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Use of Two-dimensional Finite Element Analysis to Represent Bending Response of Asphalt Pavement Structures

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Use of the finite element method (FEM) and other advanced analysis techniques is suitable for evaluation of pavement response and performance. Three-dimensional FEM analysis provides most accurate representation of pavements; however, it is costly, particularly for predictions that involve continuously changing structures and thousands of load applications of varying magnitudes and positions. Axisymmetric and two-dimensional analyses provide simpler, more cost-effective solutions at the expense of accuracy. This paper describes a study undertaken to evaluate discrepancies between two- and three-dimensional analysis of asphalt pavements, and to determine whether a modified two-dimensional analysis could be used as a reasonable approximation of three-dimensional bending response. Discrepancies between two- and three-dimensional analyses were found to be dependent upon the pavement structure. An approach was developed to use pavement structural characteristics to define an adjustment factor which could be applied to the loading in the two-dimensional case such that two-dimensional analyses would reasonably estimate the critical tensile pavement stresses as computed from three-dimensional analyses. The benefits and limitations of the approach are discussed, and an example of its use in evaluating crack growth is illustrated.

Keywords: Finite element; Pavement response; Axisymmetric solutions; Bending stress ratio; Tensile stress prediction

INTRODUCTION

Background

Recent advances in the understanding of asphalt mixture behavior and the failure mechanisms of asphalt pavements illustrate the need to model complex tire loading conditions and development of damage and crack growth within pavements. Therefore, the use of advanced analysis techniques, such as the finite element method (FEM), are fast becoming

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*Corresponding author. E-mail: rroqu@ce.ufl.edu indispensable tools for the evaluation of pavement response and performance. Although three-dimensional FEM provides the most accurate representation of a pavement structure, it remains a relatively challenging and costly technique, particularly for pavement performance predictions that involve a continuously changing structure and many thousands of load applications of varying magnitudes and positions.

Axisymmetric and two-dimensional analyses provide simpler, more cost-effective solutions at the expense of accuracy. Axisymmetric solutions have long been used to analyze pavement structures (e.g. it forms the core of the FEM program ILLIPAVE, 1990). However, these solutions are generally limited to the application of a single symmetrical tire load, although recent work has been done that allows axisymmetric solutions to handle multiple loads and nonlinear analysis. In any case, discontinuities in the form of damage zones and/or cracks cannot be properly modeled using axisymmetric solutions. As shown in Fig. 1, in an axisymmetric model, a crack will essentially be modeled as a discontinuous ring around the symmetrical load, which would result in inaccurate stress distributions and/or stress concentrations at the crack tip. This would be a particularly poor way to model the mechanism of surface-initiated longitudinal wheel path cracking, as described by Myers *et al.* (1998).

As shown in Fig. 1, a two-dimensional model results in a much better representation of a continuous longitudinal crack in a pavement system. In addition, multiple loads and non-symmetrical tire contact stresses can be represented in the two-dimensional model. Unfortunately, the analysis is conducted by assuming either plane stress or plane strain conditions, and the load(s) are essentially considered to be strip loads, which result in different bending patterns than a true wheel load applied in three-dimensional analysis. Therefore, before attempting to use two-dimensional analysis for the evaluation of pavement response and performance, one must develop a thorough understanding of the differences in stress distributions between two- and three-dimensional analyses. Furthermore, it would be useful to develop an approach to determine stress distributions for pavement analysis using a two-dimensional model that reasonably estimates the stresses predicted by a true three-dimensional model. This tool would be particularly useful for parametric studies to show relative effects of different factors on pavement response and performance, as well as for the development of a design system where the use of a full-blown three-dimensional analysis may be prohibitive or impractical.

Objectives

Recent advances in the understanding of asphalt mixture behavior and the failure mechanisms of asphalt pavements has clearly illustrated the need to model complex tire loading conditions as well as the development of damage, permanent deformation, and crack growth within asphalt pavement systems.

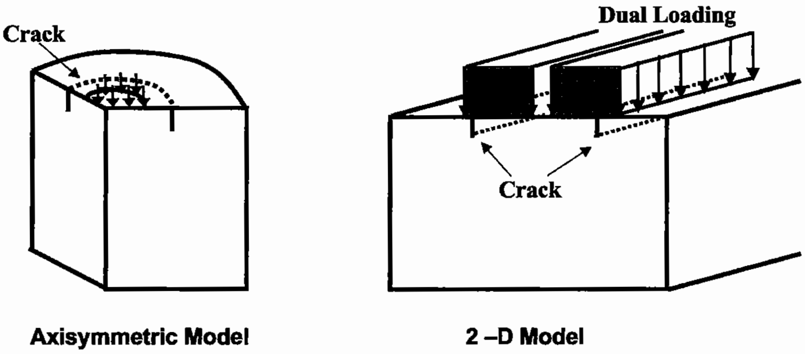

FIGURE 1 Schematic of axisymmetric and 2D finite element pavement models.

Merrill *et al.* (1998), Roque *et al.* (1998) and Myers *et al.* (1999) showed how measured contact stresses under radial truck tires appeared to explain the relatively recent prevalence of surface-initiated cracking and near-surface rutting in pavements. This work, and the work of other researchers (e.g. Jacobs *et al.* (1992); Woodside *et al.* (1992); de Beer *et al.* (1997)) has left little doubt that tire contact stress distributions must be modeled accurately to properly evaluate asphalt pavement response and performance. Jacobs *et al.* (1992) and Myers *et al.* (1998) successfully applied principles of superposition and elastic layer analysis to model response of pavements subjected to complex contact stresses. However, the process was exceedingly tedious and the results were relatively inaccurate because of limitations of applying circular, uniformly distributed loads, and the inability to introduce a yield condition in elastic analysis. In addition, other sources of material nonlinearity, including the effects of stress state and micro-damage, and discontinuities resulting from cracks cannot be modeled in elastic layer analysis. This precludes the investigation of more advanced failure theories currently being pursued for the analysis of pavement performance, such as continuum damage mechanics (e.g. see Kim *et al.* (1997)) and fracture mechanics (e.g. see Jacobs *et al.* (1996); Roque *et al.* (1999)).

The primary objectives of this study were as follows:

- To develop a procedure for using two-dimensional analysis to predict pavement response at critical locations with respect to fracture propagation for several structural and loading cases.
- To evaluate and illustrate the differences between two- and three-dimensional bending response of asphalt pavement structures.
- If possible, to identify/develop an approach to modify two-dimensional analyses for reasonable approximations of the three-dimensional response of asphalt pavements.
- To illustrate how the modified approach may be used in practice for the analysis and evaluation of pavement systems.

Scope

The evaluation conducted in this investigation was restricted to the following:

- Only the stress–strain response of the asphalt concrete layer was considered in the evaluation. The accuracy of stress distributions within base and subgrade were not considered. Therefore, the evaluations and approach presented herein are primarily suitable for near-surface distress modes of load-associated cracking and rutting within the asphalt surface layer.
- A broad range of conventional pavement structures (i.e. asphalt surface on aggregate base and subgrade) were considered. However, overlays on rigid pavements were not addressed.
- Well-established principles of pavement response (i.e. layered systems) indicate that near-surface stresses within the asphalt concrete surface layer are almost exclusively governed by surface thickness, surface stiffness, and base course stiffness. Therefore, these were the three primary variables investigated and used to define the wide range of pavement structures investigated. Some limited analyses were conducted and are presented herein that verified the negligible effects of subgrade stiffness and base layer thickness on near-surface response.
- All two-dimensional and axisymmetric* analyses were conducted using the ABAQUS finite element computer program (Hibbitt *et al.*, 1997). Plane strain conditions were assumed for non-symmetrical simulations. All analyses were conducted using symmetry.

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*It should be noted that from this point forward, axisymmetric models and analyses shall be denoted as three-dimensional (3D) within the context of the paper.

Research Approach

The primary objectives of the research were met by comparing stresses obtained from three-dimensional finite element analyses to stresses obtained from two-dimensional plane strain analyses using the same contact stress and width of load on a broad range of pavement structures. The observed differences were evaluated to identify characteristic patterns in the differences, and to determine whether specific relationships could be established between these solutions. Specifically, relationships were sought that would allow reasonable estimates of the three-dimensional solutions based on the two-dimensional analyses.

MODELING PAVEMENT STRUCTURES IN ABAQUS

The range of pavement structures evaluated is summarized in Table I. Asphalt concrete layer thickness was varied from 5 to 20 cm, which encompasses the range of surface layer thickness typically used on conventional pavements with aggregate base. Furthermore, as will be shown later in this paper, preliminary analyses indicated that the difference between two- and three-dimensional analysis was found not to change for thicknesses greater than 20 cm. Base course and subgrade thickness was held constant at 30 and 840 cm, respectively. As discussed earlier, it is common knowledge that base course thickness has a negligible effect on near-surface stress distributions.

Three levels of asphalt concrete modulus (1400, 5516, and 8274 MPa) and two levels of base course modulus (140 and 300 MPa) were used. These resulted in surface to base layer stiffness ratios (E_1/E_2) ranging from 4.6 to 59.0. The asphalt modulus values were selected to encompass asphalt concrete stiffness within the in-service temperature range. The base course values represent a poor and a good granular base course. Two subgrade layer modulus values were used (48.3 and 100 MPa) to verify that subgrade modulus has a negligible effect on near-surface stress distributions.

An applied contact stress of 793 kPa, which corresponds to a standard inflation pressure for a typical radial truck tire was used to conduct all analyses. Also, a contact width (two-dimensional) or diameter (three-dimensional) of 20 cm, which corresponds to the width of a typical radial truck tire, was used for all analyses.

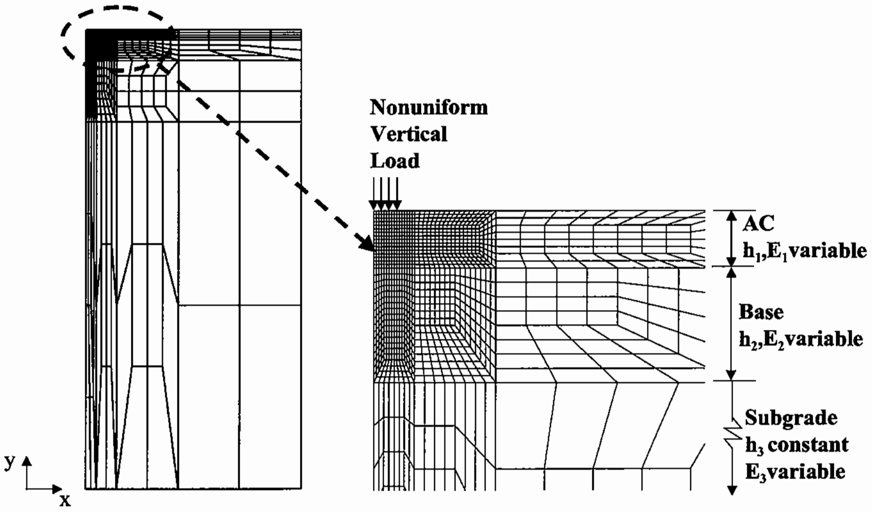
A general schematic of a typical finite element mesh used to model the pavement structures in ABAQUS is shown in Fig. 2, which also shows a more detailed view of the typical mesh structure used near the loading area. Since it was only necessary to use one load to meet the objectives of this study, an axisymmetric model was used to represent the three-dimensional loading case for comparison to the two-dimensional analyses. Therefore, the same mesh structure was used for both two-dimensional and three-dimensional (axisymmetric) analyses.

The accuracy of the mesh structures used were evaluated by comparing the ABAQUS solutions to solutions obtained with the BISAR elastic layer

TABLE I Parameters used in development of pavement finite element models

AC layer thickness (cm)	Stiffness modulus (MPa)						
	Asphalt concrete layer			Base layer		Subgrade layer	
5	1400	5516	8274	140	300	–	100
7.5	1400	5516	8274	140	300	48.3	100
10	1400	5516	8274	140	300	48.3	100
15	1400	5516	8274	140	300	48.3	100
20	1400	5516	8274	140	300	48.3	100

Note: Applied contact stress on models = 793 kPa; base thickness = 30 cm, subgrade thickness = 840 cm



ABAQUS Finite Element 2-D and Axisymmetric Model

Detailed View of Model Near Loading Area

FIGURE 2 Schematic and detailed view of pavement system modeled using the finite element program, ABAQUS.

computer program (de Jong *et al.*, 1973). Although detailed results are not presented herein for the sake of brevity, excellent correspondence was obtained between stress distributions predicted by the two programs. This indicated that the ABAQUS code was working properly.

EVALUATION OF PREDICTED STRESSES

Figures 3 and 4 show that differences between two-dimensional and axisymmetric solutions are highly dependent upon the characteristics of the pavement structure. These figures show the transverse (horizontal) stress distributions beneath the loaded area at the bottom of the asphalt concrete surface layer as predicted by two- and three-dimensional representation of the pavement structure. The tensile response immediately underneath the load has traditionally been considered to be the critical response related to fatigue cracking in pavements (critical tensile stress). Figure 3 shows that for a pavement structure with low stiffness ratio ($E_1/E_2 = 4.6$), the two- and three-dimensional solutions predict almost exactly the same critical tensile stress. On the other hand, Fig. 4 shows that the two-dimensional solution grossly over-predicts the tensile stress for a pavement with high stiffness ratio ($E_1/E_2 = 59.0$). Tensile stress at the bottom of the asphalt concrete layer was nearly a factor of four greater for the two-dimensional analysis than for the three-dimensional analysis (2300 vs. 600 kPa). Figures 3 and 4 also indicate that significant differences were observed between the two- and three-dimensional stress distributions at distances further from the center of the loaded area. However, the accurate prediction of stresses in this region is less critical for two reasons: (1) the stresses are compressive for pavements with low stiffness ratios (Fig. 3); and (2) even when the stresses are tensile (Fig. 4), they are significantly lower than under the center of the loaded area.

An evaluation of similar comparisons for the range of pavement structures investigated indicated that the difference between tensile stresses predicted by two- and three-dimensional analyses was related to the relative stiffness between the surface and base layers. In other words, the relative difference between the two solutions appeared to be primarily governed by the stiffness ratio (E_1/E_2) and the thickness of the surface layer.

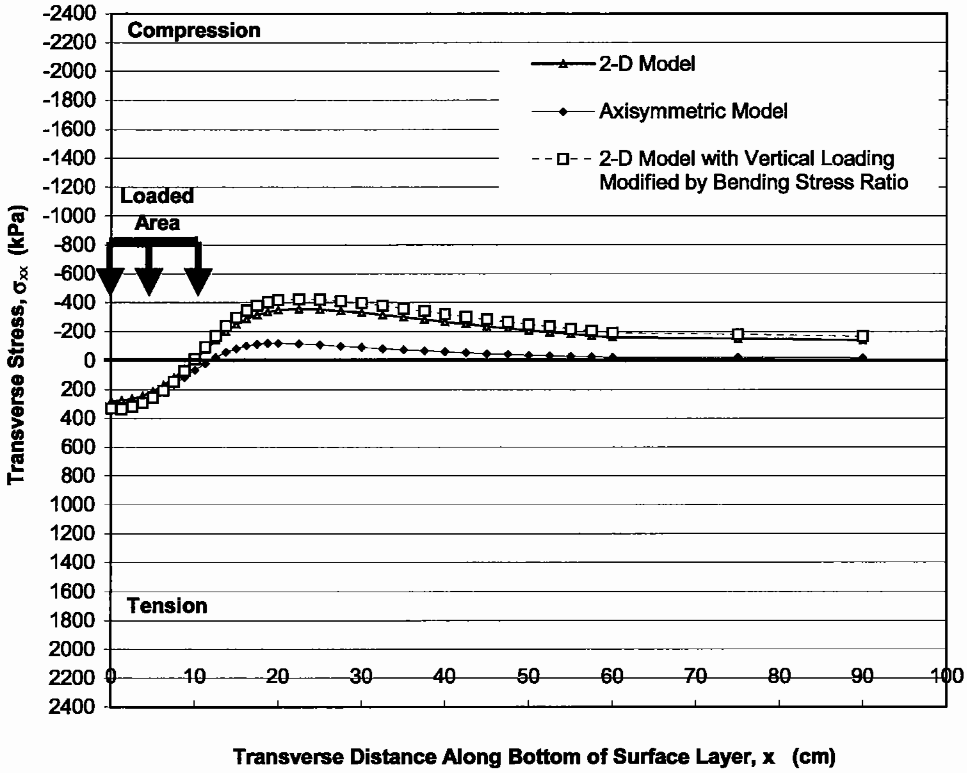


FIGURE 3 Transverse stress distribution along bottom of 10 cm asphalt concrete layer for stiffness ratio of 4.6 ($E_1 = 1400$ MPa: $E_2 = 300$ MPa).

Based on these observations, analyses were conducted to determine whether a structurally-dependent correction factor could be identified to estimate three-dimensional tensile stresses using results of the two-dimensional analysis. The idea involved the determination of a factor that could be used to modify surface loads (pressure) applied to the two-dimensional analysis, such that the predicted bending stress (specifically, the critical tensile stress) would closely approximate the bending stress predicted by three-dimensional analysis.

Definition of Bending Stress Ratio

A ratio between the critical tensile stress predicted by three-dimensional analysis and the critical tensile stress predicted using two-dimensional analysis was defined to normalize the difference between the two stresses. In addition, if the ratio could be related to pavement structural characteristics, then it would also serve the purpose of acting as modifying factor for two-dimensional loads (strip load) to obtain accurate three-dimensional stress predictions using two-dimensional analysis.

The bending stress ratio was defined as follows:

$$\mathrm{BSR} = \frac{\sigma_{\mathrm{XX(3\text{-}D)}}}{\sigma_{\mathrm{XX(2\text{-}D)}}} \qquad (1)$$

where BSR is the bending stress ratio, $\sigma_{\mathrm{XX(3\text{-}D)}}$, critical tensile stress based on three-dimensional analysis, $\sigma_{\mathrm{XX(2\text{-}D)}}$ is the critical tensile stress based on two-dimensional analysis.

A BSR was calculated for each of the pavement structures analyzed. For the pavement structure used to obtain the results presented in Fig. 3, the BSR was approximately 1.0, whereas a BSR of 3.8 was determined for the pavement structure used to obtain the results presented in Fig. 4. Figures 3 and 4 also

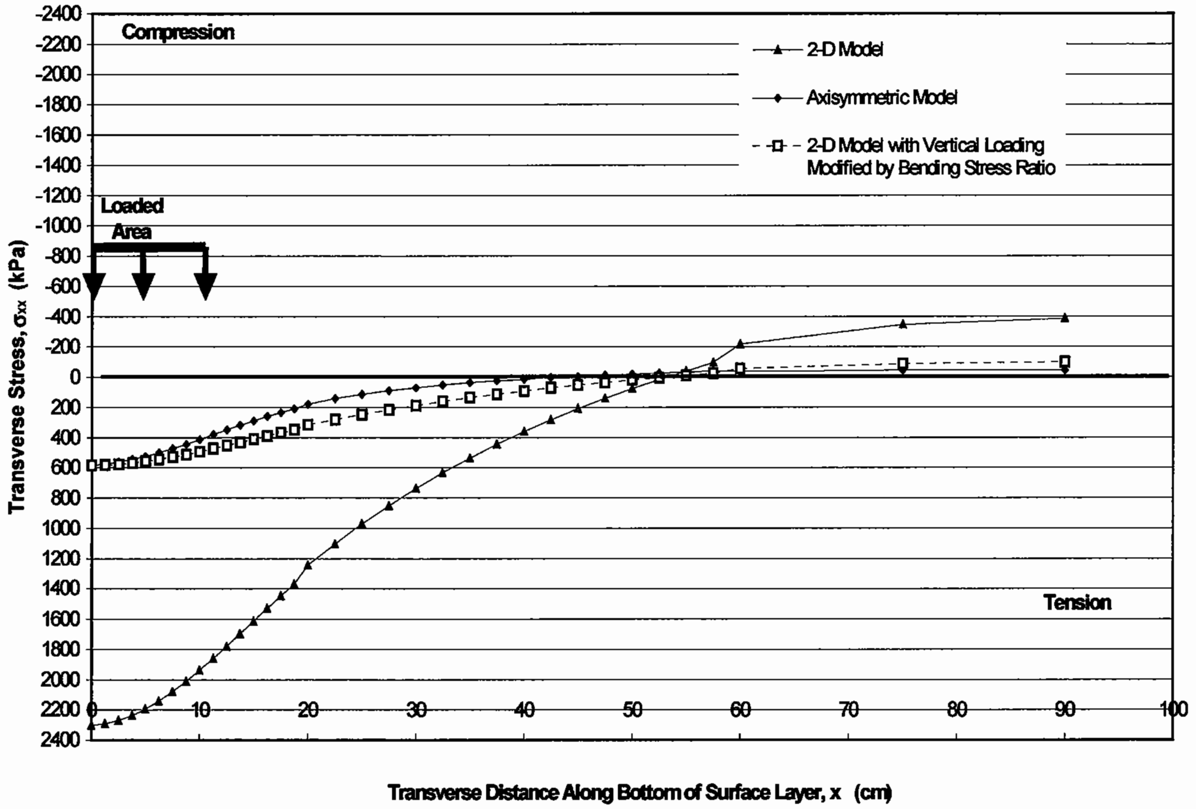


FIGURE 4 Transverse stress distribution along bottom of 20 cm asphalt concrete layer for stiffness ratio of 59 ($E_1 = 8274\,\text{MPa} : E_2 = 140\,\text{MPa}$).

show modified stress distributions obtained by multiplying the two-dimensional results by the corresponding BSR. As shown in Fig. 3 (low stiffness ratio case), the modified two-dimensional results agree well with the three-dimensional stress distribution immediately underneath the load, but the correspondence between the compressive stresses further from the load did not improve. Figure 4 shows that for the high stiffness ratio case, the correspondence was excellent immediately underneath the load, and also improved significantly further from the load. As mentioned earlier, the area of tensile stress immediately under the load is generally considered the critical area for evaluating load-associated fatigue cracking of asphalt pavements. Therefore, it is logical to define the bending stress ratio such that response is matched most accurately in this zone.

Because the critical tensile stresses are found at or close to the center (line of symmetry) of the analyzed pavement structure, the BSR value will only be applicable at a reasonable distance from the edge of a pavement (or pavement layer).

Relations Between Bending Stress Ratio and Structural Parameters

As mentioned earlier, the relative difference in critical tensile stresses between the two- and three-dimensional solutions appeared to be primarily governed by the stiffness ratio (E_1/E_2) and the thickness of the surface layer (h). Therefore, the bending stress ratio should be related to E_1/E_2 and h. Figures 5 and 6 show relationships between BSR and h, and BSR and E_1/E_2. The two figures show essentially the same data presented in two ways.

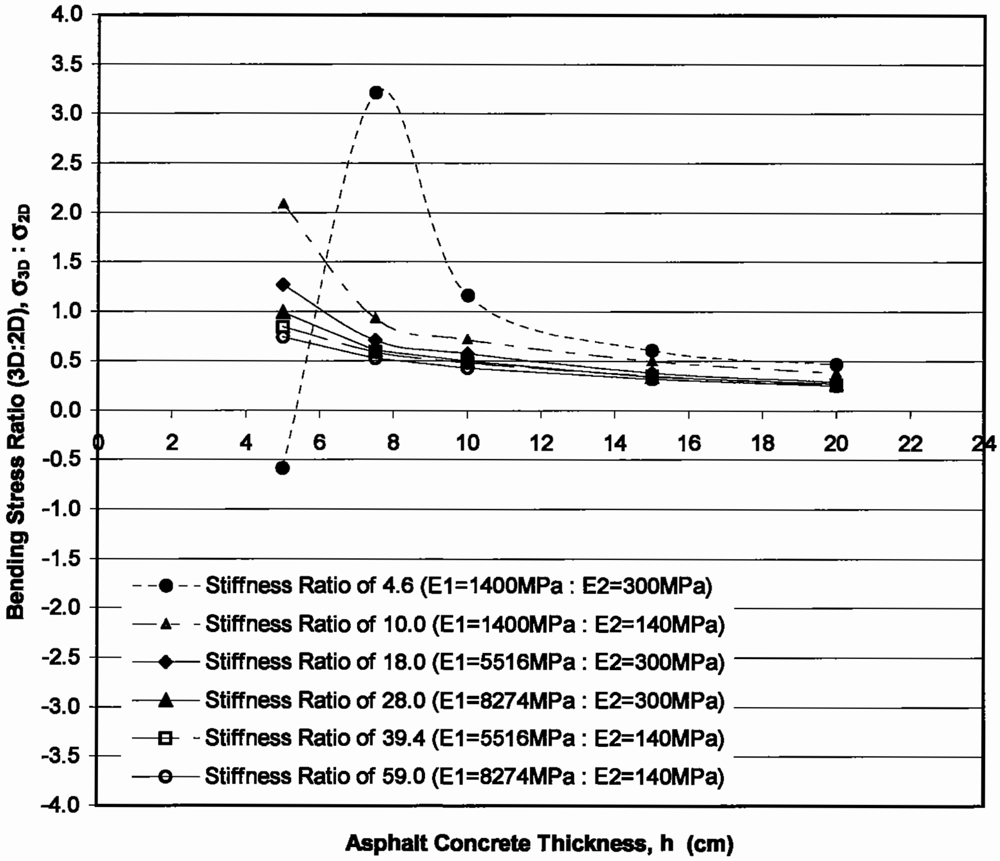


FIGURE 5 Effect of asphalt concrete thickness on bending stress ratio.

The following observations may be made on the basis of the results presented in Figs. 5 and 6:

- In general, BSR increases as stiffness ratio or surface layer thickness decreases.
- In general, BSR decreases at a decreasing rate as surface layer thickness increases or as stiffness ratio increases.
- For a given stiffness ratio, the BSR approached a constant value as the surface layer thickness was increased. In other words, beyond a certain surface layer thickness (approximately 20 cm) the relative difference between the two- and three-dimensional solutions did not change.
- For a given surface layer thickness, the BSR approached a constant value as stiffness ratio was increased. In other words, beyond a certain stiffness ratio (approximately 40) the relative difference between the two- and three-dimensional solutions did not change.
- For the majority of pavement structures, BSR was less than 1.0. This indicates that two-dimensional analysis over-estimates the critical tensile stress for most pavement structures.
- BSR exceeded 1.0 (i.e. two-dimensional analysis under-estimated critical tensile stress) for cases with thin surface layers and low stiffness ratios. However, a sharp reversal, and even negative BSR's were observed in cases of very thin (5 cm) surface layers with low stiffness ratios. These results are explained by the fact that the bottom of a very thin surface layer may be in compression rather than tension, particularly in cases where the stiffness ratio is low.

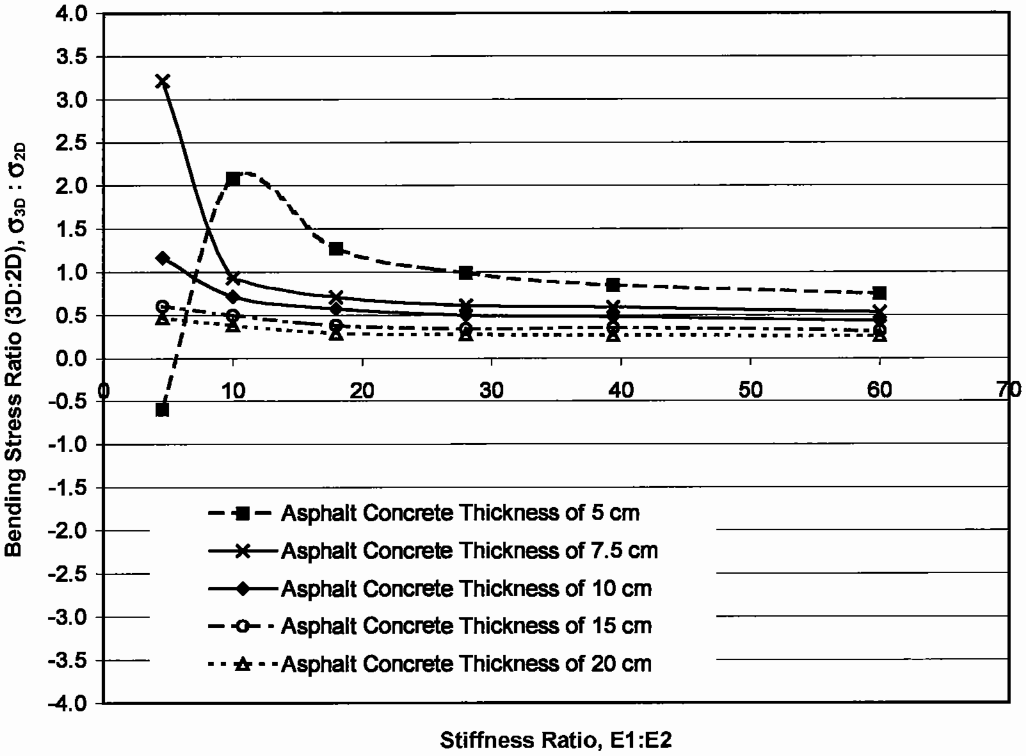


FIGURE 6 Effect of stiffness ratio ($E1/E2$) on bending stress ratio.

It should be noted that highway pavements, particularly those in relatively high-traffic areas, rarely have surface layer thickness less than 7.5 cm. Therefore, the observed reversal in the BSR relationship has little or no practical significance.

Based on the observations from Figs. 5 and 6 discussed above, the following non-linear relationship was developed for BSR as a function of stiffness ratio (E_1/E_2) and thickness ratio (h_1/h_2), where h_1 is the thickness of the surface layer and h_2 is the thickness of the base layer:

$$\log(\text{BSR}) = -0.29655(E_1/E_2)^{0.29531}(h_1/h_2)^{0.95659}$$
$$R^2 = 0.97 \qquad (2)$$

This following range of parameters were used to develop Eq. (2):

- Surface layer thickness from 7.5 to 20 cm, which corresponds to surface to base layer thickness ratios (h_1/h_2) from 0.25 to 0.67.
- Stiffness ratios (E_1/E_2) from 4.6 to 59.0.

In other words, pavement structures that resulted in reversals in the BSR trends were not included in the development of the equation.

It must be noted that the relationships presented in Figs. 5 and 6 assume the following:

- BSR is only a function of the stiffness ratio (E_1/E_2) and not of the magnitude of the stiffness of the individual layers (E_1 or E_2) used to determine stiffness ratio.
- BSR is independent of subgrade stiffness.
- The area of interest is not near the edge of any pavement layer as BSR was developed on the basis of a semi-infinite layer assumption.

Therefore, additional analyses were conducted to evaluate the validity of these assumptions. Figure 7 clearly shows that the magnitude of E_1 and E_2 had no effect on the relationship between BSR and surface layer thickness. As shown in the figure, stiffness ratios

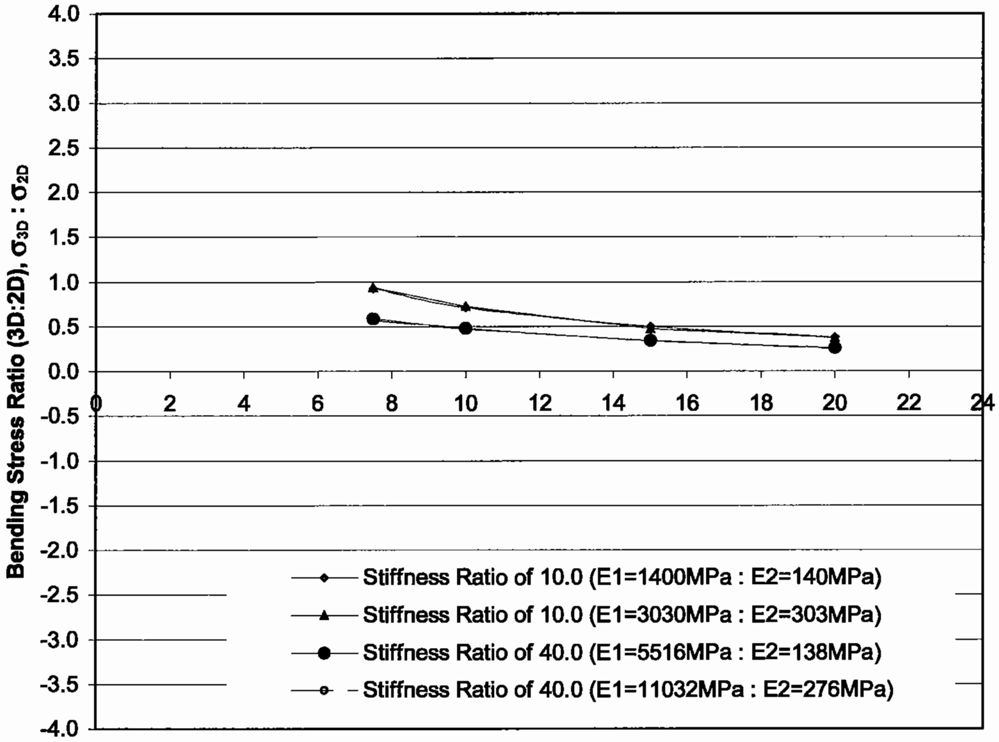


FIGURE 7 Effect of asphalt concrete and base layer stiffness on bending stress ratio.

of 10 and 40 were achieved by using two different levels of surface and base layer stiffness. Results of the analyses indicated that identical BSR's were determined regardless of how the stiffness ratio was achieved.

Similarly, Fig. 8 shows that subgrade stiffness had a negligible effect on the relationship between BSR and surface layer thickness for stiffness ratios ranging from 10 to 28. As shown in the figure, essentially identical BSR's were determined at a given surface layer thickness and stiffness ratio for different values of subgrade modulus.

APPLICATION OF BENDING STRESS RATIO

Overview

The bending stress ratio (BSR) described in the previous section provides a useful tool for predicting the three-dimensional bending stresses in asphalt pavement systems using two-dimensional finite element analysis. The benefits are particularly important for evaluating highly complex contact stress conditions or for cases where a large number of computer runs are required to predict pavement performance. For example, the prediction of crack propagation using fracture mechanics, not only requires a large number of runs for a pavement structure and wheel loads that are continually changing, but also requires continually changing the finite element mesh as crack growth progresses. The use of a two-dimensional model would result in considerable benefit in terms of reduced complexity and computer run times for such a comprehensive design procedure.

The applicability of using finite element analysis for complex pavement structures was assessed in a study carried out by Roque *et al.* (2000). The vertical and transverse stresses at the surface of the

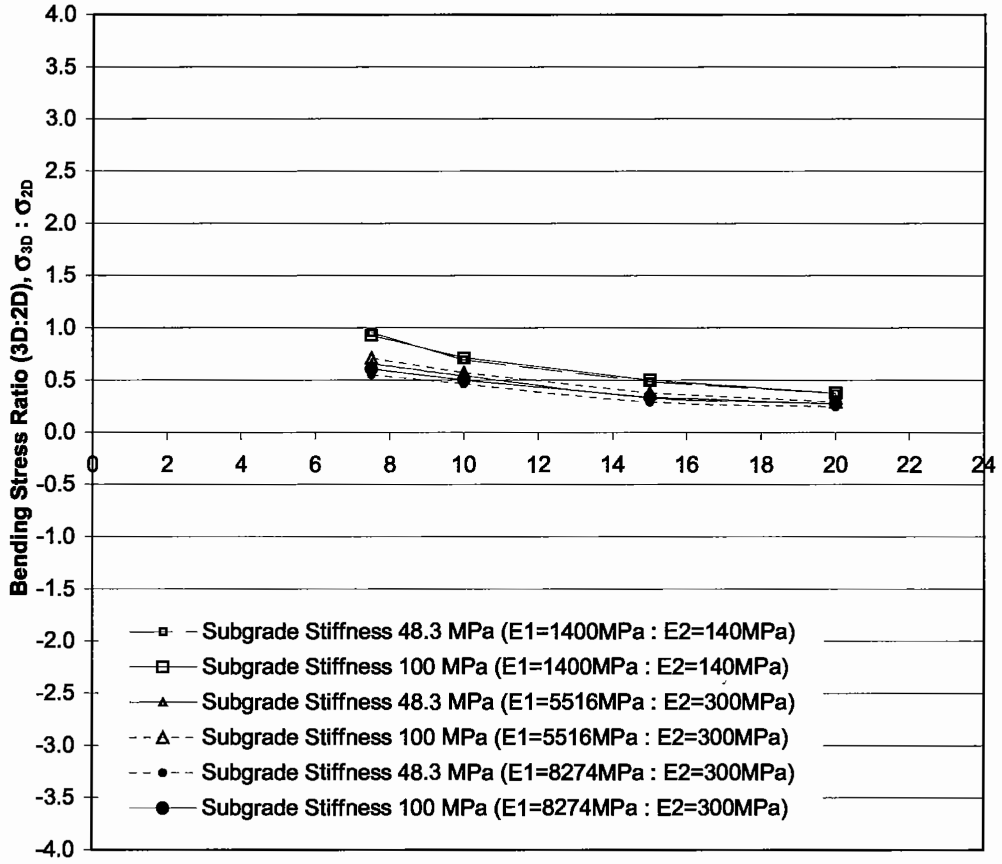


FIGURE 8 Effect of subgrade stiffness on bending stress ratio at various stiffness ratios ($E1/E2$).

pavement system were predicted for the following two cases:

1. A finite element tire model developed in the study was applied directly to the two-dimensional pavement structure.
2. Contact stresses predicted by applying the tire model to a steel bed were converted to nodal point forces that were applied to the surface of the pavement structure. This corresponds to the case of using contact stresses measured on a real-life steel bed to predict pavement response.

The comparison of actual measured tire–pavement interface stresses to those predicted on a two-dimensional finite element model gave a good indication of the practicality of using two-dimensional models to approximate three-dimensional response. As seen in Fig. 9, these analyses clearly indicate that use of contact stresses measured on a steel bed, predicted pavement stresses well in terms of both the pattern of the stress distributions and the magnitude of stresses. In the interest of space, these comparisons are not presented herein.

An example of the generalized two-dimensional model that could be used to represent this situation is shown in Fig. 10, which shows a pavement surface with multiple cracks loaded using a realistic tire contact stress distribution involving non-uniform vertical and transverse stresses. An axisymmetric model would be unsuitable for this problem because it would not properly model the tire contact stresses or the discontinuities caused by the cracks. On the other hand, modeling this problem in three dimensions for a broad range of pavement structural characteristics,

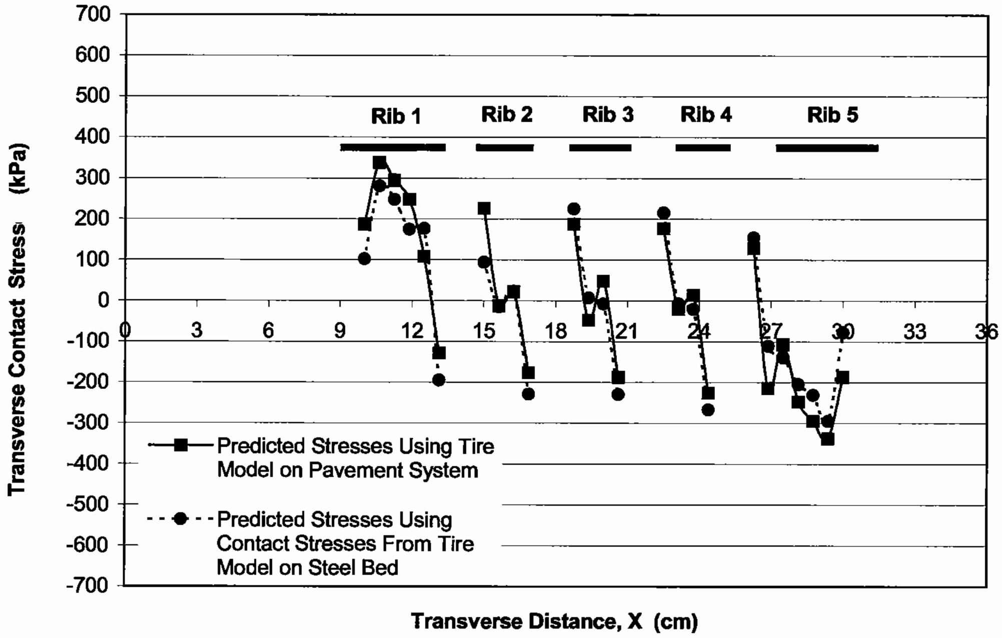


FIGURE 9 Comparison of finite element tire model to measured tire contact stresses: transverse contact stresses predicted at surface of 10 cm pavement system.

load positions and crack lengths would pose a formidable and time-consuming problem. The modified two-dimensional approach presented below would provide reasonable solutions comparable to those obtained using a three-dimensional model, but with considerably less complexity and cost.

Procedure

The following procedure would be followed to use the BSR relationships presented earlier (Figs. 5 and 6 or Eq. (2)) to obtain a modified two-dimensional solution that approximates the true three-dimensional bending response of typical pavement structures:

1. Calculate the surface-to-base layer stiffness ratio (E_1/E_2) and the surface-to-base layer thickness ratio (h_1/h_2) for the pavement structure being analyzed.
2. Use these ratios to determine the BSR using either Figs. 5 and 6, or Eq. (2). Only use Eq. (2) if the pavement structural parameters are within the range used to generate the equation (stipulated earlier in the paper).
3. Multiply only the *vertical* contact stresses by the BSR. The calculated stresses are the modified vertical contact stresses. The transverse tire contact stresses should not be modified for two-dimensional analysis since the bending response at the bottom of the pavement under the load is the desired response.
4. Apply the modified vertical contact stresses and the transverse contact stresses, if any, to the two-dimensional finite element representation of the pavement structure. The width of the wheel load(s) used in the two-dimensional analysis should be equal to the width or diameter of the actual tire.

Based on the analyses conducted in this investigation, the resulting tensile stresses within the asphalt concrete surface layer in the vicinity of the tire would reasonably approximate the tensile stresses for the true three-dimensional loading condition. Furthermore, for cases similar to the one shown in Fig. 10, the modified two-dimensional analysis could be used to determine realistic stress intensity factors and crack

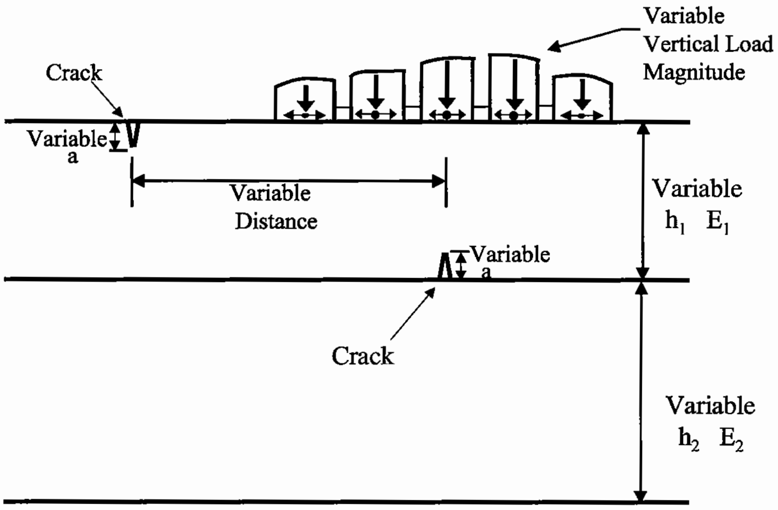


FIGURE 10 Example application: parametric study of a cracked pavement.

growth rates for variable loading conditions. The authors are presently using the modified approach in this way to evaluate the effects of different factors on crack growth rates in pavements.

OTHER OBSERVATIONS

The correspondence between two- and three-dimensional analysis presented in this paper was obtained for the case of linear elastic layered systems. The development of a similar approach for a layered system composed of materials exhibiting non-linear behavior would need to be investigated; however, it was clearly shown that the assumption of a homogeneous, linear elastic layered material can be used to obtain reasonable predictions of measured field loading responses on typical Interstate flexible pavement systems (1997). At first glance, it would appear that the number of structural and material parameters influencing the bending stress ratio between two- and three-dimensional analysis may be overwhelming, such that the development of a simplified approach would not be possible. However, earlier research work suggests that a modified version of the approach presented herein may be suitable for the case of predicting bending stresses within the asphalt concrete layer. Roque *et al.* (1992) showed that for a broad range of pavement structures and non-linear material properties, linear elastic analysis could be used to accurately determine the stress–strain response within the surface layer if suitable effective layer modulus values are used in the analysis. They presented a procedure for determining suitable effective layer modulus values of non-linear layers that involved predicting the non-linear deflection response of the pavement system, then back-calculating effective layer moduli using the linear elastic layer model. This suggests that a stiffness ratio calculated using the effective layer modulus values determined in this manner, could be used along with the surface-to-base layer thickness ratio to apply the BSR concept presented in this study. However, it is obviously recommended that this approach be fully investigated and evaluated before it is put to use.

SUMMARY AND CONCLUSIONS

This study was undertaken to evaluate discrepancies between two- and three-dimensional analysis of pavement structures, and to determine whether a modified two-dimensional analysis could be used as a reasonable approximation of the three-dimensional response of asphalt pavements. Two- and three-dimensional analysis of a range of pavement structures typically encountered in highway pavements indicated that discrepancies between two- and three-dimensional analyses were highly dependent upon the structural characteristics of the pavement. A BSR was defined as the ratio between the critical tensile stress from three-dimensional analysis and the critical tensile stress from two-dimensional analysis. It was determined that the BSR was primarily a function of surface-to-base layer stiffness ratio (E_1/E_2) and surface-to-base layer thickness ratio (h_1/h_2) and specific relationships were developed between BSR and these parameters. An approach was developed to use the pavement structural characteristics and BSR to modify two-dimensional loads such that two-dimensional analyses would reasonably estimate the true three-dimensional pavement stresses.

Based on the comparisons presented in this study, it was concluded that the modified two-dimensional analysis developed in this study can be used to reasonably approximate the three-dimensional tensile stresses within the asphalt concrete surface layer of the typical range of conventional pavement structures encountered in highway pavements. Conventional pavements structures include pavements with asphalt concrete surface, aggregate base, and subgrade (or subbase and subgrade).

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