Stress-Strain characteristics of flexible pavement using Finite Element Analysis

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ABSTRACT

Design of flexible pavement is largely based on empirical methods using layered elastic and two-dimensional finite element (FE) analysis. Currently a shift underway towards more mechanistic design techniques to minimize the limitations in determining stress, strain and displacement in pavement analysis. This research documents the use of 3D finite element application for predicting mechanical behavior and pavement performance subjected to various traffic factors. Different axle configuration, tire imprint areas and inflation pressure are investigated here to analyze the considerable impact on pavement damage initiation from fatigue and permanent deformation point of view. In this study, flexible pavement modeling is done using ABAQUS software in which model dimensions, element types and meshing strategies are taken by successive trial and error to achieve desired accuracy and convergence of the study. Thus proper tire imprint area is determined to apply in economical design of pavement for various axle configurations.

Keywords: Fatigue, Finite Element Analysis, Flexible Pavement, Inflation Pressure, Tire Imprint Areas.

1. Introduction

The interstate and highways connecting cities and sustaining economic exchange are integral to the infrastructure of a country. Transportation is considered to be one of the most important infrastructure components influencing production and economic activities. Presently there are 6-7% of roadways with respect to the total land area of Bangladesh; more than 98% are topped by asphalt. Though scarcity of lands, demand of road pavement is increasing considerably to mitigate the need of basic movements and enhance economic activities.

So there exists considerable pressure for investment in the transportation sector. But unit length of construction cost of pavement is massive as per empirical design guideline because the complex interaction of materials of different layers cannot be assessed and investigated easily. Economic and efficient pavement system can be designed through mechanistic behavioral analysis using the application of finite element. This research is a part of a broader study (Rahman M.T., 2009) and an attempt is made in this study to analyze stress-strain characteristics of asphalt pavement through proper understanding of various traffic and loading factors and their interaction with the pavement distress and failure initiation.
The specific objectives of this study can be summarized as follows:

- Develop proper element type and effective meshing strategies for flexible pavement in finite element software. Analyze proper tire imprint area for inflation pressure.

- Estimate the appropriate tire inflation pressure.

2. Methodology

The traffic and loading is considered as the prime factor in designing the pavement system. These includes axle loads, configuration of axles, tire contact areas, the number of load repetitions, vehicle speed etc. Heavy vehicles, such as trucks, significantly influence pavement distresses and failure. As a primary variable of pavement design, accurate configuration of truck loading and investigation on the impact of heavy traffic on the pavement performance is an important issue.

Both two-dimensional (2D) and three-dimensional (3D) methods can be employed to capture the structural response of flexible pavements. Many researchers have investigated the response of flexible pavements and 2D programs have been developed specifically for flexible pavements such as MICHPAVE and ILLI-PAVE. However, 2D analysis cannot accommodate non-uniform tire contact pressure and multiple-wheel loads; 3D finite element models must be used to properly capture these effects.

Three-dimensional finite element analysis tools are increasingly viewed as the best approach to answering certain fundamental questions about pavement performance (Chen, et al), but the tedious processing and time required to accurately model pavement systems have hampered the use of these analyses. While two-dimensional axi-symmetric models can be utilized for a single wheel load analysis, such a constraint would lead to an inaccurate three-dimensional analysis, particularly for pavements subjected to multiple wheel loads and wander. Only 3D FE modeling was considered in this study to allow for several modifications that were judged essential to accurately simulate pavement responses to vehicular loading.

In this study, an approach being made to establish the proper tire configuration i.e. tire contact area and inflation pressure using the finite element software ABAQUS to analyze stress-strain behavior of flexible pavement regarding the application of finite element in design purpose. As stresses and strains are used more and more to predict pavement distresses, and thus the relative condition of the various layers in the pavement structure, the constitutive relationship of stress and strain in FEM is required to understand.

2.1 ABAQUS as Finite Element Software

ABAQUS, a commercial finite element modeling program, has been widely applied for pavement analysis. Chen et al did a comprehensive study of various pavement analysis programs and showed that the results from ABAQUS program were comparable to those from other programs. Zaghloul and White simulated the pavement responses under FWD loading for flexible pavements using three-dimensional dynamic analysis in ABAQUS.

ABAQUS provides many element types that are useful for pavement analysis. An infinite element model can be used to model the infinite boundary conditions in the horizontal and vertical directions in a pavement system. ABAQUS also includes many material models such
as linear elastic, viscoelastic, hypoelastic and elasto-plastic models. Finite element method calculates the values of stresses and strains by node to node lumping of loads. So, appropriate element selection and meshing is also very important.

2.1.1 Material Characterization
Assuming three layers of pavement- asphalt surface, granular base and subgrade. All pavement materials were assumed to respond linearly and elastically to the applied load as static load were applied in the linear perturbation step. Elastic properties (modulus of elasticity and Poisson’s ratio) were obtained from previous investigation (Zaghloul and White, 1993). Some random material properties were also given to understand the pavement response under different condition.

2.1.2 Model Dimensions and Element Type
Model dimensions were selected to reduce any edge effect errors, while keeping the elements’ sizes within acceptable limits (modeling constraints). The generated mesh was designed to give an optimal accuracy (small elements around the load and large elements away from it). To improve the rate of convergence, 8-node linear brick reduce integration elements (C3D8R) were used. All layers were simulated with the same shape to preserve the continuity of nodes between consecutive layers. More elements are used around the wheel loads where stresses and displacement gradients are higher.

2.1.3 Boundary and Contact Modeling
Displacement or rotational constraints were used to simulate the subgrade’s support of the pavement structure. These elements, which act as springs to the ground, provide a simple way of including the stiffness effects of the subgrade without fixation of nodes at the bottom of the model. Interaction properties between two adjacent layers were assumed as perfectly bonded so frictionless contact was given.

3. Evaluation of Stress-Strain Characteristics
Finite element software, ABAQUS, is used effectively in measuring horizontal tensile and vertical compressive strains under the application of static wheel load in the modeled flexible pavement structure. Though critical model dimension, appropriate element type, meshing strategy, boundary condition significantly affect the results using software; variation of strain value is observed for a specific modeled structure for different contact area, inflation pressure and axle load configuration. Element type and meshing strategy used in this study is shown in Fig. 1.
Only maximum principal strain contour is shown in Fig. 2. From the figure, it can be seen that lowest value strain is found at the top layer and maximum strain occurs within the subgrade material just under the wheel load application point. This can be easily justified because of the arrangement of successive weaker material from top to bottom of the pavement layer. Usually vertical strain component (compressive) is found to be maximum just beneath the top layer. Stress contour is not shown here because of less generation of stress for static load cases, especially for low wheel pressure (0.5-1.5 MPa). Only maximum stress value is taken for the comparison for various contact area or inflation pressure.

3.1 Analysis for Traffic Related Factors

Traffic related factors like axle load configuration, tire imprint area, tire inflation pressure, numbers of wheel load repetition have significant effect in the design of flexible pavement system. Stress-strain based analysis procedure is used in the finite element method to estimate those factors. Different loading conditions are selected to analyze pavement response. These represent the low, middle and high combinations of tire load and tire inflation pressure used for a given tire during the analysis. The low load high inflation pressure and the high load low inflation pressure combinations are not considered in this study as these conditions show
extreme deviations from tire manufacturer recommended tire load/tire inflation pressure guidelines.

3.1.1 Contact Area
To calculate damages per pass by the wheel load in the pavement, it is required to identify the proper contact area. Contact area may be circular, rectangular, ellipsoid or another (termed as actual here) imprint area of a rectangle and two semicircles. Contact areas for different tire imprint are specified in Table 1.

For the analysis and selection of the appropriate contact area, same tire pressure is applied for different imprint shape of equal contact area and thus the effect of maximum principal stresses and strains are measured. Tire contact dimension is selected from the suggested rules of PCA method, that is circular, rectangular or ellipsoid area which is equivalent to actual contact area and difference in stresses and strains are observed. To satisfy convergence criteria in finite element method, analyses is done for increasing amount of elements and thus observe the difference in results.

Table 1: Contact area for different tire imprint

<table>
<thead>
<tr>
<th>Imprint shape</th>
<th>Wheel pressure (MPa)</th>
<th>Contact area (sq. mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>0.67</td>
<td>60000</td>
</tr>
<tr>
<td>Rectangular</td>
<td>0.67</td>
<td>61575</td>
</tr>
<tr>
<td>Ellipse</td>
<td>0.67</td>
<td>60416</td>
</tr>
<tr>
<td>Actual</td>
<td>0.67</td>
<td>60318</td>
</tr>
</tbody>
</table>

Critical model dimension of roadway segment for the analysis is chosen as 10m by 5m to avoid the boundary effects. Material property and thickness of different layers are taken as Zaghloul and White (1993) applied previously in pavement application shown in Table 2.

Table 2: Material property used in contact area and pressure analysis

<table>
<thead>
<tr>
<th></th>
<th>Asphalt Surface</th>
<th>Base Layer</th>
<th>Subgrade Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>100</td>
<td>250</td>
<td>2000</td>
</tr>
<tr>
<td>Modulus of Elasticity (Mpa)</td>
<td>2175</td>
<td>415</td>
<td>52</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.35</td>
<td>0.4</td>
<td>0.45</td>
</tr>
</tbody>
</table>

From the stress and strain comparisons shown in Fig. 3 and 4, it can be noted that the actual tire imprint area has greater values for stress and strain than all other possible tire area. Also, increasing the number of elements increases the degree of accuracy.
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Figure 3: Stress variation for different contact area

Figure 4: Strain variation for different contact area
So, using circular, rectangular or ellipsoid areas instead of the actual tire imprint area are to be avoided if the actual condition for stresses and strains are to be taken into account accurately.

3.1.2 Tire pressure

Though uniform contact pressure throughout the contact area is assumed for previous study, it is not readily true. To investigate the effect of spatially varied tire pressure, it is assumed that two-thirds of the total wheel load is applied in the centre rectangular region which is approximately half of the total contact area (145mm*200mm = 29000 mm$^2$) and other load in two semicircle regions. Effect of stress and strain values are observed for different wheel loads. Model geometry and material properties are same as previous.

It is seen from Fig. 5, there is about 30% increase in stress due to varied contact pressure than constant pressure. Linear relationship exists in the figure indicates the static load application and linear analysis. But strain value does not vary significantly for spatially varied pressure (Fig. 6). So when strain is applied as design criteria, fatigue or permanent deformation for wheel load application, uniform contact pressure does not affect the result.

![Stress comparison](image1.png)  
**Figure 5:** Stress comparison for different tire inflation pressure

![Strain comparison](image2.png)
4. Conclusion

Application of the software ABAQUS for the particular design features, like traffic related factors, is quite reasonable applying in the analysis of pavement performance of present roadway and finding total traffic carrying capacity of the existing pavement. Thus this paper documents the preliminary research of traffic related factors in the design of flexible pavement under specific material properties, model geometries etc.

Based upon the results presented in this study, tire imprint area is needed to be rectangle with two semicircles at both sides. Circular, rectangular or ellipsoid tire contact area is not appropriate because they generate fewer amounts of stresses and strains for the equal area. Tire pressure is never being uniform throughout the imprint area. Varied test indicates that parabolic variation of tire pressure which is constant only within the center region of contact area. Implication of stress-strain behavior in the design phase of flexible pavement is quite massive work. This paper has included a very small part of it. The major limitation here is pavements are generally subjected to moving truck loads instead of static loads and material response is viscoelastic. Further study on the effect of moving loads and asphalt viscoelasticity is warranted. Again, stress, strain and deflection will be further implemented in pavement failure criterion, fatigue and permanent deformation and then be used in calculating ESAL for varying axle load condition. Sufficient governmental funding is needed to invest in laboratory based test environment to validate the software application and thus develop an economical design procedure based on finite element analysis.

5. References