Implementing the Energy Based Fatigue Equation

Samuel H. Carpenter
Shannon Beranek
University of Illinois at Urbana - Champaign
Presentation Outline

• Introduction
• Status of the Development of Fatigue Equation
  – Various forms and reasons
• Fatigue Life Design Equation
  – Working Engineer’s Equation
  – Researcher’s Equation
• Requirements for Use
• Needs for Implementation
Introduction

• FAA Support – Development of Energy Based Approach for Fatigue Damage

• Successful Unification of Damage Accumulation Over Entire Strain/Stress Regime
  – Ratio of Dissipated Energy Change (RDEC)
  – Plateau Value
ENERGY CONCEPT: DISSIPATED ENERGY

INITIAL LOAD CYCLE

SECOND LOAD CYCLE

DIFFERENT DISSIPATED ENERGY BETWEEN FIRST AND SECOND LOAD CYCLE

STRESS

STRAIN

Ratio of Dissipated Energy Change (RDEC)
Typical RDEC Plot

\[ RDEC_a = \frac{\Delta DE}{DE} = \frac{DE_a - DE_b}{DE_a \times (b - a)} \]

- **Plateau Value**
- **50% Stiffness**
- **Plateau Stage**
\[ N_f = 0.4801(PV)^{-9.0074} \]

Normal: \[ y = 0.4428x^{-1.1102} \]

\[ R^2 = 0.996 \]

Low: \[ y = 0.3461x^{-1.1031} \]

\[ R^2 = 0.9988 \]
Design Equation

• Initial (2005)
  – 19 IDOT mixes
  – 85 Mixes

• 2007 AAPT (101 mixes)
  – Removed specialty non mix-designed mixes

\[ PV = 44.422(\varepsilon^{5.140})(S^{2.003})(VP^{1.850})(GP^{-0.4063}) \]
Variables

• $\varepsilon$: Tensile Strain at Bottom of HMA Layers
• S: Flexural Modulus, MPa
  • During Fatigue Test
• VP: Void Parameter
  • (1-VFA)
• GP: Gradation Parameter
  • Coarse Aggregate Interlock
Current FAA Equation (H&K)

• \( \log_{10}(C) = 2.68 - 5\log_{10}(\varepsilon_h) - 2.65\log_{10}(E_A) \)

• \( C \) : Coverages to failure
• \( \varepsilon_h \) : Tensile strain at bottom of Surface mix
• \( E_A \) : Modulus
H&K Limitations

• Based on Heukelom and Klomp Modulus
  – Some were creep
  – Some were sinusoidal
  – Some were flexural
  – Conversion was incorrect between them
PV Model Improvements

- Includes Mix Variables
- Includes Aggregate Factor
- Incorporates Modulus Value related to Failure Mode
- Based on Energy Damage Accumulation Including all modes of Failure
PV Model Limitations

- Flexural Modulus Not Normally Available
- Verified Only at 20°C, 10 Hz
  - Fatigue curve changes with temperature
  - Fatigue curve may change with frequency
  - Modulus changes with frequency and temperature
E* - E_f Comparison
10 Hz, 20 C

19 IDOT Gyratory

Dynamic Modulus, MPa

Flexural Stiffness, MPa

y = 200.32x^{0.4787}

R^2 = 0.8373
Neat Asphalt in Binder Mix

Binder Mix, 7% Voids

Log Freq. Hz

Modulus, MPa

Flexural

E*

Log Freq. Hz

0.01 0.10 1.00 10.00 100.00

100000

10000

1000

100
Modified Asphalt in Binder Mix

Binder, Modified, 7%

Shift Factor to 40 C is Similar (2.7)
Modified Asphalt in Surface Mix

Modified Surface Mix, 7% voids

- Modulus, MPa
- Flexural
- $E^*$

Log Freq. Hz

- 100000
- 10000
- 1000
- 100
E* to Flexural

• Flexural Modulus “Mirrors” E*
  – Can Develop Input From Standard E* testing

• What Reduction Factor?
  – High E* - 0.60
  – Low E* - 0.40
  – Field Value 0.45 (Khanal & Mamlouk, TRR 1492)
    • Elastic analysis, not appropriate
Pulse Duration Effects

![Graph showing the relationship between Load Repetitions and Microstrain (um/m) for different conditions. The graph includes three lines representing SHRP(100), -700, and -1000, with corresponding data points.]
Load Mode Effects

![Graph showing Load Mode Effects](image)

- SHRP(100)
- Const Stress
- Const Stress, rest

Microstrain (um/m) vs Load Repetitions

- 1.E+03
- 1.E+04
- 1.E+05
- 1.E+06
Wheel Load Pulses

![Graph showing wheel load pulses with various markers representing different load repetitions and microstrains.]
Temperature Effects

Temperature Effect

Load Repetitions

Micro Strain

1.0E+00

1.0E+01

1.0E+02

1.0E+03

1.0E+04

1.0E+05

1.0E+06

1.0E+07

1104 - 20 C

1104 - 30 C
Viscoelastic Model

\[ PV = 2.612 \times 10^{-10} (\text{IDE}^{2.758}) (\text{S}^{2.493}) (\text{VP}^{3.055}) (\text{GP}^{-2.445}) \]

Currently Only for 19 IDOT Mixes

Utilizes Initial Dissipated Energy (IDE), a viscoelastic response

Future computer programs

All Lab Data Relates Directly to Pavement Calculation
PV Model (E* - 1.2 $10^6$)

![Graph showing PV Model and Load Repetitions vs. Micro Strain with data points for 2070, 4135, and 8270.](image-url)
Comparison

Flex and E* Comparison

Load Repetitions

Micro Strain

- 4135
- 8270
- 200,000 psi
- 450,000 psi
In Pavement Comparison Needed

• Strain at Bottom of HMA is Greater than at Bottom of Surface Layer
• Modulus of Top Layer Different than Bottom Layer
  – Temperatures not same
  – Load pulse not same
Modulus Selection

• Flexural Reduction From $E^*$
  – 0.6 to 0.4 times $E^*$

• Can Match FAA H&K Model Well, as is
Equation Matches Lab Test Results

10 Hz, 20 C

- Need Temperature Effect
  - Fatigue Curve
  - Flexural Modulus

- Need Pulse Duration Effect
  - Fatigue Curves at Different Frequencies

- Need Healing Effect
  - Published for two binders
    - 5 times and 10 times life extension
Implementation

• Requires “In-Pavement” Comparison
• Requires Temperature Effects
  • Flexural Modulus
  • Fatigue Curves
• Validation of Pulse Duration Effects
  • Fatigue Curves
Remaining Work

• This Year
  – Finalize Report
    • Modulus selection
    • In-Pavement Analysis
    • Pavement Life Comparisons

• Next Year
  – Conduct Temperature tests
  – Conduct frequency tests
  – Implementation report
Thank you!
Questions?