Digital Model of Flexural Fatigue Testing for Asphalt Mixtures with Micromechanical Finite Element Method

Yu Jiang-miao, Chen Ye-kai, Zhang Xiao-ning

Abstract

This paper presents a digital model of four point bending fatigue test for asphalt mixture at a microstructural level. Digital image processing techniques were applied to convert image into a digital specimen consists of the information of actual material heterogeneity and microstructures of asphalt mixtures. Subsequently, the model was transferred into Finite Element (FE) software to analyze the damage behavior through flexural fatigue test. It was found that the material heterogeneity, the properties aggregates and air voids have significant effects on the fatigue behavior which is different from the conventional results based on the hypothesis of homogeneous material. The results indicate that the proposed method for establishment of digital model of fatigue test can be extended for further analysis due to the single specimen can be retested with various loading conditions and material properties, which is inconceivable to laboratory real material test.

Keywords: asphalt mixtures; fatigue testing; digital image processing; finite element method

1. Introduction

Asphalt mixture is normally regarded as complex heterogeneous material which made up of aggregates, asphalt binders and air voids. The volumetric properties, distribution and interactions of the three-phase compositions cause the complexity of asphalt mixture’s micromechanical behavior. The consideration of material heterogeneity is necessary when studying the micromechanical properties of the asphalt mixture [1-4].

The application of digital image processing technology and numerical analysis of asphalt mixture’s micromechanical behavior has attracted growing interests from researchers. It is considered to be a promising technique to reveal the complex micromechanical behavior of asphalt mixture. Masad, Kuty, Wang, Coenen, Cai [5-9] et al. have used digital image processing method for evaluating the microstructure characteristic of asphalt mixtures. You, Liu, Abbas, Dai, Mishnaevsky, Sadi, Kim, Mun, Papagiannakis, Birgisson, Masad [10-21] et al. have used discrete-element method, finite element (FE) method, or boundary element method to study the asphalt mixture’s micromechanical behavior. With the application of X-ray computerized tomography (CT) method, the three-phase compositions of asphalt mixture can be easily identified. The volumetric properties and micromechanical behavior based on three-phase compositions have been studied in recent years [22-26].

In 1993 American Strategic Highway Research Program (SHRP) recommended the four-point bending beam fatigue test to estimate the fatigue cracking of asphalt mixtures [27], currently, it has become a standard test adopted into the specification of the American Association of State Highway and Transportation Officials (AASHTO) [28]. Four-point bending beam fatigue test has been used by various researchers to evaluate the fatigue performance of asphalt pavements and has become a world-wide popular fatigue test for asphalt mixture [29-30]. It has advantages such as high sensitivity to mixture variables, larger portion of the specimen is subjected to a uniform maximum stress level, and similar bending behavior to real pavement deformation, etc. However, the procedure for specimen preparation and test is quite complicated and strict which is easy to be influenced by contrived factors, besides fatigue tests take an unacceptable long period in some cases. In this study, a digital...
micromechanical model of four point bending fatigue test for asphalt mixtures were established to seek the possibility of using digital virtual test to replace the real fatigue test.

2. Establishment of FE model

2.1 Digital Image Processing

In order to establish the FE model, an original digital image was taken from rolling wheel compacted slab of asphalt mixes (Figure 1), the surface was cut by high-precision diamond saw to make the three phase of asphalt mixture (aggregate, mastic, and void) recognizable. The real size of the beam section is 380mm (in length) × 50mm (in height). The measured airvoid content is 12.7%, asphalt content is 4.2%. The digital processing technique was applied to identify the boundary between each phase in Figure 1 [26], an identified three-phase boundary model is shown in Figure 2. Subsequently, boundary model was imported into ABAQUS [31] which is a FE analysis program. Figure 3 shows the digital four point bending beam model in ABAQUS. Quadrilateral isoparametric element was used to mesh the digital beam model which led to 176147 elements in total.

2.2 Load setting

Followed by the AASHTO T321 test procedure, the two pairs of outside clamps which fixed the ends of the digital beam, the desired repeated dynamic loads were applied on the two pairs of inside clamps. A strain controlled fatigue test mode was followed which means the beam was repeatedly bent downward and back to the original position with a fixed maximum deflection of $\delta$ (Figure 4). A standard haversine loading wave form was applied during the virtual fatigue testing.

2.3 Material properties and parameters
The aggregates were modeled as linear elastic materials. The asphalt mastics were modeled as damaged plasticity materials, as shown in Figure 4. The evolution of the yield (or failure) surface is controlled by hardening variables $\hat{\varepsilon}_p$, linked to failure mechanisms under tension loading.

![Figure 5. Response of asphalt mastic to tensile load](image)

Under direct tension the stress-strain response follows a linear elastic relationship until the value of the failure stress $\sigma_0$ is reached. The failure stress corresponds to the onset of micro-cracking in the asphalt mastic. Beyond the failure stress the formation of micro-cracks is represented macroscopically with a softening stress-strain response, which induces strain localization in the asphalt mastic.

It is assumed that the uniaxial stress-strain curves can be converted into stress versus plastic-strain curves. Thus:

$$\sigma_i = \sigma_i(\tilde{\varepsilon}_i^p, \dot{\tilde{\varepsilon}}_i^p, \theta, f_i)$$  

Where $\tilde{\varepsilon}_i^p$ is the equivalent plastic strain, $\dot{\tilde{\varepsilon}}_i^p$ is the equivalent plastic strain rate, $\theta$ is the temperature, and $f_i (i=1, 2, 3...)$ are other predefined field variables.

As shown in Figure 5, when the asphalt mastic is unloaded from any point on the strain softening branch of the stress-strain curves, the unloading response is weakened: the elastic stiffness of the material appears to be damaged (or degraded). The degradation of the elastic stiffness is characterized by damage variables $d_i$, which are assumed to be functions of the plastic strains, temperature, and field variables:

$$d_i = d_i(\tilde{\varepsilon}_i^p, \dot{\tilde{\varepsilon}}_i^p, \theta, f_i); \quad 0 \leq d_i \leq 1$$  

The damage variables can take values from 0 (representing the undamaged material) to 1 (which represents total loss of strength).

If $E_0$ is the initial (undamaged) elastic stiffness of the material, the stress-strain relations under uniaxial tension loading is:

$$\sigma_i = (1 - d_i)E_0(\varepsilon_i - \tilde{\varepsilon}_i^p)$$  

The “effective” tensile stresses are defined as:

$$\bar{\sigma}_i = \frac{\sigma_i}{(1 - d_i)} = E_0(\varepsilon_i - \tilde{\varepsilon}_i^p)$$  

The postfailure behavior of asphalt mastic for direct straining is modeled with tension stiffening. The tension stiffening is specified by applying a fracture energy cracking criterion. Hillerborg [32] defined the energy required to open a unit area of crack as a material parameter by using brittle fracture concepts. Under tensile stress the asphalt mastic will crack across some section. This fracture energy cracking model can be invoked by specifying the postfailure stress as a tabular function of cracking displacement $u^c$ as shown in Figure 6.
Figure 6. Postfailure stress-displacement curve of asphalt mastic used in this analysis

The material parameters of aggregate and asphalt mastic used in this damage evolution analysis of splitting test are indicated in Table 1.

Table 1. Material parameters of aggregate and asphalt mastic

<table>
<thead>
<tr>
<th>Material</th>
<th>Young Modulus $E$ (MPa)</th>
<th>Poisson Ratio $v$</th>
<th>Friction Angle $\phi$ (degree)</th>
<th>Failure Stress $\sigma_{t0}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>15000</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Asphalt Mastic</td>
<td>3000</td>
<td>0.35</td>
<td>32.3</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Note: "-" represent no value in linear elastic model.

2.4 Fatigue failure criteria

For the strain controlled fatigue test, normally define a stiffness reduction of 50% as the fatigue failure point [28]. The stiffness $S$ of the beam specimen can be calculated with Equation 5.

$$S = \frac{\sigma_t}{\varepsilon_t}$$ (5)

Where $S$ is flexural stiffness (kPa), $\sigma_t$ is the tensile stress at the mid-bottom of the beam (kPa) which is an value acquired from the calculation results, and $\varepsilon_t$ is the maximum tensile strain at the mid-bottom of the beam which can be calculated with Equation 6.

$$\varepsilon_t = \frac{12 \times \delta \times h}{3 \times L^2 - 4 \times a^2}$$ (6)

Where $\varepsilon_t$ is the maximum tensile strain (mm/mm), $\delta$ is maximum deflection at center of beam (mm), $L$ is the length of beam between outside clamps (357mm), $a$ is $L/3$.

3. Analysis of test results

Due to the limitation of computing speed of personal computer, virtual fatigue tests with a relatively larger $\varepsilon_t$, of $6 \times 10^{-4}$mm/mm were performed. The damage factor distributions when the beam reaches the fatigue failure are shown in Figures 7. Figure 7b is a result from reversed beam model (upside down) of Figure 7a. For the same fatigue criteria, the model in Figure 7a experienced 11297 cycles bending, however only after 7315 cycles the beam reached the failure point when the bending surface reversed (Figure 7b). The uneven distributed air void might be the main reason caused the difference on fatigue lives (for the middle 1/3 section of beam in Figure 7a, the air void mainly distributed close to the up part). It can be found from both of Figures 7a and 7b, that the majority damages were occurred at the low-middle area of the beam which is consistent as the expectation of the original real material test design.

Figure 8 shows the maximum principal stresses of asphalt mastics. Similar to Figure 7, it can be found from both of Figure 8a and 8b, the larger value of the maximum principal stress occur at the lower part of the middle 1/3 section of beam, which also is consistent as the expectation of the original real material test design.
Figures 9 and 10 are partial section plots cut from the black rectangle area illustrated in Figure 7a and 7b, which plot the damage evolution approaches at different stages during the whole fatigue tests. Parts (a), (b), (c), and (d) of Figure 9 represent the damage distributions when the loading cycles reach 50, 1000, 5000, and 11297, respectively. Similarly, the plots in Figure 10 show the loading cycles reach 50, 800, 3000, and 7315, respectively.

From the Figure 9 and 10, it can be found: 1) Figure 9b shows the initial damage point occurred at a point close to top surface area, while Figure 10b shows the initial damage point occurred at a point close to bottom surface area, actually they lie in almost the same place of asphalt mixture, but both of them are not located at the expected mid-bottom point. The location of initiation point lies in asphalt mastics and has the relationship with the distribution of airvoid and aggregate; 2) instead of theoretically one main damage evolution approach, there can be several damage evolution approaches, which means small fatigue cracks can be generated and propagated at different locations; 3) the aggregate orientation and the distribution of air voids are the main factors decides the property fatigue cracking approaches.
4. Conclusions and recommendations

The following conclusions and suggestions can be obtained or recommended based on this study:

1) The same specimen can have different fatigue lives and damage behavior when the loading direction is changed. The location of initiation point of fatigue cracking and fatigue damage evolution approach are significantly influenced by the material heterogeneity of asphalt mixtures, especially the aggregate orientation and the distribution of airvoid.
2) The consideration of material heterogeneity especially air void properties (air void content, air void shape, and air void distribution) is essential when the micromechanical analyses of asphalt mixtures are conducted.

3) The proposed method for establishment of digital model of fatigue test can be extended for further analysis due to its convenience on single specimen retesting with various loading conditions and material properties, which is inconceivable for laboratory real material test.

4) Computing speed is a limitation for longer or more complex fatigue life test if use personal computer, super computer or faster personal computer developed in the future will be more efficient for this kind of analysis.

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6. References


