constant due to negligible effect (Huang, 2004). A uniformly distributed standard dual wheel load of 20kN with tyre pressure of 0.7MPa over its contact area has been adopted for all the cases.

Table 2. Layers information used for 3-layred pavement analysis.

Layer	Thickness (cm)	*E*-value (MPa)	Poisson's ratio
Flexible layer	15 – 20	800 – 2000	0.3
Granular base layer	30 – 50	200 – 400	0.35
Subgrade	100	40 – 100	0.35

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For different combinations of layers input as given in Table 2, the strain parameter (ε_t) are computed through ABAQUS. Figure 2 shows the strains contour in one case obtained from the ABAQUS analysis. The variations of ε_t with flexible modulus (E_1) is shown in Figure 3. Negative value indicates compression. Similarly, ε_t variation with other variable parameters is also presented in Figures (4) – (7).

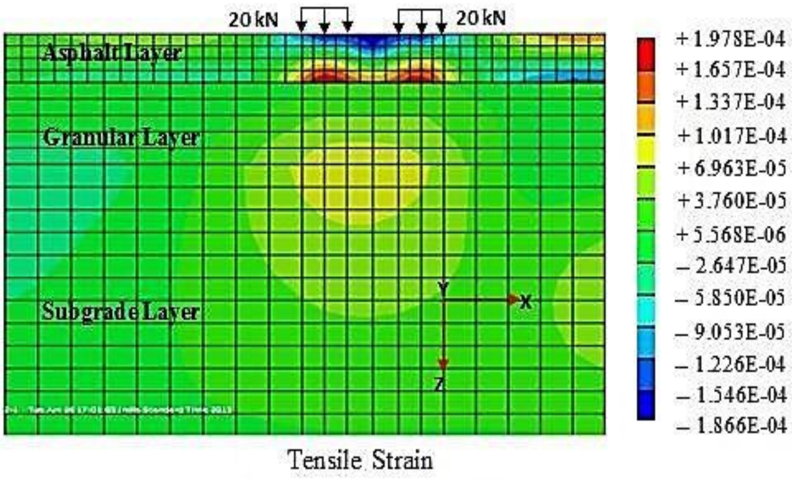

Figure 2.Contour plots of tensile strain in 3-layered pavement structure.

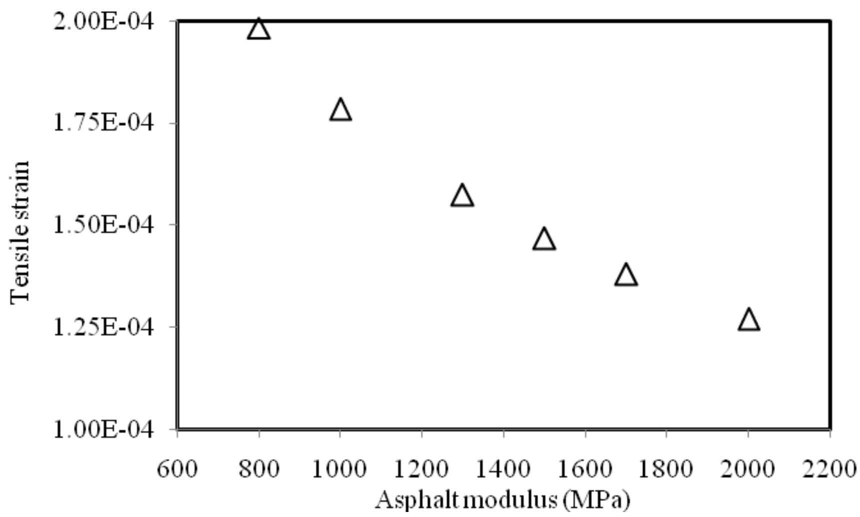

Figure 3. Strain variations with modulus (E_1)of flexible layer.

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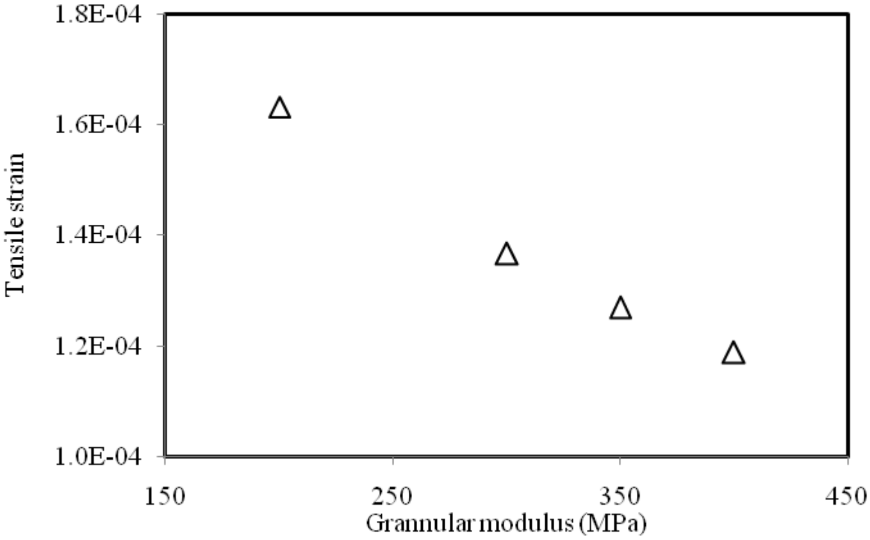

Figure 4. Strain variations with modulus (E_2) of granular layer.

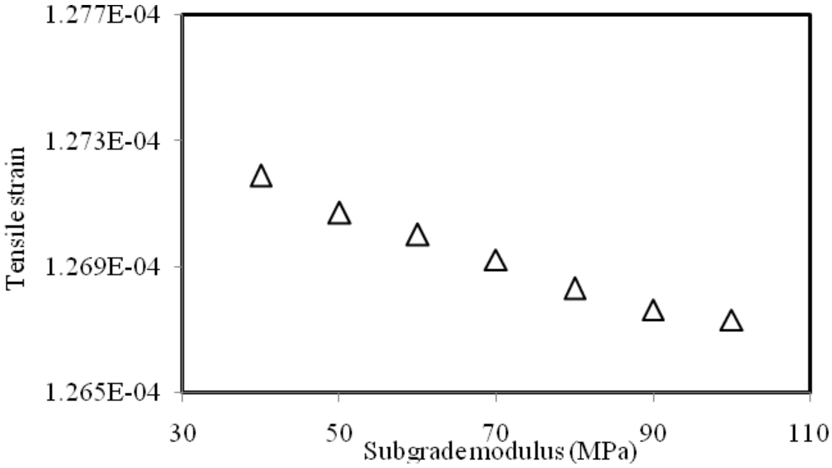

Figure 5. Strain variations with modulus (E_3) of subgrade layer.

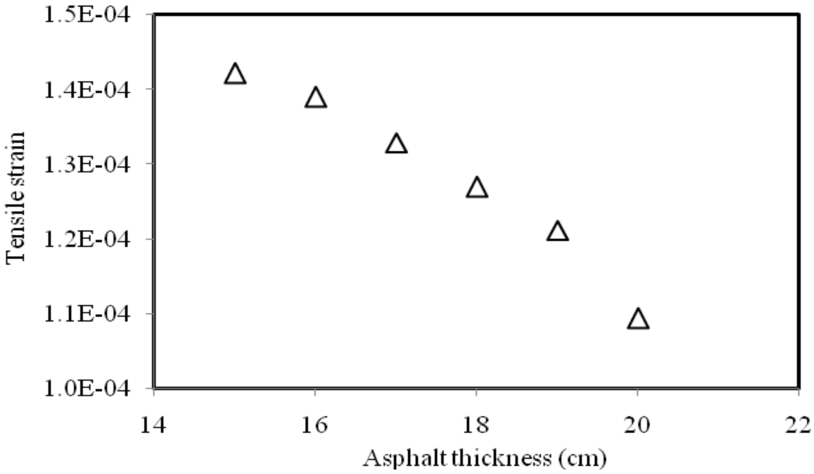

Figure 6. Strain variations with flexible layer (h_1) thickness.

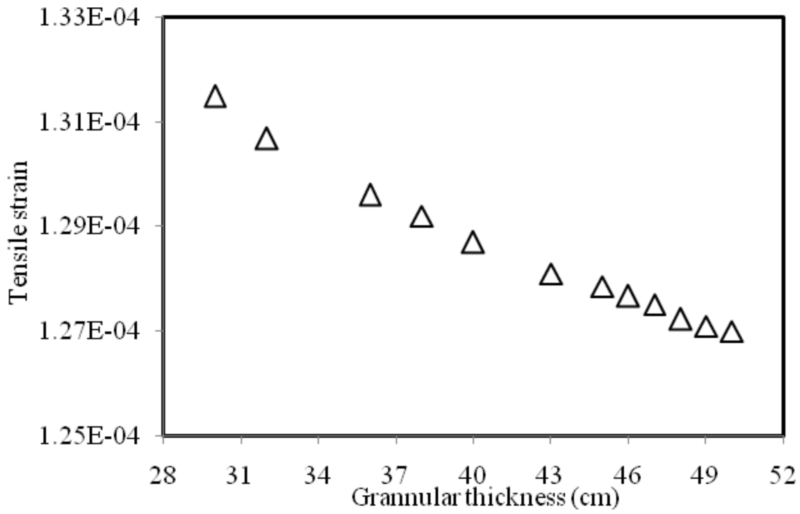

Figure 7. Strain variations with granular layer (h_2) thickness.

From Figures (3) – (7), it is observed that ε_t parameter isclosely correlated with the independent parameters. Combining all the independent variablestogether, the nonlinear multivariable best fit curves for a 3-layred pavement structure are derived using EViews as given in Eq.(2).

$$\varepsilon_t = f_1 + f_2 \ln(E_1) + f_3 \ln(E_2) + f_4 \ln(E_3) + f_5 \ln(h_1) + f_6 \ln(h_2) \quad (2)$$

where, E_1, E_2 and E_3 are the moduliiof flexible, granular and subgrade layer respectively in MPa; h_1 and h_2 are the thicknesses of flexible and granular layer respectively in cm, and f_i are the model parameters. The f_i parameters are tabulated in Table 3. From Table 3, it is seen that the E_3 and h_2 parameters are not significant to ε_t, as compare to other parameters. This is what it is expected also.

Table 3. Parameters of strain model of 3-layredflexible pavement.

Parameter	Value
f_1	1.453×10^{-03}
f_2	$- 7.998\times10^{-05}$
f_3	$- 6.595\times10^{-05}$
f_4	-1.421×10^{-07}
f_5	$- 1.060\times10^{-04}$
f_6	$- 6.913\times10^{-06}$

Eq.(2) is obtained statistically and therefore, it is essential to justify its confidence level in prediction. To this effect and to examine the adequacy of model, various statistical parameters of the strain model are evaluated and are tabulated in Table 4. As seen in the table, it may be concluded that the independent parameter possesgood correlation with the dependent parameter(i.e. ε_t) and maybe acceptable.

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Table 4. Statistical parameters of the strain model for 3-layredflexible pavement.

Parameter	Tensile strain model
R-squared	0.995
Adjusted R-squared	0.994
Std. error of regression	1.95×10^{-06}
Sum squared residue	1.14×10^{-10}
F-statistic	1234
Prob. of F-statistic	0.000

In a similar way, the strain transfer functions are also developed for 4-layered pavement structures viz. flexible, granular base, granular sub-base and subgrade layers, and found that the strain parameter (ε_t) is closely correlated with the structural input parameters. The nonlinear multivariable best fit curves for ε_t in 4-layred pavement structure are derived as given in Eq.(3).

$$\varepsilon_t = f_1 + f_2 \ln(E_1) + f_3 \ln(E_2) + f_4 \ln(E_3) + f_5 \ln(E_4) + f_6 \ln(h_1) + f_7 \ln(h_2) + f_8 \ln(h_3) \quad (3)$$

where, E_1, E_2, E_3 and E_4 are the modulii of flexible, granular base, granular sub-base and subgrade layer respectively in MPa; h_1, h_2 and h_3 are the thicknesses of flexible, granular base and granular sub-base layer respectively in cm; and f_i, are the model parameters. The f_i parameters are tabulated in Table 5.

Table 5. Parameters of strain model for 4-layreda flexible pavement.

Parameter	Value
f_1	1.405×10^{-03}
f_2	$- 7.25\times10^{-05}$
f_3	$- 7.39\times10^{-05}$
f_4	-5.12×10^{-06}
f_5	$- 1.31\times10^{-06}$
f_6	$- 8.21\times10^{-05}$
f_7	$- 4.37\times10^{-06}$
f_8	$- 1.14\times10^{-06}$

To examine the adequacy in strain prediction, various statistical parameters of the strain model are evaluated using EViews and are tabulated in Table 6. As seen in the table, it may be concluded that the independent parameter posses good correlation with the dependent parameter (i.e. ε_t) and thus, the correlation may be acceptable.

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Table 6. Statistical parameters of the strain model for4-layredflexible pavement.

Parameter	Tensile strain model
R-squared	0.999
Adjusted R-squared	0.999
Std. error of regression	3.93×10^{-07}
Sum squared residue	5.10×10^{-12}
F-statistic	7232
Prob. of F-statistic	0.000

Further, it is attempted to validate the developed models using separate sets of input data, through ABAQUS and KENPAVE analysis as well. This is illustrated in the next section.

V VALIDATION

In order to validate the statistical strains transfer functions, different flexiblepavement sections are analyzed considering separate sets of input data. The strain (ε_t) values are evaluated using both ABAQUS and KENPAVE analysis program. The comparison of ε_t value calculated from pavement analysis and the developed strain model is shown in Figure 8. To compare the strain transfer functions in terms of the fatigue life (N_f) and prediction, a comparison of N_f in million standard axles (msa) is presented in Figure 9.Regression constants of the fatigue equation are adopted as per TRL models (Huang, 2004). Thus, from Figure 8 or Figure 9 it may be concluded that the model prediction is sufficiently good as that of ABAQUS or KENPAVE analysis programs.

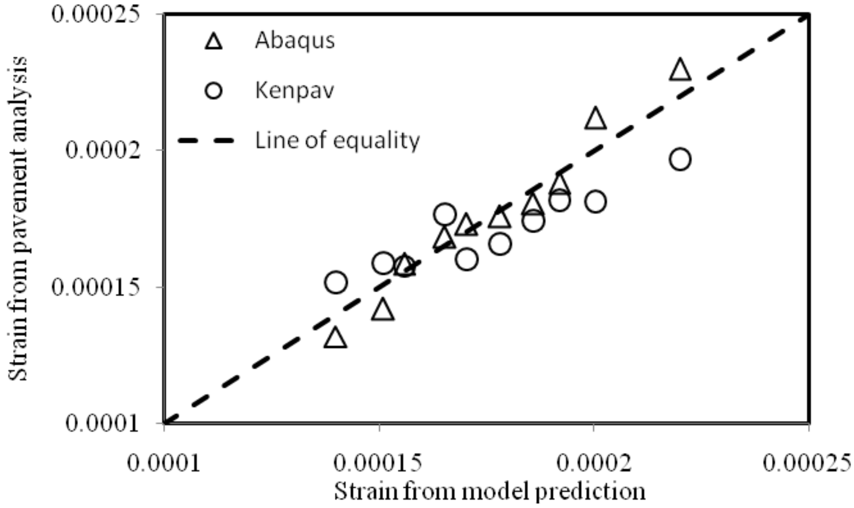

Figure 8. Comparison of tensile strain parameter inflexiblepavements.

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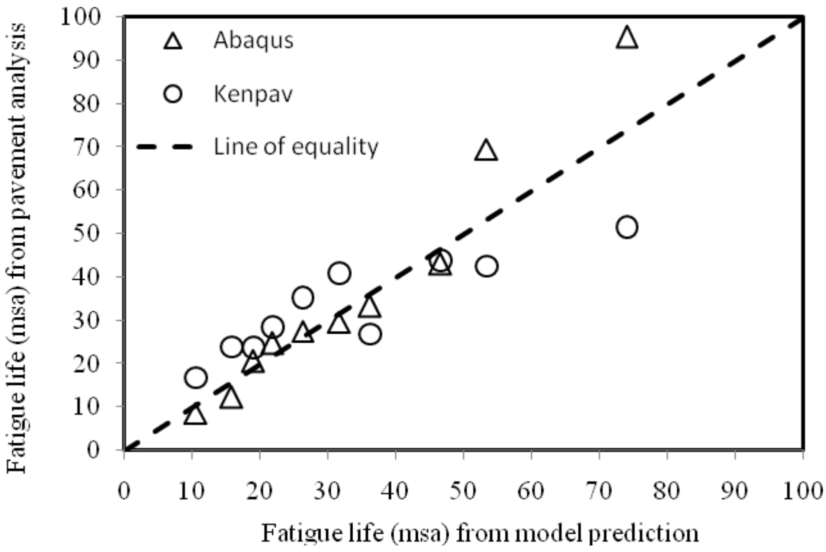

Figure 9. Comparison of fatigue life in flexiblepavements.

VI CONCLUSIONS

Simple strain transfer function for horizontal tensile strain (ε_t)in flexible pavements has been developed and presented in the paper. The proposed ε_t function is validated and found adequate in prediction. Statistically also, this transfer function is tested and found confident. Thus, the proposed strain model can easily be adopted for fatigue life estimation in the pavement design process, and can be avoided complex analysis and high computational effort.Also, to incorporate the reliability or probability in pavement design, one can easily know the distribution of ε_t for any given distributions of their input parameters. For example, the ε_t parameter would follow normal distribution, in case the inputs E_i and h_i in the strain functions (Eqs. (2) and (3)) are log-normally distributed.

Towards M-E fatigue design of flexible pavements, this work focuses on establishing an acceptable statistical correlation between the strain parameter (ε_t) and layers informationin 3-layred and 4-layred pavement structures. However, they have few limitations like the effect of moving loads, visco-elastic behavior etc are not accounted and are recommended for further studies.

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