Implementation of a User Material Routine in 3D-FE Codes for Viscoelastic Modeling and Simulation of Highway and Airport Pavements

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Abbreviations:

3D-FE	Three Dimensional-Finite Element
A	Nondimensional A Parameter
AASHTO	American Association of State Highways and Transportation Officials
ADCP	Automated Dynamic Cone Penetrometer
BULK	Bulk Modulus
CR0	Initial Crack Size
ESAL	Equivalent Standard Axle Load
ESWL	Equivalent Single Wheel Load
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
G	Shear Modulus
GAO	General Accounting Office
MDOT	Mississippi Department of Transportation
PEDD	Pavement Evaluation Based on Dynamic Deflections
TAU or τ	Relaxation Time
UMAT	User Material Subroutine
V_{MAX}	Limiting Value of Average Crack Radius Growth Rate
XKT	Threshold Value of Stress Intensity
XM	Stress Intensity Parameter
XMU or μ_s	Static Coefficient of Friction

Keywords:
Pavement, finite element, simulation, material, model, elastic, viscoelastic

ABSTRACT

Traditional static analysis procedures using linear elastic pavement properties may lead to incorrect structural response analysis of pavements. Many of these procedures do not appropriately consider the effects of dynamic loading and pavement nonlinearities such as joints and cracking. It is imperative to use appropriate and correct material properties for meaningful advanced computer simulations. This paper presents some results of traditional analysis and three dimensional-finite element simulations carried out on selected pavement-subgrade models of highway pavements. Results of static and dynamic analysis are presented using measured falling weight deflectometer (FWD) load pulses and deflections. Effects of viscoelastic material properties on pavement responses to dynamic FWD loading are investigated. A user defined material subroutine UMAT is described. The UMAT material routine incorporates a generalized Maxwell viscoelastic model and microcracking propagation methodology. The UMAT material routine is being implemented in the LS-DYNA code.

BACKGROUND

Highway and airport pavement design methods and analysis are based on extrapolations of the full-scale loading tests which relate pavement performance empirically to the accumulated 80-KN (18-kip) equivalent standard axle load (ESAL) application for highway pavement design and standard equivalent single wheel load (ESWL) for airport pavement design. The concept of converting mixed vehicular traffic to 80-KN (18-kip) ESAL applications for highways uses the empirical AASHTO pavement damage equations (AASHTO, 1993). These equations are not applicable to modern high-performance modified asphalt pavements. It is imperative to use mechanistic analysis to design modern pavements. Accurate structural response analysis using appropriate material properties is necessary to develop reliable performance models for mechanistic design of pavements.

Asphalt highway and airport pavements are modeled as static linear elastic systems for mechanistic structural response analysis. However, the structural response of an asphalt pavement is time-dependent and affected by load-time history. Appropriate and accurate material inputs are essential for meaningful advanced three dimensional-finite element (3D-FE) dynamic analysis procedures which are recommended by the General Accounting Office (GAO, 1997) to the Federal Highway Administration in the GAO report Highway Design Guide is Outdated.

A Falling Weight Deflectometer (FWD) and the Automated Dynamic Cone Penetrometer (ADCP) are being used for structural evaluation of highway and airport pavements. Material properties are backcalculated from the FWD deflection data using layer thicknesses which are estimated from the ADCP test data for pavement sublayers and subgrade. This work is being conducted in a study sponsored by the Mississippi Department of Transportation (MDOT). FWD deflections measured on an unpaved pavement are analyzed to backcalculate Young s modulus for each layer using the PEDD modulus backcalculation methodology. Several advanced 3D-FE computer models have been developed for pavement simulation studies. Reasonably good agreement is shown between deflections calculated from the model subjected to a simulated FWD force and the measured FWD deflections (Uddin, 1998a; Uddin, 1998b). This paper describes a new user defined viscoelastic material model, UMAT. This model has been implemented in the ABAQUS three dimensional-finite element code (ABAQUS, 1998) and is being implemented in the LS-DYNA code (LS-DYNA, 1999). The paper presents the

results of a three-layer pavement model using the UMAT material model.   The surface layer is characterized by the UMAT model. The backcalculated Young s modulus values are used to compute bulk and shear modulus values for the UMAT inputs. The base and subgrade layers are modeled as linear elastic materials. Responses and cracking are analyzed by subjecting the pavement model to an impulse dynamic load. The results show the time-dependent viscoelastic behavior. The UMAT model for advanced pavement structural response analysis leads to a better understanding of pavement behavior under different loads.

MATERIAL MODELS FOR ASPHALT PAVEMENTS

Linear Elastic Material Model
This is an isotropic elastic material, identified as Type 1 in the LS-DYNA code, and is available for beam, shell, and solid elements. Each pavement layer is characterized by its Young s modulus (E) and Poisson s ratio ( ).

Rutting or permanent deformation is the main reason for premature failure of asphalt pavements, and it can also be observed in granular and soil layers. This behavior can not be modeled by an elastic material model. A viscoelastic material model is more appropriate for this purpose.

Viscoelastic Material Model
The basic viscoelastic model, material Type 6, in the LS-DYNA code has been used in a previous study for viscoelastic dynamic analysis of asphalt pavements (Uddin, 1998a). This model allows the modeling of viscoelastic behavior for beams, shells, and solids (LS-DYNA, 1999). The shear relaxation behavior is described by

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t} \tag{1}$$

where G_0 is the short-time shear modulus, G_∞ is the long-time shear modulus, and β is the decay constant.

A Jaumann stress rate formulation is used

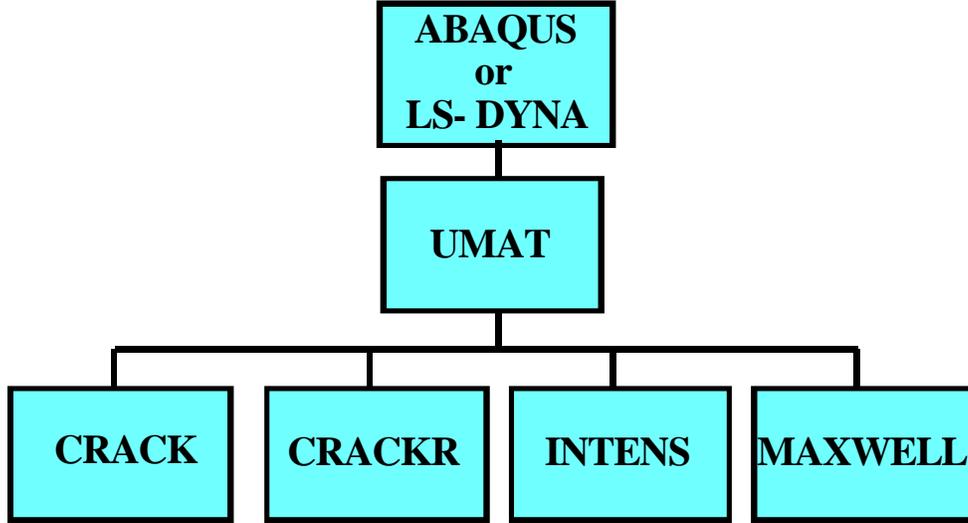$$\overset{\nabla}{\sigma}{}'_{ij} = 2\int_0^t G(t-\tau)D'_{ij}(\tau)d\tau \tag{2}$$

where the prime denotes the deviatoric part of the stress rate, $\overset{\nabla}{\sigma}_{ij}$, and the strain rate D_{ij} , and τ is the relaxation time (LS-DYNA, 1999).

UMAT User Defined Pavement Material Model
A schematic of the UMAT material model is shown in Figure 1. It is based upon a generalized Maxwell model to simulate material viscoelastic behavior. Additionally, the model incorporates microcracking and crack propagation. The UMAT model is implemented using FORTRAN subroutines, and requires pavement material properties such as bulk modulus, shear modulus, Poisson s ratio, mass density and relaxation time. The required parameters for crack propagation analysis are: initial crack size, stress intensity threshold, crack growth rate, and static coefficient of friction. The UMAT model is implemented for both static

and dynamic loads.

Figure 1. A Schematic of the UMAT Material Model

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          │   ABAQUS     │
          │     or       │
          │   LS- DYNA   │
          └──────┬───────┘
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          ┌──────┴───────┐
          │    UMAT      │
          └──────┬───────┘
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   ┌──────┬──────┴──────┬──────────┐
┌──┴──┐ ┌─┴────┐ ┌──────┴──┐ ┌─────┴────┐
│CRACK│ │CRACKR│ │ INTENS  │ │ MAXWELL  │
└─────┘ └──────┘ └─────────┘ └──────────┘
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UMAT User Material Subroutine Model Formulation
For the viscoelastic solid, represented by a generalized deviatoric Maxwell model, with the strain being common for all elements of the model and the stresses for the individual elements being additive, i.e.,

$$s_{ij} = \sum_{n=1}^{N} s_{ij}^{(n)} \tag{3}$$

where N is the number of elements in the generalized Maxwell model and $s_{ij}^{(n)}$ is the deviatoric stress component for the nth element, the relationship between the deviatoric stress rate and the viscoelastic deviatoric strain rate and deviatoric stress is given by

$$\dot{s}_{ij} = \sum_{n=1}^{N} \left(2G^{(n)} \dot{e}_{ij}^{ve} - \frac{s_{ij}^{(n)}}{\tau^{(n)}} \right) \tag{4}$$

where $G^{(n)}$ and $\tau^{(n)}$ are the shear modulus and relaxation time, respectively, for the nth Maxwell element, and e_{ij}^{ve} is the viscoelastic deviatoric strain. The deviatoric stress in terms of combined viscoelastic and microcracking response is given by

$$\dot{s}_{ij} = \psi \, \dot{e}_{ij} - \theta \left(s_{ij} + \lambda_{ij} \right) \tag{5}$$

where ψ is the Airy stress function, and θ is the angle with respect to the crack plane:

$$\psi = \frac{2G}{1 + \left(\dfrac{c}{a} \right)^3} \tag{6}$$

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$$\theta = \frac{3\left(\dfrac{c}{a}\right)^2 \dfrac{\dot{c}}{a}}{1+\left(\dfrac{c}{a}\right)^3} \tag{7}$$

and

$$\lambda_{ij} = \frac{\displaystyle\sum_{n=1}^{N} \dfrac{s_{ij}^{(n)}}{\tau^{(n)}}}{3\left(\dfrac{c}{a}\right)^2 \dfrac{\dot{c}}{a}} \tag{8}$$

where G is the shear modulus, c is the average crack radius, a is the initial flaw size, and τ is the relaxation time. Equations (3) through (8) are the formulation for the Subroutine UMAT.

The expression for the deviatoric stress rate for the nth Maxwell element is given by

$$\dot{s}_{ij}^{(n)} = 2G^{(n)}\dot{e}_{ij} - \frac{s_{ij}^{(n)}}{\tau^{(n)}} - \frac{G}{G^{(n)}}\left[3\left(\frac{c}{\dot{a}}\right)^2 \frac{\dot{c}}{a} s_{ij} + \left(\frac{c}{a}\right)^3 \dot{s}_{ij}\right] \tag{9}$$

and is the basis for the Subroutine MAXWELL (called from UMAT).

An evolution equation defining crack growth rate is required. It is assumed that the growth rate of the average crack radius is functionally dependent upon the stress intensity. This dependence is defined by

$$\dot{c} = v_{max}\left(\frac{K_I}{K_I}\right)^m , K_I \le K' \ \text{ or } , \ \dot{c} = v_{max}\left[1-\left(\frac{K_{0\mu}}{K_I}\right)^2\right], K_I \ge K' \tag{10}$$

where v_{max} is the maximum value of the rate growth of the average crack radius, K_I is the stress intensity factor and the subscript I stands for mode I (opening mode under normal stress):

$$K_I = \left(\frac{3\pi c}{2} s_{ij}s_{ij}\right)^{\frac{1}{2}}, \sigma_m \le 0 \ \text{ or } \ K_I = \left(\frac{3\pi c}{2}\sigma_{ij}\sigma_{ij}\right)^{\frac{1}{2}}, \sigma_m \ge 0 \tag{11}$$

where the mean stress $\sigma_m = 3K\varepsilon_m$ (K is the bulk modulus of the material) and ε_m is the mean strain.

and

$$K' = K_{0\mu}\left(1+\frac{2}{m}\right)^{\frac{1}{2}} \tag{12}$$

$$K_I = K'\left(1+\frac{m}{2}\right)^{\frac{1}{m}} \tag{13}$$

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$$K_{0\mu} = K_0 \left[1 - \frac{\pi\mu'\sigma_m c^{\frac{1}{2}}}{K_0} \left(1 - \frac{\mu'\sigma_m c^{\frac{1}{2}}}{K_0} \right) \right]^{\frac{1}{2}} \tag{14}$$

$$\mu' = \left[\frac{45}{2(3 - 2\mu_s^2)} \right] \mu_s \tag{15}$$

where K_0 is the threshold value of stress intensity, m is a cracking parameter and $_s$ is the static coefficient of friction. Equations (10) through (15) are the formulation for the Subroutines CRACK, CRACKR and INTENS (all called from UMAT).

PAVEMENT NONDESTRUCTIVE EVALUATION AND BACKCALCULATION OF YOUNG S MODULUS

Pavement deflection response is usually analyzed using a multilayered linear elastic pavement-subgrade model subjected to a static load. Assuming a semi-infinite subgrade and infinite lateral boundaries, unique values of surface deflections at specified distances from the load can be theoretically predicted. Pavement nondestructive evaluation is performed through the measurement of surface deflections under a known dynamic load. The backcalculation of the in situ Young s modulus of each pavement layers involves an iterative application of the multilayered elastic theory for matching computed and measured deflections.

In this study the PEDD backcalculation methodology has been used to backcalculate the pavement modulus for each layer. This program uses the multilayered linear elastic theory for structural analysis of a pavement system subjected to FWD loads. Each layer is characterized by its Young's modulus and its Poisson's ratio. The PEDD program ensures the uniqueness of backcalculated moduli 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 thickness and quality of base and subbase materials (stabilized or granular). Calculated surface deflections are matched with measured deflections and moduli are adjusted until the percentage of matching error is reduced to an acceptable low value; the final pavement moduli are considered as the values of effective in situ Young's moduli of the pavement layers (Uddin, 1986; 1998b). For unpaved sections, a new backcalculation program has been developed using the PEDD backcalculation methodology.

3D-FE SIMULATIONS

UMAT Material Parameters Used for Simulation

The simplified 3D-FE pavement model consists of an unpaved granular surface layer 305 mm (12 in), a granular base layer 203 mm (8 in) and soil (20 in). Linear brick 8-node C3D8 type elements are used to develop this simple 3D-FE model in the ABAQUS code. The base of the model is fixed and roller supports are used on the sides. A load of 1,000 lb is applied at the center node. The surface layer is characterized in the first simulation as elastic material and in later simulations by the UMAT viscoelastic material model. The base and soil layers are modeled as linear elastic materials.

The material properties shown in Table 1 correspond to the pavement of Highway US 45 North, Section 03, Station 67+550 under construction near Okolona, Mississippi. The Young s modulus values are backcalculated from the FWD data collected from the test site. The bulk and shear modulus values are derived using the Young s modulus values. The assumed values of other parameters are based upon preliminary studies.

Table 1. Material Properties Used for Implementing the UMAT Model

Properties	Values
Layer 1 (Material = Soil 1)	
(1) Initial Crack Size, *CR0*	0.001 in
(2) Nondimensional A Parameter, *A*	0.03
(3) Threshold Value of Stress Intensity, *XKT*	230 psi
(4) Stress Intensity Parameter, *XM*	10 psi
(5) Limiting Value of Average Crack Radius Growth Rate, V_{MAX}	12,000 in/sec
(6) Static Coefficient of Friction, *XMU*	0.3
(7) Bulk Modulus, *BULK*	68,333 psi
(8) Shear Moduli, *G1*	3,412 psi
(9) Shear Moduli, *G2*	3,412 psi
(10) Relaxation Time, *TAU*	0.5 sec
(11) Young s Modulus (Backcalculated), *E*	20,500 psi
(12) Poisson Ratio,	0.45
(13) Mass Density, ρ	0.0001873 lb.sec^2/in^4
Layer 2 (Material = Soil 2)	
Young s Modulus (Backcalculated), *E*	14,600 psi
Poisson Ratio,	0.45
Mass Density, ρ	0.0001873 lb.sec^2/in^4
Layer 3 (Material = Soil 3)	
Young s Modulus (Backcalculated), *E*	13,020 psi
Poisson Ratio,	0.45
Mass Density, ρ	0.0001873 lb.sec^2/in^4

IMPLEMENTATION OF UMAT IN THE ABAQUS CODE

ABAQUS Procedure for User Defined Material Model
The ABAQUS 3D-FE modeling involves three stages: (1) pre-processing, where the finite element mesh is generated, loads and boundary conditions are assigned, and material properties are defined, (2) analysis, where displacements, stresses, and strains are computed, and (3) post-processing, where the results are graphically presented. The PATRAN software is used as a pre-processor (PATRAN, 1996), and ABAQUS for the analysis and post-processing (ABAQUS, 1998).

To implement the UMAT user material subroutine in ABAQUS, the input file generated by PATRAN for the elastic material case is modified. This routine is called at each material calculation point for which the *MATERIAL definition includes the *USER MATERIAL option, and is used to define the mechanical constitutive behavior of the material. In this study, UMAT is called only for Layer 1 and the inputs of the parameters shown in Table 1, are required. The bulk and shear modulus values are calculated using the Young s modulus backcalculated with the PEDD program and the Poisson ratio, the other parameters are based on the results of preliminary studies. The other two layers are modeled as linearly elastic materials.

The UMAT user material subroutine also requires the input of initial conditions to run the analysis. The SDVINI user subroutine written also in FORTRAN defines initial solution dependent state variable fields. ABAQUS will call this routine at particular material points whenever the *INITIAL CONDITIONS, TYPE=SOLUTION, USER option is used. The number of solution dependent state variables is defined using the *DEPVAR material option. For this subroutine 26 variables are defined.

ABAQUS Results
Two different types of loads have been applied to the same US45N pavement model using the UMAT viscoelastic user material routine, as shown in Figure 2: (a) 1,000 lb static load on the center of the model surface and (b) 1,000 lb peak pulse load on the model surface.

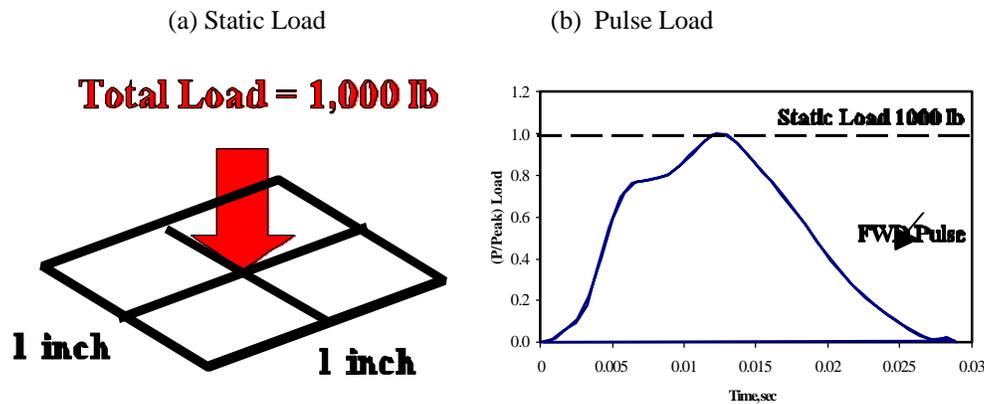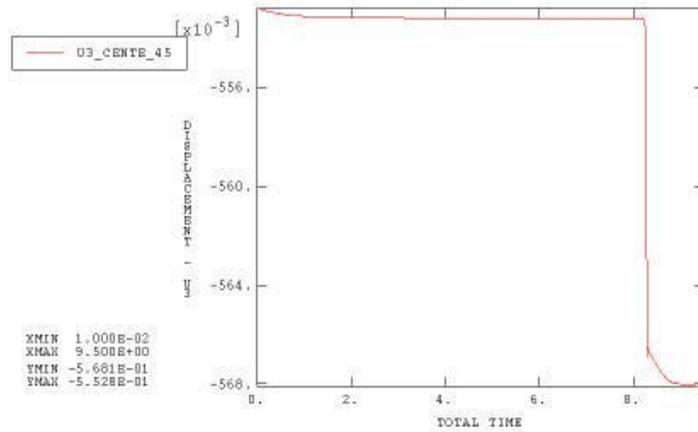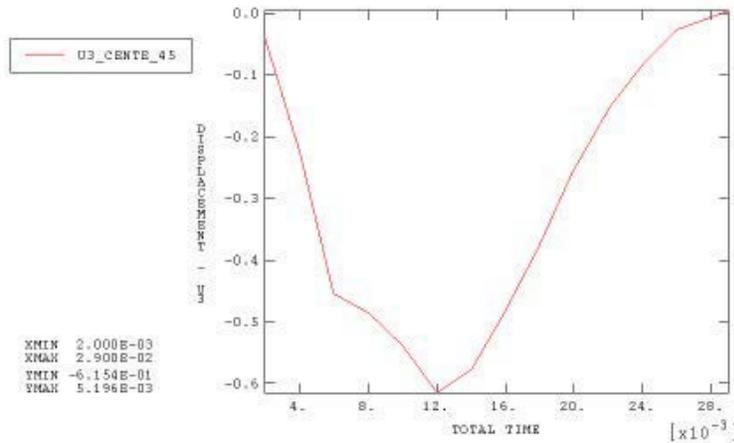(a) Static Load   (b) Pulse Load

Figure 2. Simulation of the US45N Pavement Model

Figure 3 shows the vertical displacement on node 45, which corresponds to the center of the model surface, for the two load cases analyzed (a) static load and (b) pulse load, using the UMAT viscoelastic user material subroutine. The value of the applied peak load, material properties and boundary conditions are the same in both cases; only the load-time history differs. In the static load case, the application is directly on the center node 45. In the pulse load case, the pulse is applied on the model surface, elements 13, 14, 15 and 16 during 29 msec. The maximum vertical displacements differ in both cases. In the static load case the displacement has an insignificant change during the first 8 seconds; subsequently it reaches 0.5528 in. In the pulse load case the displacement is consistent with the shape of the applied pulse with a maximum vertical displacement of 0.6154 inches at 12 msec.

(a) Model subjected to static load

(b) Model subjected to pulse load

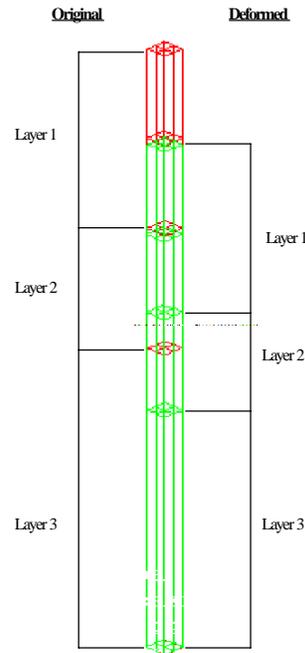Figure 3. Vertical Displacements Calculated Under the Center of Simulated Loads Using UMAT

Figure 4. The Original and Deformed Shapes of thePavement Model

Figure 4 shows the original and deformed shapes of the pavement model subjected to the static load. This is similar to the deformed shape of the pavement model subjected to the pulse load. Table 2 compares the results of the UMAT model simulations with the results of a linear elastic model for the surface layer.

Table 2. Comparison of the UMAT Results with the Results of the Linear Elastic Model

ABAQUS Material Model	Vertical Displacement, in	
	Static Load	Pulse Load
UMAT - Layer 1	0.5528	0.6154
Linear Elastic - Layer 1	0.7216	0.7660

The maximum vertical displacements in the elastic material case are: (a) 0.7216 in for the static load and (b) 0.7660 in for the pulse load. To compare these results it is important to note the area of load application. In the static load case, the peak load is applied to one node while in the other case the pulse is applied to 1 in^2 area. These simulations are conducted on a soft pavement. Although not reported here, microcracking growth has been observed in the simulation results of a stiff (concrete like surface) pavement.

IMPLEMENTATION OF UMAT IN THE LS-DYNA CODE

LS-DYNA Procedure for User Defined Material Model
The LS-DYNA version 950c code is used in this paper for developing a three dimensional pavement model. This new version has the capabilities of a pre-processor, analysis solver, post-processor, and graph-processor. From the LS-DYNA Program Manager menu, we select the pre-processor, Finite Element Model Builder Version 26 NTFEMB, which allows the modeling of a finite element model, specifying materials and properties for the model, and creating boundary conditions. An input file is created and the results of the LS-DYNA3D analysis are post-processed.

UMAT 41 Material User Subroutine
This is an LS-DYNA isotropic elastic material user subroutine. The addition of user material subroutine into LS-DYNA is achieved replacing in the dyna elastic material file generated by the FEMB pre-processor the option *MAT_ELAST with MAT_USER_DEFINED_MATERIAL_MODELS. A bulk modulus and a shear modulus are required for transmitting boundaries, contact interfaces, rigid body constraints, and time step size calculations. The required input data are the LS-DYNA material identification number (mid), mass density (ro), LS-DYNA material title number (mt), Young s modulus (e), Poisson s ratio (nu), bulk modulus (k), and shear modulus (g).

For this study a pavement model was created using the FEMB pre-processor with the material properties shown in Table 1. This simplified 3D-FE model corresponds to the pavement of Highway US 45 North, Section 03, Station 67+550 under construction near Okolona, Mississippi. This same model was used for the ABAQUS study. The generated dyna file was modified replacing the option *MAT_ELAST with *MAT_USER_DEFINED_MATERIAL_MODELS, and using the LS-DYNA material title number 41. The option *DEFINE_CURVE was also modified introducing the time-load curve shown in Figure 5. This time-load curve established the pseudo static load application.
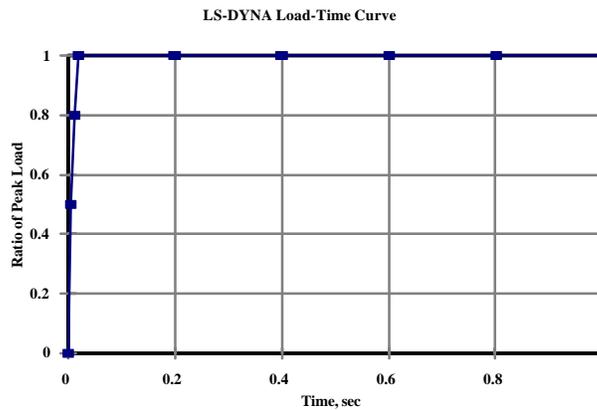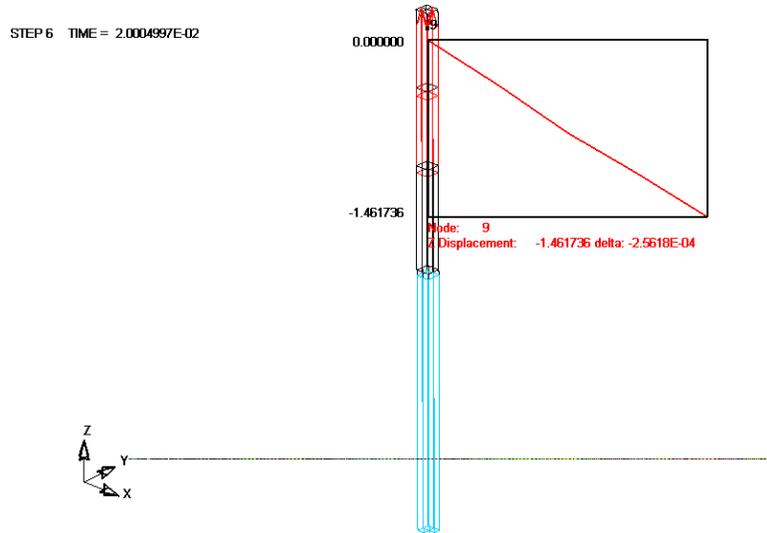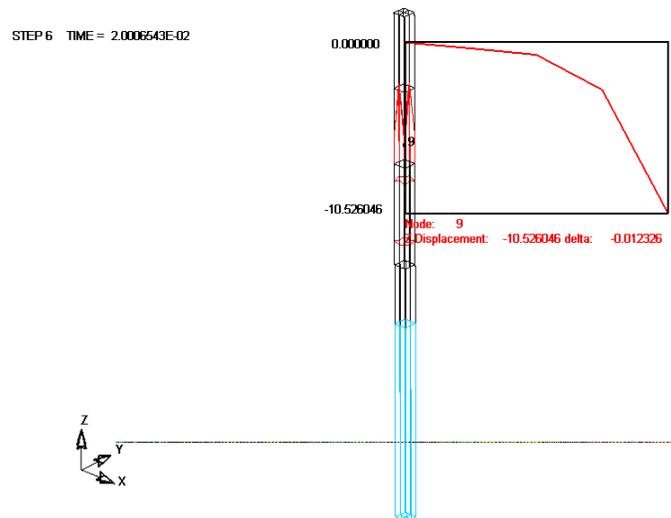

Figure 5. LS-DYNA Load-Time Curve

The US45 North pavement model was analyzed using (a) LS-DYNA elastic material Type 1 option and (b) LS-DYNA UMAT 41 material user subroutine. Figure 6 shows the post-processed results of the analyzed model. The same 1,000 lb peak load value and load-time

curve are used in both cases as shown in Figure 5. The peak load is reached at 20 msec and remains at the peak value until the time is equal to 1 second. This simulates a pseudo-static load case.

(a) Elastic material option

(b) UMAT 41 User material option
Figure 6. The LS-DYNA Vertical Displacement Results

UMAT Pavement Material Model
The implementation of the UMAT viscoelastic material subroutine in LS-DYNA would permit microcracking and enhance the accuracy of the results of pavement response analysis. Currently the UMAT model is being implemented in LS-DYNA. Some modifications have

already been introduced in the ABAQUS version of the UMAT subroutine to adapt it for LS-DYNA.

SUMMARY AND CONCLUSIONS

This paper describes a new viscoelastic material model, UMAT, which incorporates microcracking. The UMAT model has been implemented in the ABAQUS three dimensional-finite element code for enhanced modeling and response analysis of pavements. The UMAT material model is currently being implemented in the LS-DYNA 3D-FE code.

The paper compares the results of a three-layer unpaved pavement model using the UMAT material model in the ABAQUS code.   The surface layer is characterized by the UMAT model. The backcalculated Young s modulus values are used to compute bulk and shear modulus values for the UMAT inputs. The base and soil layers are modeled as linear elastic materials. Responses are analyzed by subjecting the pavement model to a static load and an impulse dynamic load. The results show the time-dependent viscoelastic behavior.

It is expected that the implementation of the UMAT model for advanced pavement structural response analysis will lead to better understanding of pavement behavior considering a variety of pavement layer materials and different loads.

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DISCLAIMER

The contents of this paper reflect the views of the authors who are solely responsible for the facts, findings and data presented herein.

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