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A Critical Discussion on Mechanistic-Empirical Fatigue Evaluation of Asphalt Pavements

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Abstract: Mechanistic-empirical fatigue equation is used for evaluation of fatigue life or fatigue performance of asphalt pavements. To evaluate fatigue performance, an appropriate field fatigue equation is necessary. It is experienced that the fatigue performance of an in-service pavement is significantly uncertain while using such equation. This paper attempts to identify some of the possible reasons of inadequacy involved with field fatigue equation. Certain issues have been addressed which may improve the fatigue prediction level.

***Key words**: Asphalt pavement; Fatigue failure.*

Introduction

Mechanistic-empirical (M-E) design of asphalt pavements is popularly being used in various countries [1-7]. In M-E design approach, fatigue is considered as one of the primary modes of pavement failure. Fatigue life of any pavement structure is defined as the numbers of traffic repetition that the pavement can sustain before fatigue failure. Fatigue failure is specified by certain percentage of surface fatigue cracking (*FC*).

Fatigue equation primarily establishes a correlation between the initial tensile strain at the bottom of asphalt layer and the load repetition at failure *FC*. This is also known as bottom-up *FC*, where the cracks initiate at the bottom of asphalt layer and subsequently propagates toward the pavement surface in the form of map cracking. The propagation of *FC* in asphalt pavement is a complex phenomenon due to various factors like material characteristics, loading conditions, climatic factors, uncertainty of input parameters etc. As a result, the fatigue equation used in pavement design seems to be more empirical than mechanistic. While developing such equation in the form of regression equation, certain issue needs to consider. The present paper addresses some of the critical observations of fatigue consideration in asphalt pavements. Some possible suggestions are drawn which may improve the fatigue performance evaluation.

This paper has six sections of which this is the first section. Next section discusses about the fatigue life evaluation in asphalt pavements. The issue related to the calibration of fatigue equation has been addressed in the third section. Evaluation of fatigue performance is discussed in the next section. Fifth section explains the consideration of load equivalency factor. Finally, the closing remark is placed as last section.

Evaluation of Fatigue Life

Fatigue life of an asphalt pavement is obtained using field fatigue equation. A generic form of field fatigue equation is [1, 4, 6, 8],

$$N_f^F = f_1 \times \left(\frac{1}{\varepsilon_t}\right)^{f_2} \times \left(\frac{1}{E_1}\right)^{f_3} \tag{1}$$

where, N_f^F is the field fatigue life; ε_t is the initial critical tensile strain at the bottom of asphalt layer; E_1 is the initial stiffness of asphalt material; and f_1, f_2, and f_3 are regression constants. A large pool of f_1, f_2, and f_3 values can be found in various literatures [8-10]. Table 1 shows the value of these parameters recommended by three different guidelines. Fig. 1 presents the graphical representation for these fatigue equations. A comparison of the fatigue life is shown in Fig. 2. In figures, fatigue life is represented in million axles (ma).

From Eq. (1), it is important to note that E_1 has two opposite effects on N_f^F. First, increasing E_1 value, N_f^F decreases (since f_3>0). In the same time, increasing E_1 value, ε_t decreases and thus, N_f^F increases. Therefore, combining these two effects the resultant

Table 1. Parameters of Field Fatigue Equation.

Fatigue Equation (Eq. (1)*)	f_1	f_2	f_3
Asphalt Institute (AI) [1]	1.133×10^{-3}	3.291	0.854
Shell [6]	5.35×10^{-7}	5.671	2.363
Indian Roads Congress (IRC) [4]	2.21×10^{-4}	3.89	0.854

* E_1 is in *MPa*

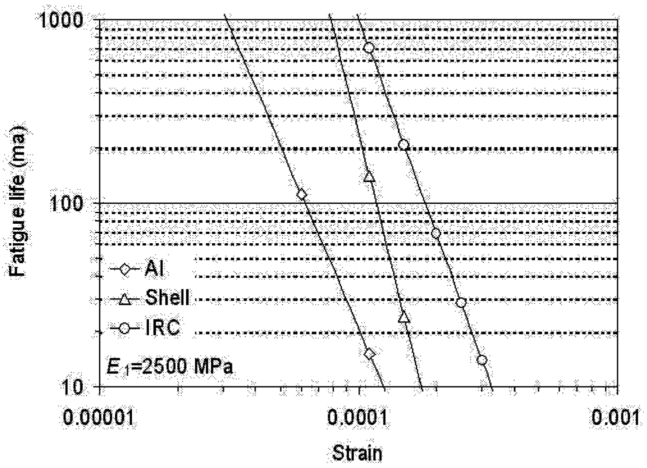

Fig. 1. N_f^F Prediction Using Different Fatigue Equations.

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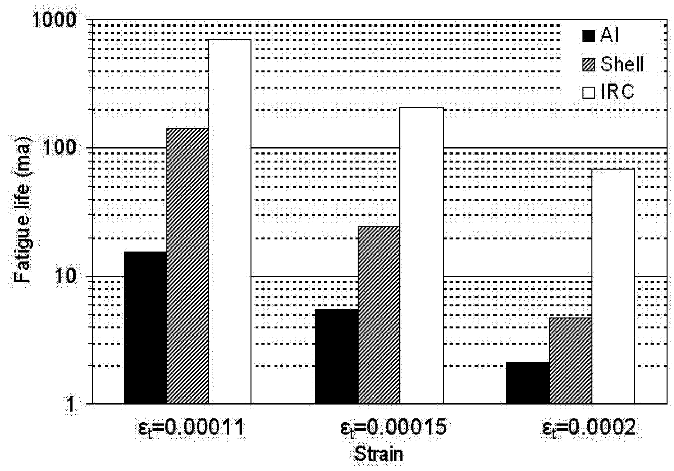


Fig. 2. Comparison of N_f^F Values for Different Fatigue Equations ($E_1 = 2500 MPa$).

effect of E_1 on N_f^F becomes controversial. Of course, this controversy does not occur if $f_3 = 0$. This has happened because of ε_t and E_1 assumed to be independent while developing Eq. (1) in the form of regression equation. In fact, ε_t is an implicit function of various structural input parameters (including E_1), and thus, the parameter ε_t can accommodate the effect of pavement temperatures, subgrade conditions etc.

From Fig. 2, it can be seen that the predicted N_f^F values are significantly different for different equations. For example, for ε_t = 0.00011 the N_f^F values are 15.2, 140.7, and 694.3ma as per AI, Shell, and IRC equation, respectively. Fatigue life prediction using NCHRP proposed equation is further a higher value [5, 9]. Due to differences in material characteristics, environmental conditions etc, certain differences in N_f^F prediction are expected. Moreover, such incomparable N_f^F value for the same value of ε_t and E_1 is questionable. This is possibly because of inadequate calibration adopted during the conversation of laboratory equation into field equation. This has been discussed in the next section.

Calibration of Fatigue Equation

An appropriate field calibration using field data is important due to differences in failure definitions, environmental conditions, boundary and loading conditions (including lateral movement, rest period etc) between the laboratory and field conditions. The primary differences in fatigue life evaluation between the laboratory and field conditions are presented in Fig. 3.

For calibration, a laboratory developed fatigue equation is used which may be expressed as,

$$N_f^L = l_1 \times \left(\frac{1}{\varepsilon_t}\right)^{l_2} \times \left(\frac{1}{E_1}\right)^{l_3} \tag{2}$$

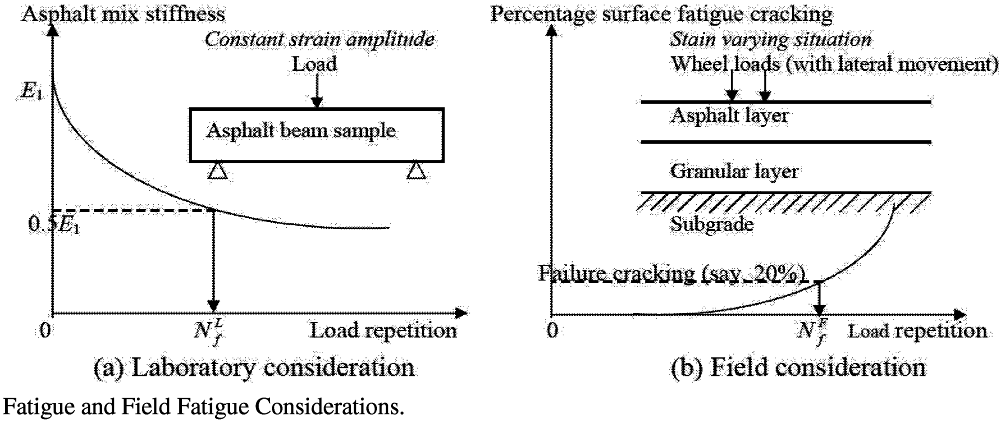
where, N_f^L is the laboratory fatigue life; and, l_1, l_2, and l_3 are regression constants. Normally, N_f^L is obtained based on 50% reduction of E_1 value under constant stress or strain amplitude test. However, this failure criterion does not have any direct implication to the field failure criteria (say, FC = 20 or 50%).

During the calibration process, the known parameters l_1, l_2, and l_3 are converted into f_1, f_2, and f_3 respectively based on field performances/field data. While doing this, the observed traffic repetition at failure (i.e. N_f^F), ε_t, and E_1 values of Eq. (1) to be known (f_1, f_2, and f_3 are being unknown) for the sections considered. Thus, the Eq. (1) in the form of regression equation can be developed directly using field data, provided sufficient reliable data are available. In other words, for a given set of field data a parameter named as shift factor (SF) can be obtained as,

$$SF = \frac{T_f}{N_f^L} \tag{3}$$

where, T_f (= N_f^F) is the observed traffic repetition corresponding to failure FC (in terms of a common axle load). Different SF values are reported by different researchers [11, 12] and it can even vary between 5 to 700 [13]. SF may be taken as constant [1, 4, 8] or varied with parameter(s) like ε_t, E_1 etc [5, 9, 14]. It may be mentioned that for such wide range of SF value, the use of constant SF is less meaningful.

To calculate the SF value, the data like layer thicknesses, material properties, axles load, and traffic count till failure are necessary for the section considered. Therefore, the sections without rehabilitation shall be considered while obtaining T_f. Further, only the traffic repetition corresponding to failure FC can be used for calibration (refer to Eq. (3)) and there is no scope of using intermediate traffic data (say, traffic repetition corresponding to FC < 5%). However, various researchers [5, 15] used the traffic repetition corresponding to



(a) Laboratory consideration

(b) Field consideration

Fig. 3. Laboratory Fatigue and Field Fatigue Considerations.

Table 2. Comparison of *LEF*.

Axle load (kN)	LEF as per Eq. (5)	Empirical LEF [4]
27.2	0.031	0.009
36.3	0.083	0.031
45.4	0.171	0.080
54.4	0.302	0.176
63.5	0.481	0.350
72.6	0.714	0.610
81.6	1.000	1.000
90.7	1.383	1.550
99.8	1.780	2.300
108.9	2.376	3.270
117.9	3.140	4.480
127.0	3.910	5.980
136.1	4.861	7.800
145.2	5.942	10.000
154.2	7.135	12.500
163.2	8.452	15.500
172.3	9.910	19.000

$FC = 0\%$. As a result, an unexpected poor correlation between the predicted and observed value is observed. In fact, 0% fatigue cracking (bottom-up) at the pavement surface does not provide any meaningful information about the traffic repetition passed or fatigue damage factor (D_f) [16]. This is because, most of the traffic repetition on an in-service pavement pass before the bottom-up fatigue cracks reflect at the surface (i.e. $FC = 0\%$) and thus, $FC = 0\%$ does not mean that fatigue damage is zero. The evaluation of fatigue damage in asphalt pavements has been discussed in the next section.

Fatigue Performance Evaluation

Field calibrated fatigue equation (i.e. $N_f^F = SF \times N_f^L$) is used to evaluate the field fatigue performance. Fatigue performance can be obtained using fatigue damage factor D_f or safety margin parameter S_f, where $D_f = T/N_f^F$ and $S_f = T - N_f^F$; and T is the numbers of traffic repetition applied. Miner's hypothesis of linear damage accumulation [17-19] can also be used for evaluation of D_f. $D_f = 1$ and $S_f = 0$ at the failure situation (deterministically). Evaluation of D_f or S_f is essentially useful for intermediate pavement condition evaluation or failure probability (or reliability) calculation. However, D_f and S_f values do not represent any specific value of FC at the intermediate state of pavements. Some researchers [18, 19] interpreted that the probability of $D_f \geqq 1$ (in percentage) is the percentage of FC. In fact, the probability of $D_f \geqq 1$ represents the failure probability, i.e. the probability of exceeding certain pre-specified amount of FC. In addition, it may be mentioned here that the probability of $D_f \geqq 1$ is same as probability of $S_f \geqq 0$ for any distribution of T and N_f^F [20].

To calculate D_f, S_f, or SF value, the numbers of traffic repetition and fatigue life shall be in terms of a common axle load (say, standard axle load of 81.6kN for dual wheel assembly). Under mixed loading condition, the different axles load can be converted to standard axle load by using different load equivalency factors (LEF). This has been explained in the next section.

Load Equivalency Factor

From the basic definition of load equivalency factor LEF, LEF_i for ith axle load can be expresses as,

$$LEF_i = \frac{N_{fs}^F}{N_{fi}^F} \tag{4}$$

where, N_{fs}^F and N_{fi}^F are the pavement life corresponding to standard axle load and ith axle load respectively. Thus, from Eqs. (1) and (4), a relationship can be established as follows,

$$LEF_i = \left(\frac{\varepsilon_{ti}}{\varepsilon_{ts}}\right)^{f_2} \tag{5}$$

where, ε_{ts} and ε_{ti} are the strains corresponding to standard axle load and ith axle load respectively. Further, different literature [1, 4, 21, 22] recommend different empirical LEF for the axle load conversation. Table 2 shows the comparison of empirical LEF as adopted by IRC [4] and the LEF as per Eq. (5).

To develop the Table 2, f_2 value is used as per IRC equation (refer to Table 1). Various input data used for strain (ε_t) calculation are: E-value of asphalt, granular, and subgrade layers are 2,000, 300, and 60MPa respectively; Poisson ratio are 0.3, 0.35, and 0.4 for asphalt, granular, and subgrade material respectively; layer thicknesses are 150 and 250mm for asphalt and granular layer respectively; and the tyre pressure is 0.7MPa with a centre to centre wheel spacing of 300mm. Thus, for different axles load the ε_t value can be obtained using multilayer elastic analysis [23].

From Table 2, it can be seen that the LEF based on Eq. (5) is significantly different than that of empirical LEF. It may be mentioned that LEF as per Eq. (5) depends on ε_t which in turn depends on axle load as well as the pavement structure. This conversation of axle load seems to be more logical. This is because, the parameter ε_t is also used to measure the fatigue failure or fatigue life.

Closing Remarks

A reliable fatigue equation is essential for reliable fatigue performance evaluation of any pavement structure. The present work critically examines the mechanistic-empirical fatigue evaluation of pavements. Some of the important considerations have been pointed out which need further look into the development of field fatigue equation and subsequently, into the process of fatigue evaluation.

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