Simulation of Falling Weight Deflectometer for In-Situ Material Characterization of Highway and Airport Pavements

Waheed Uddin
Assistant Professor
Department of Civil Engineering
The University of Mississippi
University, Mississippi 38677
Telephone: (662) 915-5363 Fax: (662) 915-5523
cvuddin@olemiss.edu

Abbreviations:

3D-FE	Three Dimensional-Finite Element
AASHTO	American Association of State Highways and Transportation Officials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GAO	General Accounting Office
LTPP	Long-Term Pavement Performance
MDOT	Mississippi Department of Transportation
SHRP	Strategic Highway Research Program

Keywords:
Pavement, nondestructive, deflection, modulus, tire, finite element, simulation

ABSTRACT

Nondestructive evaluation of highway and airport pavements is performed by deflection testing, such as a falling weight deflectometer (FWD). Many agencies use FWD deflection data to backcalculate pavement moduli using subjective inputs and forcing the moduli within a pre-selected range for each material. The failure of many pavement projects can be attributed to the uncertainties in these material inputs. The use of static elastic layered analysis and two-dimensional static finite element analysis programs is inadequate to calculate pavement responses and to relate these to pavement performance. This paper presents some results of advanced three dimensional-finite element (3D-FE) computer simulations carried out on selected pavement-subgrade models of asphalt pavements, subjected to a standard FWD impact load. Good agreement is shown between simulated and measured FWD deflections. Examples of nonlinear FWD moduli for an aircraft wheel load are presented. Effects of viscoelastic material properties on pavement responses to dynamic FWD loading are discussed. The LS-DYNA contact surface definitions are applied for dynamic analysis of pavements. The paper demonstrates the use of advanced finite element dynamic analysis procedures for correctly simulating pavements subjected to dynamic loads produced by nondestructive evaluation equipment and dynamic wheel loads.

BACKGROUND

Nondestructive FWD pavement deflection data and deflection-time history data have been collected for over a decade from numerous in-service pavement sections included in the long-term pavement performance (LTPP) and asphalt research studies. These studies started as a part of the Strategic Highway Research program (SHRP) and are being continued by the Federal Highway Administration (FHWA). The LTPP data are now publicly available for university researchers through the Datapave CD (DATAPAVE, 1998). The availability of Datapave CD provides a good opportunity to implement advanced 3D-FE modeling and simulation for accurate pavement response analysis, as recommended by the General Accounting Office (GAO, 1997) to the Federal Highway Administration in the GAO report Highway Design Guide is Outdated .

In recent years accelerated loading tests have been conducted by the FHWA, state highway agencies, and Federal Aviation Administration (FAA) to develop improved performance models. In many cases data processing and analysis are being conducted without reliable and advanced dynamic response analysis. Subsequently, this may result in inadequate pavement performance modeling, nondestructive evaluation, and pavement design. Accurate moduli of pavement materials are essential for calculating correct pavement responses, developing pavement performance models, and designing longer lasting pavements. In situ material properties backcalculated from FWD deflection data lead to better assessment of material degradation over time. The traditional static analysis procedures may lead to incorrect structural evaluation of pavements because many of these procedures are user-dependent and do not appropriately consider the effects of dynamic loading and pavement nonlinearities such as joints and cracking. Without accurate mechanistic pavement modeling and dynamic analysis, correct pavement responses may not be calculated. The development of improved mechanistic analysis methods will also enhance pavement performance models, improve design, and replace the traditional empirical methods of relating pavement distresses to performance such as the regression techniques used for the AASHO Road test performance models (AASHTO, 1993).

PAVEMENT NONDESTRUCTIVE EVALUATION

Pavement Deflection Testing

Impact deflection testing by FWD for pavement nondestructive evaluation (NDE) is a widely used testing device among many nondestructive testing technologies available for pavement condition evaluation (Uddin, 1986; Hudson, 1997). Figure 1 shows a schematic of FWD test operation. The FWD device applies an impact load on a steel loading plate and measures peak deflections on the pavement surface using seismic velocity transducers at the center and at several locations away from the loading plate. A deflection basin can be constructed from the data as shown in broken lines in Figure 1. The advantage is that a test can be conducted within a couple of minutes and the FWD trailer can be towed to the next location along the pavement, thus permitting a large number of in situ tests in a few hours. Deflection data are the best indicators of pavement quality and variability. Sensor 1 plots in Figure 2 (a) show the variability in the section and the seasonal effects. Sensor 7 plots in Figure 2(b) indicate relatively homogeneous subgrade for the same highway pavement. A deflection basin represents the response of whole pavement-subgrade system under in situ state of stresses and strains. The FWD load pulse simulates the load pulse generated by a moving wheel load. With appropriate use of theory, deflection data and layering information can be used to backcalculate in situ modulus values of pavement layers. On the other hand, a few undisturbed material samples tested in the laboratory for resilient modulus (M_R) tests are time consuming, expensive, and do not truly represent the in situ conditions.

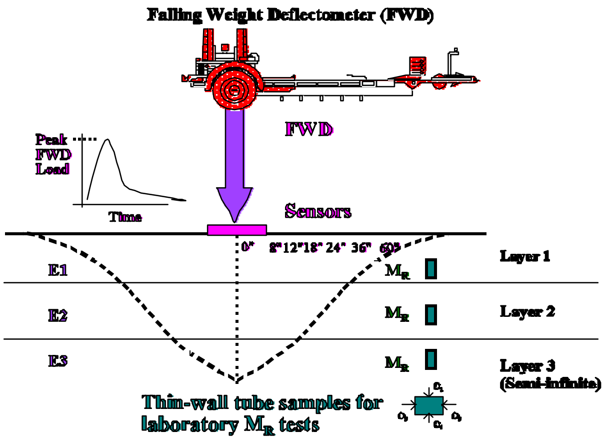
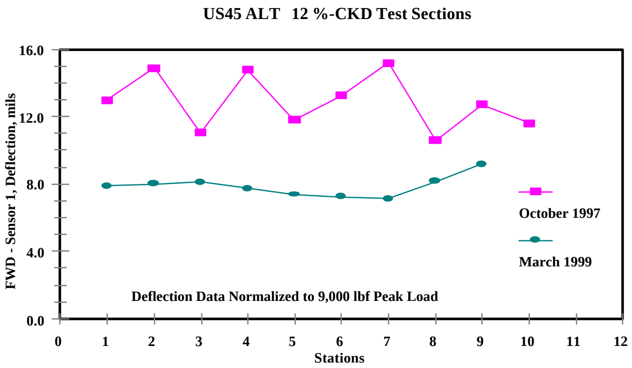


Figure 1. An Illustration of FWD Nondestructive Test and Measured Deflection Basin

Figure 2(a). Sensor 1 Maximum Deflection Profiles



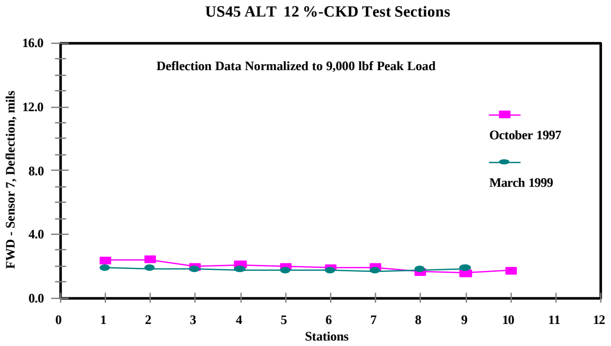


Figure 2(b). Sensor 7 Deflection Profiles

Backcalculation of In Situ Moduli

Material degradation with time due to environmental and dynamic loading conditions can be assessed by correct interpretation of deflection data. Accurate characterization of pavement materials is the key for correct assessment of structural capacity and improved pavement design. The use of multilayered linear elastic theory for structural analysis of a pavement-subgrade system subjected to FWD load or moving wheel load is based on the assumption that the pavement-subgrade system behaves as a linearly elastic system. Other key assumptions include: static loading ignoring loading mode and duration, infinite horizontal extent of pavement layers, and homogenous and isotopic material properties. Each layer of known thickness is characterized by its Young's modulus and its Poisson's ratio. The modulus backcalculation procedure involves an iterative application of the multilayered linear elastic theory. Surface deflections are predicted using assumed seed values of the Young's modulus and the Poisson's ratio for each pavement layer. Calculated surface deflections are matched with measured deflections and moduli are adjusted until the percentage of matching error is reduced to an acceptably low value; the final adjusted moduli are considered as the effective in situ Young's moduli of the pavement layers.

Assuming a semi-infinite subgrade and infinite lateral boundaries, unique values of surface deflections at specified distances from the load can be theoretically predicted. However, several combination of moduli may generate the same deflection basin, resulting in nonunique combination of backcalculated moduli. The possibility of nonuniqueness of the backcalculated moduli is a serious limitation of the iterative backcalculation procedures (Uddin, 1986).

The PEDD Backcalculation Methodology

Many available backcalculation programs use subjective inputs and/or inappropriate seed moduli and force the moduli within pre-selected ranges which may lead to inaccurate backcalculated moduli (Uddin, 1999). During the development of the PEDD backcalculation program this problem was recognized, and the uniqueness of backcalculated moduli was ensured by using nonlinear deterministic equations for seed moduli. The seed moduli are uniquely related to measured peak FWD force, deflections, radial distances of FWD sensors from the load center, and layer thicknesses and types of layer materials (Uddin, 1986).

Calculation of Nonlinear Moduli

The PEDD program incorporates a self-iterative routine to correct the backcalculated moduli of unbound layers and subgrade by using an equivalent linear analysis procedure which employs the normalized shear modulus versus shear strain attenuation curves used in earthquake engineering (Uddin, 1999). Backcalculated moduli for each unbound layer and subgrade are adjusted until a reasonable convergence in the shear strain is achieved. This procedure has been implemented in the PEDD program to calculate nonlinear moduli from FWD backcalculated moduli. The PEDD output provides both the uncorrected moduli from the linear analysis and corrected nonlinear moduli for granular layers and subgrade from the equivalent linear analysis. The moduli of granular base/subbase and subgrade can be smaller than the backcalculated values, as shown in Table 1 for a taxiway pavement (Uddin, 1999). This approach of considering nonlinear moduli related to each truck or aircraft axle-load configuration allows the use of mechanistic pavement design concepts more efficiently without using ESALs or ESWLs.

Table 1. Pavement Structure and Backcalculated Young's Moduli for Taxiway Fillet Section at Kaneohe Marine Air Station, Hawaii (Uddin, 1999)

Backcalculation Method1[1]	Average Backcalculated Modulus, MPa (ksi)			
	Asphalt Surface 101.6 mm (4.0 in)	Granular** Base 609.6 mm (24 in)	Granular** Subbase 609.6 mm (24 in)	Subgrade** +
PEDD Static Analysis[2]	3,213 (466)	214 (31)	214 (31)	207 (30)
PEDD Static Analysis[3]	2,772 (402)	193 (28)	193 (28)	193 (28)
PEDD Static Analysis[4]	2,772 (402)	145 (21)	165 (24)	179 (26)

[1] Heavy FWD Data - 3rd Drop only (Peak force = 25,000 to 35,000 lbf)
** [2] Linear analysis without rigid layer option ** [3] Linear analysis with rigid layer option
** [4] Nonlinear analysis with rigid layer option (20,000 lbs wheel load; 200 psi tire pressure)
+ A subgrade depth of 21.8 m or 71.6 ft (from the top of subgrade to a rigid bottom) predicted by the program

Table 2. Pavement Structure and Backcalculated Layer Moduli for MS Highway 6 East

Backcalculation Method	Backcalculated Modulus, MPa (ksi)			
	Asphalt Surface 139.7mm (5.5 in)	Asphalt Base 127 mm (5 in)	CTB * 152.4mm (6 in)	Subgrade + Semi-infinite
PEDD Static Analysis	3,259 (473)	4,134 (600)	395 (57)	300 (43.6)
3D-FE Dynamic Analysis	3,259 (473)	4,134 (600)	395 (57)	300 (43.6)

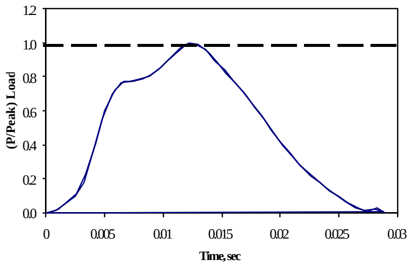
* Cement Treated Base

\+ A subgrade depth of 12.2 m (40 ft) assumed for the PEDD and 3D-FE programs

3D-FE DYNAMIC ANALYSIS OF FWD DATA USING THE ABAQUS CODE

The finite element method allows for the dynamic analysis of pavements and the consideration of finite or infinite dimensions of the physical pavement structure. The PEDD moduli backcalculated for some asphalt and concrete pavements have been verified by 3D- FE dynamic analysis, as reported in an earlier paper (Uddin, 1998a). The results of MS 6 East asphalt highway section are presented again in this paper. Table 2 shows layer materials, thicknesses, and moduli backcalculated by PEDD and used for 3D-FE dynamic analysis.

The nonlinear, explicit, three dimensional-finite element computer code ABAQUS (ABAQUS, 1998) was used for this simulation. The PATRAN pre-processor (PATRAN, 1997) was used to modify the US78 concrete highway pavement model to simulate MS Highway 6 asphalt pavement. Figure 3 shows a half-model of this pavement with layer thickness details. Note the refined mesh in the area where the FWD load pulse is applied. The deflection data were measured at a peak load of around 4,083 kg (9,000 lb) in the outer wheel path, about 1 m (3 ft) from the pavement edge. Figure 4 (a) shows a closeup view of the original pavement at a magnified scale. Figure 4 (b) shows a closeup view of the deformed pavement at maximum deflection. Figure 5 shows reasonably good matching of ABAQUS computed and measured deflections. Damping was not considered in the dynamic analysis which is reasonable considering the small load pulse duration.



FWD Load Pulse Used for 3D-FE Dynamic Analysis

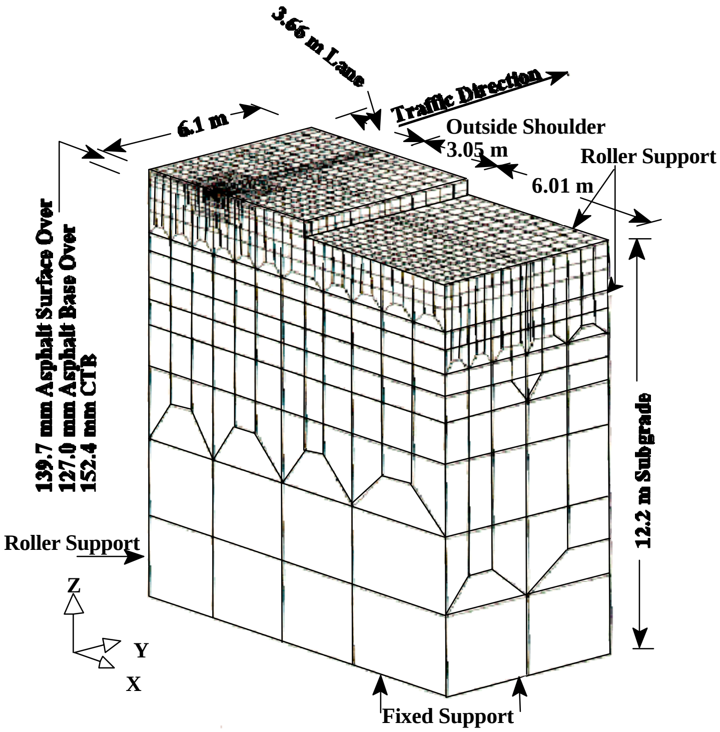
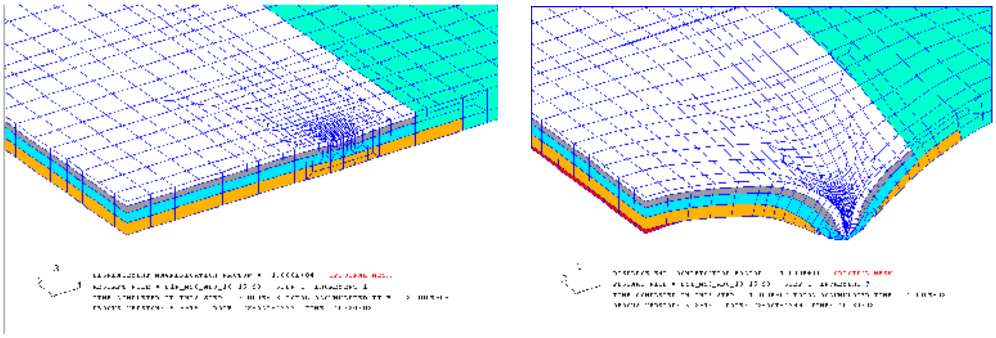


Figure 3. 3D-FE Model of MS Asphalt Highway 6 Pavement (UDDIN 1998a)



(a) Before FWD Load (b) Maximum Deformation Under FWD Load

Figure 4. Close-up Views of ABAQUS Simulations Before and After FWD Load Impact

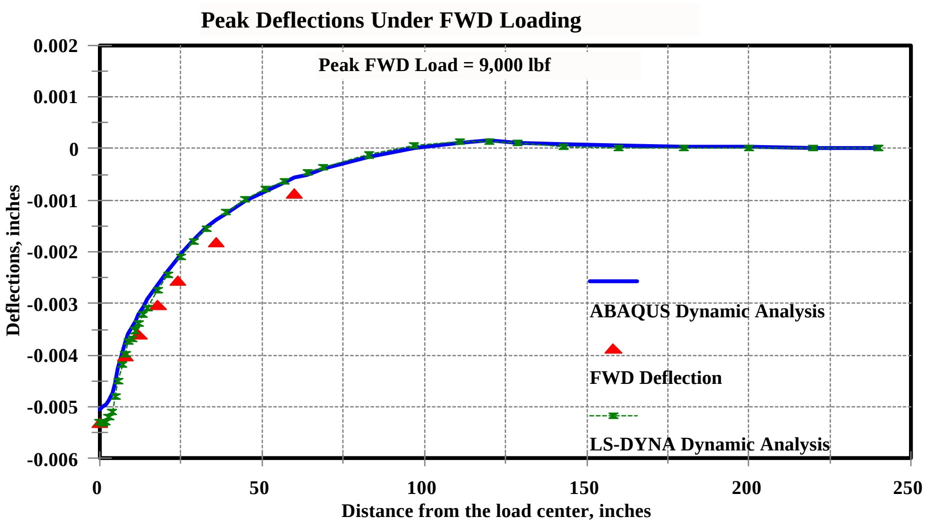


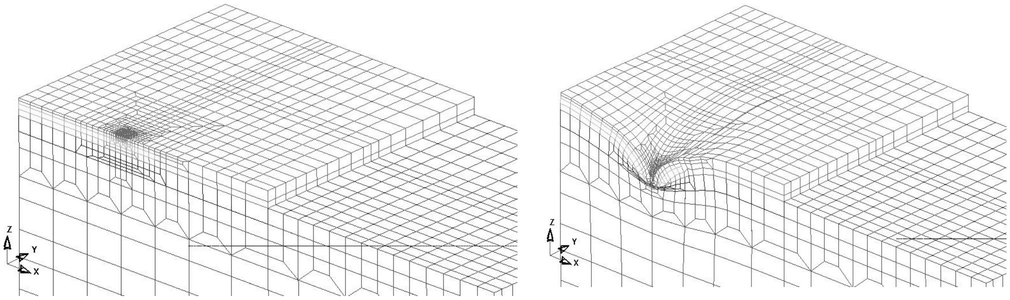
Figure 5. Matching of FWD Deflections with Deflections Computed by 3D-FE Analysis

3D-FE SIMULATIONS USING THE LS-DYNA CODE

3D-FE Dynamic Analysis

The nonlinear, explicit, three-dimensional finite element computer code LS-DYNA version 950c and the pre- and post-processor FEMB were used for pavement simulations (LSDYNA, 1999). The latest pavement simulations have been conducted using a Windows-95 Pentium 200 Pro microcomputer at the University of Mississippi. The original LS-DYNA version 940 database for MS 6 asphalt highway pavement from the earlier study (Uddin, 1998a) was saved again using the version 950c pre-processor. The measured FWD load pulse history shown in Figure 3 was incorporated in the dyna input file.

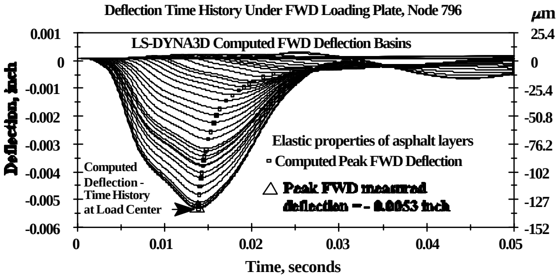
Table 2 presents the pavement structure and effective in situ elastic moduli for MS 6 asphalt highway pavement backcalculated using the PEDD program. The PEDD modulus values were the most reasonable, as shown in Figure 5 by the matching values of surface deflections computed by the ABAQUS and LS-DYNA codes. Figures 6 (a) and (b) show closeup views of the original pavement and deformed pavement (maximum deflection) at a magnified scale, as analyzed by LS-DYNA. Figure 7 shows the LS-DYNA computed deflection-time history in bold line using linear elastic material properties indicating a good match with the measured FWD deflection under the loading plate. Figure 6 also shows the computed deflection-time history in broken line when viscoelastic material properties were used for the asphalt layer by specifying Material 6 parameters. The bulk modulus value of the asphalt layer was increased by 16 percent to obtain a better match with the measured deflection (Uddin, 1998a). This analysis is not possible with existing static pavement analysis methods.



(a) Before FWD Load (b) Maximum Deformation Under FWD Load

Figure 6. Close-up Views of LS-DYNA Simulations Before and After FWD Load Impact

(a) Elastic Properties



(b) Effect of Viscoelastic Properties

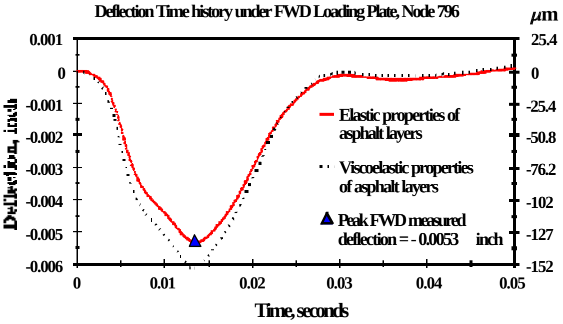
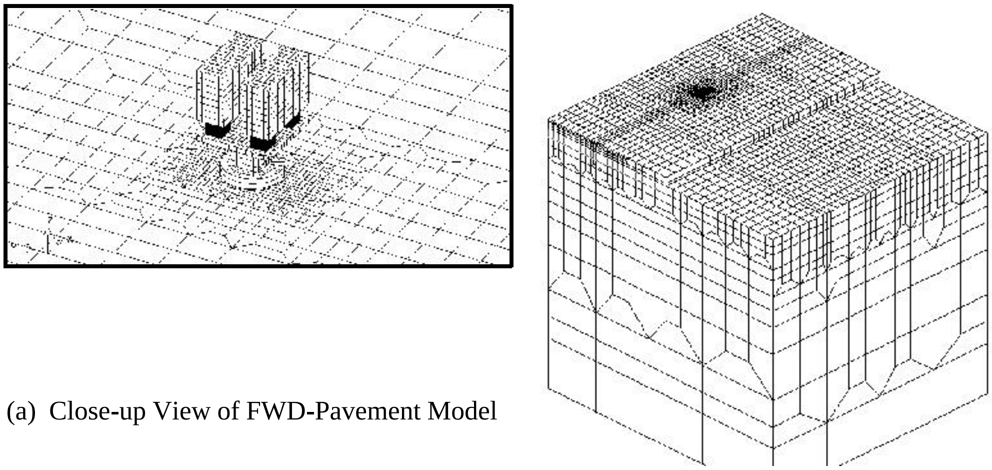


Figure 7. Deflection-Time History Computed by LS-DYNA and Measured FWD Deflection

LS-DYNA CONTACT SIMULATIONS

FWD-Pavement Contact Model

Figure 8 shows an application of contact mechanics for dynamic analysis of pavement deflections using the LS-DYNA sliding contact surface definitions. Figures 8(a) and 8(b) show a closeup view of the FWD model and a full view of the pavement model, created for FWD-pavement contact simulations. The purpose of this research is to understand the variations in the generated loading pulse shapes and their effects on measured deflections. A typical contact simulation problem takes 9 CPU hours on Windows-95 computer to complete, as compared to 1 CPU hour for the load pulse simulation problem (Uddin, 1998a).



(a) Close-up View of FWD-Pavement Model

(b) Full Model

Figure 8. Views of FWD-Pavement LS-DYNA Contact Simulation Model

Tire-Pavement Contact Model

Further three dimensional-finite element modeling of highway and airport pavements is currently underway at the University of Mississippi. The simulation efforts include 3D-FE modeling of truck and aircraft wheel loads using sliding contact surface definitions available in the LS-DYNA code. The preliminary tire model is based on the tires of a pickup truck model developed by the National Crash Analysis Center for vehicle impact simulations and crashworthiness analysis of roadside safety structures (Uddin, 1998b). Shell elements are used for the tire exterior, and an air bag model is used to simulate tire pressure. Figure 9 shows a tire-pavement model which is being investigated. This approach will lead to improved simulation of contact stresses which are generally assumed uniformly distributed on either circular or elliptical contact areas in current pavement simulation and design procedures.

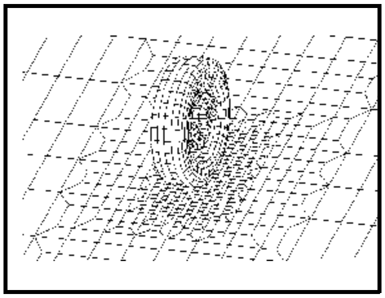


Figure 9. A View of LS-DYNA Tire-Pavement Contact Simulation Model

CONCLUSIONS

This study demonstrates the extensive usefulness of 3D-FE dynamic analysis to simulate the effects of pavement geometry, material moduli, and FWD load-time history which is not possible with traditional layered elastic analysis, as well as other two dimensional-finite element programs. For asphalt pavements in good condition the effective in situ moduli backcalculated from the PEDD static analysis provide good match of measured FWD deflections with the deflections computed by the three dimensional-finite element dynamic analysis. The PEDD modulus values, corrected for granular layers and subgrade soils exhibiting nonlinear behavior, provide valid material inputs for use in mechanistic analysis and advanced finite element dynamic analysis procedures. This paper demonstrates the effect of viscoelastic material properties on pavement responses to dynamic FWD loading. Work is currently underway to analyze FWD deflection data measured on airport pavement sections and to evaluate tire-pavement contact simulation models. It is shown that advanced dynamic analysis and appropriate material models are necessary to accurately analyze and design pavements which is not possible with traditional pavement analysis and design procedures.

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DISCLAIMER

The contents of this paper reflect the views of the author who is responsible for the facts, findings and data presented herein.

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