Mixed mode deformation in a cracked asphalt pavement subjected to traffic loading

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ABSTRACT. *Asphalt cracking is one of the main causes for the overall damage in the pavement of roads and highways. Since the cracks can be initiated in various locations and orientations relative to the direction of traffic loads, the crack growth may occur in a mixed mode manner. Therefore, it is important to investigate the crack growth behaviour in asphalt pavements in order to estimate the lifetime and service capability of the roads and highways. In this paper, the mixed mode fracture behaviour of a cracked asphalt layer is investigated under different loading conditions using various 3D numerical analyses. A semi-circular crack with a plane normal to the road axis was considered in the finite element models. The loads induced from the wheels of a typical vehicle were applied to these models in different distances from the crack in order to calculate the stress intensity factors. It was found from the finite element results that the analyzed cracks were generally subjected to mixed mode loading and the effects of all three modes (I, II and III) can influence significantly the crack growth behaviour in the pavement. The locations of loads induced from the wheels and their distances from the crack plane are two major parameters affecting the sign and magnitude of the stress intensity factors. It was also shown that the sign of stress intensity factors changes by moving the vehicle, relative to the crack plane implying that the cracks can be subjected to fatigue loads due to reversing the state of crack deformation from opening to closing or positive shear to negative shear.*

INTRODUCTION

Performance life of asphalt pavement is an important issue in most countries having long and speared networks of roads and highways. Annually huge amount of money is spent for maintenance of asphalt pavements [1,2]. Cracking is a primary mode of deterioration and one of the main causes for overall failure of asphalt pavement of roads and highways especially in cold regions [3-5]. Top-down cracks in the surface of asphalt pavements initiate due to cyclic thermal loads and mechanical traffic loading and thus they can increase noticeably the maintenance and rehabilitation cost of pavement [6]. Since cracking in asphalt layers is inevitable, the investigation of crack growth behavior in asphalt pavements is important for estimating the service life or the suitable rehabilitation time of pavement and service capability of the roads and highways. Generally, the pre-existing cracks may grow because of traffic loading [7]. Since the cracks can be initiated in various locations and orientations relative to the direction of traffic loads, the crack growth may occur in a mixed mode manner. In other words, most of the cracks in the surface of asphalt layer usually experience combined opening-sliding deformations. However, a review of literature [8-11] indicates that most of the research studies have only focused on pure mode I loading conditions and mixed mode fracture behavior of cracked asphalt pavements has received little attention. Hence, in this paper the mixed mode fracture behavior of a cracked asphalt layer is investigated using various 3D numerical analyses and under different loading conditions. It is shown that the analyzed asphalt pavement is generally subjected to mixed mode loading and the effects of three modes I, II and III can influence significantly the crack growth behavior of the pavements. Accordingly, the location of applied loads induced from the wheels and their distances from the crack plane are the main affecting parameters on the sign and magnitude of the stress intensity factors.

Finite element modeling

Asphalt pavement used for construction of roads and highways consists of four main layers namely (i) asphalt concrete layer (ii) base layer, (iii) sub-base layer and (iv) sub-grade or soil layer. These layers are usually made of a mixture of bitumen and fine or coarse aggregates. Although, many types of cracks can be found in an asphalt pavement, the aim of this research was to study the behavior of cracks that exist in the surface of asphaltic upper layer. Thickness of this layer typically ranges between10 to 20 cm. Top-down cracks in the asphalt surface layer are often initiated because of severe aging of the HMA near the surface. They may then propagate due to tensile stresses and strains induced by wheel loads at the surface.

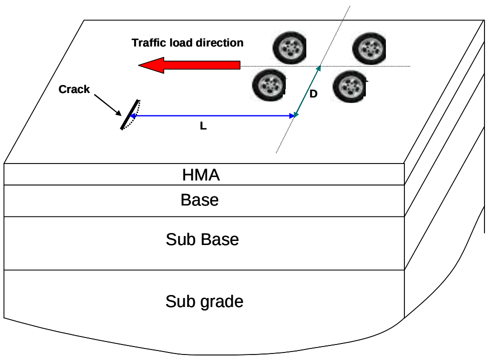

Figure 1: Schematic representation of an asphalt pavement containing a surface semi-circular crack perpendicular to the traffic loading direction.

Fig. 1 shows different layers of an asphalt pavement schematically and a typical semi circular transverse surface crack (with respect to the axes of road) initiated on the upper layer. In general, a surface crack in asphalt pavement can be considered semi-elliptical, since according to Lin and Smith [12], a crack with any initial arbitrary shape becomes semi-elliptical and then propagates in a semi-elliptical shape. The locations of the four wheels of a typical vehicle on the surface of road relative to the plane of crack are also shown in Fig. 1. By moving the wheels towards the crack plane (i.e. by changing the distances D and L in Fig. 1), the crack can be subjected to different combinations of opening and sliding deformations. In the next section, the finite element method is employed for analyzing the influence of wheels locations on fracture parameters of the crack.

Numerical analysis of the cracked pavement

Since the existing cracks in the surface of roads are usually subjected to complex and variable state of traffic loads, numerical methods can be used as a powerful tool for simulating and investigating their fracture behavior. Furthermore, 3D finite element models would provide more acceptable and reliable computational results for the asphalt pavements in comparison with the simple 2D models. Hence, a typical semi-rigid asphalt pavement structure was selected for our analysis using the finite element code ABAQUS. For each layer of asphalt pavement, the construction material was generally assumed to be isotropic, homogenous and linearly elastic. The elastic constants and the thickness of each layer for a typical asphalt pavement used in the roads of Iran's are listed in Table 1.

Table 1.Mechanical properties and the thicknesses of the pavement layers used in finite element modeling

Layer	Young modulus , (E) MPa	Poisson's ratio, ν	Thickness of layer t (cm)
asphalt concrete (HMA)	2760	0.35	14
base	276	0.35	20
Sub-base	104	0.35	25
Sub-grade	34.5	0.45	200

For finite element modeling, the following dimensions were considered for the road pavement: 18 m long, 4 m wide and approximately 2.5 m deep. The x and y axes represent the longitudinal and the transverse directions of road respectively. For applying the boundary conditions, the side faces of the created model (i.e. front, back, left and right) were fixed in the normal direction, and the other two degrees of freedom were free. The bottom face of model (i.e. the bottom of 2m thick soil layer) was also completely fixed in all directions. The interfaces between different layers of the pavement were also assumed to be perfectly bonded. The vertical loads induced from the four wheels of a typical vehicle having a mass of 1000 kg were considered in the top surface of the model and at different locations relative the crack plane. One forth of the vehicle weight was assumed to be distributed uniformly on each wheel over a rectangular area of contact between the road and the wheel. In the models, the distance between the front and rear wheels was 2.34 m. A semi-circular surface crack with radius of R = 70 mm perpendicular to the road axis was also created in the middle of top layer in the finite element model. A total number of 36732 solid brick elements were used for creating the finite element model. A large number of singular elements were also used in the first ring of crack front line for producing the square root singularity of stress/strain field. Fig. 2 shows the finite element mesh pattern for the pavement and a zoomed view of the crack region.

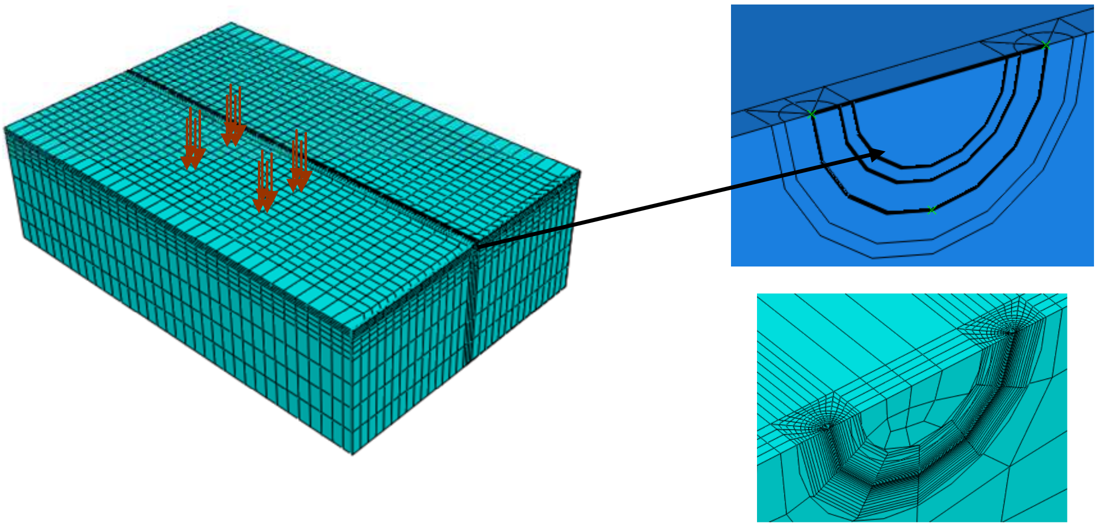

Figure 2: Finite element mesh pattern created for modeling the asphalt pavement and the semi circular crack.

The stress intensity factors (K_{I}, K_{II} and K_{III}) are functions of the induced wheel loads and their distances from the crack line and can be written as:

$$K_i = f(L, D, P, t, R) \qquad i = \mathrm{I, II, III} \tag{1}$$

where t is the thickness of each layer and R is the radius of the crack. A J-integral based method built in ABAQUS was used for obtaining the stress intensity factors directly from software. Hence numerous 3D finite element models with different L and D distances were analyzed and the corresponding values of K_{I}, K_{II} and K_{III} were computed. The obtained numerical results are presented in the next section.

Results and discussion

The results obtained for mode I, mode II and mode III stress intensity factors (SIF) from the finite element analysis have been presented in Figs. 3 to 5 for different locations of vehicle relative to the crack plane (i.e. various D and L distances). The results are related the deepest point in the semi-circular crack where often the maximum stress intensity factor is seen. It is seen from these figures that the state of crack deformation and consequently the stress intensity factors is strongly affected by the distances L and D. According to Fig. 3, a transversely crack experiences different variable positive - negative states of stresses by changing the location of wheels. For example, when the vehicle moves from the far distances towards the crack location, first the mode I stress intensity factor (K_I) increases until a distance L about 2m from the crack plane. Then by moving the wheels further (typically for the range of -2 m $<L<$-1.5 m) K_I decreases dramatically and its sign switches from positive to negative. This means that the crack flank deformation changes from opening to closing. This is mainly because for such loading distances where the front wheels locate very close to the crack, a downward deformation tends to close the crack flanks. Then, by increasing L from approximately -1.5 m to zero, K_I increases again noticeably and its sign turns again from negative into positive. When L becomes zero (i.e. when the crack is located exactly in the middle of front and rear wheels), K_I reaches its maximum value. In this loading situation, the tensile bending stress induced from the wheels is highest and tends to open the crack flanks. Hence for L = 0 and D = 0, pure mode I conditions is achieved. Moreover, because of symmetry in the loading condition, for $L > 0$ the obtained results as expected are exactly mirror reflection of the results obtained for $L < 0$.

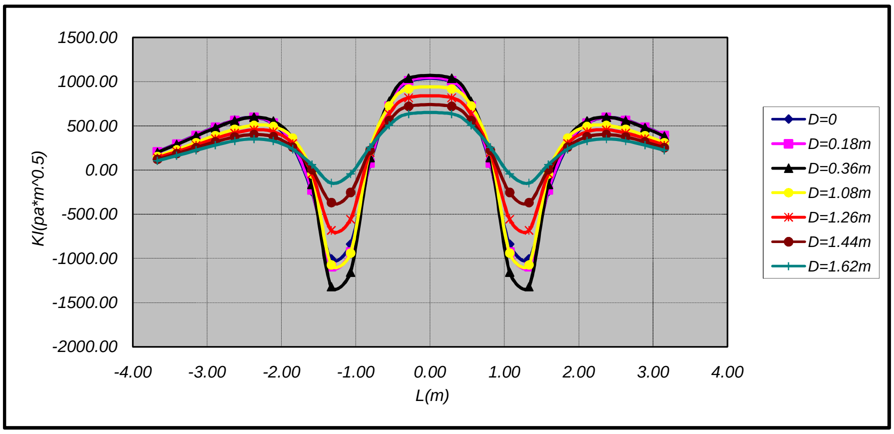

Figure 3. Variations of mode I stress intensity factor (K_I) for different wheel locations (L and D) in the analyzed asphalt pavement containing a semi-circular surface crack.

Similar trends discussed here for switching signs of K_I, can be found for mode II and mode III stress intensity factors (see Figs. 4 and 5). However, the maximum values of K_{II} and K_{III} values were obtained at a distance L about $\pm$1.5m.

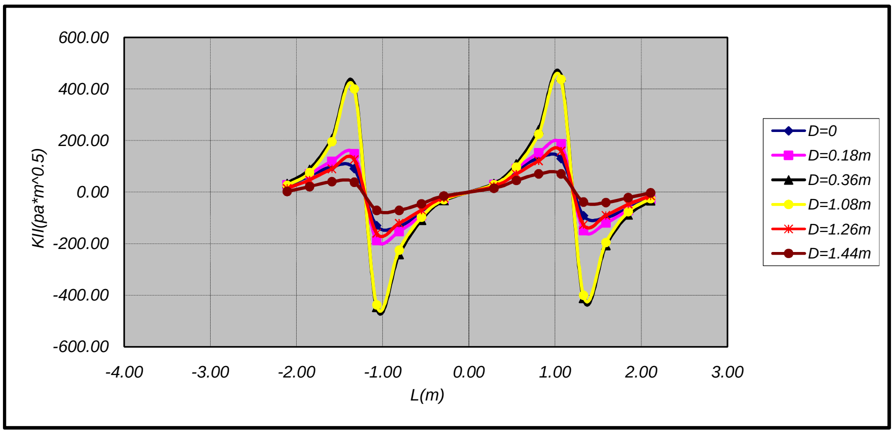

Figure 4. Variations of mode II stress intensity factor (K_{II}) for different wheel locations (*L* and *D*) in the analyzed asphalt pavement containing a semi-circular surface crack.

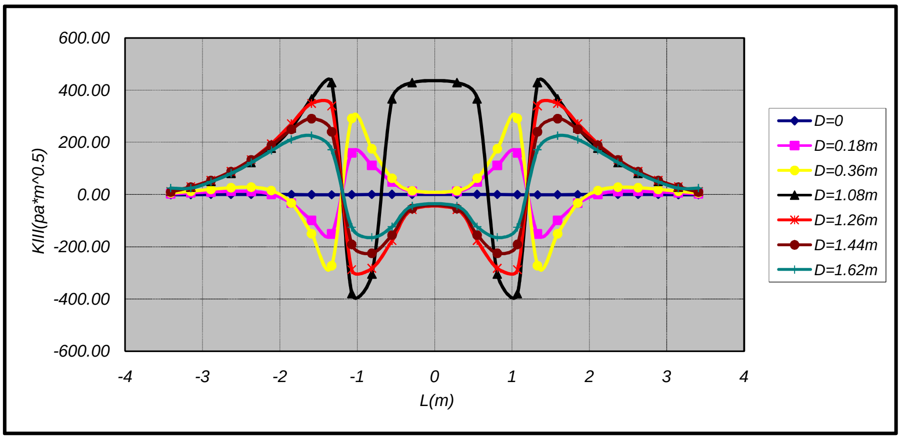

Figure 5.Variations of mode III stress intensity factor (K_{III}) for different wheel locations (*L* and *D*) in the analyzed asphalt pavement containing a semi-circular surface crack.

Also a comparison of the results obtained for the considered asphalt pavement indicates that the influence of opening mode deformation (K_I component) is more pronounced than the other crack deformation modes although K_{II} and K_{III} and still considerable. As seen from Fig. 6, for a constant value of *D*, K_I varies in a wider range and larger amplitude for different *L* distances in comparison with K_{II} and K_{III} components. However, in general the crack is subjected to a combination of all the three modes of deformation. In particular, the significant contribution of mode III stress intensity factor which was observed in this research has not been reported in the past. This is mainly because previous researchers have studied the pavement cracks only by a Two-dimensional crack model. Therefore, for estimating the crack growth behavior, the onset of fracture and consequently the lifetime and service capability of the cracked asphalt pavements, the use of, mixed mode fracture criteria is inevitable.

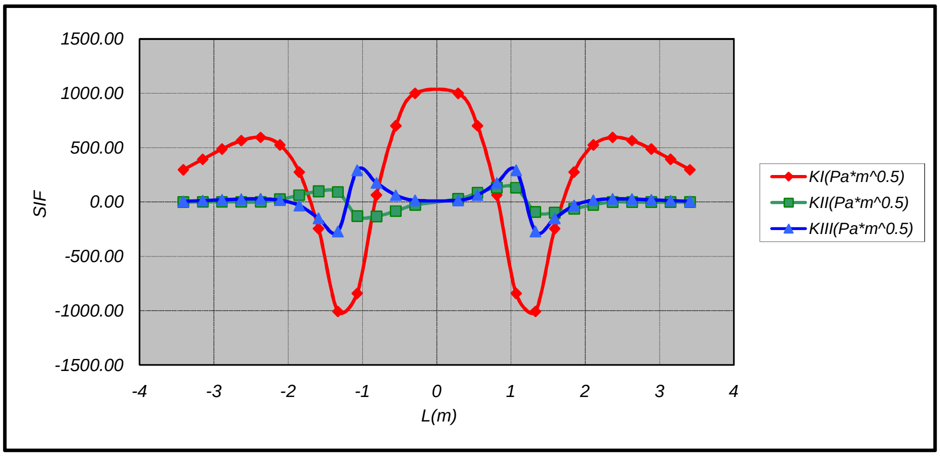

Figure 6. Comparison of stress intensity factors (K_{I}, K_{II} and K_{III}) obtained for different L distances

Furthermore as mentioned earlier, the sign of stress intensity factors (SIF) switch from negative to positive and vice versa by changing the wheels positions. It is seen from Figs. 3 to 5 that, for each vehicle passing over a crack on the surface of road, the sign of SIFs changes twice. This implies that the surface crack in the asphalt layer can be subjected to variable fatigue loads due to reversing the state of crack deformation from opening to closing or positive shear to negative shear due to traffic loading. The cumulative damage induced from the complex triaxial state of stress/deformation of heavy traffic loads can therefore cause the propagation of the crack in mixed mode manner.

Conclusions

- Stress intensity factors (K_{I}, K_{II} and K_{III}) of an asphalt pavement containing a vertical semi-circular surface crack and subjected to traffic loading were computed numerically using a large number of finite element analyses.
- According to the finite element results, the cracked asphalt pavement is generally subjected to mixed mode loading and the effects of all the three fracture modes may affect the crack propagation behaviour.
- It was concluded that the location of applied loads induced from the wheels and their distances from the crack plane (L and D) are the main affecting parameters on the sign and magnitude of the stress intensity factors.
- The existing cracks on the surface of asphalt pavement can be subjected to complex triaxial fatigue loads due to reversing the state of crack deformation from opening to closing or from positive shear to negative shear induced by traffic loading.

Acknowledgement

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