Modelling Of Crack Propagation in Flexible Pavement Using X-FEM Method

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Abstract. A research aim was to achieve a finite element model for predictive pavement cracking implementing ABAQUS software ver.6.12.1. A simulation model for pavement structure was implemented to analyze the propagation of cracks within flexible pavement. The X-FEM method adopted in this research based on the functions of interpolation that can characterize the displacements near the crack zone, initial crack was defined at the bottom of asphalt layer. The estimated results illustrated that X-FEM was efficient for the simulation of cracks in pavement structures without the need for re meshing during crack propagation evolution process. Finally, inclusive simulation results probed the considerable effect for improvement of bonding layers to enhance the service life of pavement in terms of decreasing the rate of crack propagation. The crack was propagated upwards from depth end of asphalt layer to pavement surface and deviated from center of applied pressure with an inclination of almost 30° in the third upper zone of asphalt layer while the pre-crack point was always located in the bottom of asphalt layer in pavement model because of the different characteristics of their bonding bases. In the crack zone the permanent deformation was increased gradually from the crack edge along vertical direction of crack spread due to tensile stresses concentration at the crack zone. The action of horizontal and vertical stresses affect crack propagation and growth vertically to the direction of higher horizontal tensile stresses, and along direction of higher compression vertical stresses.

Keywords: Crack propagation; X-FEM; Finite element method; Flexible pavement; Numerical Simulation.

Highlights
- The X-FEM is utilized to investigate interface crack propagation in flexible pavement.
- Numerical simulation and analyzing of crack propagation for layered structure of flexible pavement.
- Develop a finite element model for predictive pavement cracking.
- Analyze the effect of crack zone on permanent deformation and stresses in flexible pavement.
- Explore the direction of crack propagation in layered structure of flexible pavement.

1. Introduction
The initiation of crack, propagation and growth are the most important failure characteristics that limit the service life for flexible pavement under traffic loading. Cracks have been increased recently due to the need for pavement construction that forced most agencies to try to understand cracks mechanisms near the surface of loading area and modelling failure conditions at field using finite element method. Alkaissi Z.A. (2020) utilized the numerical method to investigate the effect of thermal and loading conditions on pavement performance. It have been found that the resistance to pavement rutting based on both high temperature and traffic loading. A higher damage was occurred...
due to effect of traffic and thermal loading when compared with traffic loading model conditions only [1]. The fracture toughness of asphalt mixtures increased with reduction of test temperature, which reveals that hot mix asphalt (HMA) at low temperature becomes more brittle. Also the asphalt mixture with 5% binder content at (0 and 20°C) keep the highest average value and the reduction of test temperature increased the critical stress intensity factor by (57.5%). So, the temperature decreased, the fracture energy decreased but the fracture toughness increased [2]. The mechanisms of spread cracks in composite pavement was analyzed using the finite element ANSYS software version (5.4). The initiation of surface cracks was due to high vertical and shear wheel stress then propagated down wards due to generated tensile stresses at the end depth of asphalt layer [3]. Alkaissi Z.A, (2006) developed visco-elasto plastic model for flexible pavement considering the effect of dynamic traffic loading on the behavior of the paving system. The obtained results illustrated the validity of developed model to simulate the performance characteristics of flexible pavement [4]. Alkaissi et.al. (2020) investigated the effect of nanomaterial’s technology on pavement improvement. The adding (0.1%) of Nano carbon tube (NCTs) improved the stability and flow values by about (15%) and (2%) respectively and increased the resistance of asphalt mixture to cracking [5]. A viscoelastic and axisymmetric finite element with a dissipated energy model was implied to investigate surface initiated cracks and determined the extent of top-down cracking at predefined locations due to repeated loading [6].

2. Modeling Approach and Methodology

The modeling of stationary and evolving discontinuities with geometry that are independent of the finite element mesh is depend on extended - finite element method (X-FEM). The X-FEM method used functions of interpolation that can described the displacements field near crack. Therefore, it have been appeared as an efficient approach for analysis of cracks growth and evolution. A refinement mesh was needed near the crack end to seize the singular asymptotic fields appropriate and must have updated continuously to resemble the discontinuity of crack geometry as the cracks grow from minor to larger opening cracks.

2.1. The Extended - Finite Element method (X-FEM)

Belytschko and Black (1999) and Moës et al. (1999) first introduced the X-FEM. It’s incorporating enrichment functions and degree of freedom to model discontinuities and singularities. In XFEM, discontinuous behavior embedded into elements using local enrichment functions, additional nodal DOFs. Eq.1 shows the approximation for a displacement vector with the partition of unity enrichment [7], [8]:

\[ u(x) = \sum_{i=1}^{n} N_i(x) [u_i + H_i(x) a_i + \sum_{\alpha=1}^{k} N_{\alpha,i}(x) b_{i}^{\alpha}] \]  

Where:
- \( N_i(x) \): traditional nodal shape functions,
- \( u_i \): is the nodal displacement vector associated with the continuous part of the finite element solution;
- \( a_i \): the second term is the product of the nodal enriched degree of freedom vector, and \( H_i(x) \): the function of associated discontinuous jump across the surfaces of crack;
- \( b_i^{\alpha} \): Product of the nodal enriched degree of freedom vector,
- \( N_{\alpha,i}(x) \): function of associated elastic asymptotic crack tip.

Fig.1 illustrated of normal and tangential coordinates for a smooth crack and the functions of asymptotic crack tip in an isotropic elastic material, \( F_{\alpha}(x) \) which are given by Eq.2 [9]:

\[ F_{\alpha}(x) = \left[ \sqrt{\rho} \sin \frac{\theta}{2}, \sqrt{\rho} \cos \frac{\theta}{2}, \sqrt{\rho} \sin \theta \sin \frac{\theta}{2}, \sqrt{\rho} \sin \theta \cos \frac{\theta}{2} \right] \]
Where:

\((r, \theta)\) : Polar coordinate system with its origin at the crack end and,

\(\theta = 0\) : Tangent to the crack at its end.

![Diagram](image)

**Figure 1.** Normal and tangential coordinate’s illustration for a smooth crack (ABAQUS, user Manual, 2009).

The extended - finite element method is efficient to overcome the difficulties of conventional techniques of the finite element method in mesh design and computational issues of cases with discontinues such as material interfaces, cracks, etc., standard functions of approximation were enriched locally with enrichment functions, representing solution for local behavior. Fig. 2 illustrate main differences of extended and finite element standard methods in terms of possibility of arbitrarily locating the discontinuity within the problem structure [10].

![Diagram](image)

**Figure 2.** Finite element mesh with a discontinuity represented by (a) Interface elements (b) discontinuity enrichments (Hasan, et.al, 2010).

Strategy of enrichment used in the extended - finite element method comprised functions of polynomial enrichment, asymptotic enrichment functions and step functions.

- Functions of polynomial enrichment were used to increase the order of approximation of a whole domain or a specified subdomain.
- The step functions explored the displacement jumps across faces of crack whereas;
The elasticity solution of asymptotic expansion was used near the crack faces to perform singular crack tip behavior. The second types of enrichments were discontinuity enrichments was used in this research, see Fig.3, as strategy for extended finite element method and the enrichments of discontinuity were provided by step functions and imposed on the nodes of all elements cut through crack.

![Figure 3. The influence of discontinuity enrichments on nodes with a boundary value problem crossed by a crack (Hasan, et.al, 2010).](image)

3. Pavement Model
In this division of research, a pavement simulation model present in Fig.4 was implemented to analyze the crack propagation in flexible pavement. The adopted pavement structure was modelled and solved using finite element software [11]. A typical structure for heavy traffic loading was modelled consisting of asphalt layer (100mm) and compacted subgrade layer (1000 mm) and length of entire pavement structure was assumed (4000mm). In the X-FEM crack analysis, the initial crack location was defined at the bottom of asphalt layer because it should contained in crack domain propagation as shown in Fig.4. A wire part instant was utilized to simulate the crack feature in which its thickness and depth were considered small compared to structure length, see Fig.5. The parameter for the material properties are listed in Table 1.
Figure 4. Model of Pavement with induced Crack using ABAQUS.

Figure 5. Model of Pavement with Boundary Conditions and Applied Tire Pressure.

Table 1. Input Parameters.

| Local Layer Properties          | Elastic Modulus (MPa) | Poisson ratio |
|---------------------------------|-----------------------|---------------|
| The Layer of Asphalt Surface [2] | 7500                  | 0.35          |
| Subgrade Layer [12]             | 40                    | 0.40          |

4. Crack Propagation in Pavement Structure
The pavement model to capture crack propagation, a crack was inserted at location in the vicinity of applied tire pressure to detect critical locations and orientation for crack evolution. Fig. 6 shows the crack propagation from the toe of asphalt layer to the pavement surface in terms of elements reached failure criteria, 1.0 for completely cut through element (damaged zone). Also the evolution of crack surface is shown in Fig.7, for PSLIM coordinate results. This would implied the crack
surface will shift location to keep the enrichment scheme stable. The crack was propagate upwards from end depth of asphalt layer to pavement surface deviated from center of applied pressure with an inclination of almost 30° in the third upper zone of asphalt layer while the pre-crack point was always located in the bottom of asphalt layer in pavement model because of the different characteristics of their bonding bases layers. The results illustrate that X-FEM is efficient for the simulation of cracks in pavement structures without the need for re-meshing during crack propagation evolution process. Finally, extensive simulation results support the major significant for improvement of bonding layers to enhance the service life of pavement in terms of decreasing the rate of crack propagation.

5. Deformation and Stress Distribution in Pavement with Crack Propagation

During loading process, a significant deformation was observed at crack zone causing fracture and propagation of crack to the entire depth of asphalt layer up to the surface of pavement. The displacements results of crack region for the pavement model were investigated and presented in
Fig. 8. In the crack zone the permanent deformation have been increased gradually from the crack end along vertical crack propagation direction because the concentration of tensile stress at crack zone. The FE results of crack stress concentration are presented in Figs 9 and 10. It can be demonstrated the effect of horizontal and vertical stresses on crack propagation in which crack grew vertically to the maximum tensile stresses direction, and along direction of high vertical compression stresses.

**Figure 8.** Displacement Field of Cracked Pavement.

**Figure 9.** Horizontal Stress Distribution and Crack Propagation in Pavement.
6. Conclusions
This research has investigated the crack propagation in pavement using finite element software (ABAQUS ver.6.12) and finally, the concluding remarks are stated as follow:
1. The results has explored the effectiveness of using X-FEM for the simulation of cracks in pavement structures without the need for remeshing during crack propagation evolution process. Finally, extensive simulation results support the major significant for improvement of bonding layers to enhance the service life of pavement in terms of decreasing the rate of crack propagation.
2. The crack was propagate upwards from end depth of asphalt layer to surface of pavement deviated from the center of applied pressure with an inclination of almost 30° in the third upper zone of asphalt layer while the pre-crack point was always located in the bottom of asphalt layer in pavement model.
3. In the crack zone the permanent deformation was increased gradually from the crack end along vertical of crack propagation direction because tensile stress concentration at crack zone.
4. The crack propagation was influenced by the horizontal and vertical stresses and the crack grew vertically to the maximum tensile stresses direction, and along the direction of high vertical compression stresses.

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