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Research on pavement longitudinal crack propagation under non-uniform vehicle loading

Lu Yongjie [a,b,*], Yang Shaopu [a,b], Wang Jianxi [a]

[a] Shijiazhuang Tiedao University, Shijiazhuang 050043, China
[b] Key Laboratory of Traffic Safety and Control in Hebei, Shijiazhuang 050043, China

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ABSTRACT

The top-down crack (TDC) has become the major cracking mechanism in thick pavement structure, especially for the perpetual pavement. The heavy-vehicle load condition plays a key role in the fracture characteristics of pavement cracks. A three-dimensional finite element (FE) model of the tire tread rubber-block and the pavement is established to describe the stress–strain field of the pavement with TDC. The three-directional friction condition and non-uniform distribution between tire and pavement are especially considered. Then the orthogonal Design of Experiment method is applied to discuss the effect law of fracture characteristics for the longitudinal crack affected by the multiple loading parameters simultaneously. Based on the statistics and data analysis of the diverse test results, it is found there is a nonlinear relationship between the equivalent stress intensity factor of the pavement and the load parameters.The longitudinal distance (from the load location to the center of the crack port) has a great influence on the equivalent stress intensity factor. The equivalent stress intensity factor of the crack port is more than double the crack tip buried in pavement, which extends in II/III composite type mostly. The simulation results can be used as reference for the further study on the fracture mechanism of pavement cracks and their control technique.

1. Introductions

A large number of early pavement failures occur as a result of the repeated vehicle load, environment change and poor maintenance strategies. The two main load-associated distresses of pavement are rutting and fatigue crack [1]. The top-down crack (TDC) of the road surface is a kind of road crack, which is proposed in the 8th Asphalt Pavement Structure Design Proceeding [2]. Some field investigation has proven that the surface crack has become the major cracking mechanism in thick pavement structure, especially for the perpetual pavement. The TDC begins from the road surface and gradually extends to the depth of pavement. At the same time, it shows longitudinal extension along the vehicle driving direction. The longitudinal length of the crack propagation can reach few meters or even dozens of meters deep.

Scholars have done a lot of theoretical and experimental research on the propagation mechanism of TDC and great achievements are reached [3–5]. Li think that the road surface longitudinal cracking along the wheel-path (or TDC) is one of the main damage types of heavy-duty asphalt pavement. Based on the actual measurement of tire contact force, they proposed a 3D finite element model of pavement structure and computed the maximum tensile stress, shear stress and their

* Corresponding author at: Shijiazhuang Tiedao University, Shijiazhuang 050043, China. Tel.: +86 13513217835.
E-mail address: lu-yongjie@163.com (L. Yongjie).

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locations. The analysis shows that the shear stress under the wheel load is a major reason causing the TDC [6]. Nunn investigated the TDC in UK and found that the TDC had been a common phenomenon in asphalt pavement. He believed that the horizontal tensile stress in asphalt surface layer is the major reason to cause the TDC [7]. Luo studied the influence of base layer on the stress intensity factor of pavement with the continual layers and researched the method to calculate the stress intensity factor of asphalt pavement's edge crack [8]. In the works of Terhi et al., three asphalt pavements in different operations were investigated in the field, all of them had the TDCs. But the reason that caused the cracks was uncertain [9]. Miao researched the cracking mechanism and propagation analysis of asphalt pavement with top-down and reflect crack under vertical loads are studied by FEM numerical simulation [10]. The stress–strain field of the pavement cracks is the direct factor that influences the fracture characteristics of pavement cracks, which is the response to the pavement structure under the vehicle load. Of all these studies above, we can find that the pavement material parameters and the load parameters are considered to study the fracture characteristics of pavement cracks. However, the three-dimensional loading (including vertical, longitudinal and transverse loading) and the loading position on the actual pavement are varied. The characteristics of the crack propagation under the vehicle load cannot be analyzed only by several simple load combinations.

In this paper, the external load parameters causing pavement crack are classified. And the diverse combination of the vehicle load is given to research the fracture characteristics of the pavement cracks according to the orthogonal test method. Based on the statistics and data analysis of the diverse test results, the main factors that influence the crack propagation are determined.

2. Tire and pavement interaction model

2.1. Tire and pavement modeling

It is well-recognized that the complex tensile or shear stresses induced by tires at the pavement surface are the main load factor that contributes to the surface crack (TDC) initiation and propagation [11–13]. The accurate modeling of the tire-pavement contact behavior (distribution of contact force at the interaction surface) plays a crucial role in the prediction of pavement responses. The model will affect the stress–strain field of the road surface structure, especially the computational accuracy of the pavement stress–strain field with cracks. Furthermore it is difficult to solve the tire-pavement contact problem analytically. In this paper, a non-linear FE model of the tire tread rubber-block and the pavement is established to describe the friction interaction. The Yeoh model is used to describe the isotropic incompressible material of the tire tread rubber-block. The strain energy potential is given by:

$$U = \sum_{i+j=1}^{N} C_{ij}(\bar{I}_1 - 3)^i(\bar{I}_2 - 3)^j + \sum_{i=1}^{N} \frac{1}{D_i}(J-1)^{2i} \tag{1}$$

where N is the order of the polynomial, C_{ij} are known as Rivlin coefficients (describes the shear properties of material, D_i define material compressibility (When the material is fully incompressible, $D_i = 0$), $\bar{I}_1$ and $\bar{I}_2$ are the first and second invariants of the deviatoric strain, J is elastic volume ratio. When $N = 3$, the polynomial Eq. (1) is reduced as Yeoh model:

$$U = \sum_{i=1}^{3} C_{i0}(\bar{I}_1 - 3)^i + \sum_{i=1}^{3} \frac{1}{D_i}(J-1)^{2i} \tag{2}$$

The Yeoh model can be chosen to describe the hyperelastic properties of rubber compounds, which is able to predict the stress–strain behavior for a much wide range of deformation [14]. The Yeoh model parameters of tire tread-block are listed in Ref. [15].

In the traditional pavement design theory, the tire vertical stress acting on the road is always assumed as the uniform distributed circular, ignoring the heterogeneity of distribution of contact stress in the contact patch. However, the actual shape of the tire and the road surface is a complex that. Large number of test results show that the shape of the tire acts on the road surface is closer to a rectangle and show a non-uniform distribution. Lippmann [16] indicated that the vertical contact stresses under tires should be regarded as non-uniform. Among the wheel load model, the non-uniform distribution of internal stress in different contact patch is particularly considered in this paper. In this paper, the road surface is modeled as flat and the tread rubber-block with non-uniform shape in the finite element simulations. The distribution of contact patch stress varies in terms of the tire tread, the simplified footprint of pressure distribution are obtained from the measured data [17], the dimension is shown in Fig. 1. The tire tread contact pressure under different static axle load is listed in Table 1.

In the design and calculation of asphalt pavement structure, the pavement model is usually simplified as the multi-layer elastic system. The material parameter and the thickness in each layer are shown in Table 2. The interfaces between different layers of the pavement are assumed to be perfectly bonded. In the assumption of the elastic layered theory, the continuous system is infinitely long in the horizontal and the vertical direction. But it is found that the influence on boundary is very small when the length, width and height of the pavement in the finite element model are taken as 5 m, 5 m and 2 m based on the repeated calculation.