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Temperature fatigue reflective crack in asphalt pavement using extended finite element method

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ABSTRACT

Temperature fatigue reflective crack is a major distress in asphalt pavement and may induce further destroys. Many methods have been conducted to solve this problem. However, the arbitrary cracking path has not been investigated. In this paper, the extended finite element method (XFEM), which has the advantage in considering the arbitrary cracking propagation, is used to investigate the temperature fatigue reflective crack. Firstly, the temperature field model and XFEM model are built with same math but different element types. In the temperature field model, the temperature distribution was obtained using DFLUX subroutine and FILM subroutine. Then the temperature distribution is applied to XFEM model and the thermal fatigue reflective cracking mechanism is investigated. Moreover, the inclined degree of initial crack in up-base is considered. This better understanding is expected to provide more scientific insights to advance the current structural pavement design practices and pavement repairing.

1. INTRODUCTION

Reflective crack is a major distress in semi-rigid base asphalt pavement structure, which may accelerate further destroys. The crack can be resulted by a single temperature drop, several cyclic temperature changes or traffic passing. Many researches had demonstrated that temperature was more important than traffic load that induced reflective crack (MOLENAAR, 1993, Millien A, 2012). The cracks existing in semi-rigid base could induce stress concentration and propagated up to the asphalt overlay when temperature changed. In order to better understand the mechanism leading to reflective crack, several methods had been conducted.

In mechanistic-empirical pavement design guide, thermal-cracking prediction model was used to predict the thermal cracking behavior and amount of thermal cracks (Hiltunen, 1994). In this model, tensile strength was used as the cracking threshold for cracking initiation (Paris, 1961). AASHTO T321-07 (AASHTO, 2007) conducted four points bending beam test to determine the fatigue life of asphalt mixture. Then many researchers investigated the fatigue cracking resistance of asphalt mixture using this

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method(Li, 2012, Islam, 2012, Ameri, 2017, Davar, 2017). Many single-edge notched beam tests were carried out to evaluate the fracture behavior of asphalt concrete (Song, 2006, Braham, 2012, Yang, 2014). Seo (2008) used acoustic emission to monitor fatigue damage and healing in asphalt concrete. Ahmed (2013) investigated cracking resistance of thin-bonded overlays by compact tension. Moreover, numerous notched semi-circle bending tests were conducted to investigated the cracking propagation of asphalt mixture (Wang, 2013, Liu, 2014, Cannone Falchetto, 2017). Gonzalez-Torre (2015) studied the effectiveness geosynthetics as anti-reflective cracking system and the influence of loading frequency on cracking propagation. However, in these studies, only fracture of asphalt mixture samples and the anti-fracture property of asphalt mixture were emphasized, the cracking mechanism of reflective cracking was not analyzed.

In order to better understand the cracking mechanism of thermal reflective cracking of asphalt pavement, numerous numerical methods were also carried out (Dave, 2007, Kim, 2009, Dave, 2010, Yekai, 2010, Ban, 2017, Gajewski, 2014). However, in these studies, a single temperature drop that induced thermal reflective cracking of asphalt pavement was only discussed. M. I. Hossain (2017)investigated the thermal fatigue of asphalt pavement using XFEM. But only crack propagation depth was studied.

In this study, a XFEM simulation to evaluate thermal fatigue reflective crack in semi-rigid base asphalt pavement is carried out. Temperature distribution in pavement structure is obtained using DFLUX subroutine and FILM subroutine. Then the temperature distribution is applied to XFEM model and the fracture mechanism is analyzed. The influences of inclined degrees of initial crack on fracture life, cracking width, cracking path and stress distribution are evaluated.

2. TEMPERATURE FIELD IN PAVEMENT STRUCTURE

2.1 Thermal condition analysis

As the external temperature changes continuously with time, the pavement structure also undergoes changing of temperature. So in this section, solar radiation, surface heat flux and pavement surface radiation are taken into consideration to accurately determine the temperature distribution in pavement structure.

The solar radiation is:

$$q(t)=\begin{cases}0 & 0\le t\le 12-\dfrac{c}{2}\\ q_0\cos m\omega(t-12) & 12-\dfrac{c}{2}\le t\le 12+\dfrac{c}{2}\\ 0 & 12+\dfrac{c}{2}\le t\le 24\end{cases} \tag{1}$$

$$q_0=0.131mQ \tag{2}$$

$$m=12/c \tag{3}$$

In which, q_0 is maximum solar radiation; Q is the total solar radiation; c is the effective sunshine hours; ω is circular frequency, ω=2π/24.

According to Fourier Series, equation (1) can be expressed as:

$$q(t)=\frac{a_0}{2}+\sum_{k=1}^{\infty}a_k\cos\frac{k\pi(t-12)}{12} \tag{4}$$

$$a_0=\frac{2q_0}{m\pi} \tag{5}$$

$$a_k=\begin{cases}\dfrac{q_0}{\pi}\left[\dfrac{1}{m+k}\sin(m+k)\dfrac{\pi}{2m}+\dfrac{\pi}{2m}\right] & k=m\\ \dfrac{q_0}{\pi}\left[\dfrac{1}{m+k}\sin(m+k)\dfrac{\pi}{2m}+\dfrac{1}{m-k}\sin(m-k)\dfrac{\pi}{2m}\right] & k\neq m\end{cases} \tag{6}$$

The minimum external temperature is nearly at 5 am, and the maximum external temperature is at 14 pm. The function that simulates the surface heat flux is expressed as:

$$T_a=\bar{T}_a+T_m\left[0.96\sin\omega(t-t_0)+0.14\sin 2\omega(t-t_0)\right] \tag{7}$$

In which, $\bar{T}_a$ is daily average temperature, $\bar{T}_a=\frac{1}{2}\left(T_a^{\max}+T_a^{\min}\right)$; T_m is daily temperature range, $T_m=\frac{1}{2}\left(T_a^{\max}-T_a^{\min}\right)$; $T_a^{\max}$ and $T_a^{\min}$ is maximum temperature and minimum temperature, respectively; t_0 initial phase, t_0=9.

The heat transfer coefficient between pavement surface and external temperature is meanly influenced by air speed and it can be expressed as:

$$h_c=3.7v_w+9.4 \tag{8}$$

In which, h_c is heat transfer coefficient; v_w is Daily-mean air speed.

The pavement surface radiation boundary can be expressed as:

$$q_F=\varepsilon\sigma\left[\left(T_1|_{z=0}-T_z\right)^4-\left(T_a-T_z\right)^4\right] \tag{9}$$

In which, q_F is pavement surface radiation; ε is pavement emissivity, ε=0.81; σ is Stefan-Boltzmann parameter, σ=5.6697×10-8; $T_1|_{z=0}$ is the temperature of pavement surface; T_a is air temperature; T_Z is absolute zero, T_Z=-273℃.

2.2 Pavement model

In order to better understand the cracking mechanism of semi-rigid asphalt pavement, a kind of typical 2D asphalt pavement model is developed. Fig.1 illustrates the pavement modal as well as the thickness of layers, initial crack and thermal boundary. As can be seen in the Fig.1, the thermal boundaries, which include solar radiation, surface heat flux and pavement surface radiation, are taken into consideration. Different inclined degrees of initial crack are also considered in this paper showed in Fig.2. The initial crack penetrates the up-base with the inclined degrees of the initial crack 0℃, 10℃, 20℃ and 30℃.

In this paper, two kinds of model, temperature field model and XFEM model, are meshed uniformly but different element types are used. DC2D3, a 4-node linear heat transfer quadrilateral element is used in temperature field model, and CPS4R, a 4-node bilinear plane stress quadrilateral element is used in XFEM model. Firstly, the temperature distribution in the temperature field model is obtained according to the temperature boundary. Then, the temperature field is applied to the XFEM model to simulate the cracking initiation and propagation induced by cyclic temperature.

In the temperature field model, the thermal properties including thermal conductivity, specific heat, expansion coefficient, solar radiation absorption and surface emissivity are listed in Table 1. In addition, the fracture parameters which are needed in XFEM model are provided in Table 2.

Table 1 The thermal properties of the pavement materials

Properties	Overlay	Upper-base	Sub-base	Soil base
Density(kg/m^3)	2300	2200	2100	1800
Thermal conductivity (J/m.h.℃)	4680	5616	5148	5616
Specific heat (J/Kg.℃)	924.9	911.7	942.9	1040.0
Solar radiation absorption	0.9			
Surface emissivity	0.81			

Table 2 The fracture parameters of pavement materials

Parameters	Overlay	Upper-base	Sub-base	Soil base
Modulus (MPa)	8500	9073	5636	1500
Poisson ratio	0.35	0.25	0.3	0.35
Expansion coefficient (℃$^{-1}$)	2e^{-5}	0.98e^{-5}	0.98e^{-5}	0.45e^{-5}
Tensile strength (MPa)	2	2	**1**	-
Fracture energy (mJ/mm^2)	1.5	0.98	0.98	-

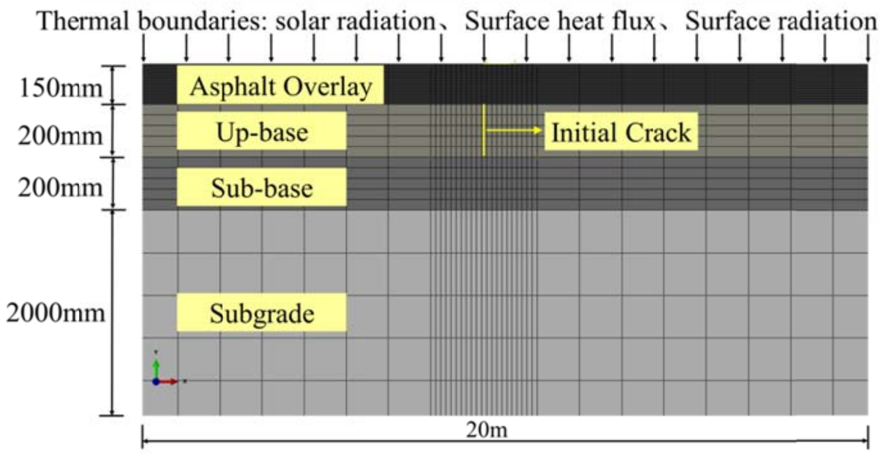


Fig. 1 Asphalt pavement structure

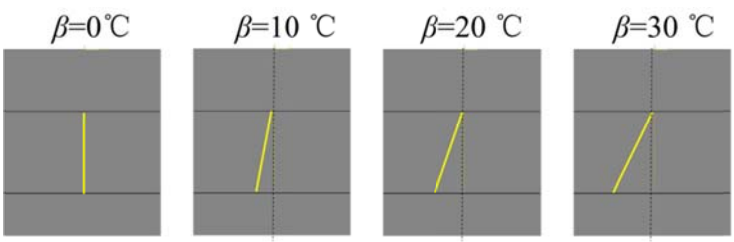


Fig. 2 Different lengths of initial crack and inclined degrees of initial crack

2.3 Temperature distribution

According to the thermal boundary in temperature field model, the temperature distribution changing with time can be obtained. Fig. 3 shows the temperature distribution in the asphalt pavement structure. As can be seen, the temperature gradient exists in the pavement structure and the distribution is conformed to the practical situation. What's more, the temperature in different depths changing circularly with time is showed in Fig. 3. The cyclic temperature is applied to the XFEM model, and the thermal stress is produced. Then the cracking initiation and propagation is analyzed.

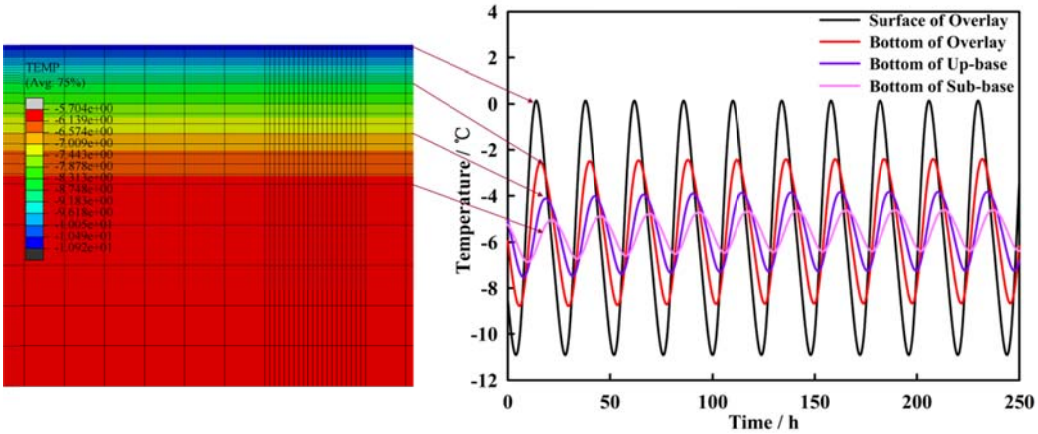


Fig. 3 Temperature distribution in asphalt pavement structure

3. RESULTS AND DISCUSSIONS

A series of models with different inclined degrees of initial crack are performed. The influences of inclined degree of initial crack on cracking propagation are analyzed. What's more, the mechanisms of thermal fatigue reflecting cracking are investigated.

3.1 Fracture life

Many researches have testified that the inclined degree of initial crack has great influence on stress distribution. So in this section the influence of inclined degree of initial crack on fracture life is analyzed.

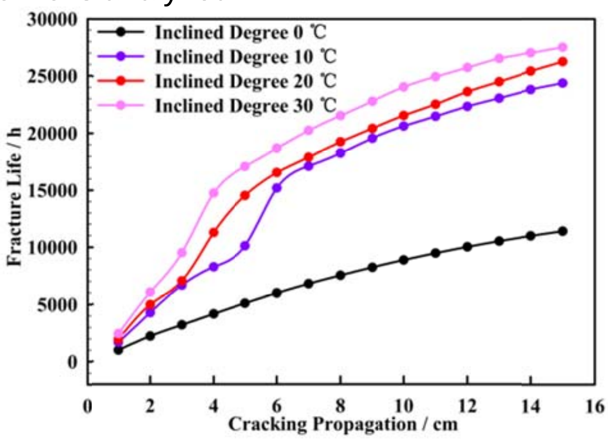
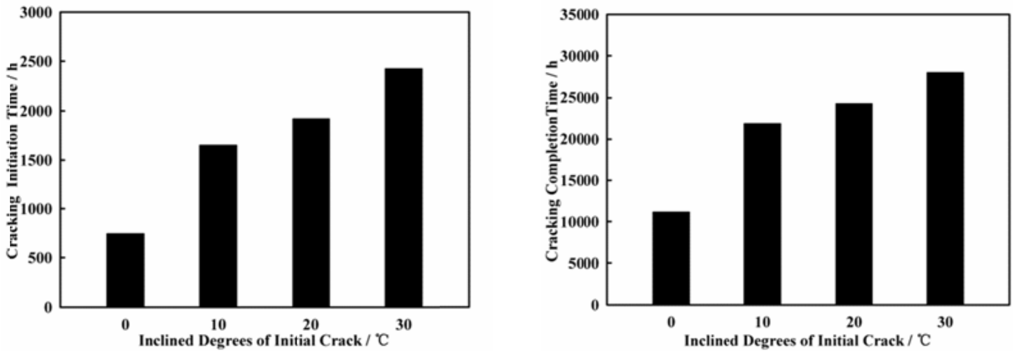


Fig. 4 Fracture life versus cracking propagation

Fig. 4 presents the fracture life versus cracking propagation with different inclined degrees of initial crack in different models. As shown in the figure, the crack propagates fastest in the models with inclined degree 0℃, and the crack propagates slowest in the models with inclined degree 30℃. The crack propagates faster with decrease of the inclined degree. It indicates that the inclined degrees of initial crack have great influence on fracture life. What's more, the crack propagates smoothly in the models with inclined degree 0℃. However, the crack propagates unsmoothly if there is inclined degree of initial crack in the models. This is because that in the model with inclined degree 0℃, there is meanly tensile stress (S11 in this paper) at the cracking tip. The crack propagates up straightly. But if the inclined degree is not 0℃, there is not only tensile stress but shear stress at the cracking tip.



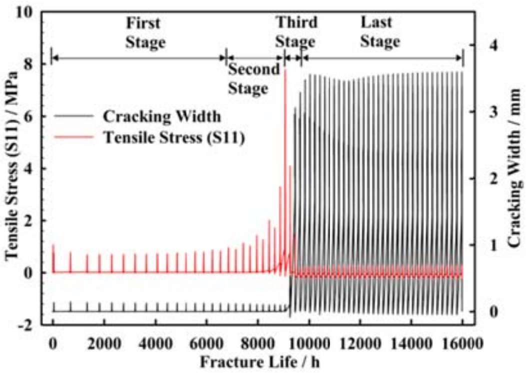
(a) Cracking initiation time Cracking completion time

Fig. 5 Cracking initiation time and completion time in different models with various inclined degrees

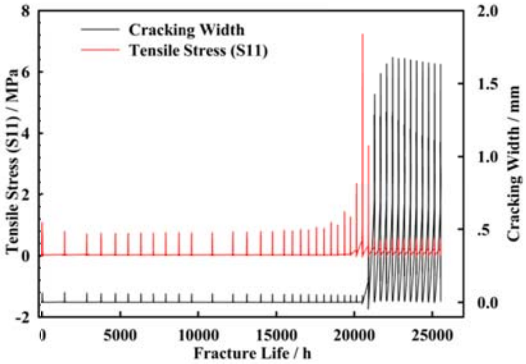
Fig. 5 compares the effect of inclined degree of initial crack on the cracking initiation time and cracking completion time for different models. The cracking initiation time and cracking completion time both increase with the increase of inclined degree. In addition, the cracking initiation time and cracking completion time in the model with inclined degree 30℃ are 3.5 times and 2.5 time as long as that in the model with inclined degree 0℃. It indicates that the propagating velocity is seriously influenced by the inclined degree of initial crack.

3.2 Analysis of stress distribution

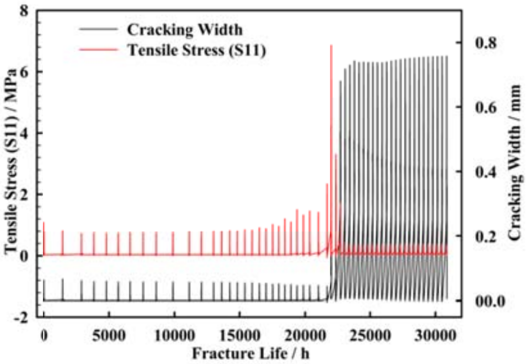
The tensile stress and cracking width are both important factors to the reflective crack in asphalt pavement. Fig. 6 shows the tensile stress and cracking width at 1cm above the initial crack tip and at overlay surface. As shown in Fig. 6, the maximum tensile stress at surface does not change in the first stage. Then the tensile stress increases with the cracking propagation in the second stage. In the third stage, the crack penetrates the overlay and the tensile stress decrease rapidly and there is no capacity near the reflective crack. After reflective crack penetrating the overlay, there is a visible crack in overlay. Moreover, the cracking width increases to the peak value with the increase of temperature cycles.



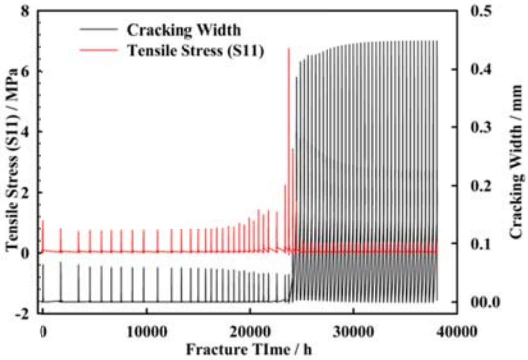
(a) inclined degree 0℃



(b) inclined degree 10℃



(c) inclined degree 20℃



(d) inclined degree 30℃

Fig. 6 Tensile stress and cracking width at surface

In addition, the influence of inclined degree of initial crack on maximum tensile stress and maximum cracking width at 1cm above the cracking tip and surface are briefly discussed. Fig. 7 shows the influence of inclined degrees of initial crack on maximum tensile stress. It illustrates that the maximum tensile stresses at 1cm above the cracking tip and surface both decrease with the increase of inclined degree of initial crack. Fig. 8 shows the influence of inclined degrees of initial crack on maximum cracking width. It illustrates that the maximum cracking width at 1cm above the cracking tip and surface also decrease with the increase of inclined degree of initial crack. This is because that in the models with the inclined degree 0℃, there is only tensile stress that affects the cracking propagation. But in other kinds of models, there is not only tensile stress, but also shear stress that induces the reflective cracking propagation.

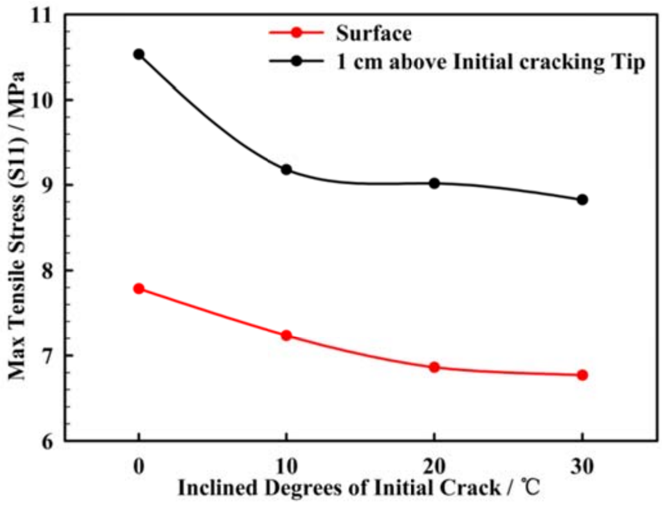


Fig. 7 Influence of inclined degrees of initial crack on max tensile stress (S11)

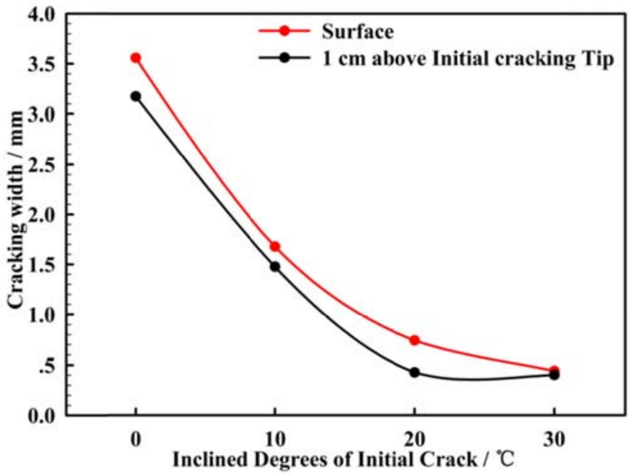


Fig. 8 Influence of inclined degrees of initial crack on cracking width

Fig. 9 shows the progressive stress (S11) contours during the crack has initiated and propagated through pavement structures. In Fig. 9(*a*), stress concentration appeared at the cracking tip before cracking initiation. In Fig. 9(b), the crack propagated up and the cracking width increased. However, the stress at cracking tip was still greater than in other element. In Fig. 9(c), the crack propagated through the pavement overlay and the stress near the crack released. Moreover, an obvious V-crack was formed in the overlay.

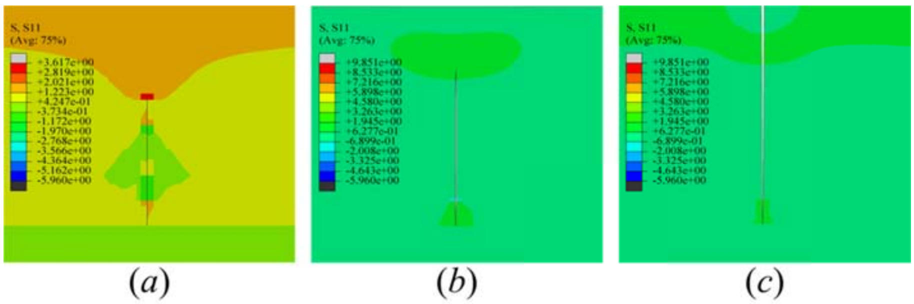


Fig. 9 Tensile stress contour of pavement crack propagation

3.3 Mechanisms of thermal fatigue reflecting cracking

Fig. 10 gave an insight into the fracture path. It obviously showed that the inclined degree of initial crack had a great influence on fracture path. If the initial degree was 0℃, the crack propagated up straightly. If the initial degree was greater than 0℃, the crack propagated along arbitrary path. Moreover, the fracture degree got smaller than the initial cracking degree.

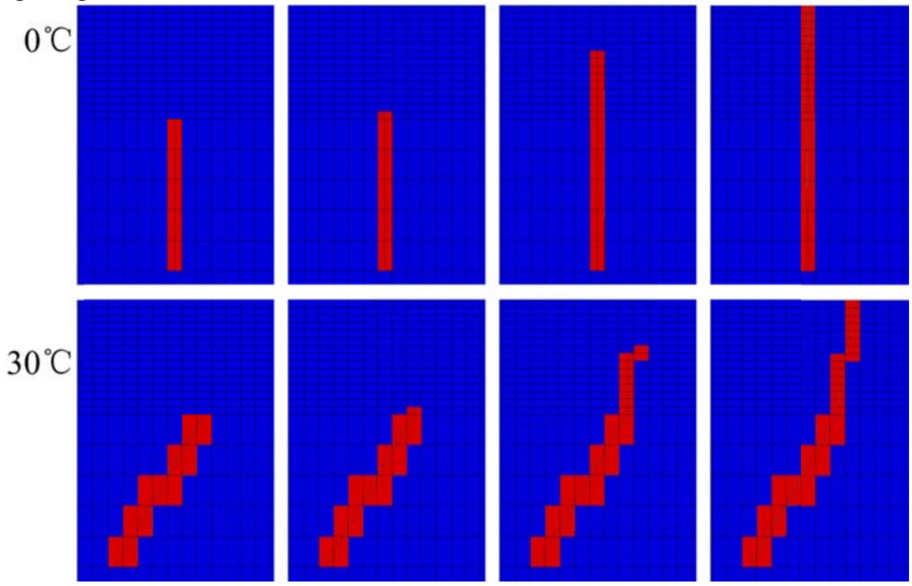


Fig.10 Fracture path

4 Conclusion

This paper presented mechanistic modeling approach to investigate the thermal fatigue reflective cracking in semi-rigid base asphalt pavement. It had been proved that the temperature distribution could be obtained by DFLUX subroutine and FILM subroutine and XFEM was an effective method to analyze the thermal crack. Stress distribution and cracking width were the important indications to analyze the cracking initiation and propagation. Moreover, the inclined degree of initial crack was primary factor to thermal reflective crack. This better understanding was expected to provide more scientific insights to advance the current structural pavement design practices and pavement repairing. Based on the simulation results, the following conclusions could be drawn:

The temperature distribution in pavement structure and circularly changing with time was accurately obtained with the subroutines of DFLUX and FILM. It could present significant insights into the temperature distribution in the layered pavement structure.

The stress response and cracking width were significantly affected by the variation of inclined degree of initial crack. This study clearly demonstrated that the fracture life had great difference in the models with variations of initial cracking condition.

In XFEM models, the reflective crack propagating along arbitrary path could be successfully simulated. Inclined degree of initial crack had great influence on fracture path. In addition, fracture geometry during the cracking propagation could be clearly understood. Finally, a V-crack was formed in the pavement overlay after the reflective crack penetrated the overlay.

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