Finite Element Analysis of Asphalt Pavement under Projectile Impact Load

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Abstract. A three-dimensional model for the surface texture of asphalt pavements is constructed by ANSYS LS-DYNA to simulate the boundary conditions of asphalt pavements under impact load in this paper. The stresses of the asphalt surface under impact load are calculated and plotted. The process of asphalt layer stress development and the variation of the maximum stress are analyzed specifically. Finally, the effects of the elastic modulus and the angle of impact on the stress changes are presented.

1. Introduction
Asphalt concrete is widely applied to roads at all levels, airports and hydropower projects in China and it is viscoelastic at room temperature. Nowadays, most of the researches on asphalt concrete focused on the fatigue, creep and the fracture characteristics, but few were about the impact load. In fact, to facilitate safety design and protection of airports and highways, it is important to analyze the destructive impacts of explosive or kinetic weapons on airports or highways.

Due to the high cost of the on-site impact test, the large number of materials and the limitation of instrument, it is difficult to describe the stress condition completely during the destructive process. With the development of computer technology and numerical methods, it is more effective to analyze the multi-layer pavement system under the impact load by numerical stimulation in which various parameters can be adjusted for analysis of the influence rules. Therefore, this study made use of the finite element analysis method to analyze the destructive process of asphalt pavements under projectile impact load; it also analyzes the influence of the pavement-surface elastic modulus and the angle of impact load on the distribution and strength of stress. The study result is expected to provide a scientific basis for safety design and maintenance of highways.

2. Calculation model

2.1. Road model equation
This paper deals with a problem of highly non-linear dynamics. In this paper, the roads are the plastic materials with strain rate dependence. Then, the Cowper-Symonds model is applied and the strain rate coefficient is used to present the yield strength (σₚ). The equation is shown as follows:
(1)

\[ \sigma_y = \left[ 1 + \left( \frac{\dot{\varepsilon}}{C} \right)^P \right] \left( \sigma_0 + \beta E_p \varepsilon_{pl}^e \right) \]

where \( \sigma_0 \) is the initial yield strength and \( \dot{\varepsilon} \) is the strain rate; \( C \) and \( P \) are Cowper-Symonds strain rate parameters and \( \varepsilon_{pl}^e \) is the effective plastic strain. Moreover, the meanings change as the numerical value of \( \beta \) change. Kinematic hardening is adopted. That is, \( \beta = 0 \), \( E_p \) is the plastic hardening modulus. It can be calculated by the following formula:

\[ E_p = \frac{E_{tan} E}{E - E_{tan}} \]  

(2)

where \( E \) is the material elastic modulus and \( E_{tan} \) is the tangent modulus. The strain rate \( \dot{\varepsilon} \) can be calculated by the following formula:

\[ \dot{\varepsilon} = C \left( \frac{\sigma_0^e}{\sigma_0} - 1 \right)^P \]  

(3)

where \( \sigma_0^e \) is the dynamic stress. According to Cowper-Symonds, the dynamic stress, which is related to the given strain rates, was first estimated. Then the static stress were replaced by the dynamic stress and the results were applied to the next calculation. Last, the two steps mentioned above were repeated until the materials were damaged and defunct.

Taking into account the MP and TB commands of the finite element software, the road model material equation requires eight material parameters. They are elastic modulus \( E \), density \( \rho \), Poisson's ratio \( \mu \), yield strength tangent modulus \( E_{tan} \), yield strength \( \sigma_y \), kinematic hardening parameter \( \beta \), strain ratio parameters \( C \) and \( P \), and failure strain \( \varepsilon_f \).

2.2. Model parameter

The model is built by the ANSYS software. As can be seen, the road consists of three courses. In detail, the surface course is AC-20 asphalt concrete, the middle course is cement-stabilized macadam base and the base course is made of soil. The impact object is a mild steel material, which impacts the road surface in the negative direction of \( y \)-axis at a certain speed. The sizes of all parts are shown in Figure 1.

![Figure 1. Sizes of all parts](image1)

![Figure 2. Finite element model](image2)

LS-DYNA is used to simulate the collision between the impact loads and the roads. Moreover, to ensure the authenticity of the non-linear simulation and the accuracy of the impact, the software has been applied to define the contact mode. Table 1 shows the model material parameters.
Table 1. Model material parameters

| Material   | Elastic Modulus $E$ (Mpa) | Poisson's ratio $\mu$ | Density $\rho$ (kg/m³) | Yield Strength $\sigma_Y$ (Mpa) | Tangent modulus $E_{tan}$ (Mpa) | Strain rate coefficient $C$ (s⁻¹) | Strain rate coefficient $P$ | Failure strain $\varepsilon_f$ | Hardening parameter $\beta$ |
|------------|---------------------------|-----------------------|------------------------|--------------------------------|----------------------------------|----------------------------------|------------------------------|-----------------------------|-----------------------------|
| Impact body | 210                       | 0.29                  | 7800                   | -                              | -                                | 815                              | 40                           | 5                           | 0.8                         |
| Asphalt concrete | 2200              | 0.35                  | 2400                   | 200                            | 815                              | 40                               | 5                            | 5                           | 0.8                         |
| Cement base | 1500                      | 0.25                  | 2200                   | 180                            | 600                              | 40                               | 5                            | 5                           | 0.8                         |
| Soil base   | 4500                      | 0.40                  | 1800                   | 600                            | 160                              | 40                               | 5                            | 5                           | 0.8                         |

2.3. Mesh model and boundary condition

The model is a three-dimensional explicit SOLID164 unit. To ensure the efficiency and accuracy of calculation and the places, where the impact object contacts with the asphalt layer and other layers, bear more concentrated stresses, densification process is carried out while some meshes that are away from the impact part bear less concentrated stresses. Moreover, to make the simulated impact more accurate, this paper defines the contact mode to be STS and ESTS so that it is consistent with the reality and presents the results of interface stresses. Therefore, the interfaces between the three courses bind completely. What’s more, under the soil base, the displacements of the three directions are restricted. The model totally has 8160 meshes as shown in Figure 2.

3. Results and analysis

3.1. Influence of angle of impact on stress

In order to demonstrate the destructive process of the asphalt layer, with the same material parameters and methods of numerical stimulation but variable angles of impact, the nephogram and curve of stress was presented when the impact object pointed in directions $0^\circ, 30^\circ, 45^\circ$ and $60^\circ$ to the left of the negative y-axis. In this case, the angle of impact was the included angle between the direction of impact load velocity and the negative and vertical y-axis.

Figure 3. Stress nephogram with $0^\circ$ impact angle at different time points

Firstly, the destructive process with $0^\circ$ angle of impact was taken for example. This paper selected von Mises stress nephograms at six different time points, as shown in Figure 3.
Figure 4. Stress nephogram with 45° impact angle at different time points

Figure 5 shows the analysis of the equivalent stress changes and the curves of the maximum stress at different stages. First of all, the maximum stress was relatively small when the impact object just began to come into contact with the asphalt surface. The concentrated stress first occurred at the midpoint of the fixed boundary. After a full contact between the impact object and the asphalt surface, the maximum stress increased and concentrated stress gradually expanded to the whole impacted area. With the continuous downward impact of the impact object, the maximum stress reached 496 Mpa. Due to the bounce of collision, the impact object started to lose contact with the asphalt layer with an attenuation of the concentrated area toward the center of impacted zone and decrease of the maximum stress.

The destructive process with an angle of impact of 45° was taken for example. The stress development of asphalt pavement is shown in Figure 5 when the impact object impacted the pavement with an angle of 45° with the y-axis, which was roughly equal to that with an angle of 0°. But the maximum stress had changed to 625 Mpa in this scenario, as shown in Figure 6.

Figure 5. Curve of maximum stress with 0° impact angle at different time points

Figure 6. Curve of maximum stress with 45° impact angle at different time points

Last, according to the maximum stress data derived from the impact object pointed in directions 0°, 30°, 45° and 60° to the left of the negative y-axis, the diagram of varied maximum stresses with different angles of impact is shown in Figure 7. It can be seen that at the beginning of the impact, the
maximum stress occurred at the two corner points at the bottom of the impact object. That was not only because these points were the area of contact with the asphalt, but also because of concentration of stresses. And then, the range of maximum stress enlarged. Because of the plastic deformation, the maximum stress started to concentrate towards the center and increased gradually. At the same time, changes in the angle of impact affected the maximum stress on the asphalt surface. The results indicate that with the impact object pointed in directions $0^\circ$, $30^\circ$, $45^\circ$ and $60^\circ$ to the left of the negative $y$-axis, under the same condition, the maximum stress reached its peak with the angle of $45^\circ$.

### 3.2. Influence of surface elastic modulus on stress

In order to investigate how the modulus of elasticity affect the stress, the elastic modulus of the asphalt surface was changed and the change curve of stress $t=0.8 \times 10^{-3}$s was shown in Figure 8. The maximum stress went up with the increase of the elastic modulus but they did not have a linear relationship for non-linearities of the materials. According to the definition of the elastic modulus, it can reveal the materials' ability to resist deformation. The larger the elastic modulus, the stronger the deformation resistance.

From the perspective of energy absorption, under the effect of impact load, the asphalt pavement requires to absorb the energy from the impact object. The deformation resistance will be enforced with the increase of the elastic modulus. If the deformation of the asphalt pavement decreases, its maximum stress will increase. Therefore, reducing the elastic modulus moderately can mitigate the damage of impact object to the asphalt pavement. Compared with rigid cement pavements, asphalt pavement which is known as flexible pavement has an edge as it can absorb more energy from the impact object, lower the maximum stress and hence minimize the impact on the pavement.

### 4. Conclusion

With the help of ANSYS, the author carried out finite element analysis on the asphalt surface under the influence of the projectile impact loads. The followings are the conclusions:

1. Better analytical results are shown when the elastoplastic model is applied to the asphalt surface model.
2. At the initial stage of vertical impacting on the asphalt surface, the midpoint of the boundary constraints is where stress concentration occurs first, and then stress concentration extends to the impacted areas.
3. Changing the impact direction of the impact load can affect the maximum stress. The results show that with the impact object pointed in directions $0^\circ$, $30^\circ$, $45^\circ$ and $60^\circ$ to the left of the negative $y$-axis, the maximum stress reaches the highest reading with the angle of $45^\circ$, with other conditions unchanged.
4. Changes in the elastic modulus of the asphalt layer have an effect on the maximum stress. According to the data analysis, the maximum stress went up with the increase of the elastic modulus in
a nonlinear way. Reducing the elastic modulus of the asphalt layer properly can fully demonstrate the advantages of the flexible pavement, cut down the minimum stress and mitigate the damage of impact load to the asphalt layer.

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