Research on fracture parameters of asphalt mixture based on XFEM and J Integral method

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Abstract. The fracture toughness and load displacement relationship of the three point bending (3pb) asphalt mixture specimens with different notch position were experimentally and numerical investigated. Firstly, the extended finite element was used to simulate the three-point bending and fracture process of asphalt mixture beam, and the load and displacement curves were obtained, which were compared with the test results to verify the accuracy of the XFEM model. Secondly, J contour integral method in ABAQUS software was used to solve the stress intensity factor under the three-point bending of asphalt mixture, and the fracture parameters of asphalt mixture were provided by the numerical calculation results. The results showed that the offset distance increases, the influence of the type II crack in the fracture process increases, but the type I crack still was dominant.

1. Introduction
Experiment research can be considered as a crucial method to evaluate cracking behaviour of asphalt mixture. However, experiments have significant limitations which are only mainly providing visual understanding, while the cracking mechanism difficult to observe the whole process and details of crack initiation and propagation in the fracture zone. Additionally, Due to the random aggregate distribution and orientation, there are large disparities in the test samples. As a result, a large number of test specimens are made to evaluate a certain influencing factor, which is time-consuming and costly.

With the development of calculation technology, numerical simulation method is widely used in different engineering field[1]. In order to reveal the fracture mechanism of quasi-brittle materials, numerical simulation can be considered as a powerful numerical analysis tool. In recent years, more and more researchers[2-5] chose numerical simulation method to study the fracture problem of concrete materials. In their research work, the simulation results have a good agreement with the experimental results, and both the total trend is consistent, which construct a basis for the microstructure of semi-rigid asphalt pavement research.

In this paper, using the extended finite element method of ABAQUS software, the cracking process of the asphalt mixture beam was simulated, and the load displacement curve was obtained. The simulation results verified the accuracy of the test, which in turn proved the effectiveness of the extended finite element simulation. Then the stress intensity factor of the crack tip is calculated by the method of contour integration.
2. FE model

2.1. XFEM model
The extended finite element (XFEM) in ABAQUS software is used to simulate the crack propagation of asphalt mixture under three-point bending load under the pre-crack condition. The model size is set to equal to the test specimen size (Figure 1), and the material parameters are shown in Table 4.1. Asphalt mixture was considered as a homogeneous material. Based on the Saint Venant principle, the aggregate far away from the middle crack has no significant influence on the stress distribution and crack propagation. In order to balance the computational efficiency and accuracy, the mesh is refined near the pre-crack. 4-node linear reduction integral CPS4RA is selected and total number is 4,378. The grid attribute was the quadrilateral element specified by XFEM, which shown in Figure 2.

Two simple support constraints are set at the lower edge of the beam. The left end constrains the displacement in the X and Y directions, and the right end constrains the displacement in the Y direction. The displacement rate of 5mm is applied at the loading point of the beam span.

The loading history is 1s, the minimum and maximum incremental step was set as 0.01s and 0.05s, respectively. The maximum principal stress criterion is used to determine damage situation, and the bilinear damage evolution model based on energy is coupled to simulate the initiation and evolution of micro crack in the whole process.

Table 1. The parameters of XFEM model.

| Elastic modulus/MPa | Poission's ratio | maximum principal stress/MPa | Fracture energy/N·m⁻¹ | Viscosity Coefficient |
|---------------------|-----------------|-------------------------------|-----------------------|----------------------|
| 8230                | 0.3             | 1.765                         | 258                   | 0.0001               |

Figure. 1 Simplified diagram of three-point bending experiment (unit:mm)

2.2. J-Integral model
In order to calculate the fracture toughness, the stress intensity factor K is calculated by J-integral in the ABAQUS. The complex stress-strain field near the crack tip can be avoided to analyzing and, and the crack resistance of asphalt mixture can be effectively evaluated.
For plane stress, the relationship between stress intensity factor $K$ and $J$ integral can be expressed as:

$$ J = \frac{K^2}{E} $$  \hspace{1cm} (1)

$E$ is the elastic modulus.

For plane strain, it can be expressed as:

$$ J = \frac{1 - \nu^2}{E} K^2 $$  \hspace{1cm} (2)

$\nu$ is the Poisson ratio.

The stress intensity factor is solved by the function of Contour Integral method in ABAQUS, whilst the model elements, size and parameter are same to the XFEM model. Crack is generated in the Interaction module. The small circle represented the crack tip area, which singularity attribute is set. The local mesh near by the crack tip is shown in Figure 3.

![Figure 2. Meshing and boundary condition of a typical 3pb sample.](image)

![Figure 3. Meshing nearby crack tip in J-integral model.](image)

### 3. Result and discussion

#### 3.1. Load displacement relationship of XFEM model and test results

Extended finite element analysis was conducted for three different pre-crack site specimens and compared with the three-point bending test results of asphalt mixture beam. The results are shown in...
Fig. 4. It can be seen that the off middle distance increases, the peak load obtained by simulation also increase, which are 2160N, 2360N and 3050N, respectively. Since the numerical model is homogeneous material and the model parameters are adjusted from other literatures, the calculated results are different from the experimental curves in minority scale. Namely, the fracture energy calculated by the extended finite element method is greater than the experimental fracture energy. However, the load-displacement curve obtained by numerical simulation shows good agreement with the experimental results generally, and the peak value is also agreed with the experimental value. Therefore, the numerical model in this paper is verified to be reasonable.

![Figure 4. Comparison between the experimental and numerical load versus displacement curves for 3pb beam with different pre-notches orientation.](image)

3.2. Stress intensity factor (SIF) result of J-Integral model

Table 2 listed the stress intensity factor (SIF) result for different offset distance model. When the crack is offset from the center, not only type I cracks, but also type II cracks are generated. However, according to Table 2, it can be found that type I cracks are dominant in the fracture process.

| Contours | middle K1=1468 | OFFSET20 K1=1456 | OFFSET40 K1=1448 |
|----------|----------------|------------------|-------------------|
| 1        | K2=13.68       | K2=86.2          | K2=246.7          |
| 2        | K1=1446        | K1=1449          | K1=1426           |
| 3        | K2=19.54       | K2=79.6          | K2=240.2          |
| 4        | K1=1462        | K1=1443          | K1=1445           |
| 5        | K2=15.23       | K2=87.3          | K2=224.6          |
| 6        | K1=1454        | K1=1438          | K1=1433           |
| 7        | K2=17.41       | K2=92.5          | K2=232.4          |

In order to quantificational analyse the effect of pre-crack position, the value of SIF of different type are compared. It can be seen that with the offset distance increases, type II SIF increases. Meanwhile the mode I stress intensity factor of crack stable generally, which is the major cause in the process of fracture. The most common forms are type I and type II cracks in the asphalt pavement structure layer. Type I cracks are the most dangerous and important and easy to cause brittle fracture of materials. However, the influence of Type II crack on the fracture propagation process becomes
significant when the offset middle distance increases. Similar results were suggested by M.R.M. Aliha[6,7] team, where in the research of mixed mode fracture behavior of PMMA.

4. Conclusions
The extended finite element method was introduced to simulate the three-point bending fracture behaviour of asphalt mixture beam and the load displacement curve calculation results were obtained. By comparing with the laboratory experiment results, the load peak value obtained based on the numerical simulation is close to the experimental value and both the tendency is similar. The effectiveness of the extended finite element simulation is validated.

(2) J-Integral method was used to calculate the stress intensity factor under the three-point bending state of three different middle-distance. Compared with the stress intensity factor of type II crack increase slightly, type I crack is still dominant in the fracture process.

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