

Use of a Three-Dimensional, Dynamic Finite Element Program for Analysis of Flexible Pavement

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Predominantly flexible pavement structural response to loads is predicted by using an elastic multilayer analysis. This type of analysis is based on the assumption that pavements are subjected to static loads and that paving and subgrade materials are linear elastic materials. In this paper, ABAQUS, a three-dimensional, dynamic finite element program (3D-DFEM), was used to analyze flexible pavements subjected to moving loads at various speeds. A number of material models were used to represent actual material characteristics such as viscoelasticity and elastoplasticity. The validity and then the application of 3D-DFEM to flexible pavement analysis were examined. Validation was accomplished by analysis of both static and dynamic cases. The static and dynamic verification studies indicated that 3D-DFEM can be used with confidence to predict actual pavement response from moving loads.

A predominantly flexible pavement structural response to loads is predicted by using an elastic multilayer analysis. This type of analysis is based on the assumption that pavements are loaded only statically (1), whereas in reality pavements are subjected to both static and moving loads. Also, this analysis assumes that paving and subgrade materials are linear or piecewise linear elastic materials. However, asphalt mixtures are viscoelastic materials, and clays exhibit plasticity. The inability of multilayer analysis to represent actual loading conditions and pavement materials is significant. This significance is reflected in differences between predicted and measured pavement response. The simplicity and speed of multilayer analysis have been used as justification for the relative results obtained. However, a three-dimensional, dynamic finite element method (3D-DFEM) is available and provides a more realistic analysis for predicting pavement response.

ABAQUS, a three-dimensional, dynamic finite element program (2), has the capability to simulate actual pavement loading conditions. A number of material models can be used to represent material characteristics such as elasticity, viscoelasticity, and plasticity.

The purpose of this paper is to examine the validity and then the application of 3D-DFEM to flexible pavement analysis. Validation was accomplished by analysis of both static and dynamic cases. First, because of industry acceptance, elastic multilayer analysis was used as a basis of comparison for the static case. Static loads were assumed to be applied on a pavement section with linear elastic material properties. The pavement response was predicted using 3D-DFEM and

an elastic multilayer analysis program, Bitumen Structures Analysis in Roads (BISAR) (3). It was found that the results obtained using 3D-DFEM and BISAR are highly correlated. Second, a nonlinear dynamic analysis was conducted of pavements in which actual pavement response had been measured under moving trucks. In a Canadian study (4), pavement response was measured for 14 pavement sections subjected to moving trucks of varying speeds. Selected pavement cross sections from this study were modeled with 3D-DFEM. Loads were applied to the modeled pavement sections at the actual field test speed. The predicted pavement response was found to agree with the measured pavement response. These static and dynamic verification studies showed that 3D-DFEM can be used with confidence to predict actual pavement response from moving loads. Using the 3D-DFEM nonlinear dynamic analysis capabilities, a sensitivity analysis was conducted. Factors ignored by elastic layer analysis were addressed, such as moving loads, system damping, and viscoelastic and plastic behavior of pavement and foundation materials.

FEATURES OF THE FINITE ELEMENT MODEL

Model Geometry

Conventional flexible pavements consist of layers, that is, surface, base, and subbase on a subgrade. At some depth the subgrade can be considered as a deep foundation. The deep foundation may be an extension of the subgrade soil or another soil type. In some cases the subgrade or deep foundation is bedrock.

The finite element mesh (FEM) dimensions have to be small enough to allow detailed analysis of the pavement section. However, small mesh dimensions increase the number of elements. As a result, memory and computational time increase. On the other hand, a coarse FEM will not allow detailed analysis. A compromise is to use a fine FEM for a detailed analysis and a coarse mesh for other analyses. An example of the mesh used in this study is shown in Figure 1. This FEM consists of two equally spaced meshes in the horizontal (xy) plane. A coarse mesh with a 22.2-in. spacing was used in both the transverse (x) and longitudinal (y) directions. In the region of the load path, finer mesh with a 4.44-in. spacing was used in the x -direction. Mesh dimensions in the vertical direction were selected to match the pavement layer thicknesses (i.e., surface, base, and subbase). The number of layers re-

quired to model the subgrade depends on the detail desired in predicting the vertical pavement response. In this study, the surface and base course were each modeled as a single layer, whereas the subgrade was modeled as a set of five layers. The FEM presented in Figure 1 has 5,670 nodes and 5,278 three-dimensional elements. Adhesion between layers was considered a function of friction and normal pressure on the layers (Mohr-Coulomb theory).

Boundary Conditions

Boundary conditions for the finite element model have a significant influence on the predicted response. Therefore, potential boundary conditions for pavements need to be considered.

Edges Parallel to Traffic Direction (Parallel to Y-Axis)

At the pavement edge, two forces exist between the pavement edge and the adjacent soil; vertical friction (*F*) and lateral, passive pressure (*P*). Boundary conditions representing these forces were included in the analysis.

Edges Perpendicular to Traffic Direction (Parallel to X-Direction)

The analysis model should represent adequate length to reduce any edge effect error. However, analysis of an extended

length increases the size of the problem and the analysis time. An evaluation of section length was conducted with lengths ranging from 200 to 1,400 in. For sections longer than 400 in., no significant effect on the pavement response was found. The length of various sections included in this study was 600 in., and the load was applied to the middle 200 in. only.

Pavement-Shoulder Modeling

Three conditions for the degree of continuity at the pavement-shoulder joint were considered:

- 1. No crack.
- 2. Narrow crack; pavement and shoulder are in contact with friction.
- 3. Wide initial crack (1 in.) with possible interaction because of deformation.

Material Properties

It is assumed that paving materials are linear elastic in multilayer analysis. In the 3D-DFEM analysis, paving materials were divided into three groups: asphalt mixtures, granular materials, and cohesive soils. The actual material behavior for each group was considered.

Asphalt mixtures were modeled as viscoelastic materials. This type of material is time and temperature dependent (*1*). The time-dependent properties were represented by instantaneous and long-term shear moduli (*5*). Instantaneous shear modulus was selected at a loading time of 0.1 sec, which is equivalent to a speed of 40 mph. Long-term shear modulus was selected at a loading time of 1.0 sec, which is equivalent to a speed of 1.5 mph. The temperature effect was considered through the shear modulus values. Figure 2*a* shows the effect of loading time and temperature on asphalt mixture stiffness.

Granular materials, which could consist of base course, subbase, and subgrade in some cases, were modeled using the Drucker-Prager model (*5,6*). This is an elastic-plastic model in which granular materials are assumed to behave as elastic materials for low stress levels. When the stress level reaches a certain yield stress, the material will start to behave as an elastic-plastic material. Figure 2*b* shows the assumed stress-strain curve for granular materials.

The Cam-Clay model (*5,7-9*) was used for clays. This model uses a strain rate decomposition in which the rate of deformation of the clay is decomposed additively into an elastic and a plastic part. Figure 2*c* shows the assumed soil response in pure compression.

Other material and layer characteristics required in the analysis include modulus of elasticity, Poisson's ratio, damping coefficient, and bulk density.

LOADING CYCLES

The 3D-DFEM analysis can be used to simulate truck loads moving at highway speeds. A truncated sawtooth load function is used at speeds less than 20 mph, whereas a step load function is used for speeds greater than 20 mph. Figure 3

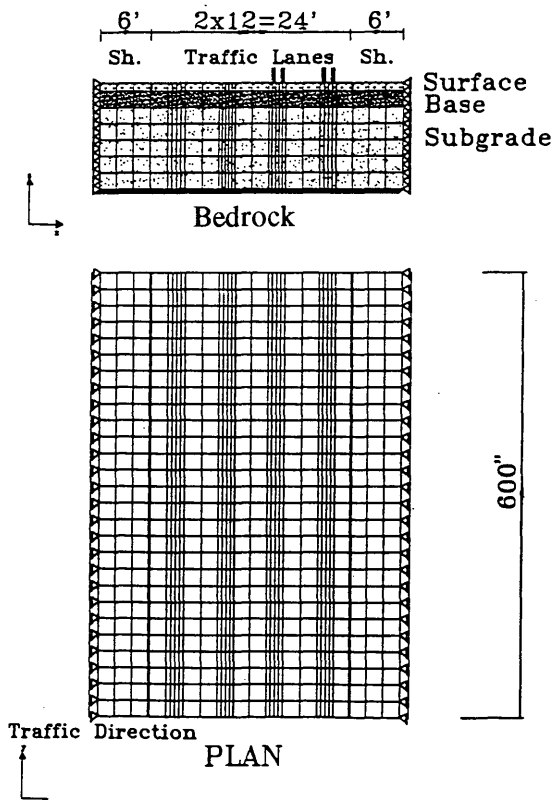


FIGURE 1 Finite element mesh.

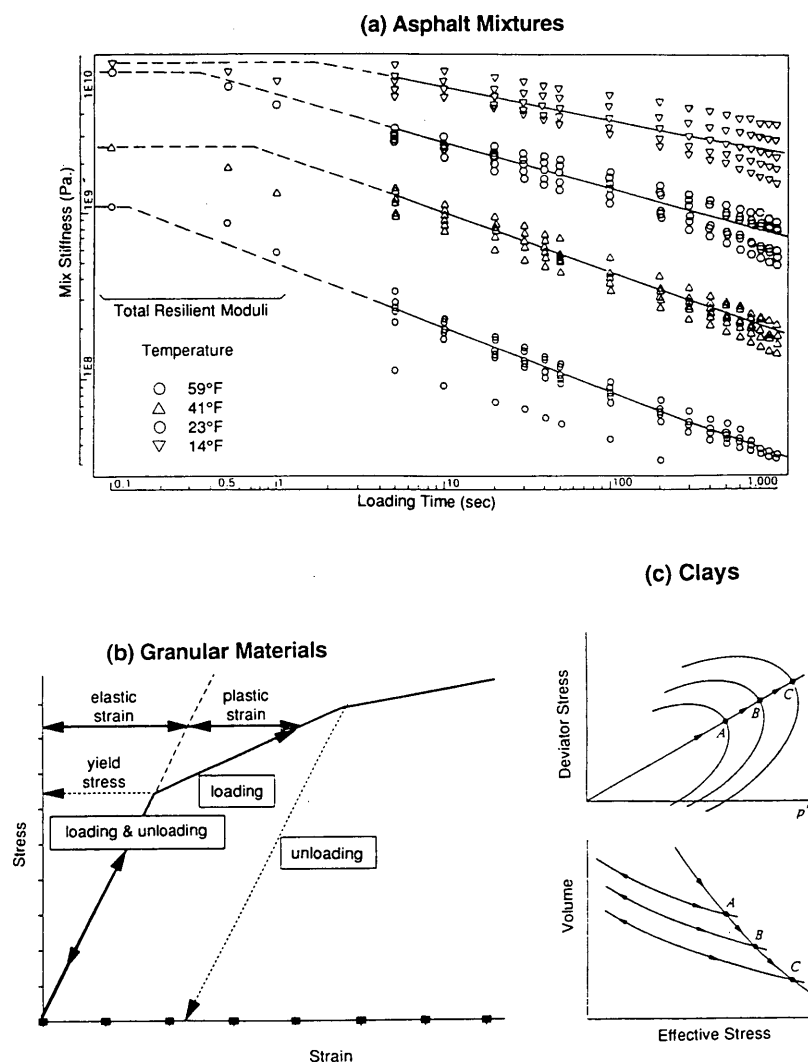


FIGURE 2 Material models.

shows the truncated sawtooth load cycle used in the analysis. The load cycle begins with a load magnitude equal to zero at time T_0 . After time T_0 , the load is increased linearly to a maximum value at time T_1 . The load magnitude remains constant between time T_1 and T_2 . After time T_2 , the load is decreased linearly to zero at time T_3 . The length of time from T_0 to T_1 , T_1 to T_2 , and T_2 to T_3 is a function of speed and the length of the contact area between the truck tire and pavement surface. The length of the contact area or tire print was calculated by assuming the area to be a combination of a central rectangle with semicircles at the ends, as shown in Figure 3 (I).

$$L = \left(\frac{A}{0.5226} \right)^{1/2}$$

where A is the contact area in square inches.

In the step function load cycle $T_0 = T_1$ and $T_2 = T_3$. Load cycle application in the 3D-DFEM analysis considers that no load is applied at a point (n) on a pavement before time T_0 . After T_0 the load cycle is applied at point n and to subsequent points at increments of time equal to the distance between the axles.

Times T_0, \dots, T_3 were calculated as follows:

$$T_i = j \frac{L}{V}$$

where

L = length of the tire print (in.);

V = speed (in./sec);

$i = 0, 1, 2$, and 3 , respectively; and

$j = 0.0, 0.3, 0.7$, and 1.0 , respectively (for $V < 20$ mph) and $0.0, 0.0, 1.0$ and 1.0 , respectively (for $V > 20$ mph).

In initial studies an 18-kip single axle with dual wheel was assumed.

FINITE ELEMENT MODEL VERIFICATION

Before general application, 3D-DFEM was verified in a two-step process. These two steps included evaluation of its ca-

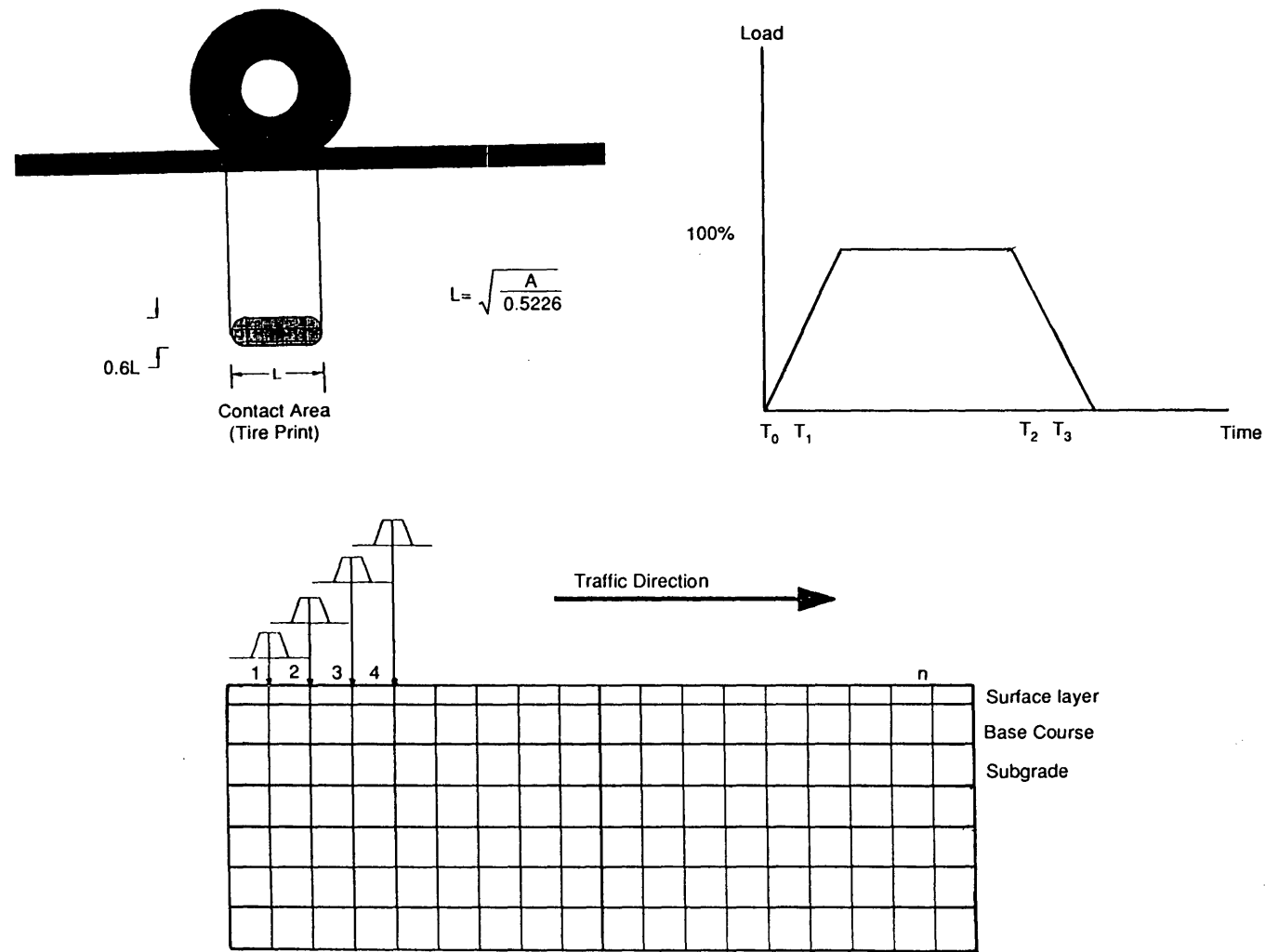


FIGURE 3 Assumed loading cycle.

pabilities to predict pavement response for both static and dynamic cases.

Static Analysis Verification

For the elastic static case, a design of the experiment was developed. Subsequently, analyses of sections with factor combinations satisfying the design of the experiment were conducted with both a layered elastic analysis (BISAR) and the 3D-DFEM analysis. In the latter case elastic material properties were used for the various layers as well as for static loading.

Three factors were included in the design of the experiment:

- Surface layer thickness (T_s) = 4 and 8 in.
- Base course thickness (T_b) = 10 and 20 in.
- Subgrade modulus of elasticity (E_{sg}) = 5,000 and 30,000 psi.

Eight different pavement cross sections were analyzed using the multilayer procedure and 3D-DFEM. Pavement deflec-

tion at various lateral distances (x) as well as at various depths (z) were predicated using BISAR and the 3D-DFEM for the eight pavement cross sections. A regression analysis of the results included three variables, deflection predicted using BISAR (DB), deflection predicted using ABAQUS (DF), and the cross-section number ($PTYPE$). Because the sections analyzed represent significantly different pavement sections, the section number was included in the analysis as a dummy variable. DB was considered the dependent variable, whereas the other two variables, DF and $PTYPE$, and their interaction, $DF*PTYPE$, were considered the independent variables. The interaction term, $DF*PTYPE$, was used to check whether the linear correlation between DB and DF depends on the range of pavement cross sections. From the regression analysis, a high linear correlation between DB and DF was found ($R^2 = 0.96$). Also, both variables DF and $PTYPE$ show a significant effect on DB . The interaction term, $DF*PTYPE$, shows an insignificant effect on DB , which means that this linear correlation is independent of pavement cross section, that is, this relationship can be generalized for the flexible pavement cross sections included in the analysis.

Dynamic Analysis Verification

A study was also conducted to evaluate the time-dependent dynamic analysis feature of 3D-DFEM. Since there is no standard dynamic analysis method for the dynamic case as there is for the static case, a decision was made to compare the predictions with the measured dynamic response of pavements due to moving loads.

A study in Canada (4) involved measuring horizontal tensile strain and surface deflection for asphalt pavements at 14 sites across Canada. Field measurements were made at three nominal speeds—6, 12, and 50 mph—for a number of load levels and load configurations. The structural numbers (SN) were estimated for the 14 sections. A total of 3 of the 14 sections with low, medium, and high values of SN were selected for analysis. These three sections are located in the Provinces of Quebec (Sections 3a and 4) and Alberta (Section 10). A finite element mesh was created for each site to match the pavement cross section given by the CanRoad report (4). Reasonable material properties were assumed for each layer on the basis of the material description given in the CanRoad report (4). Table 1a shows the assumed material properties for the three

sites. For the three selected sites, the surface deflections were predicted for two load levels of 9182 kg and 11 127 kg and for the low (6-mph), and high (50-mph) speeds. Table 1b shows the measured and predicted deflection values for the three sites. An analysis was made to check whether there was a linear correlation between the predicted and measured deflections. As can be seen from Figure 4, the deflections were found to be highly correlated ($R^2 = 99.9$ percent). This high correlation implies that 3D-DFEM can be used to predict the dynamic response of pavements subjected to moving loads.

SENSITIVITY ANALYSIS

After verification of the 3D-DFEM analysis, a sensitivity analysis was conducted to investigate the effect of various factors on pavement response. These factors were divided into two groups:

- Cross-section attributes:
 - Deep foundation type and location,
 - Shoulder width and pavement-shoulder joint, and
 - Asphalt mixture properties.

TABLE 1 Dynamic Analysis Verification

(a) Assumed Material Properties

Material	Layer	Site # 3a	Site # 4	Site # 10
Modulus of Elasticity (ksi)	Surface	200	150	200
G-Ratio		0.75	0.75	0.75
Bulk Density (pcf)		150	150	150
Poisson's Ratio		0.3	0.3	0.3
Modulus of Elasticity (ksi) [^]	Base	50	30	20
Bulk Density (pcf)		140	140	140
Angle of Internal Friction		38	38	38
Cohesion (pcf)		0	0	0
Poisson's Ratio		0.35	0.35	0.35
Modulus of Elasticity (ksi) [^]	Subbase	15	7.5	no subbase
Bulk Density (pcf)		130	130	
Angle of Internal Friction		35	33	
Cohesion (pcf)		0	0	
Poisson's Ratio		0.35	0.35	
Modulus of Elasticity (ksi) [^]	Subgrade	10	3	3
Bulk Density (pcf)		130	125	125
Angle of Internal Friction		35	0	0
Cohesion (pcf)		0	750	750
Poisson's Ratio		0.35	0.4	0.4

[^]Based on E = 1500[^] CBR

(b) Comparison Between Measured and Predicted Pavement Surface Deflections

CanRoad Section Number [^]	Load (kg)	Speed (km/h)	Measured Deflection (mils)	Predicted Deflection (mils)
3A	9,182	6.0	20.91	20.97
3A	9,182	50.0	19.29	20.3
3A	11,127	6.0	19.49	18.1
3A	11,127	50.0	17.91	17.31
10	9,182	6.0	29.88	30.16
10	9,182	50.0	24.8	23.56
10	11,127	6.0	25.2	24.9
10	11,127	50.0	22.0	23.4
4	9,182	6.0	52.0	51.61
4	9,182	50.0	46.81	45.99
4	11,127	6.0	44.8	42.59
4	11,127	50.0	40.5	37.95

[^]See Canroad Report (4).

- Load attributes:
 - Load repetitions and
 - Speed.

Material and Layer Characteristics

The characteristics of the basic cross section considered earlier and in the subsequent sensitivity study are indicated in Table 2 (5,10–13). The base course and subgrade moduli of elasticity were taken as 1,500 times the California bearing ratio. The asphalt layer properties used in this example are based on the annual average temperature in Indiana (57°F, approximately). These properties are used in the balance of the sensitivity analysis unless noted.

Cross-Section Attributes

Effect of Deep Foundation Type

Pavement response is affected by the deep foundation type and condition. An analysis was conducted to investigate the effect of deep foundation type on pavement response predicted by the 3D-DFEM analysis. The pavement section was analyzed with each of the following deep foundations:

1. Shallow bedrock, starts at 64 in. below the pavement surface.
2. Shallow, soft to medium clay layer (cohesion = 500 psf), starts at 64 in. below the pavement surface.

Dependent Variable: MEASURED DEFLECTION

R-Square	C.V.	Root MSE	DM Mean
0.998691	4.054384	1.2284444	30.299167

Parameter	Estimate	T for H0: Parameter=0	Pr > T	Std Error of Estimate
DF	1.020945219	91.60	0.0001	0.01114537

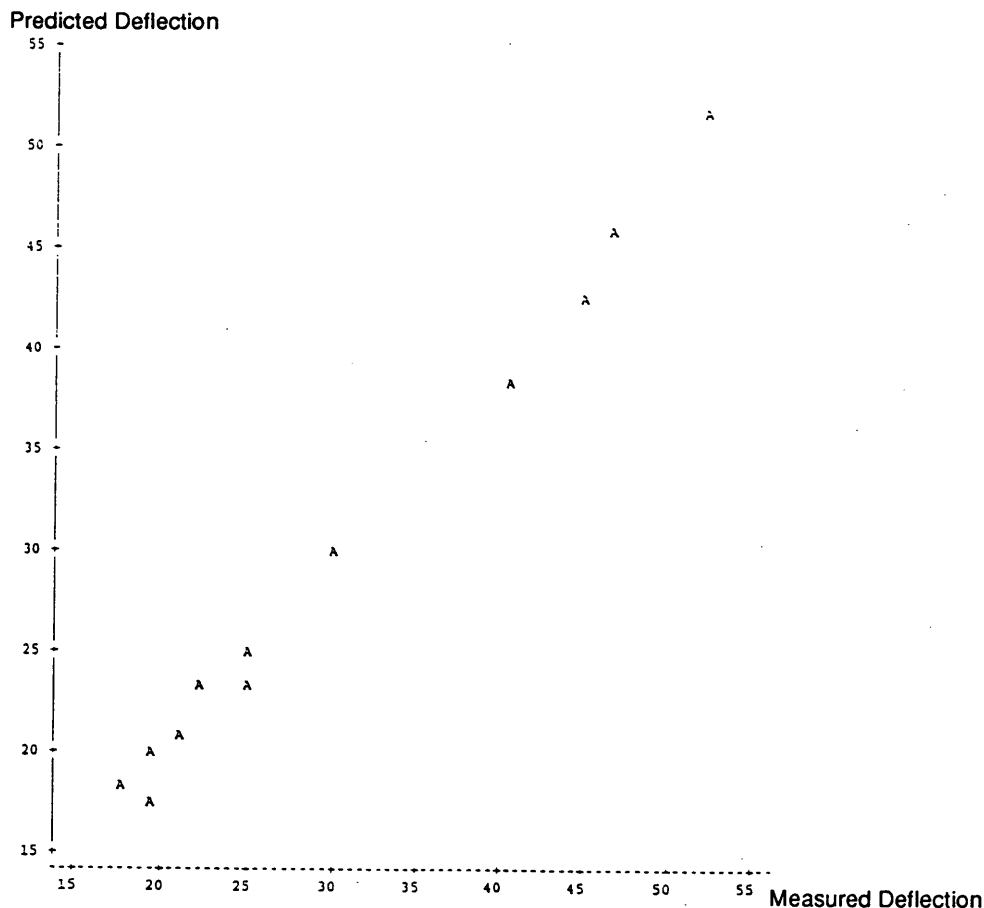


FIGURE 4 Dynamic analysis verification.

TABLE 2 Characteristics of Basic Cross Section

Characteristic	Value
Asphalt concrete surface layer	
Thickness	4 in.
Modulus of elasticity	600,000 psi
Poisson's ratio	0.3
G-ratio	0.8
Damping coefficient	0.05
Bulk density	150 pcf
Granular base course	
Thickness	10 in.
Modulus of elasticity	60,000 psi
Poisson's ratio	0.3
Damping coefficient	0.05
Bulk density	140 pcf
Angle of internal friction	38
Cohesion	0
Sandy subgrade	
Modulus of elasticity	30,000 psi
Poisson's ratio	0.3
Damping coefficient	0.05
Bulk density	125 pcf
Angle of internal friction	30
Cohesion	0

Note: $G\text{-ratio} = 1 - \frac{\text{Long term shear modulus}}{\text{Instantaneous shear modulus}}$

3. Shallow, stiff clay layer (cohesion = 1,000 psf), starts at 64 in. below the pavement surface.

4. Deep bedrock, starts at 164 in. below the pavement surface.

The subgrade above these deep foundations was assumed to be sandy silt subgrade. Load was applied as an 18-kip single-axle load moving at a speed of 1.75 mph. Figure 5 shows the variation in surface deformation with lateral distance (x). The cross section with soft to medium clay foundation showed a higher deflection than that of the other cross sections. Therefore, it is important to consider the deep foundation type in pavement design and evaluation.

Effect of Shoulder Width and Pavement-Shoulder Joint

Shoulders provide lateral support to pavement structures (14). Multilayer elastic analysis cannot be used to examine the questions of shoulder versus no shoulder and degree of disconti-

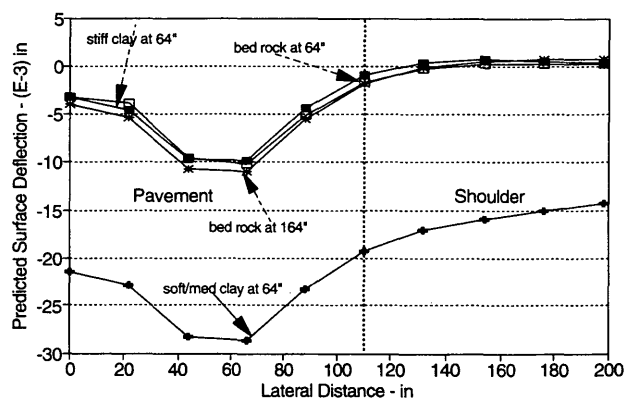


FIGURE 5 Effect of deep foundation type on pavement deflection.

nity at the pavement-shoulder joint. 3D-DFEM readily accounts for these conditions. An evaluation was conducted for two shoulder conditions. One analysis included a cross section with an 8-ft shoulder. The other analysis was for the condition with no shoulder. The shoulder structure for the 8-ft width was assumed to be the same as the traffic lane of the basic section. Load was applied as an 18-kip single-axle load, 1 ESAL, moving at a speed of 1.75 mph. The outer wheel centerline of this load was positioned approximately 3 ft from the outer edge of the traffic lane. As shown in Figure 6 (top), the surface deflection of the no-shoulder cross section is 33 percent higher than that of the section with the 8-ft shoulder.

Effect of Pavement-Shoulder Joint

To study the effect of pavement-shoulder joint conditions on pavement response, three pavement cross sections were analyzed. The three cross sections assumed 8-ft shoulders with the same structure as the traffic lanes. The first condition analyzed was a wide longitudinal crack extending to the base course. Even with a wide crack there is the possibility of interaction between the pavement and shoulder with significant deflection. Friction will develop with interaction. The second condition analyzed was a narrow crack with friction assumed. The friction force at the pavement and shoulder interface is a function of normal pressure and the coefficient of friction. Complete continuity at the interface was assumed for the third condition. As before, load was applied as an 18-kip single-axle load moving at a speed of 1.75 mph. The centerline of the outer wheelpath was positioned approxi-

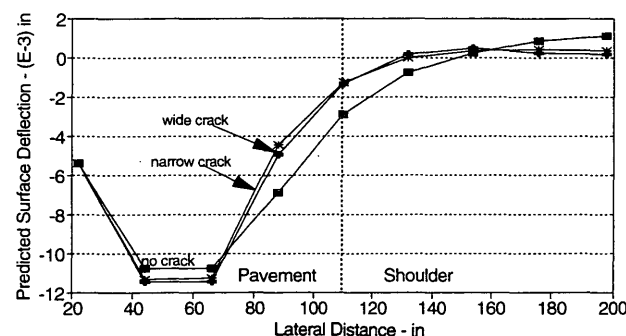
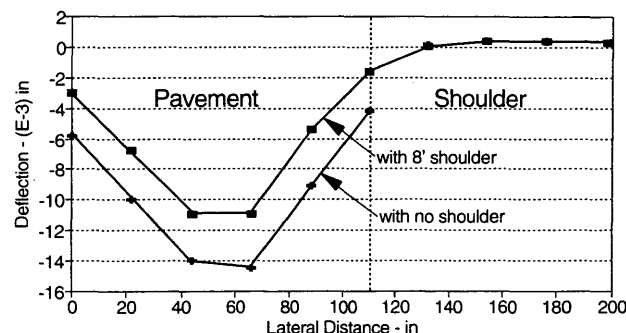


FIGURE 6 Effect of shoulders on pavement response: top, effect of shoulder width; bottom, effect of pavement-shoulder crack.

mately 3 ft from the pavement-shoulder joint. Deflection basins for the three cross sections are presented in Figure 6 (bottom). A greater deflection occurs as a result of the wide crack. The deflection basin also has a different slope at the crack. In general, the deflection basin shape for the narrow crack is similar to that for the wide crack but with lower maximum deflection. Deflection for the case with no crack is lower than for conditions with cracks. However, because of the moment transfer, the deflection at the shoulder is higher than those of the cross sections with cracks. The difference in maximum surface deflection for the three conditions was found to be small because in all three the shoulder provides lateral support to the pavement. This shows the importance of shoulders, even earth shoulders.

Effect of Asphalt Mixture Properties

The asphalt layer was modeled in this analysis as a viscoelastic material. Elastic as well as viscoelastic properties are required to define asphalt mixtures. Loading time and temperature are two significant parameters for this type of material.

To study the temperature effect on asphalt mixture stiffness and pavement response, two analyses were made of the basic pavement structure. One analysis was made with asphalt layer properties measured at 59°F (approximate annual average temperature in Indiana), whereas the other analysis was made with the asphalt layer properties at 120°F (12,15). The vertical plastic compression strain at the pavement surface for the two analyses is presented in Figure 7, in which it is indicated that as the temperature increases the asphalt mixture becomes less viscous and hence the plastic strain increases.

Load Attributes

Effect of Load Repetitions

3D-DFEM predicts the effects of load repetitions on the pavement plastic and elastic response. When a pavement is subjected to a moving load, a horizontal tensile strain develops at the bottom of the asphalt layer. This strain is associated

with fatigue cracking. The horizontal tensile strain has two components—elastic and plastic. The elastic component of this strain is fully recovered after the load is released, whereas the plastic component remains. The basic cross section was analyzed for effect of repetition of an 18-kip single-axle load. Figure 8 shows the effect of these load repetitions on the horizontal tensile strain at the bottom of the asphalt layer, in which it is indicated that, after the first loading cycle, the elastic strain is almost constant. However, the plastic strain accumulates with each loading cycle.

Effect of Moving Load Speed

Previous studies (1b) have shown that static loads are more damaging to pavements than moving loads. A comparison was made of the effect on the pavement response of trucks moving at a creep speed (1.75 mph), a slow speed (10 mph), and a relatively high speed (30 mph). These results are presented in Figure 9, in which it is indicated that the pavement deflection at 10 mph is significantly less than that at 1.75 mph. However, the difference between the pavement deflection at speeds of 10 mph and 30 mph is relatively small. It should be noted that multilayer analysis cannot account for the effect of speed on pavement response.

RUT DEPTH PREDICTION

3D-DFEM has the capability to predict pavement rutting. In this analysis rut depth is defined as the total permanent deformation that accumulates at the pavement surface. This total deformation is the sum of the permanent deformation of various pavement layers, including the subgrade.

Granular subgrades and untreated granular layers can be considered elastoplastic materials. The behavior of these types of material depends on the imposed stress level. When these materials are subjected to stress higher than their yield stress, elastic as well as permanent plastic deformation will occur. The permanent plastic deformation accumulates as pavement rutting.

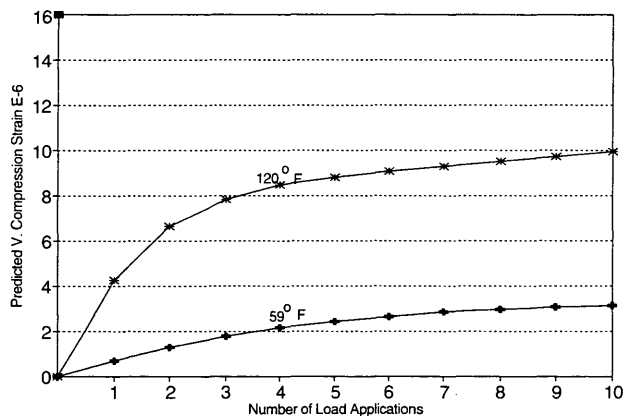


FIGURE 7 Effect of temperature on vertical plastic compression strain.

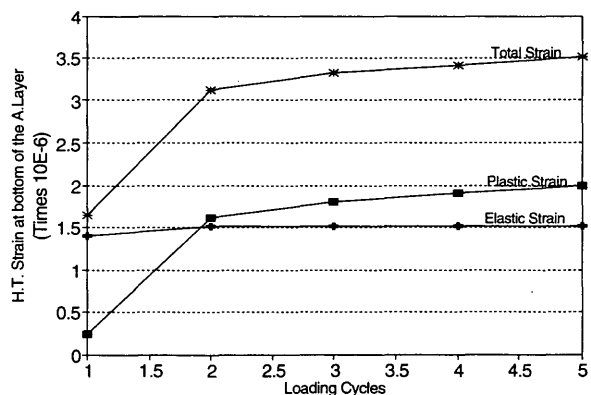


FIGURE 8 Effect of load repetitions on horizontal tensile strain.

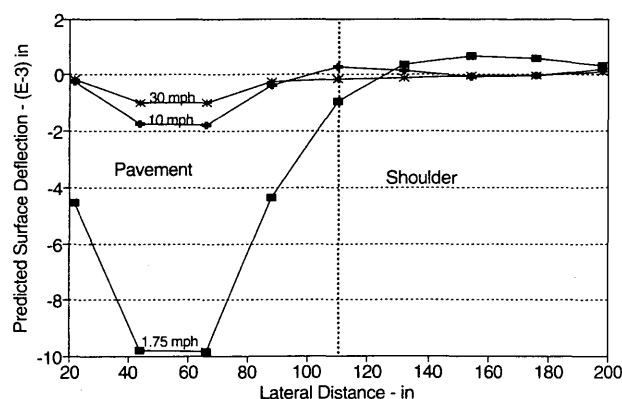


FIGURE 9 Effect of speed on pavement deflection.

Asphalt mixtures are viscoelastic materials. Viscoelastic material response is more complex than that of elastoplastic materials. The behavior depends not only on the stress level, but also on factors such as temperature, rate of loading, and loading time.

Flexible pavement rutting was predicted for two single-axle loads with dual wheels (18-kip and 58-kip). These loads were applied to the basic pavement section at a speed of 1.75 mph. Results are shown in Figure 10. The predicted rut depth of the 58-kip load was found to be approximately 100 times higher than that of the 18-kip load. To show why the 58-kip load caused this severe rutting, the permanent deformation of each layer was plotted for both loads and presented in Figure 11. Permanent deformation for the 18-kip load developed primarily in the asphalt layer, whereas 85 percent of the permanent deformation for the 58-kip axle load developed in the subgrade layer. This occurred because the 58-kip axle load subjected the subgrade to a stress level higher than its yield stress. Permanent deformation in the base course and asphalt surface as a result of the 58-kip axle load was about 10 and 5 percent of the total permanent deformation, respectively. A few passes of such heavy loads can cause considerable pavement rutting.

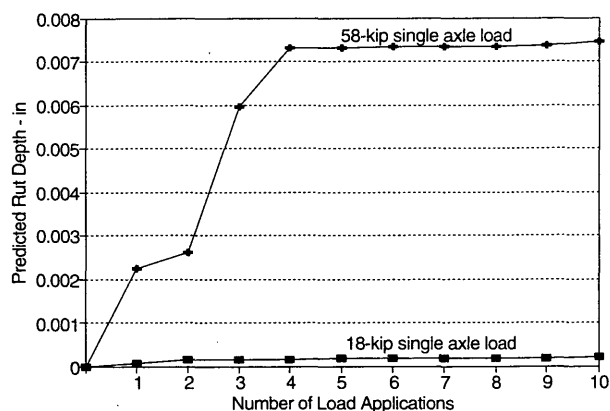


FIGURE 10 Effect of axle loads on pavement rutting.

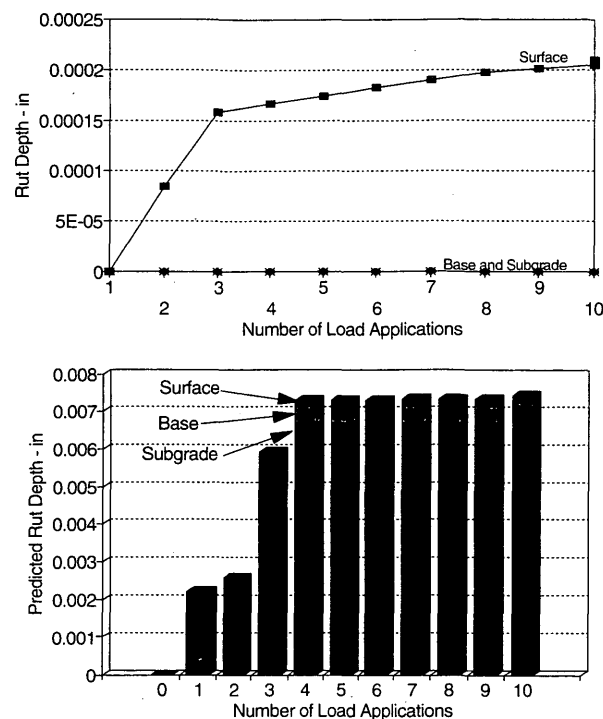


FIGURE 11 Predicted pavement rutting: top, 18-kip single-axle load; bottom, 58-kip single-axle load.

SUMMARY AND CONCLUSIONS

A truck moving over a pavement creates a load pulse that is transmitted through the pavement layers. The magnitude of the load pulse varies with time. The pavement layers respond differently to this load pulse, depending on the material characteristics of each layer. In a multilayer elastic analysis, the load is assumed to be a static load and the materials of different layers, including subgrade, are assumed to be linear elastic materials, even asphalt mixtures. The difference in the multilayer elastic analysis assumptions and the actual loading conditions and material characteristics leads to an inaccurate prediction of pavement response.

In this paper a three-dimensional, dynamic finite element model was used to analyze flexible pavements. 3D-DFEM has the capability to simulate actual truck loads moving at various speeds and can include linear and nonlinear material properties. Three material models were used to model various paving materials and subgrades. The Drucker-Prager model was used to model granular and silty materials, whereas the Cam-Clay model was used for clayey soils. Asphalt mixtures were modeled as viscoelastic materials. 3D-DFEM has the capability to predict both elastic and plastic pavement response. This capability helps to predict and explain pavement response under various loading conditions and for different material characteristics.

3D-DFEM was verified by comparing its predictions with a multilayer elastic analysis, assuming static loads and linear elastic material properties. A high linear correlation was found between the results obtained by 3D-DFEM and those obtained by the multilayer elastic analysis. To verify the dynamic, non-

linear analysis capabilities of 3D-DFEM, the 3D-DFEM predictions were compared with actual pavement deflection measurements. It was found that with a 99 percent confidence level, there is no difference between the predicted and measured deflections.

A sensitivity analysis was conducted using 3D-DFEM to study the effect of cross-section parameters and load parameters on pavement response. It was found that the moving load speed has a significant effect on elastic and plastic pavement response. The confinement effect of shoulders and degree of continuity at the pavement-shoulder joint were found to reduce pavement deflection. Temperature, loading time, and rate of loading were found to have a significant effect on pavement response. Loads that generate stresses higher than yield stresses will increase rutting significantly.

The effect of various load attributes, axle load and spacing, number of axles and number of wheels, as well as cross-section attributes, subgrade type, various material properties, and deep foundation type, was investigated and found to be significant to pavement response.

ACKNOWLEDGMENT

The research presented in this paper is part of a study sponsored by the Indiana Department of Transportation and FHWA.

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Publication of this paper sponsored by Committee on Flexible Pavement Design.