Finite Element Simulation of Pavement Discontinuities and Dynamic Load Response

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Assumption of a linear elastic system under static loading is questionable for structural response analysis of pavement-subgrade systems under dynamic nondestructive testing and moving wheel loads, especially if a deteriorated pavement is under study. Presented are the results of a parametric study using the three-dimensional finite element ABAQUS code; it investigates the effects of pavement discontinuities and dynamic analysis on the surface deflection response of a pavement-subgrade model under a standard falling-weight deflectometer (FWD) load. An optimum three-dimensional pavement subgrade model of a 18.3-m (60-ft) pavement length was established with a fixed boundary at the bottom and roller supports on the sides. ABAQUS static deflections are in good agreement with the static deflections calculated from the traditional elastic layer analysis for an uncracked pavement. The ABAQUS dynamic response using the backcalculated nonlinear moduli compares reasonably with the measured FWD deflections on an asphalt pavement site. The ABAQUS special-purpose gap elements are used to simulate longitudinal and transverse cracks in the surface layer. Dynamic deflections are 17 percent higher for a pavement with longitudinal cracks as compared with an uncracked pavement.

The current practice of using layered linear elastic theory for pavement-subgrade response analysis under static loading is a rational approach compared with older empirical pavement design methods, and the approach works reasonably well if a pavement-subgrade system behaves as a linear elastic system (*1*). However, the predicted linear elastic response can differ significantly from measured deflections under dynamic loading if the pavement-subgrade system has deteriorated, as is indicated by cracking and other pavement distresses, and if nonlinear behavior is expected from the unbound granular pavement layers and subgrade.

The results of finite element simulation of pavement discontinuities and dynamic loading are presented and selected results are compared with the measured deflection data.

BACKGROUND

Traditional Static Analysis of Pavement-Subgrade System

Pavement deflection response traditionally has been analyzed using the multilayered linear elastic model under static load (*1*) to calculate the in situ Young's modulus of elasticity for each layer in the pavement-subgrade system. In the layered linear elastic model of a pavement (Figure 1), each layer can be characterized by its Young's modulus of elasticity, E, and Poisson's ratio, μ.

Reasonable values of the Poisson's ratio can be assumed for typical pavement materials; these generally fall within a narrow range. Then assuming a semiinfinite subgrade, unique values of surface deflections can be predicted theoretically at specified distances from the load. Pavement nondestructive testing (NDT) and evaluation is performed by measuring surface deflections under a known NDT dynamic load. The backcalculation procedure involves an iterative application of the multilayered elastic theory to calculate the in situ modulus of each pavement layer. Surface deflections are predicted using assumed values of the modulus and Poisson's ratio of the pavement layers. Calculated surface deflections are matched with the measured deflections until the percentage of error is reduced to the lowest value (*1,2*). The test load is simulated by an equivalent static load, and the following assumptions are made:

- The existing pavement is considered to be a multilayered linear elastic system. Therefore, the principle of superposition is valid for calculating the response related to more than one load (e.g., for Dynaflect and design wheel loads).
- The peak dynamic force of the FWD is assumed to be equal to a pseudostatic load uniformly distributed on a circular area represented by the FWD loading plate.
- Gravity stresses are neglected.
- Effects of static trailer weight on the response of the pavement-subgrade system also are ignored. Considering the light

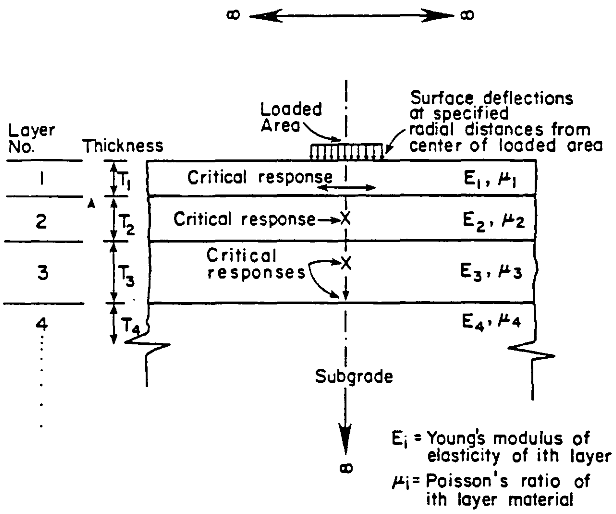

FIGURE 1 Linear elastic system.

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static weights of these trailers and the measurement of only dynamic deflections, this is not an unreasonable assumption.

- The subgrade is characterized by an average modulus value. Whereas subgrade stiffness may vary with depth, below 20 to 30 ft, stresses and strains resulting from the test load are very small, and design procedures require only a single value for the Young's modulus of elasticity of the subgrade.
- Deflections are measured at locations away from the pavement edges and discontinuities such as cracks and joints.

If these assumptions are true, the linear elastic response of the pavement will be reasonable in the absence of pavement discontinuities and strongly nonlinear materials. However, the assumptions clearly are violated if a pavement has deteriorated or if granulary layers and subgrade exhibit nonlinear behavior; such conditions lead to adverse effects of dynamic loading.

Pavement Discontinuities

Typical discontinuities in asphalt and portland cement concrete pavements are presented in Figure 2. Discontinuities appear in asphalt pavements as longitudinal, transverse, and alligator cracks; potholes; and disintegration. Cracks are caused by fatigue or load repetitions, by environmental factors, or by the interaction of the two. Cracks, joints, and voids under concrete pavements caused by pumping and erosion of subbase and base materials are additional examples of pavement discontinuities that significantly affect pavement deflection response.

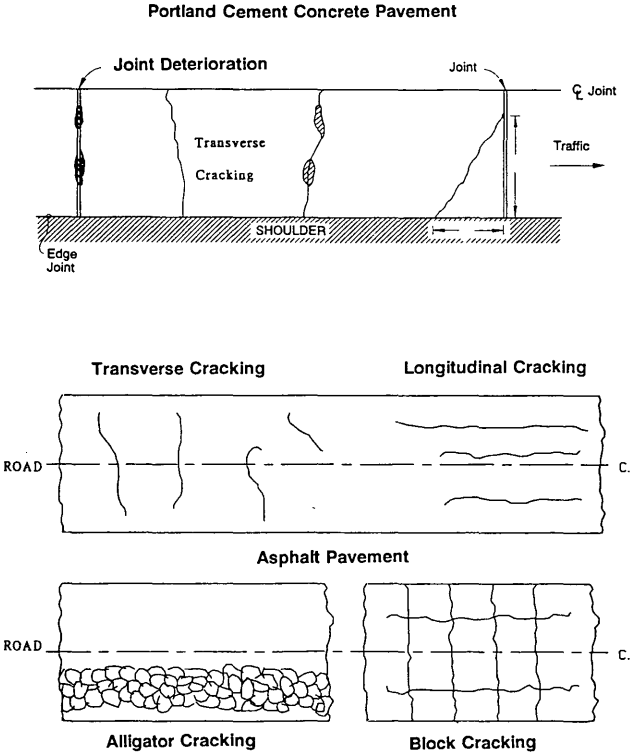

FIGURE 2 Typical pavement discontinuities.

Finite Element Analysis Approach

The traditional approach of pavement structural analysis is based on static linear elastic formulation with infinite dimensions in the horizontal plane and semiinfinite subgrade; however, it does not allow analysis of dynamic loads and discontinuities. In contrast, the finite element method analyzes pavements by considering finite dimensions of physical pavement structure. Concrete pavement joints and voids underneath the pavement have been modeled by the SLAB49 discrete element program (*3*). More recently, finite element models have been developed specially for pavement analysis, for example, ILLIPAVE for flexible pavements and ILLISLAB for rigid pavements (*4,5*). These models have been used for static load analysis.

Three-dimensional finite element codes (for example, ABAQUS) are available for comprehensive pavement structural response analysis that considers static and dynamic loads (impulse, steady-state vibratory force, and moving wheel load), linear elastic as well as nonlinear elastic and viscoelastic material constitutive models, and crack simulation models (*6,7*). Zaghloul and White (*8*) have successfully used ABAQUS for dynamic analysis of uncracked flexible pavements.

THREE-DIMENSIONAL FINITE ELEMENT SIMULATION

Basic Principles

The finite element method allows evaluation of the state of stresses and strains in a continuum medium by transforming the continuum medium into a number of finite elements. The three-dimensional finite elements must be interconnected at their common borders. Polynomial functions are used to interpolate the displacement field in order to obtain the stiffness matrix of each element. Using the stiffness matrix of each element, it is possible to assemble the global stiffness matrix as well as the global mass matrix for the complete model. Dynamic loads are considered, and displacements (dynamic deflections) are calculated using the appropriate routines and solving the dynamic governing equations. Finally, strains and stresses at each node of the elements are calculated.

ABAQUS Finite Element Code

ABAQUS software (*6*) is a comprehensive finite element program used to solve two- or three-dimensional problems under static, harmonic, transient dynamic loading, and thermal gradient conditions. Layer material can be modeled as linear elastic, nonlinear elastic, viscoelastic, and modified elastic (allowing no tension layers). The program can analyze cracks, voids, and the effects of water penetration in cracks. Simulation of the above parameters leads to a better understanding of pavement performance and estimation of loss of support over the pavement's life.

Optimization of Pavement-Subgrade Model Parameters

A three-dimensional finite element model was developed in order to optimize the size and boundary conditions of a pavement-subgrade structure. The model was formed with different lengths, widths, and subgrade depths as well as different boundary conditions. After analysis of the above parameters, the optimum dimensions and boundary conditions were established by carrying out the following analyses:

- Optimum subgrade thickness was investigated by studying the effect of different depths on surface deflections, and it was found that 12.20 m (40 ft) of subgrade depth simulates a semi-infinite subgrade.
- Nodes at the bottom of the model were fixed and a study was made with free, fixed, and roller boundary conditions of nodes in the sides of the model. It was found that the best simulation response is obtained by using rollers in the lateral sides of the model.
- Optimum subgrade width was found by studying the lateral extent of the subgrade below the pavement. The optimum dimensions are 11 m (36 ft) from the right (outside) edge and 8.3 m (27.3 ft) from the left (inside) edge of the pavement. The total width of the subgrade is 26.6 m (87.3 ft).
- To determine the optimum pavement length, lengths varying from 12.2 m (40 ft) to 73.2 m (240 ft) were studied; it was found that the optimum length is 18.3 m (60 ft).
- Shoulders (with the same material properties as the granular base layer) were added in the model. Shoulders were considered discontinuous along the pavement edges and gap elements were used, as described later. The outside shoulder is 2.4 m (8 ft), and the inside shoulder is 1.2 m (4 ft). Maximum deflection under the FWD load for the pavement with shoulders decreased by 1 percent. Discontinuous shoulders were subjected to further analysis, as reported in this paper.

ABAQUS Finite Element Model for Uncracked Pavements

The optimized pavement-subgrade model's boundary conditions were as follows: fixed at the bottom with a roller supporting the lateral sides. The pavement was modeled as a three-layer elastic system. Material properties for each layer used in the analysis are provided in Table 1. The asphalt surface layer, base layer, and subgrade are modeled as linear elastic materials.

Falling-weight deflectometer (FWD) loading is considered in the analysis. The center of the load is located at a distance of 0.91 m (3 ft) from the edge of the outside shoulder and along the center line of the pavement length.

Static Analysis

For the static analysis, the FWD load is taken as 40 kN (9,000 lbf) distributed on an area of 705.5 cm^2 (109.4 in.^{2}). Table 1 shows thickness and material properties for a flexible pavement structure used in the study. The Young's modulus of elasticity for each pavement layer and the subgrade were backcalculated from measured deflection data using the FPEDD1 program (*1*). Deflections were calculated using BISAR layered elastic static analysis and ABAQUS. Comparisons indicate a difference of 1 percent between the results of the two programs. The ABAQUS maximum static deflection was 998 μm (39.3 mils), which is in good agreement with the 985 μm (38.8 mils) calculated by the multilayer linear elastic program for a semiinfinite subgrade. That benchmark comparison establishes the adequacy of the geometry, mesh, and boundary conditions of the finite element model.

Dynamic Analysis

Dynamic analysis was performed using the ABAQUS IMPLICIT and EXPLICIT (*6,7*) approaches. The basic differences between the two approaches is that the IMPLICIT method computes the deflections at any time t by solving a set of nonlinear equations to determine the deflections at time $t - 1$. The EXPLICIT method, however, computes the deflections at any time t by adding to the deflection at time $t - 1$ the increment in deflections between time t and $t - 1$ computed by double integration of the acceleration obtained from dynamic equations at that degree of freedom. A comparison of the results indicates that the deflections obtained using IMPLICIT are closer to the static deflections and higher than the deflections obtained using EXPLICIT. Moreover, IMPLICIT generally converges better than does EXPLICIT. Therefore, the IMPLICIT method has been used for further dynamic analyses. Using the 18.3-m (60-ft) pavement model with discontinuous shoulders, the maximum deflection computed by IMPLICIT dynamic analysis was 817 μm (32.2 mils), which is 18 percent less than the corresponding ABAQUS static analysis.

TABLE 1 Pavement Subgrade Material Properties Used in Finite Element Analyses

Layer	Thickness mm	(inches)	Poisson's Ratio	Young's Modulus kPa	(psi)
AC Surface	114	(4.5)	0.35	2,928,250	(425,000)
Granular Base	152	(6.0)	0.45	199,810	(29,000)
Subgrade	12,192	(480.0)	0.45	34,450	(5,000)

Nonlinear Elastic Analysis and Field Validation

ABAQUS can be used with a variety of nonlinear material models for any layer. The current research study focuses on optimization of a three-dimensional pavement-subgrade model under dynamic loading by restricting to linear elastic material behavior for all layers. However, a preliminary study was undertaken to compare the measured FWD deflection response with the ABAQUS response and the nonlinear material behavior of the granular base and subgrade. Table 2 shows the backcalculated pavement moduli from the FWD deflection data and the nonlinear backcalculated moduli from the Dynaflect deflection data taken from a previous FHWA study (*9*). A measured FWD maximum deflection of 518 μm (20.4 mils) is reported for the selected test location.

The ABAQUS maximum static deflection under a simulated FWD load is 459 μm (18.1 mils) for the pavement-subgrade model analyzed with the FWD linear backcalculated moduli as compared with the 510-μm (20.1-mil) maximum static deflection calculated from the multilayered elastic analysis for a semiinfinite subgrade. The ABAQUS maximum static deflection is 873 μm (34.35 mils) for the pavement-subgrade model analyzed with the Dynaflect nonlinear backcalculated moduli. It is expected that the ABAQUS maximum dynamic deflection under the standard FWD load will be less than the corresponding static deflection for the same pavement structure and material properties, as was discussed earlier.

The ABAQUS maximum deflection under the simulated FWD load and nonlinear backcalculated moduli is 585 μm (23.3 mils). For the FWD linear backcalculated moduli, the ABAQUS maximum dynamic deflection is 331 μm (13.2 mils). Figure 3 illustrates the ABAQUS dynamic deflection bowl under the simulated FWD load, linear, and nonlinear backcalculated moduli, as well as the measured FWD deflections. The measured deflections agree more closely with deflections calculated from the nonlinear moduli, which leads to the conclusion that nonlinear behavior of granular layers and subgrade also can contribute significantly to the pavement structural response analysis.

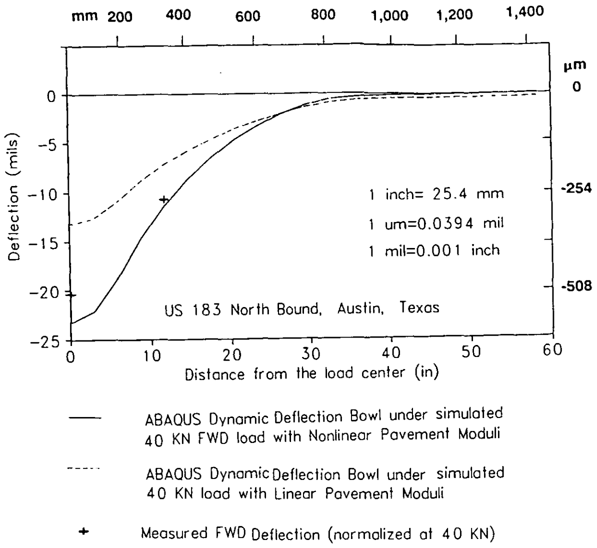

FIGURE 3 Comparison of ABAQUS dynamic deflection bowl with measured FWD deflections.

MODELING OF CRACKS

Longitudinal, transverse, alligator, and other types of cracks present critical pavement discontinuities in asphalt-surfaced pavements. Longitudinal and transverse cracks, joints, and voids beneath the concrete surface layer are the most critical discontinuities in portland cement concrete pavements. The structural response of a cracked pavement can be significantly different from that of an uncracked pavement. ABAQUS static and dynamic analyses were made to study the effect of cracks on pavement surface deflections.

Behavior of cracks in the pavement can be simulated using appropriate meshing and special-purpose elements. The present

TABLE 2 Pavement Structure and Backcalculated Young's Moduli from FHWA Study (*9*)

Layer	Thickness mm (inches)	Backcalculated Moduli, kPa (psi)	
		Texas FWD	Dynaflect
AC Surface	63.5 (2.5)	4388,930 (637,000)	1736,280 (252,000)
Granular Base	432 (17.0)	268,710 (39,000)	172,250 (25,000) *
Subgrade +	Semi-infinite	112,996 (16,400)	49,608 (7,200) *

* Moduli corrected for non-linear behavior.

\+ For the ABAQUS analysis, 12.2 meters (40 feet) subgrade was assumed.

study focuses on the simulation of longitudinal and transverse cracks. A crack is simulated in the model by having two independent nodes between continuous elements and being linked by special-purpose unidirectional gap elements known as GAPUNI. Gap elements allow two continuous surfaces to be either in or out of contact by simulating contact pressure and friction between the contacting surfaces.

The GAPUNI element is specified by two nodes separated by varying widths at the top and joined together at the bottom of two continuous elements. ABAQUS monitors the relative displacement of the two nodes of the element in the given direction. The arrangement results in two contact surfaces, A and B, which are separated by an initial selected gap width at the top. The GAPUNI element controls the interaction between Contact Surfaces A and B in such a way that these surfaces do not penetrate each other under any contact pressure. An appropriate value of the friction coefficient between Contact Surfaces A and B should be assumed in the analysis. A zero friction coefficient means that no shear force will develop and the contact surfaces are free to slide. A very large friction coefficient implies that the surfaces will lock and no sliding will occur. For this study, it is assumed that cracks are in the top asphalt layer under the loading plate.

STUDY OF CRACK GAP WIDTH

Figure 4(*a*) and (*b*) illustrate the finite element model configuration for 18.3-m (60-ft) pavement with shoulders and a longitudinal crack located 0.91 m (3 ft) from the outside pavement edge (under the central axis of the FWD load). The discontinuous shoulder was simulated by placing GAPUNI elements with a gap width of 0.51 mm (0.02 in.) and a zero friction coefficient.

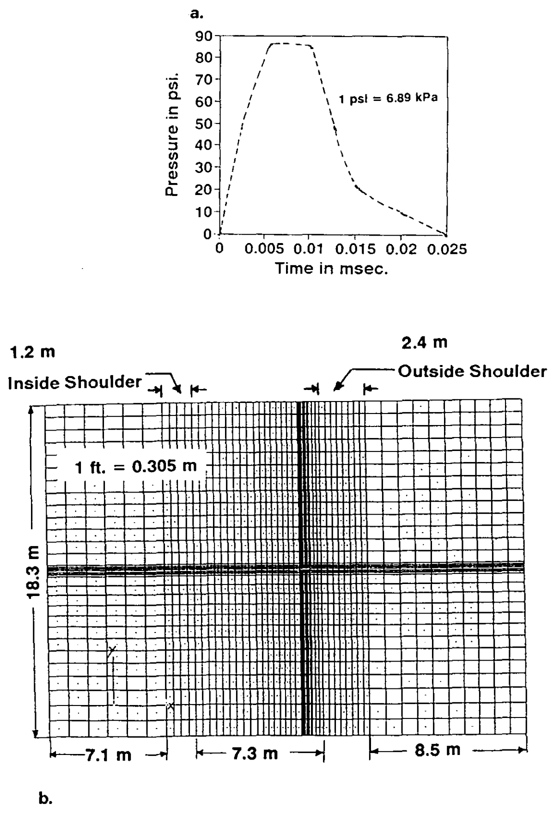

FIGURE 4 Finite element pavement subgrade model configuration for pavement crack study (*a*) FWD load pulse, (*b*) plan view of three-dimensional finite element model.

Longitudinal crack simulation in the asphalt layer initially was done by creating GAPUNI elements with a gap opening of 5.1 mm (0.2 in.) and assuming (*a*) a friction coefficient of 0.5 between the two contact surfaces of the GAPUNI element, and (*b*) a zero friction coefficient. Dynamic and static analyses were carried out, and it was observed that the effect of the friction coefficient on the calculated surface displacements is insignificant at the gap opening of 5.1 mm (0.2 in.), because the gap remained open throughout the analysis. When the gap opening was reduced to 2.5 mm (0.1 in.), 1.25 mm (0.05 in.), and 0.51 mm (0.02 in.), the effect of friction on the calculated surface displacements was still insignificant for the range of gap openings. When the gap was reduced to 0.25 mm (0.01 in.), the surface displacements were large enough to close the gap and therefore the effect of friction was significant. The study concluded that the critical gap opening is 0.25 mm (0.01 in.), at which point the friction coefficient is significant, as would be expected for a closely held crack on the pavement. A friction coefficient of 0.5 was assumed for crack simulation throughout the study.

CRACKED PAVEMENT RESPONSE

Longitudinal Cracked Pavement Response

Under Static Loads

In the cracked pavement model, a longitudinal crack in the asphalt layer in the outer wheel path was simulated using GAPUNI elements with a 0.25-mm (0.01-in.) gap opening and a friction coefficient of 0.5 between contact surfaces. Figure 5 shows a comparison of deflections in the pavement with cracking and without cracking; it is observed that the maximum static deflection in the cracked pavement is 1,162 μm (45.8 mils)—14 percent higher than that of the uncracked pavement. Figure 6 illustrates the deflection bowl caused by the FWD load in the 18.3-m (60-ft) pavement-subgrade model with shoulders using static analysis.

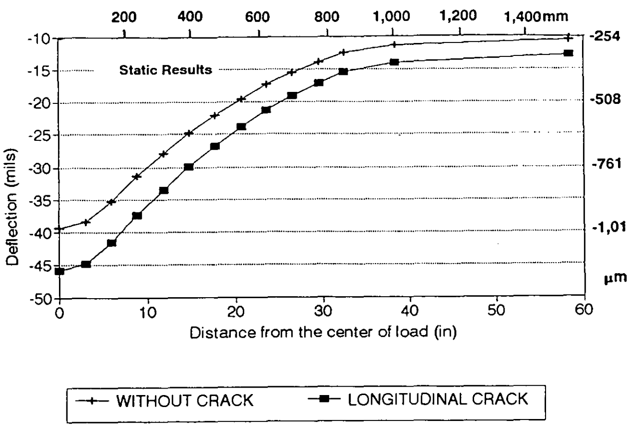

FIGURE 5 ABAQUS static load results of surface deflections for longitudinal cracked and uncracked pavements.

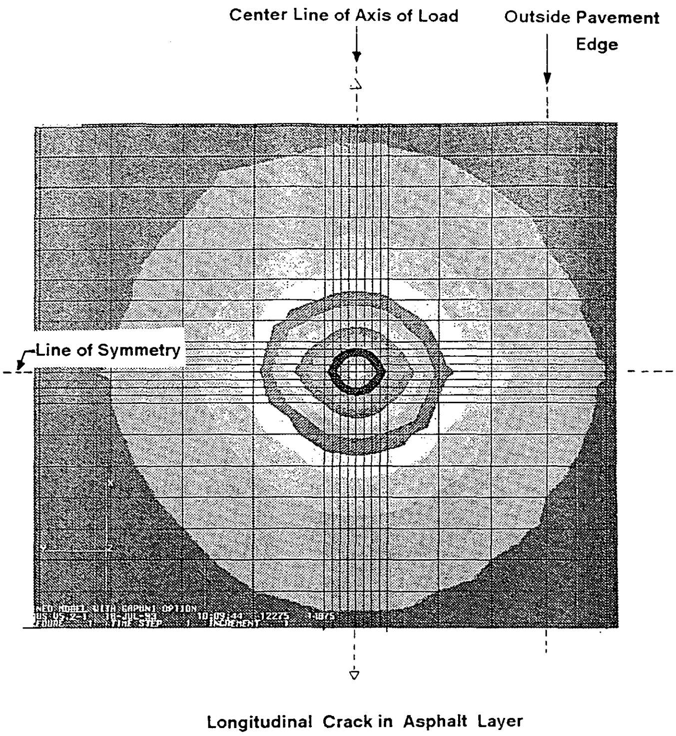

FIGURE 6 Area of concentration of surface deflections.

Under Dynamic Loads

Figure 7 indicates that dynamic loading causes a higher deflection response in the cracked pavement than the dynamic deflections calculated for the uncracked pavement. Maximum dynamic deflection under the NDT load, in the case of cracked pavement, is 985 μm (38.8 mils), which is 17 percent higher when compared with the dynamic deflection of the uncracked pavement. It is interesting to note that this difference becomes smaller farther away from the load.

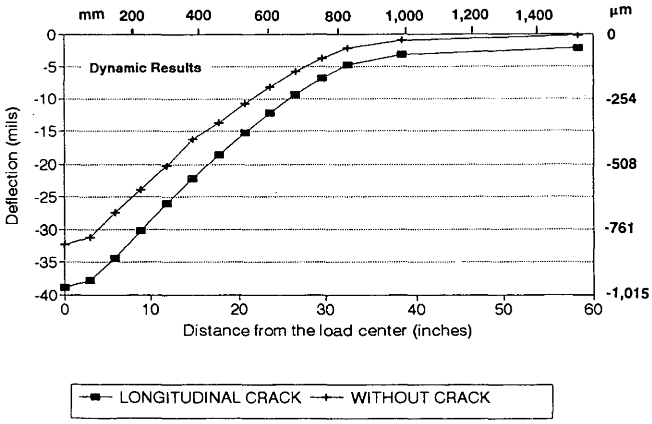

FIGURE 7 ABAQUS dynamic load results of surface deflections for longitudinal cracked and uncracked pavements.

Transverse Cracked Pavement Response Under Dynamic Loads

First, a transverse crack was simulated 75 mm (2.95 in.) from the load center; Figure 8 illustrates the results. Maximum dynamic deflection was 911 μm (35.9 mils), which is 10 percent higher than the corresponding deflection calculated for uncracked pavement. The transverse crack study was extended to investigate the effect of transverse crack spacing. Maximum dynamic deflection was 817 μm (32.2 mils) for a transverse crack simulated at 974

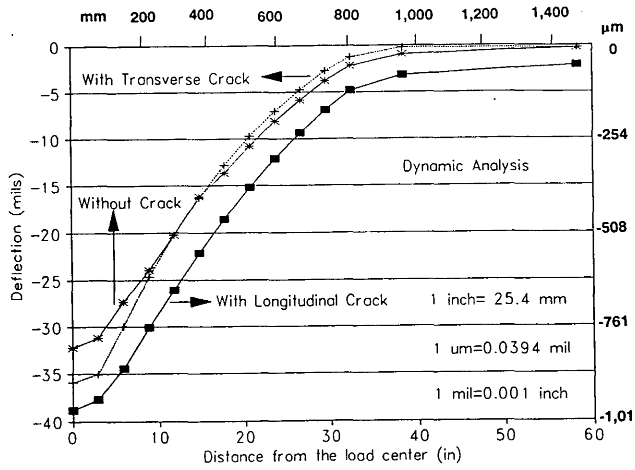

FIGURE 8 ABAQUS dynamic deflections for a pavement with transverse crack.

mm (38.35 in.) and again for a transverse crack simulated at 1 482 mm (58.35 in.) from the load center. Probably there is no significant effect on maximum dynmic deflection if a transverse crack is located beyond 1 m (3.3 ft) from the load center.

Dynamic Response of Pavement with Multiple Transverse Cracks

Multiple transverse cracks are often observed on a severely distressed pavement. In this study, multiple transverse cracks were simulated on either side of the symmetry at distances of 75, 300, 450, 974, and 1 482 mm (2.95, 11.8, 17.7, 38.35, and 58.35 in.) from the load center. Maximum dynamic deflection for the cracked pavement is 1,045 μm (41.2 mils), which is 22 percent higher than the corresponding deflection of the uncracked pavement.

SUMMARY AND CONCLUSIONS

Effects of pavement discontinuities and FWD dynamic NDT loads on the structural response of pavement-subgrade systems were analyzed using the three-dimensional ABAQUS finite element code. Principal findings are as follows:

- The optimum three-dimensional finite element model of a pavement-subgrade system used in this parametric study is 18.3 m (60 ft) long, with outside and inside shoulders measuring the lateral extent of the subgrade from the outside pavement edge of 11 m (36 ft) and a subgrade depth of 12.2 m (40 ft) with a fixed boundary at the bottom. Roller support is ideal along the sides of the model, and the ABAQUS static deflections compare very well with the static deflections computed from the traditional elastic layer analysis.
- For a linear elastic system, the ABAQUS IMPLICIT dynamic maximum deflection under a simulated FWD load is about 18 percent less than the corresponding ABAQUS static deflection.
- The ABAQUS dynamic deflection bowl computed from the backcalculated nonlinear moduli for an asphalt pavement section compares reasonably with the measured FWD deflection data taken from a previous FHWA study.
- Special gap elements are used to simulate pavement cracking and other discontinuities. An optimum crack gap width of 0.25 mm (0.01 in.) and a friction coefficient of 0.5 were established to simulate longitudinal and transverse cracks. A gap width of 0.51 mm (0.02 in.) and zero friction coefficient were used to simulate the discontinuous shoulders.
- ABAQUS dynamic maximum deflection for a longitudinally cracked pavement is about 17 percent higher than that for an uncracked pavement.
- For a severely distressed pavement with multiple transverse cracks, the ABAQUS maximum dynamic deflection is 22 percent higher than that for an uncracked pavement.

Higher dynamic deflections are expected for a cracked pavement as compared with the dynamic deflections calculated for uncracked pavements. However, the corresponding static deflection under the assumption of a linear elastic system remains higher than the dynamic deflections for a cracked pavement. This study demonstrates the usefulness of three-dimensional finite element simulation of pavement cracking and dynamic loads, simulation that is not possible using traditional layered elastic analysis and other finite element programs that do not allow crack simulation and dynamic analysis.

Further three-dimensional finite element simulations are under way to evaluate the effects of alligator cracking and crack severity on asphalt pavement responses. Studies are also being conducted to simulate pavement cracking, joint deterioration, and voids (loss of support under portland cement concrete surface layer) for concrete pavement-subgrade systems.

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