FINITE ELEMENT STUDY OF THE REHABILITATION OF FAULTED PORTLAND CEMENT CONCRETE PAVEMENTS

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16. ABSTRACT

The objective of the study was to determine the effectiveness of dowel bar retrofitting of faulted PCC pavements by (1) modeling FWD Test data for computer model development and verification, (2) evaluating long term effects by simulating material degradation of the rigid pavement system, and (3) determining and classifying deficiencies and trends of the parametric study.

The results of the finite element analysis shows that remediation in the form of dowel bar retrofitting greatly reduces fault development. Use of a dowel bar significantly raised the stress concentration of the concrete at the dowel bar-concrete interface. However, these stresses are well below the levels that cause failure. Simulated degradation of the base course increased stresses in the dowel bar and concrete area. Pressure differentials in base course were reduced with use of a dowel bar. Recommendations for future analysis are also made.

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"Finite Element-Rehabilitation of Faulted PCC Pavements"

Finite Element Study of the Rehabilitation of Faulted Portland Cement Concrete Pavements

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DISCLAIMER

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SUMMARY

In this project, researchers developed a two dimensional finite element method (2D-FEM) model to evaluate the fault remediation techniques of Portland Cement Concrete (PCC) pavement being considered by the Washington State Department of Transportation (WSDOT). Two basic models were compared: a model with a dowel bar retrofit at the transverse joint and a model with no dowel bar. The models were based on actual field dimensions of the pavement system. Falling Weight Deflectometer (FWD) data collected from a PCC pavement test section located on I-90 was used to verify the accuracy of the 2D-FEM model under a static load simulating the FWD test. Once an acceptable model for both doweled and non-doweled cases was developed, a parametric study of the model was conducted using decreasing material strengths of both the pavement and subgrade.

Evaluation of the 2D-FEM model is based on load transfer, deflection, and stress concentrations in the joint area. Results from the parametric study revealed an insignificant decrease in load transfer for the retrofitted dowel bar model over a range of subgrade and concrete strengths. The non-doweled model displayed considerable deflections and low load transfer values. Concrete stresses in the doweled model increased in response to the lower subgrade strengths, while they decreased slightly in the non-doweled model. Subgrade strains remained constant in the doweled model, but increased significantly in the non-doweled case. The doweled model distributed the applied loads to the base and subgrade in a more uniform manner. This decrease in stress differential may reduce the potential for fines migration and faulting.

Although higher concrete stresses were observed in the doweled model, this is unlikely to cause failure. The stresses were well below the failure strength of concrete. However, review of potentially unacceptable conditions in concrete stress, subgrade strain, and load transfer is warranted. This should take the form of more sophisticated models, and extensive field data collection.

INTRODUCTION AND RESEARCH APPROACH

THE PROBLEM

Greater than 50 percent of the Portland Cement Concrete (PCC) pavements in the state of Washington are 25 to 30 years old and have exceeded their design life. The majority of the PCC pavements have had their original design loads exceeded by 2 to 5 times. These conditions have led the Washington State Department of Transportation (WSDOT) to review various rehabilitation techniques in terms of both longevity and economic feasibility. In general, the alternatives being considered are aimed at rehabilitating, and over the long term, minimizing fault development across the transverse joints located between pavement slabs. The most harmful result of faulting is a decrease in ride quality. This is especially noticeable for tractor-trailer vehicles.

The mechanics of fault development in a rigid pavement system are not completely understood at this time. Extensive research (Spellman, 1972) identified the characteristics of fault development, and determined that the migration of fine particles from the approach slab subgrade to the leave slab subgrade was common to most faulted joints. Fine particle migration is believed to be associated with the combination of poor drainage and erodible subgrade or subbase material (Pierce, 1993). This results in a series of alternating low and high velocity water movements across the joint area in response to moving wheel loads. The water in this scenario aids in the transport of fines from the approach slab subgrade to the leave slab subgrade. This leads to elevation changes in the joint areas of both slabs. The loss of fine material lowers the approach slab while the corresponding build up of fine material raises the leave slab. The end result is a permanent fault providing unacceptable ride quality and a deficient service level. A schematic of the faulting process is presented in Figure 1.

Current Remedial Practice

Several approaches have been used to rehabilitate, or remedy the faulted pavement structure. Some of the most common solutions at this time include grinding the pavement surface, undersealing the slab, retrofitting the joint with steel dowel bars, and completely replacing the slab. These measures have been used in separate, in combination with each other, and in combination with other techniques.

The basic problem with the current techniques, excluding dowel bar retrofitting, is that the mechanism of fault development is not addressed directly. Consequently, faulted conditions appear shortly after maintenance is completed (Mahoney, et al., 1991). Surface grinding and slab replacement improve ride quality, but do not suspend the development of alternating water movements and subsequent fine particle migration in the subgrade. The use of dowel bars provides a means of transferring wheel loads across the joint and thereby may reduce the pumping action. However, the long term effectiveness of dowel bar retrofitting is not well documented.

In an effort to better understand the faulting process, and at the same time develop a suitable remediation technique for faulting, the Washington State Department of Transportation (WSDOT) is conducting several research programs. These programs include the implementation and analysis of different rehabilitation techniques, and the performance

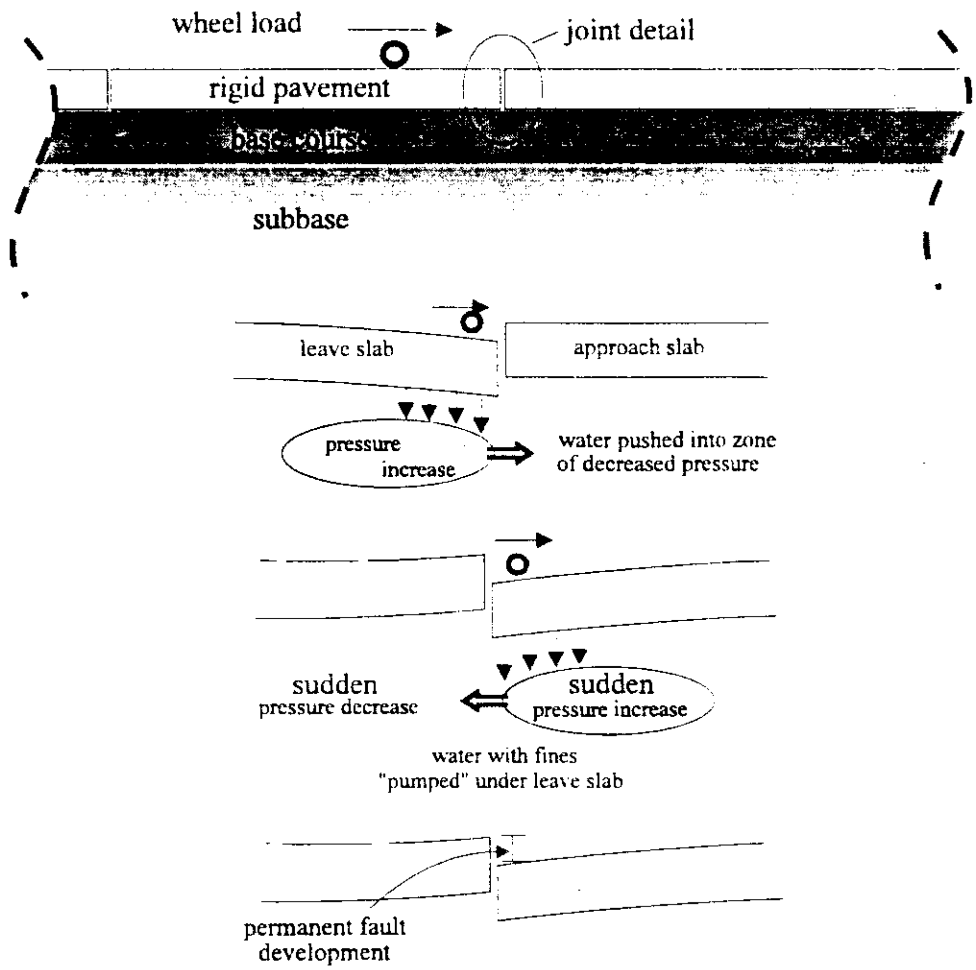

Figure 1. Schematic of fault development in PCC pavement system.

of large scale field tests. In addition to field testing, numerical and analytical models are sought to predict long term performance.

RESEARCH OBJECTIVES

Numerical models offer the advantage of studying the effects of different parameters with minimal cost increase. Evaluation of PCC pavement performance in this study is analyzed using the finite element method. The primary objective of this study is to develop a finite element method (FEM) model which can predict long term fault rehabilitation performance using current field data. This objective requires the completion of the following tasks:

- the assessment of field conditions and the collection of field data including falling weight deflectometer (FWD) test results;
- the verification of model performance using field data
- the performance of a parametric study to assess the effects of system parameters;
- the analysis of parametric study results;
- the interpretation of the FEM results with recommendations for future study.

The Falling Weight Deflectometer Test

Generation of a suitable finite element model was based on data obtained from falling weight deflectometer (FWD) testing. Figure 2 illustrates the basic components of the FWD test. The test involves dropping a standard weight onto a pavement slab 6 inches from a joint

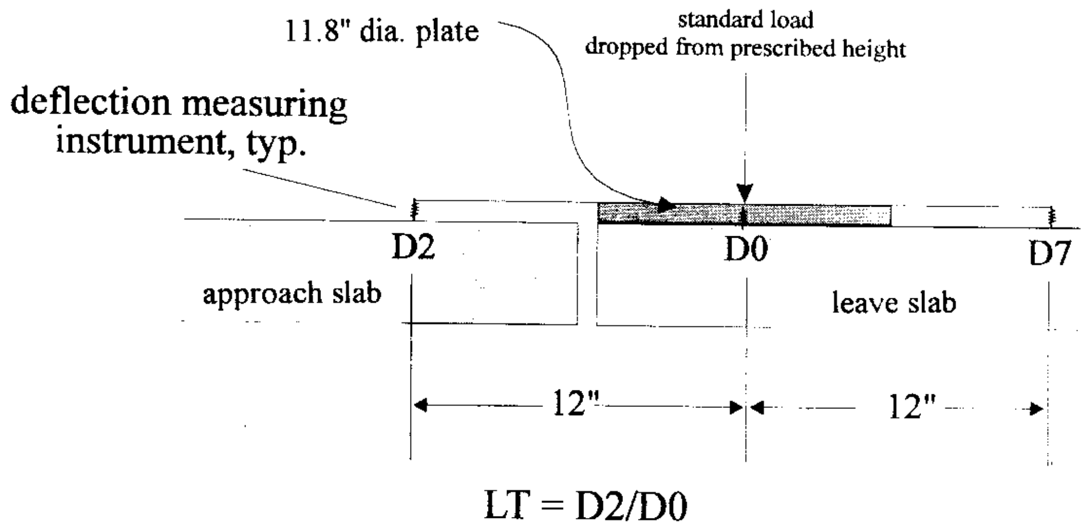

Figure 2. Falling Weight Deflectometer (FWD) Test

and measuring the deflection at the center of the load (D0) and at a point (D2) 12 inches away on the adjacent slab (Pierce 1993). Four drop heights are generally used to produce applied loads ranging from 6 kips to 12 kips. These loads and corresponding deflections are then normalized to an equivalent 9 kip load. The test provides a method for assessing the ability of a rigid pavement joint to transfer loads from one slab to another. A performance index, termed the *load transfer* and defined as the ratio of the deflection of the adjacent unloaded slab to that of the loaded slab, is used to quantify the load transfer efficiency of such joints.

Data was obtained from extensive FWD testing conducted on a PCC pavement rehabilitation section (Pierce, 1993). The test section was constructed using different load transfer restoration techniques including dowel bar retrofitting. A set of FWD measurements were taken at the start of construction and approximately four months later to compare the performance of the restoration techniques implemented in the test section.

MODEL AND SOFTWARE SELECTION

With the increasing availability of significant computational abilities, the finite element method has become an accessible modeling tool for the analysis of a variety of engineering problems. Its application to understanding the load transfer restoration of rigid pavements lends itself in a number of ways. The most noticeable is the ability to perform a parametric study on the same initial model. Additionally, depending on the capability of the finite element software being used, the method and/or positioning of loads can be altered without a major expense.

Modeling and Analysis of the PCC Pavement System

In developing the model, the primary concerns were in accurately representing, 1) the field dimensions of the PCC pavement system, 2) the specifications and mechanics of the FWD test, 3) the dynamics of moving wheel loads, and most importantly, 4) the degradation of subgrade strength resulting from the migration of fines. Since performance of the joint and the response of the materials adjacent to the joint are of interest, it requires higher resolution. By changing the material properties of certain elements, both doweled and non-doweled cases can be analyzed without sacrificing the geometrical aspects of the actual jointed condition. The effects of material degradation and different load types can also be studied using the same mesh.

Description of the Finite Element Program: ABAQUS

In this study, the software package ABAQUS was used to develop and analyze the FEM model of the PCC pavement system. ABAQUS is a commercially available finite element program developed by Hibbitt, Karlsson, and Sorensen, Inc (HKS) (ABAQUS 1992). The ABAQUS Standard Version, Release 5.0 is currently licensed to Washington State University (WSU). The program is installed on a Hewlett-Packard 9000/730 series mini-computer (workstation) environment. This particular workstation includes 128 Mb of RAM, over 3 Gb of diskspace, and uses the HP UX 8.0 operating system.

Since ABAQUS is a general finite element program, various types of elements, constitutive material models, and loading sequences are included within the program. The ABAQUS version available at WSU is capable of solving dynamic and static analyses for a variety of material behavioral properties, ranging from simple (elastic) to complex (plastic, visco-elastic, etc.), in either two or three dimensions. Additionally, consolidation and creep models that can account for pore pressure effects in soils may be employed.

Stress and Strain Tensors

In developing stress and strain measures to be used in the analysis, it is usual to begin by setting up a rectangular co-ordinate system. At a point O, three mutually perpendicular right-handed axes Ox_1, Ox_2, Ox_3 are set up. Based on this system, the components of a stress tensor, S_{ij}, and strain tensor, E_{ij}, are given respectively by (Chen and Han, 1988):

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \qquad (1)$$

$$E_{ij} = \begin{bmatrix} E_{11} & E_{12} & E_{13} \\ E_{21} & E_{22} & E_{23} \\ E_{31} & E_{32} & E_{33} \end{bmatrix} \qquad (2)$$

where the first suffix denotes the direction of the normal to the plane, and the second suffix the direction in which the component acts; for normal stresses and strains only one suffix is needed since the direction of the component is the same as that of the normal to the plane. The stresses and strains with two different suffixes are termed shear stresses and shear strains, respectively. In general, both stress and strain tensors are symmetric. Hence, $S_{12} = S_{21}$, $S_{13} = S_{31}$, $S_{23} = S_{32}$, and $E_{12} = E_{21}$, $E_{13} = E_{31}$, $E_{23} = E_{32}$.

It is evident from the definitions of stress and strain tensor that their components are dependent on the co-ordinate system. When the co-ordinate axes are rotated these components change. However, for modeling it is desirable to study the variation of parameters that are invariant with the co-ordinate system. For the present analysis, the shear stresses and strains in the octahedral plane are selected. An octahedral plane is a plane whose normal makes equal angles with each of the principal axes of stress and strain. The shear stress and strain on the face of the octahedron, τ_{oct}, and, γ_{oct}, are given respectively, by:

$$\tau_{oct} = \frac{1}{3} \left[(S_{11} - S_{22})^2 + (S_{22} - S_{33})^2 + (S_{33} - S_{11})^2 + 6({S^2}_{12} + {S^2}_{23} + {S^2}_{13}) \right]^{\frac{1}{2}} \quad (3)$$

and,

$$\gamma_{oct} = \frac{2}{3} \left[(E_{11} - E_{22})^2 + (E_{22} - E_{33})^2 + (E_{33} - E_{11})^2 + 6({E^2}_{12} + {E^2}_{23} + {E^2}_{13}) \right]^{\frac{1}{2}} \quad (4)$$

These parameters are also termed Von Mises stress and strain, respectively, as in the ABAQUS program.

The pavement-slab system is under three dimensional state of stress and strain. However, a dynamic three dimensional finite element analysis is computationally intensive and expensive. Comparison of limited 3-D analyses with 2-D plane strain analyses of the pavement system showed that the essential features are captured by the latter. Hence, the detailed analyses presented herein were performed using plane strain 2-D finite elements.

For the plane strain condition, $E_{33} = E_{13} = E_{23} = 0$ and, Eq. (2) reduces to:

$$E_{ij} = \begin{bmatrix} E_{11} & E_{12} & 0 \\ E_{21} & E_{22} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{5}$$

The corresponding stresses are related to the strains through a linear elastic constitutive law:

$$\begin{bmatrix} S_{11} \\ S_{22} \\ S_{33} \end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} (1-\nu) & \nu & 0 \\ \nu & (1-\nu) & 0 \\ 0 & 0 & \frac{(1-2\nu)}{2} \end{bmatrix} \begin{bmatrix} E_{11} \\ E_{22} \\ E_{12} \end{bmatrix} \tag{6}$$

The Finite Element Mesh

Conventional PCC pavements are constructed in a series of layers. The concrete pavement rests on a compacted base which lies on a subgrade soil. The subgrade may consist of undisturbed or recompacted soils depending on road alignment requirements (i.e. cut and fill operations). While both the thickness of the base (7" nominal) and concrete pavement (9" nominal) are fixed according to specifications, the subgrade depth is variable. Additionally, slab width and length are known as well as joint size and dowel bar dimensions.

Given the above constraints, a two dimensional mesh (2-D) incorporating two slabs and one transverse joint is created. Each of the components listed are discretized into a mesh of nodes and elements suitable for finite element analysis. Figure 3 shows the complete finite element mesh developed for the study. As the focus of this study is directed toward the transverse joints in the PCC pavement, model development is concentrated in this area. Using smaller element sizes in the immediate region of the joint, a more accurate analysis is possible.

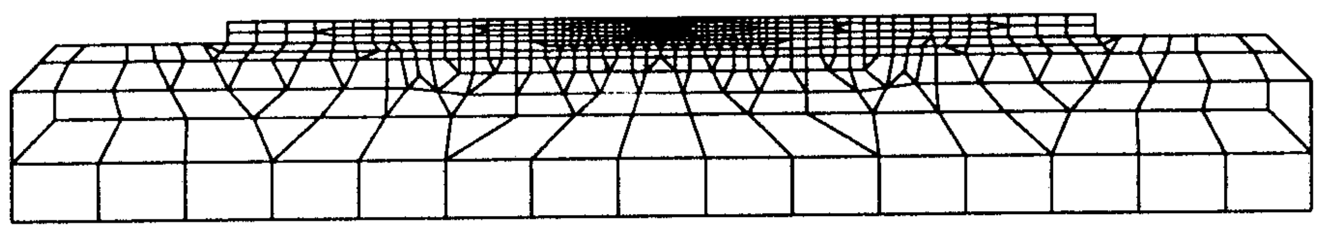

Figure 3. Complete finite element mesh for the rigid pavement model

The details around the joint area are shown in Figure 4. The element size is gradually increased in other areas of the mesh as detailed analysis is not required in these areas.

After a sensitivity study, the subgrade depth used in the model was chosen to be 5.0 feet. This selection was determined to be greater than the minimum depth required for eliminating "edge"effects. Using simulated FWD and wheel loads, stress increases in the subgrade did not reach the 5.0' depth selected. The model was developed for evaluating both the non-doweled and doweled cases. The elements in the dowel bar area were based on actual field dimensions, including hole sizes necessary for inserting the dowel bar.

Load and Response Characteristics

The loading conditions and base reaction are characterized from the schematic diagram (Figure 1) and the general discussion presented earlier. When a moving load, in this case a wheel load, passes over a slab, the pressure in the subgrade increases. The pressure increase is a function of the concrete strength, the subgrade characteristics, and the velocity and magnitude of the wheel load. As the wheel approaches the end of the leave slab, a pressure differential develops between the subgrade underneath the leave and approach slabs. As soon as the wheel load moves across the joint, the pressure differential reverses.

The reversal in subgrade pressures, reproduced each time a wheel load passes over the joint, creates a "pumping" action in the immediate area of the joint subgrade. Depending on the amount of water present in the subgrade, pore pressures may develop as well. In the event that there is sufficient water in the subgrade, the water is drawn from the approach subgrade to the leave side of the joint at the moment the wheel load is transferred from the

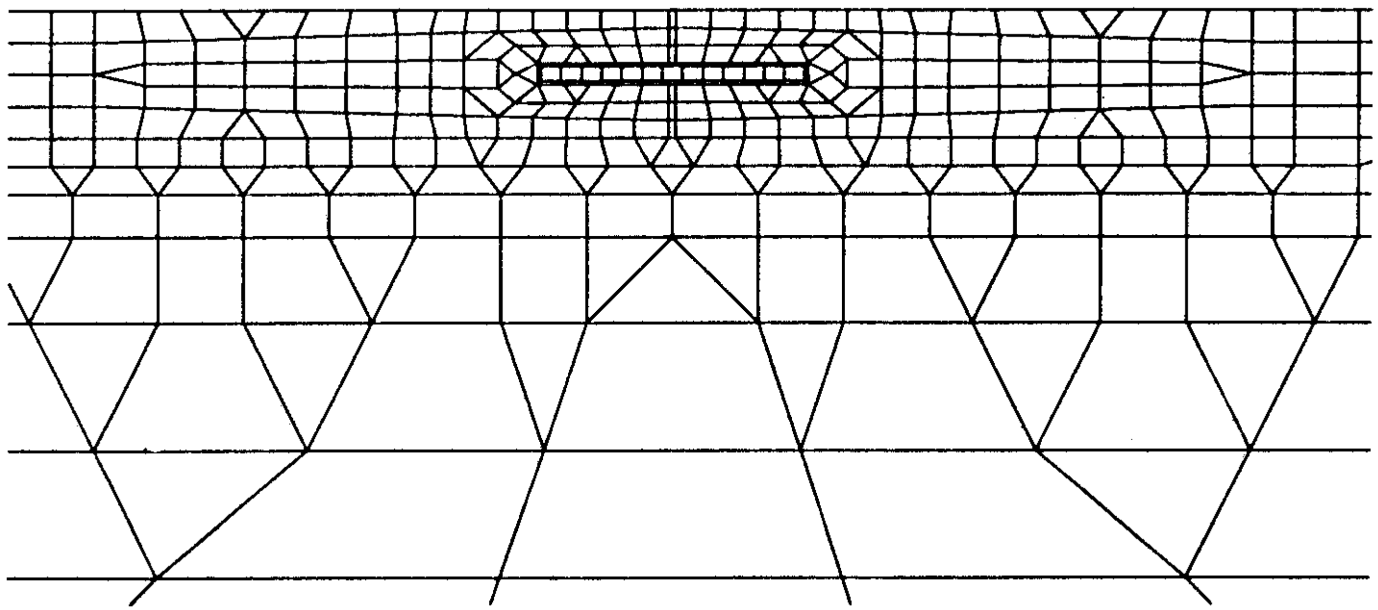

Figure 4. Detail of finite element mesh in the joint area

leave slab to the approach slab. As a result, the water aids in the transport mechanism, removing fines from the approach side subgrade and placing them under the leave slab. Repeated application of the wheel load results in an uneven subgrade at the joint area, and subsequently, an uneven joint surface. Supporting this hypothesis is the continued presence of moisture along the transverse joint and a build up of fines under the leave slab. Two major studies conducted on rigid pavement performance (Spellman et al., 1972; Gulden, 1975) concluded that the migration of fines was the primary cause of fault development.

To model the process outlined above, both the dynamics of moving wheel load and characteristics of the base and subgrade had to be addressed. The stiffness of the base material was decreased to simulate the time dependent degradation effects associated with fine particle migration. The base course and subgrade material properties were defined to simulate the effects of fault development. Based on previous research (Spellman et al., 1972), the migration of fines was restricted to the volume of the base and subgrade material in the joint area. Since this zone does not have a well defined boundary and the characteristics of the materials change with respect to time, simplification of the phenomena was made by designating a zone in the model as shown in Figure 5. The modulus in this zone was decreased to simulate both increased saturation levels, and fine migration.

The wheel load was simulated using a dynamic time step procedure available in ABAQUS. The magnitude of the load is defined by a velocity and a vertically distributed force. ABAQUS allows either of these parameters to be changed for simulation of single or double axle car or truck wheel loads. Experimental data obtained from a Canadian study showed a slow moving single axle truck load to produce the greatest deflections in a leave slab to the approach slab. As a result, the water aids in the transport mechanism, removing fines from the approach side subgrade and placing them under the leave slab. Repeated application of the wheel load results in an uneven subgrade at the joint area, and subsequently, an uneven joint surface. Supporting this hypothesis is the continued presence of moisture along the transverse joint and a build up of fines under the leave slab. Two major studies conducted on rigid pavement performance (Spellman et al., 1972; Gulden, 1975) concluded that the migration of fines was the primary cause of fault development.

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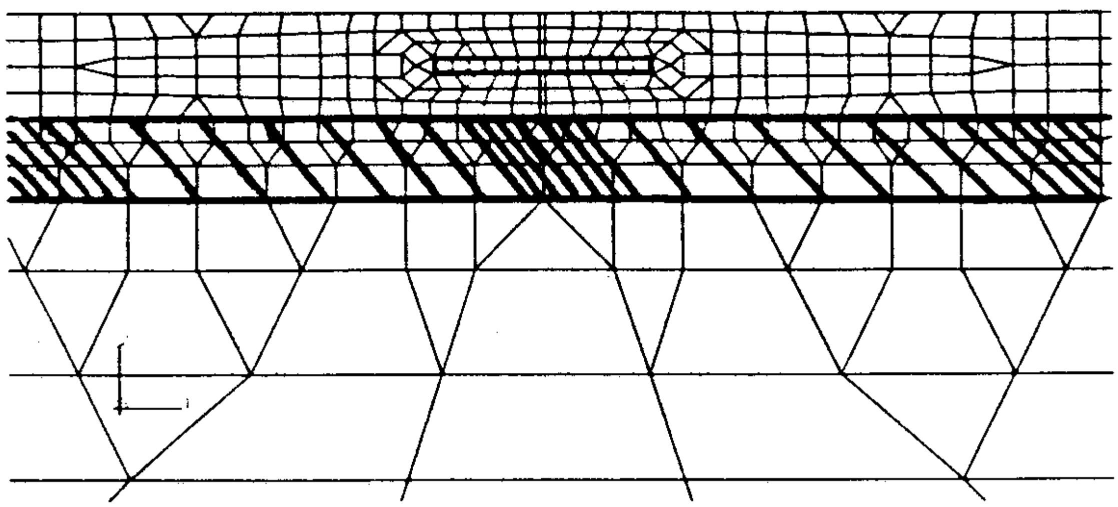


Figure 5. Zone of modulus variability used in the 2-D FEM model.

pavement section (Zaghloul and White, 1993). Their study considered an 18 kip load, supported over an area of 124 in^2, moving across the pavement surface at rates of 1.75 mph, 10 mph, and 30 mph. These researchers described the amplitude of the wheel load according to the ramp function depicted in Figure 6. At the beginning of the loading sequence, time T_o, the applied load is zero. As the sequence continues, the magnitude of the load increases linearly to a maximum value at a prescribed time T_1 determined by the velocity of the vehicle. The load remains at a maximum until time T_2 and then decreases linearly to zero at the end of the loading sequence, time T_3.

Since the single axle truck load discussed above is considered the worst case scenario, it was also used in this study. A ramp loading approach similar to that used by Zaghloul and White was adopted for the analysis. However, in reality, the wheel load at the beginning and end of the loading is non zero. To represent this, their ramp loading (Figure 6) was modified to maintain a minimum load magnitude of 75 percent of the maximum at the beginning and end of the load sequence (Figure 7).

Model Verification

Verification of the 2-D model was accomplished using deflection and load transfer results from the FWD tests. The loading characteristics of the FWD test were modeled using a distributed load applied to an area corresponding to the size of the test plate centered 5.315 inches from the joint. The location of the loading point in the model corresponds to a node in the finite element mesh which most closely simulates the position where the load would

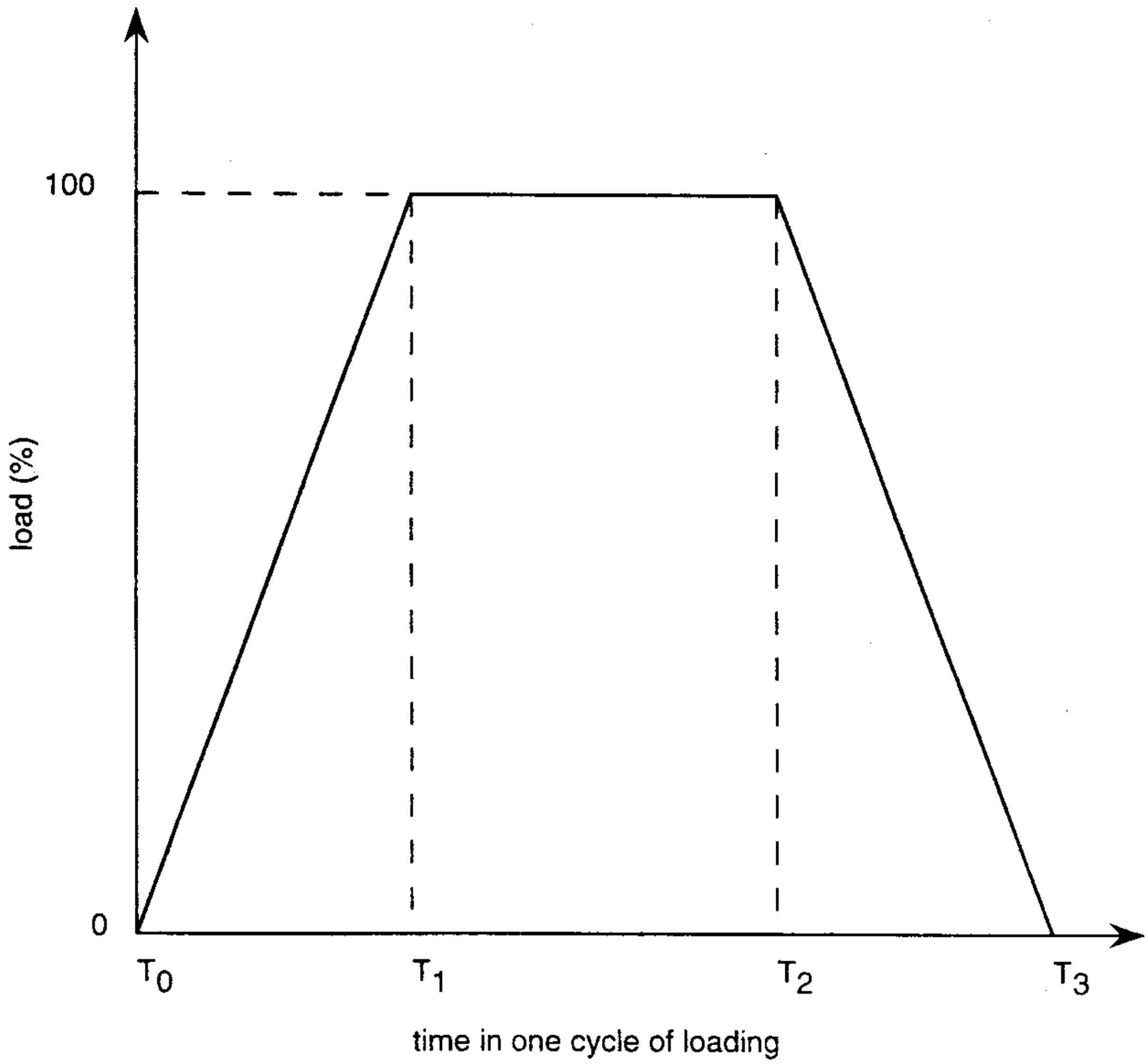


Figure 6. Simulation of moving wheel load using ramp function

(After Zaghloul and White 1993)

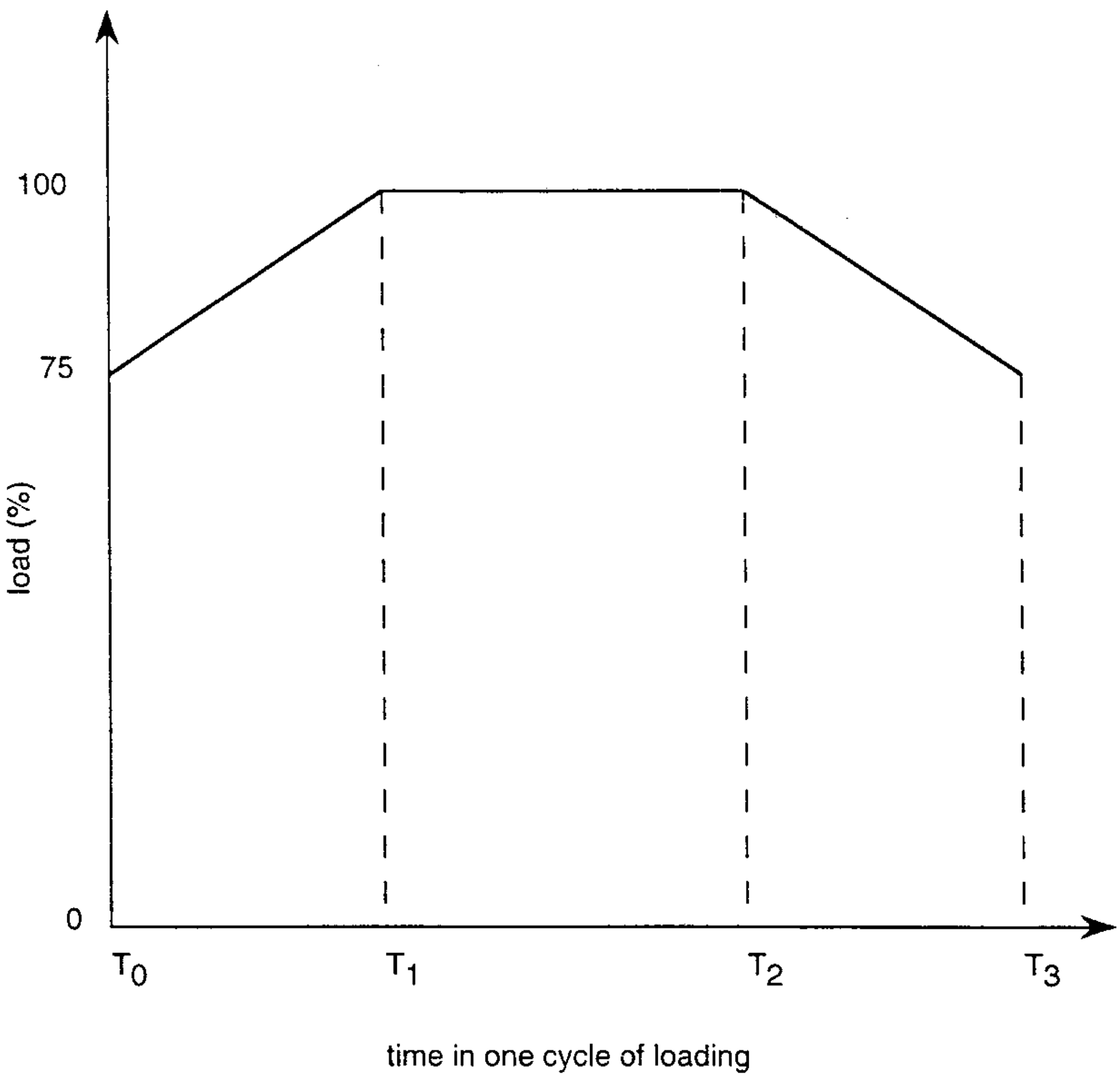


Figure 7. Simulation of moving wheel load for present study.

be applied in field testing (i.e. 6 inches from the joint). No field measured material properties were available for the concrete and base course. The material properties used in the finite element analysis were selected and refined until the load transfer characteristics and the deflections of the model at points D0 and D2 (Figure 2) matched the collected field FWD test data. The properties used were within reasonable limits for such materials (Appendix A).

Parametric Study

A parametric study was conducted to predict long term performance of the PCC pavement system. Defining the material strengths used to match FWD test data to be 100 percent of the available strength, material degradation was simulated by reducing the strengths from these initial values. The full and reduced Young's elastic moduli used in the analysis for both the doweled and non-doweled cases are listed in Table 1. The simulation of base course and subgrade stiffness (modulus) degradation resulting from fine particle migration was evaluated for both static and dynamic loads. The dynamic analysis allowed for simulation of the wheel load as well as vibrational effects generated by a non-stationary load. Also, by using a dynamic procedure, measurements of time related stress changes were examined for "pumping action" potential.

NEW (100% CONCRETE MODULUS)

concrete	base course	subgrade
3.65E+06	8.68E+04	5.97E+04
3.65E+06	7.85E+04	5.97E+04
3.65E+06	6.94E+04	5.97E+04
3.65E+06	6.08E+04	5.97E+04
3.65E+06	5.21E+04	5.97E+04
3.65E+06	4.34E+04	5.97E+04
3.65E+06	3.47E+04	5.97E+04
3.65E+06	2.60E+04	5.97E+04
3.65E+06	1.74E+04	5.97E+04
3.65E+06	8.68E+03	5.97E+04

MID-LIFE (75% CONCRETE MODULUS)

concrete	base course	subgrade
2.73E+06	8.68E+04	5.97E+04
2.73E+06	7.85E+04	5.97E+04
2.73E+06	6.94E+04	5.97E+04
2.73E+06	6.08E+04	5.97E+04
2.73E+06	5.21E+04	5.97E+04
2.73E+06	4.34E+04	5.97E+04
2.73E+06	3.47E+04	5.97E+04
2.73E+06	2.60E+04	5.97E+04
2.73E+06	1.74E+04	5.97E+04
2.73E+06	8.68E+03	5.97E+04

END OF DESIGN LIFE (50% CONCRETE MODULUS

concrete	base course	subgrade
1.83E+06	8.68E+04	5.97E+04
1.83E+06	7.85E+04	5.97E+04
1.83E+06	6.94E+04	5.97E+04
1.83E+06	6.08E+04	5.97E+04
1.83E+06	5.21E+04	5.97E+04
1.83E+06	4.34E+04	5.97E+04
1.83E+06	3.47E+04	5.97E+04
1.83E+06	2.60E+04	5.97E+04
1.83E+06	1.74E+04	5.97E+04
1.83E+06	8.68E+03	5.97E+04

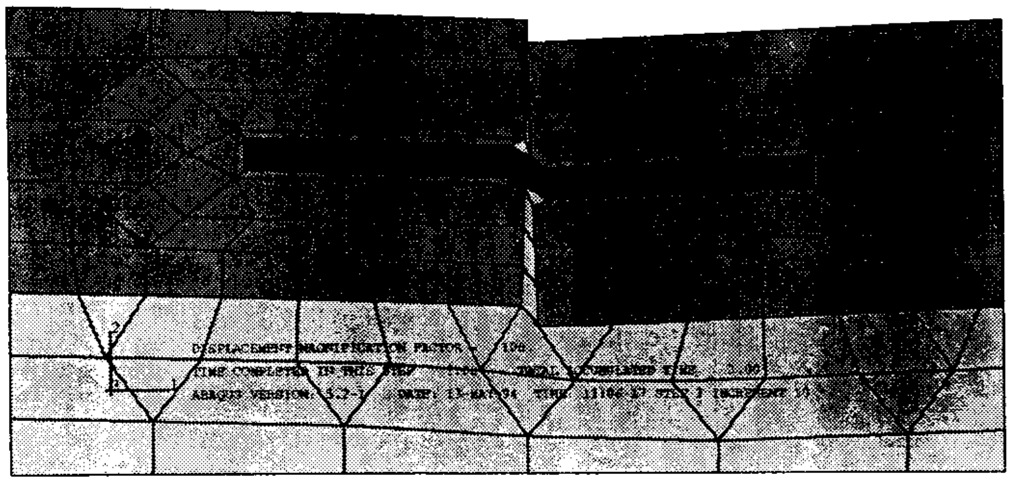
Values are Young's Elastic Moduli in psi.

Table 1. Simulated Young's Moduli used in the parametric study.

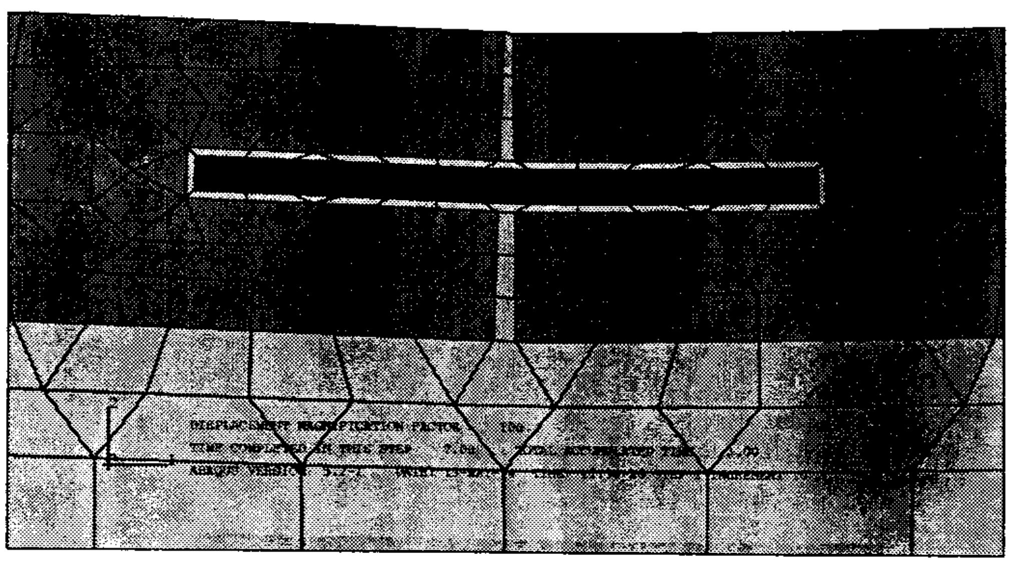
RESULTS FROM THE PARAMETRIC STUDY

The initial conditions for the parametric study were based on field measurements. In the field, the non-doweled and doweled slabs had average measured fault depths of 2 mm and 0 mm, respectively (Pierce 1993). Typical deflection profiles modeled for both cases are provided in Figures 8(a) and 8(b). From FWD test results performed before and after doweling, the non-doweled and doweled slabs had average D0 values of 15.06 mils. and 11.79 mils., respectively, and average D2 values of 9.85 mils. and 10.34 mils., respectively (Appendix A). Comparison of the two cases studied revealed decreased deflection in the doweled slabs (Figure 9). However, a significant increase in shear stress of the concrete pavement accompanied this decrease in deflection. The results of the parametric study are presented in terms of the deflection, load transfer, and stress response of the slabs in Figures 9, 10, and 11. From these figures, it appears that the reduction of subgrade performance, through modulus degradation associated with fine particle migration , also effects the actual rigid pavement system. A complete listing of deflection and load transfer data is presented in Appendix A. Stress and strain data is presented in Appendix B.

Dynamic analysis of the same finite element mesh to simulate a moving load provided similar results. The typical response of the model to a moving wheel load is shown in Figure 12. A review of the Von Mises stress (Eq. 3) developed in the base course immediately beneath the leave and approach slabs reveals a significant difference in response between the two models analyzed as shown in Figures 13 and 14. In the non-doweled model, as the load nears the end of the leave slab, the stress builds up only beneath the leave slab. As soon as the load is moved across the joint (@ time = 2.65 sec.), the stress increases in the approach



(a)



(b)

Figure 8. Typical deflection profile of (a) non-doweled and (b) doweled models.

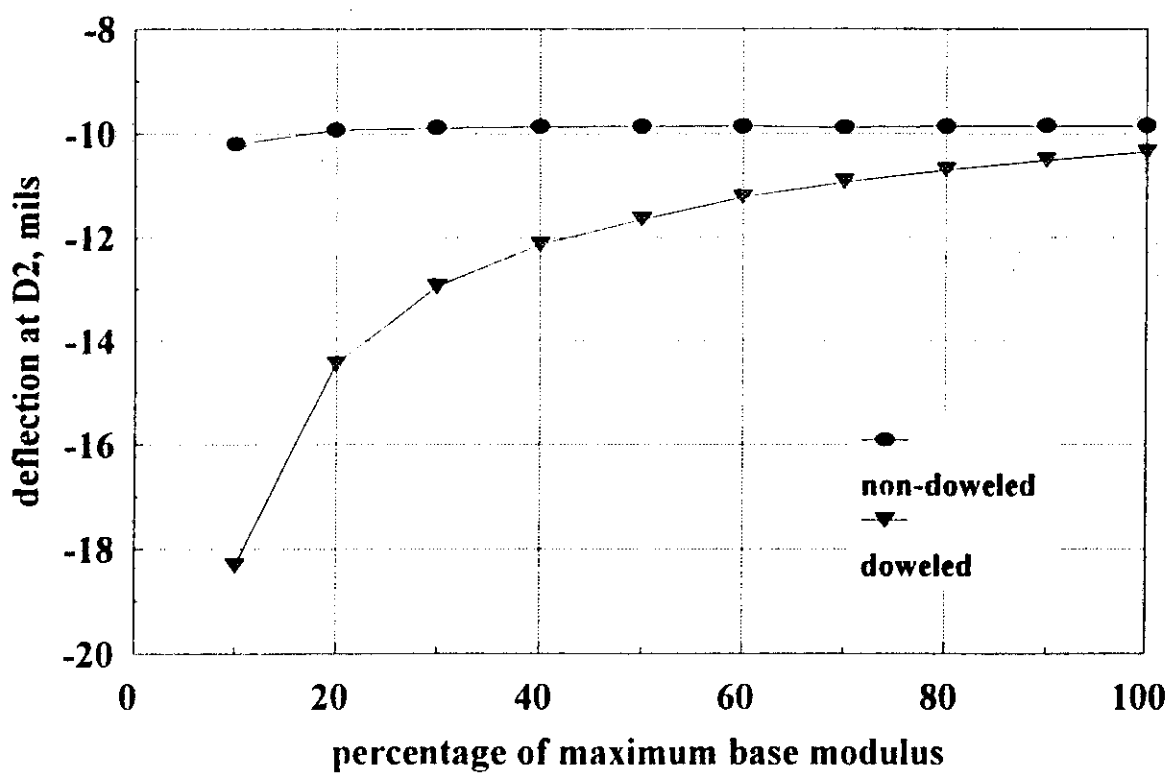


Figure 9. Deflection across the loaded slab joint.

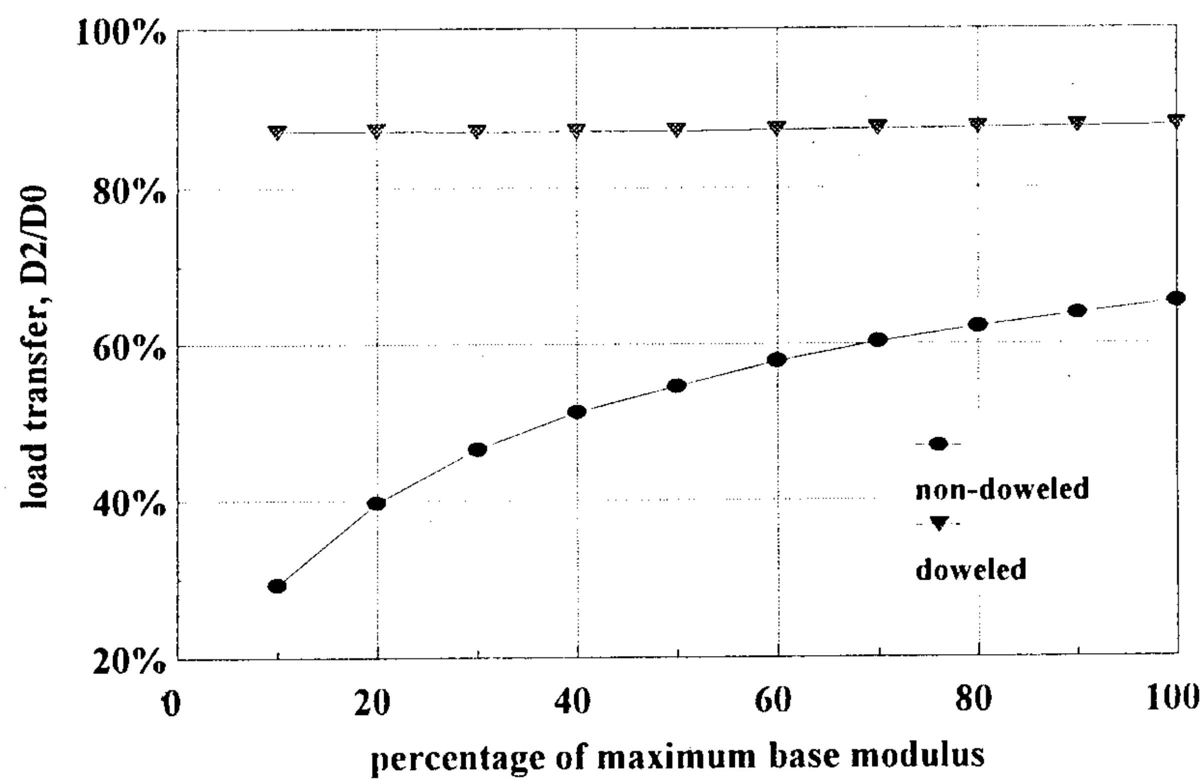


Figure 10. Load transfer as a function of base modulus degradation

for doweled and non-doweled cases.

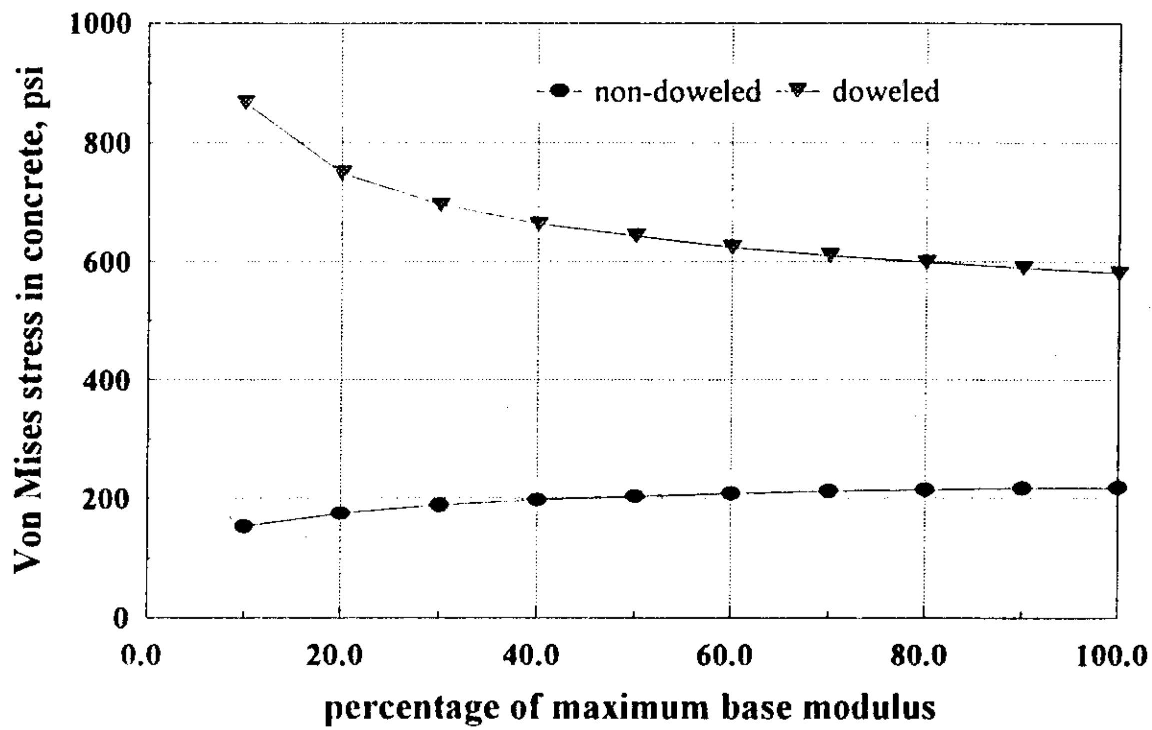


Figure 11. Stress development as a function of base modulus degradation for doweled and non-doweled cases.

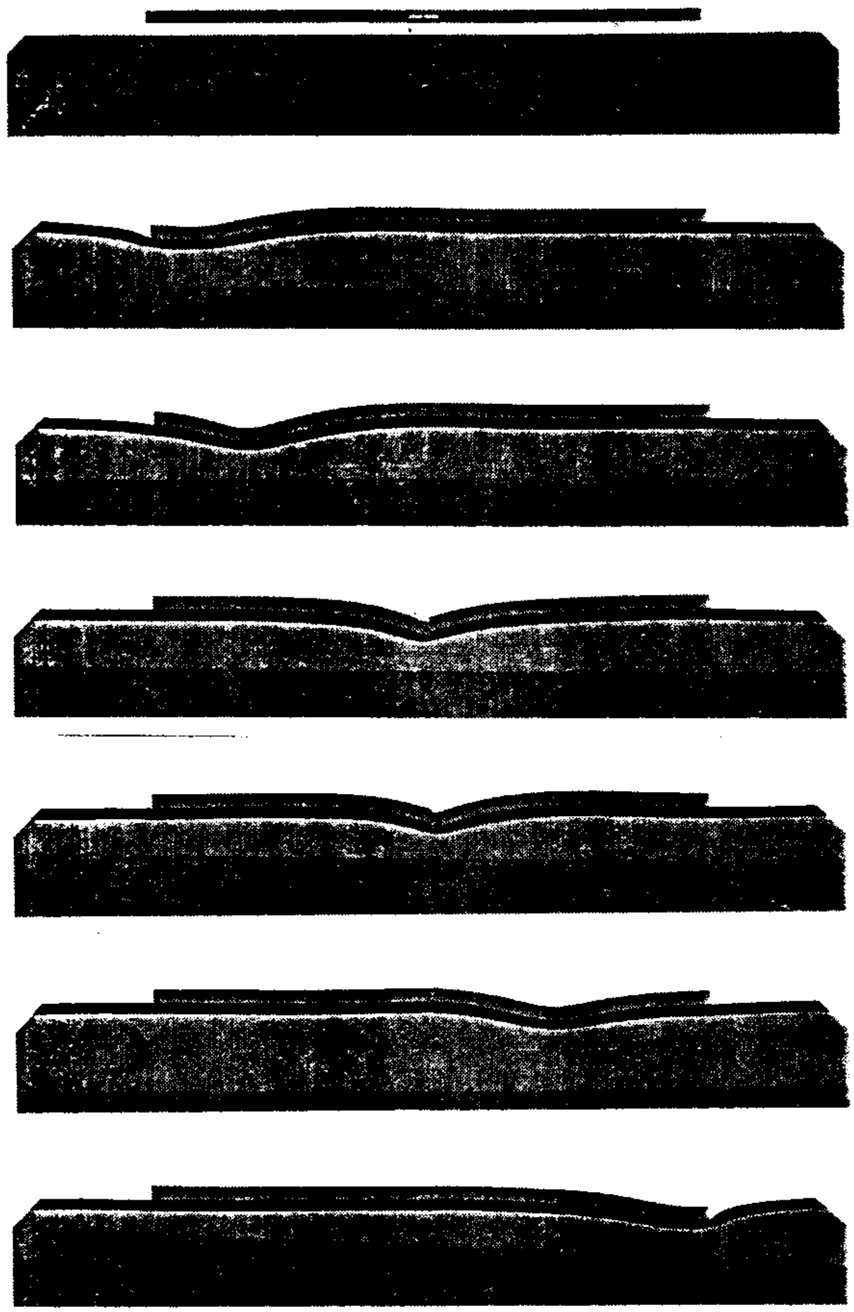


Figure 12. FEM model responding to simulated wheel load for non-doweled model.

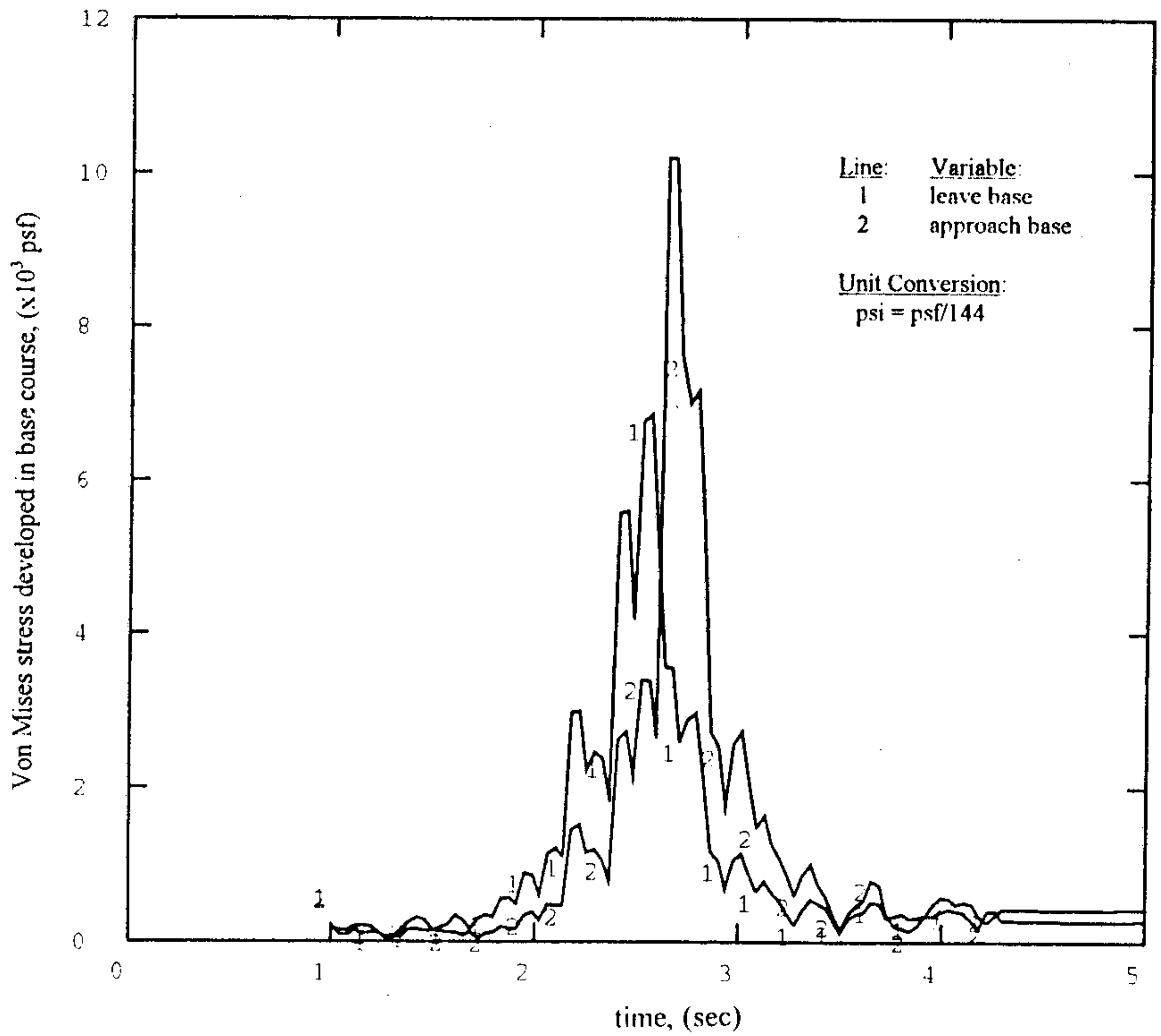


Figure 13. Base course Von Mises stress vs. time for non-doweled model.

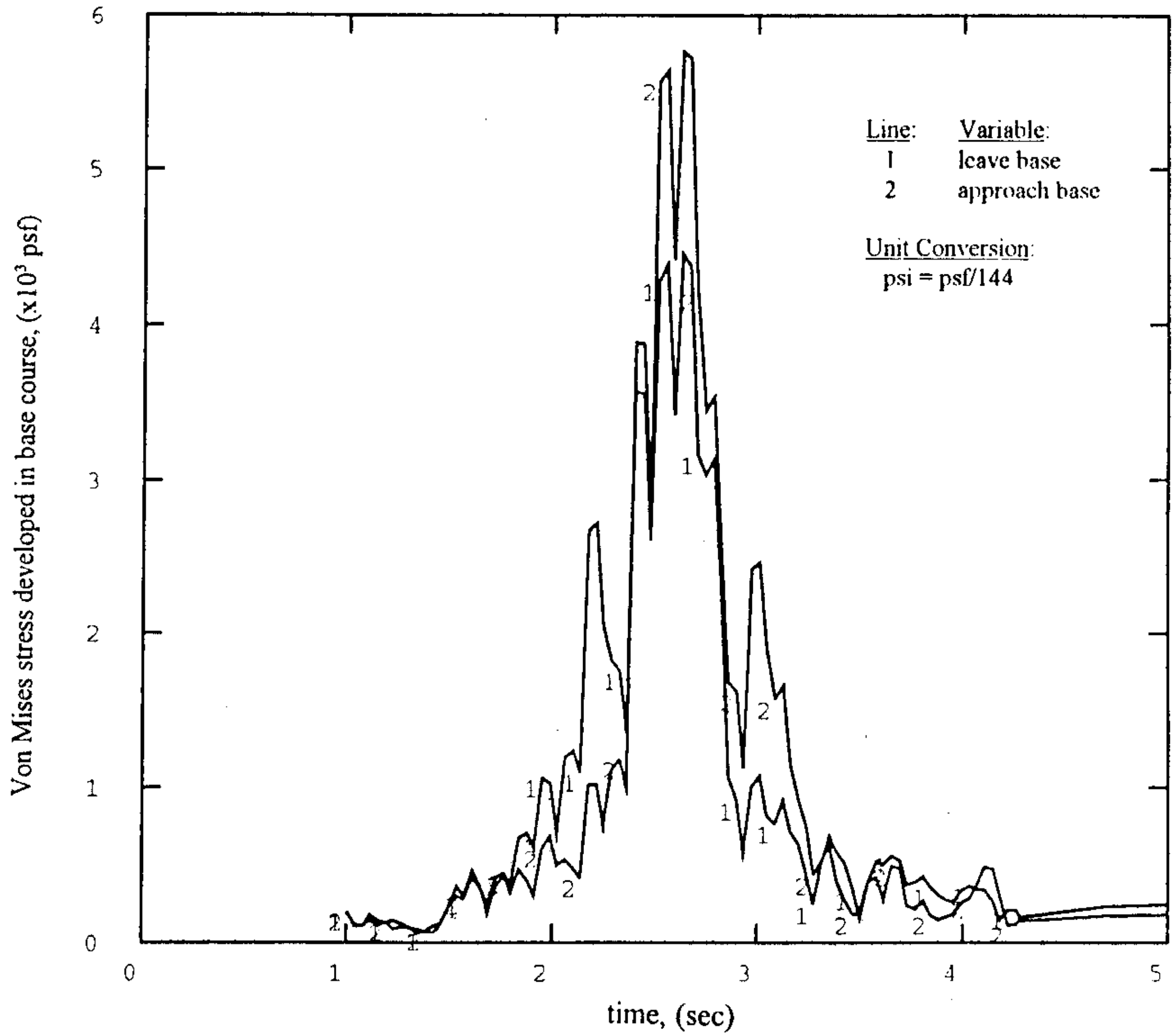


Figure 14. Base course Von Mises stress vs. time for doweled model.

slab base material. The simultaneous reversal of stress is clearly evident in Figure 13. The doweled model reduced the reversal of stress concentrations in the base course. A comparison of Figures 13 and 14 shows a 50 percent reduction in the Von Mises stress developed when using a dowel bar. Figure 14 also shows how the base material on either side of the joint responds in unison.

The response of the base course may also be evaluated using shear strains. The shear strains developed in both models exhibited time plots similar to those for stresses. The dowel bar prevented shear strain reversal, confirming the Von Mises stress plots. To determine the area affected by the moving load, a contour plot of the generated shear strains was produced for both non-doweled (Figure 15) and doweled models (Figure 16). The non-doweled model reflects the stress differential showing symmetric but opposite shear strain patterns beneath the joint area as the load crosses the joint. The area affected is limited to the base course extending approximately 6 inches to either side of the joint. Conversely, the doweled model shows a more evenly distributed shear strain contour plot directly beneath the joint.

Evaluation of Base Performance

The use of a applied vertical load in this model allows the compressive (or possibly tensile in the elastic model) vertical stresses developed in the base to be analyzed. Review of the base elements in the joint region revealed a more even stress distribution for the doweled model. The non-doweled model exhibited a pressure differential in response to the applied load (Figures 13 and 14). The base course stress response of both models over the range of base moduli used in the parametric study is shown in Figure 17. This figure shows the maximum and minimum stresses developed during the dynamic loading sequence.

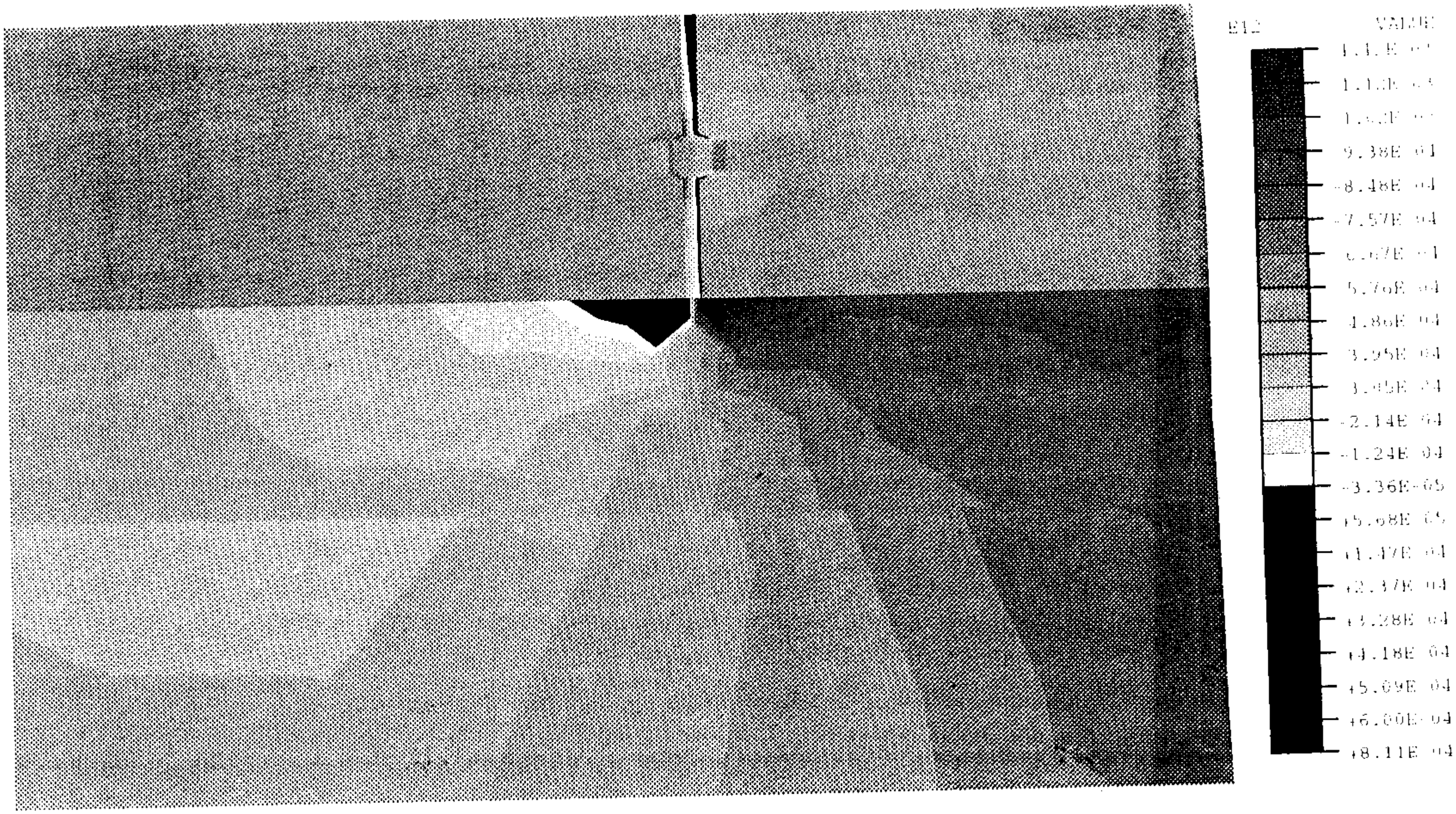


Figure 15. Shear strain contour for non-doweled model.

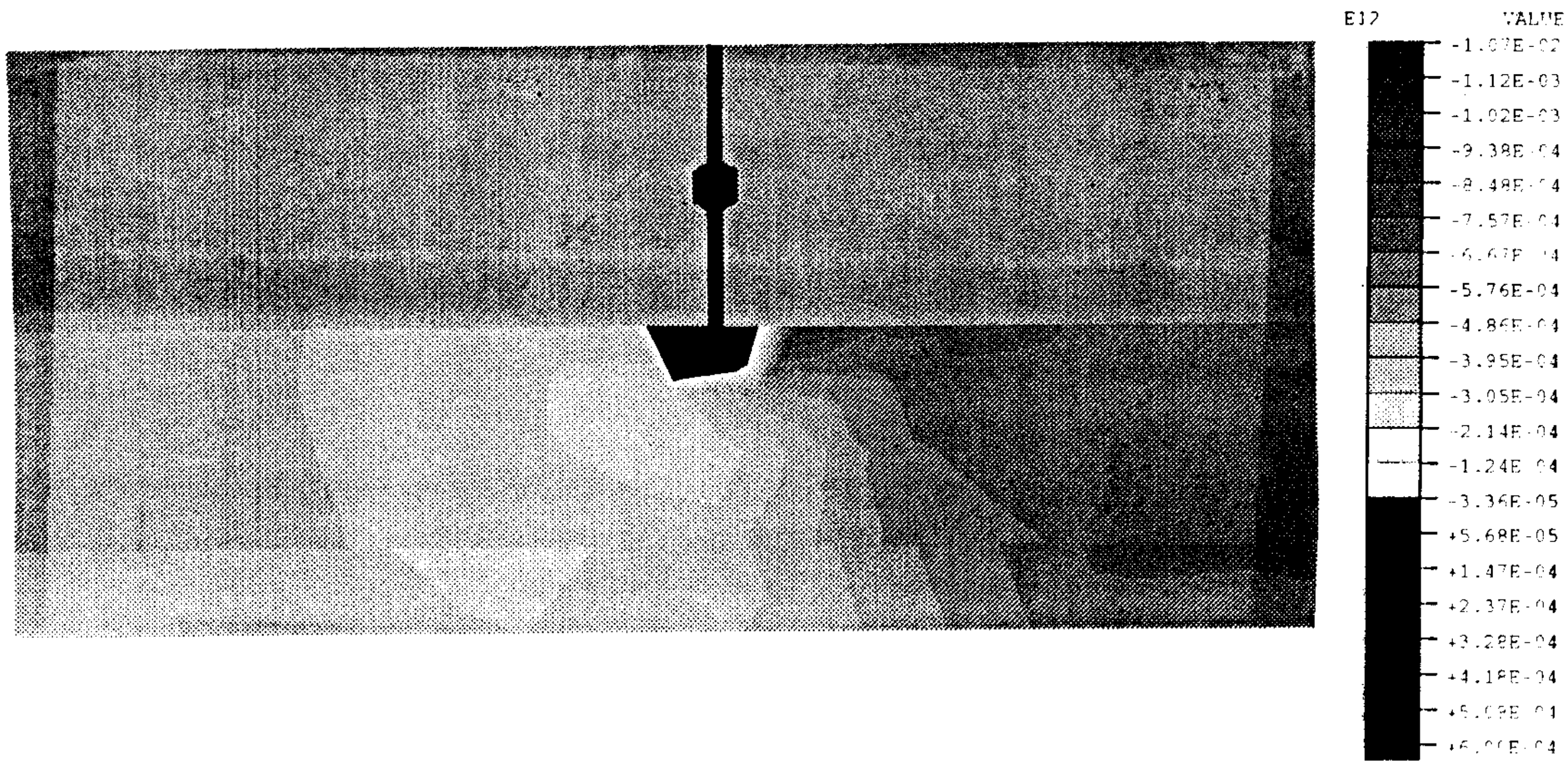


Figure 16. Shear strain contour for doweled model.

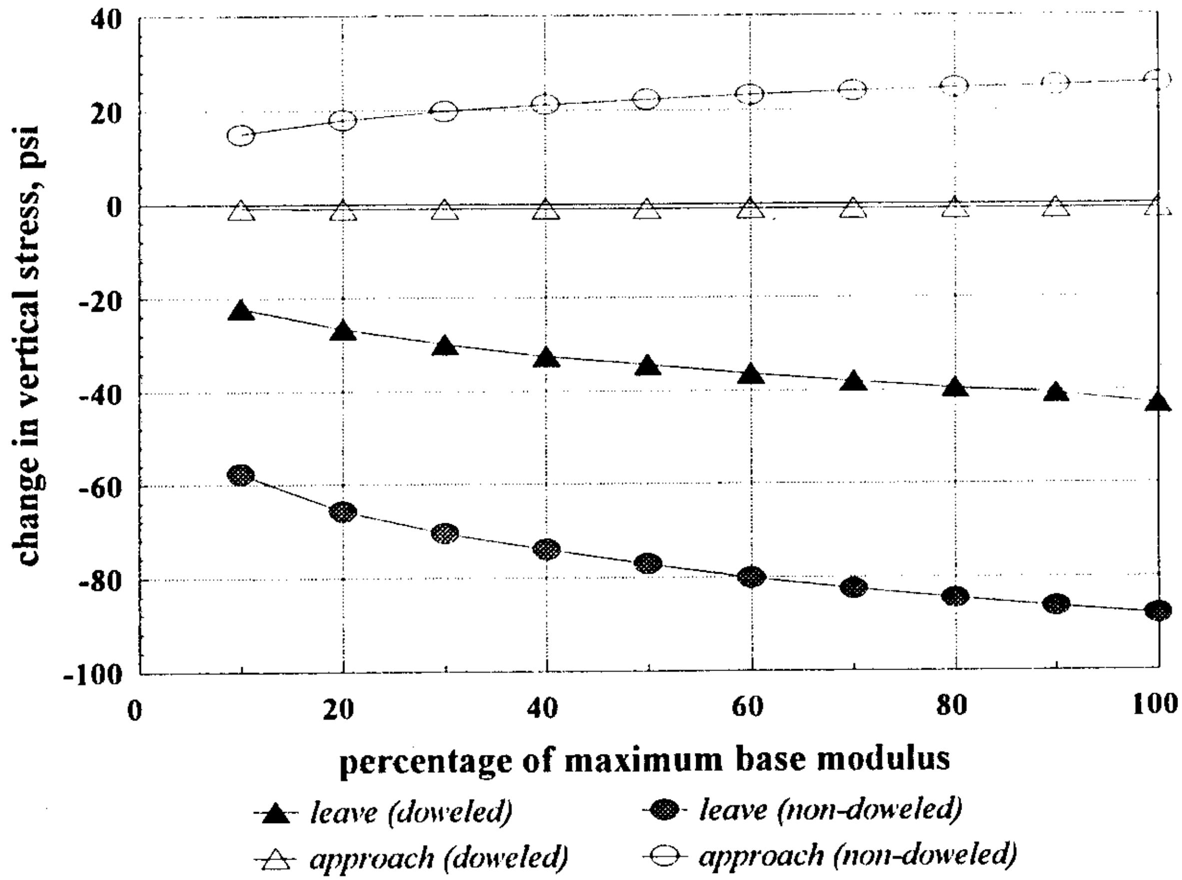


Figure 17. Stress development within the base material at the joint region.

It appears that the addition of dowel bars helps to reduce the "pumping"action, required for the migration of fines, by maintaining more equal pressures under the approach and leave slabs. The difference between the maximum and minimum stresses in the doweled case is approximately 35 psi at a base course stiffness of 70 percent. At this same stiffness, the difference between the maximum and minimum stresses in the non-doweled case is approximately 105 psi.

Performance of the PCC Pavement

Since the use of dowel bars led to increased stresses within the concrete slab, an analysis was performed to determine whether these stresses may cause failure. It is evident that the strength of concrete is a function of the state of stress and cannot be predicted by considering the applied simple tensile, compressive, and shearing stresses independently. Therefore a proper evaluation of concrete strength can be achieved only by considering interaction of the various components of the state of stress.

Various proposals have been made to describe the strength characteristics of concrete materials, and many failure criteria are presently available (Chen and Han, 1989). The Von Mises criterion is one of the simplest and most commonly used failure criterion. This criterion assumes that failure occurs when the octahedral shear stress, τ_{oct} (Eq. (3)) reaches its critical value:

$$\tau_{oct} = k \qquad (7)$$

where, k is the failure stress in pure shear. For concrete, k is determined from a simple compression test (with f_c' as the failure stress). In such case, k is equal to f_c'. Hence, for a certain stress combination, if τ_{oct} is less than f_c' failure will not occur. In other words, failure is assumed to occur if τ_{oct} / f_c' exceeds unity.

A review of the model output showed that the greatest stress development in the concrete occurred at the joint and dowel bar regions. The results of the evaluation of these elements using the Von Mises failure criterion are presented in Figure 18. It can be observed that for both the non-doweled and doweled cases, the failure criterion is never attained. Hence, both models are safe from potential failure. It is noted, however, that while the percentage of expended stress capacity in the non-doweled concrete remains relatively low and almost constant, the expended stress capacity in the doweled concrete increases with continued reduction in base strength. For example, as the simulated base degradation reaches 10 percent, 70 percent of the concrete capacity of the doweled model is consumed in response to the applied load. If such a condition is expected to arise in the field as a result of an erodible base course, a periodic evaluation of concrete strength should be made to identify any problems.

CONCLUSIONS AND RECOMMENDATIONS

The finite element analysis performed in this study showed dowel bar retrofitting to be a useful rehabilitation measure for reducing fault development in PCC pavements. In the models analyzed, the use of a dowel bar resulted in increased load transfer values and reduced

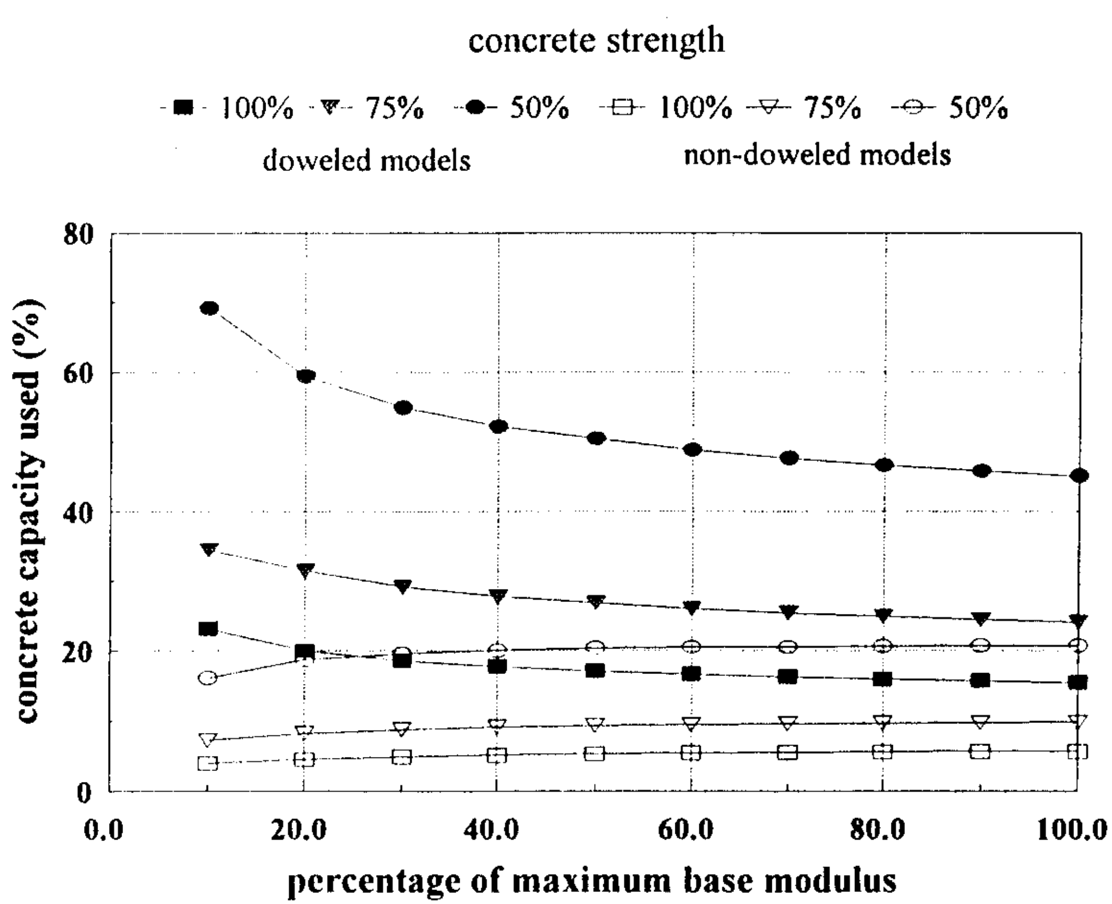


Figure 18. Concrete strength analysis.

deflections in the approach and leave slabs. While increased levels of stresses were developed in the concrete surrounding the dowel bar, the strength capacity of the concrete was never exceeded.

The use of dowels assists in the reduction of pressure differentials and subsequent fine particle migration within the base course. Stress differentials, occurring in the base course, were reduced as well. The reversal of stress concentrations, observed in the non-doweled model, was eliminated through the use of a dowel bar. Relating this to fines migration and pumping action, the potential for faulting through this mechanism appears to be reduced.

Due to the idealizations and limitations involved with the modeling process, the results should be confirmed using other techniques. Suggested techniques include more detailed computer modeling, more extensive instrumentation of randomly selected joints, and the collection of long term field data. Since the finite element model developed for this study uses complete surface contact among adjacent elements, the validity of this assumption should be qualified. Specifically, the bond between the dowel bar and the surrounding concrete should be studied.

Finally, this study focused on stress/strain developments in an elastic framework. Temperature effects, considered to be a major factor in pavement analysis and design, were not taken into account. The thermal gradients and material expansion or contraction rates for the concrete and dowel bar should be incorporated into a future study.

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APPENDIX A

Deflection and Calculated Load Transfer Data

Load Transfer Analysis of Non-Dowel Bar Rigid Pavements

The categories for analysis are based on assumed degredation of materials in the form of percentages relative to 100% concrete strength/100% base strength matching FWD Test data.

Pavement Category		No Dowel Bar				
		D (o) Node 137		D (2/7) Node 134		LT
		(ft x 10^(-4))	(mils)	(ft x 10^(-4))	(mils)	
1	100con 100base	-12.5500	-15.060	-8.2046	-9.846	65.38%
2	100con 90base	-12.8460	-15.415	-8.2079	-9.849	63.89%
3	100con 80base	-13.1990	-15.839	-8.2105	-9.853	62.21%
4	100con 70base	-13.6380	-16.366	-8.2250	-9.870	60.31%
5	100con 60base	-14.2010	-17.041	-8.2141	-9.857	57.84%
6	100con 50base	-15.0460	-18.055	-8.2162	-9.859	54.61%
7	100con 40base	-16.0320	-19.238	-8.2202	-9.864	51.27%
8	100con 30base	-17.7170	-21.260	-8.2331	-9.880	46.47%
9	100con 20base	-20.8180	-24.982	-8.2783	-9.934	39.77%
10	100con 10base	-28.9830	-34.780	-8.4954	-10.194	29.31%
11	75con 100base	-12.8750	-15.450	-8.3859	-10.063	65.13%
12	75con 90base	-13.1770	-15.812	-8.3958	-10.075	63.72%
13	75con 80base	-13.5430	-16.252	-8.4062	-10.087	62.07%
14	75con 70base	-13.9980	-16.798	-8.4176	-10.101	60.13%
15	75con 60base	-14.5820	-17.498	-8.4308	-10.117	57.82%
16	75con 50base	-15.4610	-18.553	-8.4497	-10.140	54.65%
17	75con 40base	-16.4890	-19.787	-8.4725	-10.167	51.38%
18	75con 30base	-18.2530	-21.904	-8.5157	-10.219	46.65%
19	75con 20base	-21.5160	-25.819	-8.6121	-10.335	40.03%
20	75con 10base	-30.1640	-36.197	-8.9451	-10.734	29.65%
21	50con 100base	-13.3250	-15.990	-8.6052	-10.326	64.58%
22	50con 90base	-13.6400	-16.368	-8.6241	-10.349	63.23%
23	50con 80base	-14.0220	-16.826	-8.6452	-10.374	61.65%
24	50con 70base	-14.4970	-17.396	-8.6696	-10.404	59.80%
25	50con 60base	-15.1090	-18.131	-8.6992	-10.439	57.58%
26	50con 50base	-15.9340	-19.121	-8.7374	-10.485	54.83%
27	50con 40base	-17.1170	-20.540	-8.7913	-10.550	51.36%
28	50con 30base	-18.9870	-22.784	-8.8779	-10.653	46.76%
29	50con 20base	-22.4690	-26.963	-9.0488	-10.859	40.27%
30	50con 10base	-31.7880	-38.146	-9.5558	-11.467	30.06%

Load Transfer Analysis of Dowel Bar Rigid Pavements

The categories for analysis are based on assumed degredation of materials in the form of percentages relative to 100% concrete strength/100% base strength matching FWD Test data.

Pavement Category		Dowel Bar D (o) Node 137 (ft x 10^(-4))	(mils)	D (2/7) Node 134 (ft x 10^(-4))	(mils)	LT
1	100con 100base	-9.8288	-11.795	-8.6182	-10.342	87.68%
2	100con 90base	-9.9921	-11.991	-8.7498	-10.500	87.57%
3	100con 80base	-10.1840	-12.221	-8.9062	-10.687	87.45%
4	100con 70base	-10.4170	-12.500	-9.0968	-10.916	87.33%
5	100con 60base	-10.7060	-12.847	-9.3371	-11.205	87.21%
6	100con 50base	-11.1280	-13.354	-9.6914	-11.630	87.09%
7	100con 40base	-11.6060	-13.927	-10.0990	-12.119	87.02%
8	100con 30base	-12.4030	-14.884	-10.7880	-12.946	86.98%
9	100con 20base	-13.8350	-16.602	-12.0500	-14.460	87.10%
10	100con 10base	-17.5420	-21.050	-15.2620	-18.314	87.00%
11	75con 100base	-10.0160	-12.019	-8.6971	-10.437	86.83%
12	75con 90base	-10.1860	-12.223	-8.8318	-10.598	86.71%
13	75con 80base	-10.3860	-12.463	-8.9923	-10.791	86.58%
14	75con 70base	-10.6290	-12.755	-9.1886	-11.026	86.45%
15	75con 60base	-10.9330	-13.120	-9.4370	-11.324	86.32%
16	75con 50base	-11.3770	-13.652	-9.8043	-11.765	86.18%
17	75con 40base	-11.8810	-14.257	-10.2280	-12.274	86.09%
18	75con 30base	-12.7210	-15.265	-10.9470	-13.136	86.05%
19	75con 20base	-14.2330	-17.080	-12.2650	-14.718	86.17%
20	75con 10base	-18.1420	-21.770	-15.7690	-18.923	86.92%
21	50con 100base	-10.2800	-12.336	-8.7876	-10.545	85.48%
22	50con 90base	-10.4580	-12.550	-8.9249	-10.710	85.34%
23	50con 80base	-10.6690	-12.803	-9.0893	-10.907	85.19%
24	50con 70base	-10.9250	-13.110	-9.2914	-11.150	85.05%
25	50con 60base	-11.2470	-13.496	-9.5483	-11.458	84.90%
26	50con 50base	-11.7180	-14.062	-9.9304	-11.916	84.74%
27	50con 40base	-12.2560	-14.707	-10.3730	-12.448	84.64%
28	50con 30base	-13.1550	-15.786	-11.1280	-13.354	84.59%
29	50con 20base	-14.7760	-17.731	-12.5210	-15.025	84.74%
30	50con 10base	-18.9680	-22.762	-16.2340	-19.481	85.59%

APPENDIX B

Stresses and Strains Calculated

from

Parametric Study

NO DOWEL BAR CASE STUDY

Young's Modulus		***Poisson's Ratio***	
concrete	8.00E+07	concrete	3.00E-01
dowel bar	5.00E+08	dowel bar	3.00E-01
base course	4.00E+06	base course	3.00E-01
subgrade	2.50E+06	subgrade	3.00E-01

a.) Stress Summary

concrete

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-7.05E+03	9.91E+03	-2.52E+04	9.69E+03	-7.68E+03	3.96E+03	1.40E+03	3.15E+04
2 100con 90base	-6.79E+03	1.01E+04	-2.49E+04	9.83E+03	-7.57E+03	3.98E+03	1.39E+03	3.13E+04
3 100con 80base	-6.48E+03	1.02E+04	-2.45E+04	9.56E+03	-7.43E+03	4.01E+03	1.37E+03	3.10E+04
4 100con 70base	-6.11E+03	1.03E+04	-2.41E+04	9.51E+03	-7.26E+03	4.04E+03	1.34E+03	3.06E+04
5 100con 60base	-5.66E+03	1.03E+04	-2.35E+04	9.41E+03	-7.06E+03	4.08E+03	1.30E+03	3.01E+04
6 100con 50base	-5.04E+03	1.03E+04	-2.28E+04	9.23E+03	-6.79E+03	4.13E+03	1.24E+03	2.93E+04
7 100con 40base	-4.39E+03	1.01E+04	-2.20E+04	8.99E+03	-6.51E+03	4.19E+03	1.17E+03	2.84E+04
8 100con 30base	-3.83E+03	9.72E+03	-2.08E+04	8.60E+03	-6.10E+03	4.43E+03	1.07E+03	2.71E+04
9 100con 20base	-6.14E+03	9.00E+03	-1.92E+04	7.97E+03	-5.52E+03	4.90E+03	9.52E+02	2.52E+04
10 100con 10base	-1.02E+04	7.56E+03	-1.67E+04	6.86E+03	-4.58E+03	5.80E+03	7.86E+02	2.21E+04

concrete

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-6.93E+03	8.66E+03	-2.47E+04	9.42E+03	-7.46E+03	3.76E+03	1.35E+03	3.02E+04
12 75con 90base	-6.71E+03	8.93E+03	-2.45E+04	9.38E+03	-7.37E+03	3.78E+03	1.35E+03	3.01E+04
13 75con 80base	-6.46E+03	9.18E+03	-2.42E+04	9.32E+03	-7.26E+03	3.81E+03	1.35E+03	2.99E+04
14 75con 70base	-6.15E+03	9.40E+03	-2.38E+04	9.23E+03	-7.12E+03	3.85E+03	1.34E+03	2.97E+04
15 75con 60base	-5.76E+03	9.57E+03	-2.33E+04	9.09E+03	-6.95E+03	3.89E+03	1.33E+03	2.94E+04
16 75con 50base	-5.23E+03	9.68E+03	-2.27E+04	8.94E+03	-6.72E+03	3.95E+03	1.30E+03	2.88E+04
17 75con 40base	-4.66E+03	9.68E+03	-2.20E+04	8.76E+03	-6.48E+03	4.01E+03	1.26E+03	2.82E+04
18 75con 30base	-3.83E+03	9.50E+03	-2.10E+04	8.45E+03	-6.12E+03	3.19E+03	1.18E+03	2.71E+04
19 75con 20base	-5.11E+03	9.01E+03	-1.95E+04	7.91E+03	-5.60E+03	3.56E+03	1.07E+03	2.54E+04
20 75con 10base	-8.95E+03	7.81E+03	-1.70E+04	6.93E+03	-4.73E+03	5.45E+03	8.26E+02	2.25E+04

concrete

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-6.66E+03	6.83E+03	-2.39E+04	8.91E+03	-7.09E+03	3.47E+03	1.33E+03	2.84E+04
22 50con 90base	-6.50E+03	7.21E+03	-2.37E+04	8.91E+03	-7.02E+03	3.50E+03	1.33E+03	2.84E+04
23 50con 80base	-6.31E+03	7.59E+03	-2.35E+04	8.89E+03	-6.95E+03	3.54E+03	1.34E+03	2.83E+04
24 50con 70base	-6.08E+03	7.96E+03	-2.32E+04	8.84E+03	-6.85E+03	3.58E+03	1.36E+03	2.81E+04
25 50con 60base	-5.79E+03	8.31E+03	-2.29E+04	8.76E+03	-6.73E+03	3.62E+03	1.37E+03	2.81E+04
26 50con 50base	-5.42E+03	8.63E+03	-2.25E+04	8.63E+03	-6.58E+03	3.68E+03	1.37E+03	2.79E+04
27 50con 40base	-4.92E+03	8.88E+03	-2.19E+04	8.43E+03	-6.38E+03	3.75E+03	1.87E+03	2.75E+04
28 50con 30base	-4.21E+03	9.00E+03	-2.11E+04	8.16E+03	-6.09E+03	3.86E+03	1.33E+03	2.68E+04
29 50con 20base	-3.84E+03	8.86E+03	-1.99E+04	7.77E+03	-5.67E+03	4.21E+03	1.25E+03	2.56E+04
30 50con 10base	-7.27E+03	8.06E+03	-1.77E+04	6.97E+03	-4.91E+03	4.99E+03	9.12E+02	1.66E+04

b.) Strain Summary

concrete

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-8.81E-05	1.24E-04	-3.15E-04	1.21E-04	-9.61E-05	4.95E-05	1.75E-05	3.93E-04
2 100con 90base	-8.48E-05	1.26E-04	-3.11E-04	1.20E-04	-9.46E-05	4.98E-05	1.73E-05	3.91E-04
3 100con 80base	-8.10E-05	1.28E-04	-3.06E-04	1.20E-04	-9.28E-05	5.01E-05	1.71E-05	3.87E-04
4 100con 70base	-7.63E-05	1.29E-04	-3.01E-04	1.19E-04	-9.08E-05	5.05E-05	1.68E-05	3.82E-04
5 100con 60base	-7.07E-05	1.29E-04	-2.94E-04	1.18E-04	-8.83E-05	5.10E-05	1.63E-05	3.76E-04
6 100con 50base	-6.30E-05	1.29E-04	-2.84E-04	1.15E-04	-8.49E-05	5.17E-05	1.55E-05	3.66E-04
7 100con 40base	-5.49E-05	1.26E-04	-2.75E-04	1.12E-04	-8.13E-05	5.24E-05	1.47E-05	3.56E-04
8 100con 30base	-4.79E-05	1.22E-04	-2.60E-04	1.07E-04	-7.62E-05	5.54E-05	1.34E-05	3.39E-04
9 100con 20base	-7.67E-05	1.12E-04	-2.39E-04	9.97E-05	-6.90E-05	6.13E-05	1.19E-05	3.15E-04
10 100con 10base	-1.28E-04	9.46E-05	-2.08E-04	8.58E-05	-5.73E-05	7.25E-05	9.82E-06	2.76E-04

concrete

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-8.66E-05	1.08E-04	-3.09E-04	1.18E-04	-9.33E-05	4.69E-05	1.69E-05	3.78E-04
12 75con 90base	-8.39E-05	1.12E-04	-3.06E-04	1.17E-04	-9.21E-05	4.73E-05	1.69E-05	3.77E-04
13 75con 80base	-8.07E-05	1.15E-04	-3.02E-04	1.16E-04	-9.07E-05	4.77E-05	1.69E-05	3.74E-04
14 75con 70base	-7.88E-05	1.17E-04	-2.97E-04	1.15E-04	-8.90E-05	4.81E-05	1.68E-05	3.71E-04
15 75con 60base	-7.20E-05	1.20E-04	-2.92E-04	1.14E-04	-8.69E-05	4.86E-05	1.66E-05	3.67E-04
16 75con 50base	-6.54E-05	1.21E-04	-2.84E-04	1.12E-04	-8.41E-05	4.93E-05	1.63E-05	3.60E-04
17 75con 40base	-5.82E-05	1.21E-04	-2.75E-04	1.10E-04	-8.10E-05	5.01E-05	1.57E-05	3.52E-04
18 75con 30base	-4.79E-05	1.19E-04	-2.63E-04	1.06E-04	-7.65E-05	3.99E-05	1.48E-05	3.39E-04
19 75con 20base	-6.39E-05	1.13E-04	-2.44E-04	9.89E-05	-7.00E-05	4.45E-05	1.33E-05	3.18E-04
20 75con 10base	-1.12E-04	9.76E-05	-2.13E-04	8.66E-05	-5.92E-05	6.81E-05	1.03E-05	2.81E-04

concrete

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-8.32E-05	8.53E-05	-2.98E-04	1.11E-04	-8.86E-05	4.33E-05	1.66E-05	3.55E-04
22 50con 90base	-8.13E-05	9.01E-05	-2.96E-04	1.11E-04	-8.78E-05	4.38E-05	1.67E-05	3.55E-04
23 50con 80base	-7.89E-05	9.49E-05	-2.94E-04	1.11E-04	-8.68E-05	4.42E-05	1.68E-05	3.54E-04
24 50con 70base	-7.60E-05	9.95E-05	-2.91E-04	1.11E-04	-8.56E-05	4.47E-05	1.69E-05	3.51E-04
25 50con 60base	-7.24E-05	1.04E-04	-2.87E-04	1.10E-04	-8.41E-05	4.53E-05	1.71E-05	3.52E-04
26 50con 50base	-6.77E-05	1.08E-04	-2.81E-04	1.08E-04	-8.22E-05	4.60E-05	1.72E-05	3.49E-04
27 50con 40base	-6.15E-05	1.11E-04	-2.74E-04	1.05E-04	-7.97E-05	4.69E-05	2.34E-05	3.44E-04
28 50con 30base	-5.26E-05	1.13E-04	-2.64E-04	1.02E-04	-7.62E-05	4.82E-05	1.67E-05	3.35E-04
29 50con 20base	-4.81E-05	1.11E-04	-2.49E-04	9.72E-05	-7.08E-05	5.27E-05	1.56E-05	3.20E-04
30 50con 10base	-9.09E-05	1.01E-04	-2.21E-04	8.71E-05	-6.14E-05	6.24E-05	1.14E-05	2.08E-04

NO DOWEL BAR CASE STUDY

Young's Modulus		Poisson's Ratio	
concrete	8.00E+07	concrete	3.00E-01
dowel bar	5.00E+08	dowel bar	3.00E-01
base course	4.00E+06	base course	3.00E-01
subgrade	2.50E+06	subgrade	3.00E-01

a.) Stress Summary

base

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-6.46E+03	6.81E+03	-1.27E+04	3.71E+03	-1.44E+04	2.05E+03	1.63E+02	2.89E+04
2 100con 90base	-6.11E+03	7.00E+03	-1.24E+04	3.63E+03	-1.43E+04	2.06E+03	1.62E+02	2.84E+04
3 100con 80base	-5.76E+03	7.16E+03	-1.22E+04	3.55E+03	-1.41E+04	2.06E+03	1.60E+02	2.79E+04
4 100con 70base	-5.40E+03	7.29E+03	-1.19E+04	3.46E+03	-1.39E+04	2.05E+03	1.59E+02	2.74E+04
5 100con 60base	-5.04E+03	7.36E+03	-1.15E+04	3.35E+03	-1.36E+04	2.04E+03	1.56E+02	2.66E+04
6 100con 50base	-4.65E+03	7.35E+03	-1.11E+04	3.21E+03	-1.32E+04	2.01E+03	1.53E+02	2.50E+04
7 100con 40base	-4.42E+03	7.25E+03	-1.07E+04	3.07E+03	-1.27E+04	1.96E+03	1.48E+02	2.47E+04
8 100con 30base	-4.26E+03	6.98E+03	-1.02E+04	2.87E+03	-1.20E+04	1.88E+03	1.30E+02	2.25E+04
9 100con 20base	-4.00E+03	6.45E+03	-9.48E+03	2.59E+03	-1.10E+04	1.75E+03	1.21E+02	2.12E+04
10 100con 10base	-3.53E+03	5.36E+03	-8.30E+03	2.17E+03	-9.31E+03	1.50E+03	7.91E+01	1.80E+04

base

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-7.26E+03	5.76E+03	-1.18E+04	3.58E+03	-1.39E+04	1.82E+03	1.69E+02	2.84E+04
12 75con 90base	-6.86E+03	6.03E+03	-1.24E+04	3.51E+03	-1.38E+04	1.85E+03	1.69E+02	2.80E+04
13 75con 80base	-6.45E+03	6.28E+03	-1.22E+04	3.44E+03	-1.37E+04	1.88E+03	1.68E+02	2.76E+04
14 75con 70base	-6.03E+03	6.50E+03	-1.19E+04	3.35E+03	-1.36E+04	1.90E+03	1.67E+02	2.71E+04
15 75con 60base	-5.60E+03	6.68E+03	-1.16E+04	3.25E+03	-1.34E+04	1.91E+03	1.66E+02	2.65E+04
16 75con 50base	-5.12E+03	6.81E+03	-1.12E+04	3.12E+03	-1.30E+04	1.91E+03	1.64E+02	2.56E+04
17 75con 40base	-4.72E+03	6.84E+03	-1.08E+04	2.98E+03	-1.28E+04	1.89E+03	1.60E+02	2.47E+04
18 75con 30base	-4.30E+03	6.74E+03	-1.03E+04	2.80E+03	-1.20E+04	1.85E+03	1.52E+02	2.34E+04
19 75con 20base	-4.71E+03	6.38E+03	-9.70E+03	2.54E+03	-1.11E+04	1.76E+03	1.36E+02	2.16E+04
20 75con 10base	-3.65E+03	5.49E+03	-8.60E+03	2.15E+03	-9.56E+03	1.55E+03	9.63E+01	1.85E+04

base

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-8.29E+03	4.25E+03	-1.25E+04	3.36E+03	-1.35E+04	1.46E+03	1.72E+02	2.76E+04
22 50con 90base	-7.84E+03	4.62E+03	-1.23E+04	3.31E+03	-1.33E+04	1.52E+03	1.72E+02	2.73E+04
23 50con 80base	-7.38E+03	4.97E+03	-1.21E+04	3.24E+03	-1.31E+04	1.57E+03	1.73E+02	2.70E+04
24 50con 70base	-6.89E+03	5.31E+03	-1.19E+04	3.17E+03	-1.30E+04	1.63E+03	1.74E+02	2.65E+04
25 50con 60base	-6.39E+03	5.64E+03	-1.16E+04	3.08E+03	-1.29E+04	1.68E+03	1.74E+02	2.60E+04
26 50con 50base	-5.86E+03	5.92E+03	-1.13E+04	2.98E+03	-1.27E+04	1.72E+03	1.73E+02	2.54E+04
27 50con 40base	-5.31E+03	6.15E+03	-1.09E+04	2.85E+03	-1.24E+04	1.76E+03	1.70E+02	2.46E+04
28 50con 30base	-4.74E+03	6.27E+03	-1.05E+04	2.68E+03	-1.19E+04	1.77E+03	1.65E+02	2.35E+04
29 50con 20base	-4.16E+03	6.18E+03	-9.97E+03	2.46E+03	-1.12E+04	1.74E+03	1.52E+02	2.19E+04
30 50con 10base	-3.80E+03	5.60E+03	-8.98E+03	2.12E+03	-9.85E+03	1.61E+03	1.18E+02	1.92E+04

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base

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-1.62E-03	1.70E-03	-3.17E-03	9.26E-04	-3.60E-03	5.13E-04	4.08E-05	7.22E-03
2 100con 90base	-1.53E-03	1.75E-03	-3.11E-03	9.09E-04	-3.57E-03	5.15E-04	4.04E-05	7.09E-03
3 100con 80base	-1.44E-03	1.79E-03	-3.05E-03	8.89E-04	-3.53E-03	5.15E-04	4.01E-05	6.99E-03
4 100con 70base	-1.35E-03	1.82E-03	-2.97E-03	8.65E-04	-3.47E-03	5.14E-04	3.96E-05	6.84E-03
5 100con 60base	-1.26E-03	1.84E-03	-2.89E-03	8.39E-04	-3.40E-03	5.10E-04	3.91E-05	6.66E-03
6 100con 50base	-1.16E-03	1.84E-03	-2.78E-03	8.03E-04	-3.30E-03	5.02E-04	3.82E-05	6.25E-03
7 100con 40base	-1.11E-03	1.81E-03	-2.67E-03	7.67E-04	-3.18E-03	4.90E-04	3.70E-05	6.17E-03
8 100con 30base	-1.06E-03	1.75E-03	-2.54E-03	7.17E-04	-3.01E-03	4.70E-04	3.25E-05	5.63E-03
9 100con 20base	-1.00E-03	1.61E-03	-2.37E-03	6.48E-04	-2.75E-03	4.36E-04	3.03E-05	5.31E-03
10 100con 10base	-8.83E-04	1.34E-03	-2.08E-03	5.42E-04	-2.33E-03	3.74E-04	1.98E-05	4.50E-03

base

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-1.81E-03	1.44E-03	-2.94E-03	8.94E-04	-3.48E-03	4.56E-04	4.22E-05	7.10E-03
12 75con 90base	-1.71E-03	1.51E-03	-3.10E-03	8.78E-04	-3.46E-03	4.63E-04	4.21E-05	7.01E-03
13 75con 80base	-1.61E-03	1.57E-03	-3.05E-03	8.59E-04	-3.43E-03	4.69E-04	4.20E-05	6.90E-03
14 75con 70base	-1.51E-03	1.62E-03	-2.98E-03	8.38E-04	-3.39E-03	4.74E-04	4.18E-05	6.77E-03
15 75con 60base	-1.40E-03	1.67E-03	-2.90E-03	8.13E-04	-3.34E-03	4.77E-04	4.15E-05	6.61E-03
16 75con 50base	-1.28E-03	1.70E-03	-2.80E-03	7.79E-04	-3.25E-03	4.77E-04	4.09E-05	6.40E-03
17 75con 40base	-1.18E-03	1.71E-03	-2.70E-03	7.46E-04	-3.16E-03	4.73E-04	4.00E-05	6.18E-03
18 75con 30base	-1.08E-03	1.68E-03	-2.58E-03	6.99E-04	-3.01E-03	4.63E-04	3.80E-05	5.85E-03
19 75con 20base	-1.18E-03	1.60E-03	-2.43E-03	6.36E-04	-2.78E-03	4.39E-04	3.41E-05	5.39E-03
20 75con 10base	-9.12E-04	1.37E-03	-2.15E-03	5.38E-04	-2.39E-03	3.87E-04	2.41E-05	4.63E-03

base

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-2.07E-03	1.06E-03	-3.12E-03	8.41E-04	-3.39E-03	3.66E-04	4.29E-05	6.91E-03
22 50con 90base	-1.96E-03	1.15E-03	-3.07E-03	8.27E-04	-3.32E-03	3.79E-04	4.31E-05	6.83E-03
23 50con 80base	-1.84E-03	1.24E-03	-3.02E-03	8.11E-04	-3.28E-03	3.93E-04	4.33E-05	6.74E-03
24 50con 70base	-1.72E-03	1.33E-03	-2.97E-03	7.92E-04	-3.26E-03	4.06E-04	4.34E-05	6.63E-03
25 50con 60base	-1.60E-03	1.41E-03	-2.90E-03	7.71E-04	-3.22E-03	4.19E-04	4.34E-05	6.50E-03
26 50con 50base	-1.47E-03	1.48E-03	-2.83E-03	7.44E-04	-3.17E-03	4.30E-04	4.32E-05	6.34E-03
27 50con 40base	-1.33E-03	1.54E-03	-2.73E-03	7.12E-04	-3.10E-03	[illegible]	4.25E-05	6.14E-03
28 50con 30base	-1.19E-03	1.57E-03	-2.63E-03	6.71E-04	-2.99E-03	4.43E-04	4.11E-05	5.87E-03
29 50con 20base	-1.04E-03	1.55E-03	-2.49E-03	6.15E-04	-2.80E-03	4.36E-04	3.80E-05	5.47E-03
30 50con 10base	-9.49E-04	1.40E-03	-2.25E-03	5.30E-04	-2.46E-03	4.02E-04	2.94E-05	4.79E-03

NO DOWEL BAR CASE STUDY

Young's Modulus		*Poisson's Ratio*	
concrete	3.00E+07	concrete	3.00E-01
dowel bar	5.00E+08	dowel bar	3.00E-01
base course	4.00E+06	base course	3.00E-01
subgrade	2.50E+06	subgrade	3.00E-01

a.1 Stress Summary

subgrade

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-7.41E+02	1.04E+03	-3.08E+03	7.65E+01	-8.31E+02	1.14E+03	9.99E+02	2.87E+03
2 100con 90base	-7.44E+02	9.98E+02	-2.94E+03	7.73E+01	-8.43E+02	1.14E+03	9.82E+02	2.90E+03
3 100con 80base	-7.47E+02	9.47E+02	-3.08E+03	7.83E+01	-8.55E+02	1.14E+03	9.61E+02	2.92E+03
4 100con 70base	-7.49E+02	8.84E+02	-3.01E+03	7.94E+01	-8.69E+02	1.14E+03	9.37E+02	2.94E+03
5 100con 60base	-7.49E+02	8.06E+02	-3.15E+03	8.07E+01	-8.83E+02	1.14E+03	9.03E+02	2.97E+03
6 100con 50base	-7.53E+02	6.93E+02	-3.19E+03	8.25E+01	-8.98E+02	1.15E+03	8.48E+02	2.98E+03
7 100con 40base	-7.98E+02	5.69E+02	-3.22E+03	8.44E+01	-9.10E+02	1.15E+03	7.91E+02	2.99E+03
8 100con 30base	-8.66E+02	3.77E+02	-3.24E+03	8.72E+01	-9.20E+02	1.17E+03	7.10E+02	2.98E+03
9 100con 20base	-9.64E+02	8.20E+01	-3.29E+03	9.11E+01	-9.20E+02	1.20E+03	5.97E+02	2.92E+03
10 100con 10base	-1.11E+03	-1.04E+02	-3.31E+03	9.70E+01	-8.88E+02	1.26E+03	4.29E+02	2.74E+03

subgrade

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-7.78E+02	1.19E+03	-3.20E+03	4.11E+01	-8.55E+02	8.88E+02	1.02E+03	2.94E+03
12 75con 90base	-7.81E+02	1.16E+03	-3.19E+03	4.18E+01	-8.66E+02	9.00E+02	1.00E+03	2.97E+03
13 75con 80base	-7.85E+02	1.12E+03	-3.17E+03	4.27E+01	-8.78E+02	9.12E+02	9.84E+02	2.71E+03
14 75con 70base	-7.87E+02	1.07E+03	-3.20E+03	4.37E+01	-8.90E+02	9.23E+02	9.60E+02	3.02E+03
15 75con 60base	-7.87E+02	1.01E+03	-3.24E+03	4.50E+01	-9.02E+0C	9.34E+02	9.31E+02	3.04E+03
16 75con 50base	-7.85E+02	9.20E+02	-3.23E+03	4.68E+01	-9.18E+02	9.45E+02	8.81E+02	3.05E+03
17 75con 40base	-8.30E+02	8.19E+02	-3.31E+03	4.89E+01	-9.27E+02	9.50E+02	8.25E+02	3.06E+03
18 75con 30base	+9.00E+02	6.57E+02	-3.34E+03	5.21E+01	-9.35E+02	9.48E+02	7.44E+02	3.05E+03
19 75con 20base	-1.00E+03	3.98E+02	-3.38E+03	5.72E+01	-9.35E+02	9.25E+02	6.32E+02	2.99E+03
20 75con 10base	-1.15E+03	1.00E+02	-3.25E+03	6.62E+01	-9.05E+02	9.94E+02	4.61E+02	2.82E+03

subgrade

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-8.30E+02	1.24E+03	-3.35E+03	3.23E+00	8.96E+02	9.45E+02	1.04E+03	3.05E+03
22 50con 90base	-8.35E+02	1.22E+03	-3.34E+03	3.67E+00	-9.02E+02	9.58E+02	1.03E+03	3.07E+03
23 50con 80base	-8.39E+02	1.20E+03	-3.33E+03	4.23E+00	-9.12E+02	9.71E+02	1.01E+03	3.09E+03
24 50con 70base	-8.42E+02	1.17E+03	-3.33E+03	4.95E+00	-9.22E+02	9.84E+02	9.87E+02	3.12E+03
25 50con 60base	-8.43E+02	1.13E+03	-3.37E+03	5.93E+00	-9.32E+02	9.96E+02	9.59E+02	3.14E+03
26 50con 50base	-8.42E+02	1.08E+03	-3.41E+03	7.81E+00	-9.42E+02	1.01E+03	9.23E+02	3.15E+03
27 50con 40base	-8.73E+02	1.00E+03	-3.44E+03	9.32E+00	-9.51E+02	1.02E+03	8.66E+02	3.16E+03
28 50con 30base	-9.48E+02	8.84E+02	-3.48E+03	1.25E+01	-9.57E+02	1.02E+03	7.87E+02	3.14E+03
29 50con 20base	-1.05E+03	6.85E+02	-3.50E+03	1.79E+01	-9.56E+02	1.00E+03	6.75E+02	3.09E+03
30 50con 10base	-1.20E+03	2.75E+02	-3.56E+03	2.90E+01	-9.28E+02	9.26E+02	5.04E+02	2.93E+03

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subgrade

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-2.96E-04	4.16E-04	-1.23E-03	3.06E-05	-3.32E-04	4.57E-04	4.00E-04	1.15E-03
2 100con 90base	-2.98E-04	3.99E-04	-1.17E-03	3.09E-05	-3.37E-04	4.57E-04	3.93E-04	1.16E-03
3 100con 80base	-2.99E-04	3.79E-04	-1.23E-03	3.13E-05	-3.42E-04	4.56E-04	3.85E-04	1.17E-03
4 100con 70base	-2.99E-04	3.54E-04	-1.20E-03	3.17E-05	-3.47E-04	4.56E-04	3.75E-04	1.18E-03
5 100con 60base	-2.99E-04	3.22E-04	-1.26E-03	3.23E-05	-3.53E-04	4.57E-04	3.61E-04	1.19E-03
6 100con 50base	-3.01E-04	2.77E-04	-1.27E-03	3.30E-05	-3.59E-04	4.59E-04	3.39E-04	1.19E-03
7 100con 40base	-3.19E-04	2.28E-04	-1.29E-03	3.38E-05	-3.64E-04	4.61E-04	3.17E-04	1.20E-03
8 100con 30base	-3.46E-04	1.51E-04	-1.30E-03	3.49E-05	-3.68E-04	4.67E-04	2.84E-04	1.19E-03
9 100con 20base	-3.86E-04	3.28E-05	-1.31E-03	3.64E-05	-3.68E-04	4.79E-04	2.39E-04	1.17E-03
10 100con 10base	-4.43E-04	-4.16E-05	-1.33E-03	3.88E-05	-3.55E-04	5.06E-04	1.72E-04	1.10E-03

subgrade

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-3.11E-04	4.75E-04	-1.28E-03	1.64E-05	-3.42E-04	3.55E-04	4.08E-04	1.18E-03
12 75con 90base	-3.13E-04	4.62E-04	-1.27E-03	1.67E-05	-3.46E-04	3.60E-04	4.02E-04	1.19E-03
13 75con 80base	-3.14E-04	4.47E-04	-1.27E-03	1.71E-05	-3.51E-04	3.65E-04	3.94E-04	1.08E-03
14 75con 70base	-3.15E-04	4.28E-04	-1.28E-03	1.75E-05	-3.56E-04	3.69E-04	3.84E-04	1.21E-03
15 75con 60base	-3.15E-04	4.04E-04	-1.30E-03	1.80E-05	-3.61E-04	3.74E-04	3.72E-04	1.21E-03
16 75con 50base	-3.14E-04	3.68E-04	-1.29E-03	1.87E-05	-3.66E-04	3.78E-04	3.52E-04	1.22E-03
17 75con 40base	-3.32E-04	3.27E-04	-1.33E-03	1.96E-05	-3.71E-04	3.80E-04	3.30E-04	1.22E-03
18 75con 30base	-3.60E-04	2.63E-04	-1.34E-03	2.08E-05	-3.74E-04	3.79E-04	2.98E-04	1.22E-03
19 75con 20base	-4.00E-04	1.59E-04	-1.35E-03	2.29E-05	-3.74E-04	3.70E-04	2.53E-04	1.20E-03
20 75con 10base	-4.59E-04	4.00E-05	-1.30E-03	2.65E-05	-3.62E-04	3.98E-04	1.84E-04	1.13E-03

subgrade

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-3.32E-04	4.96E-04	-1.34E-03	1.29E-06	3.59E-04	3.78E-04	4.18E-04	1.22E-03
22 50con 90base	-3.34E-04	4.89E-04	-1.34E-03	1.47E-06	-3.61E-04	3.83E-04	4.11E-04	1.23E-03
23 50con 80base	-3.35E-04	4.80E-04	-1.33E-03	1.69E-06	-3.65E-04	3.88E-04	4.04E-04	1.24E-03
24 50con 70base	-3.37E-04	4.68E-04	-1.33E-03	1.98E-06	-3.69E-04	3.93E-04	3.95E-04	1.25E-03
25 50con 60base	-3.37E-04	4.53E-04	-1.35E-03	2.37E-06	-3.73E-04	3.99E-04	3.83E-04	1.25E-03
26 50con 50base	-3.37E-04	4.32E-04	-1.36E-03	2.92E-06	-3.77E-04	4.03E-04	3.69E-04	1.26E-03
27 50con 40base	-3.49E-04	4.01E-04	-1.38E-03	3.73E-06	-3.80E-04	4.07E-04	3.46E-04	1.26E-03
28 50con 30base	-3.79E-04	3.54E-04	-1.39E-03	4.99E-06	-3.83E-04	4.08E-04	3.15E-04	1.26E-03
29 50con 20base	-4.21E-04	2.74E-04	-1.40E-03	7.14E-06	-3.82E-04	4.01E-04	2.70E-04	1.24E-03
30 50con 10base	-4.82E-04	1.10E-04	-1.42E-03	1.16E-05	-3.71E-04	3.71E-04	2.02E-04	1.17E-03

DOWEL BAR CASE STUDY

a.) Stress Summary

concrete

		S11		S22		S12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1	100con 100base	-3.70E+04	2.65E+04	-5.70E+04	2.47E+04	-3.84E+04	1.17E+04	1.48E+03	8.36E+04
2	100con 90base	-3.77E+04	2.75E+04	-5.76E+04	2.60E+04	-3.91E+04	1.22E+04	1.53E+03	8.49E+04
3	100con 80base	-3.85E+04	2.87E+04	-5.83E+04	2.75E+04	-3.99E+04	1.28E+04	1.58E+03	8.63E+04
4	100con 70base	-3.95E+04	3.01E+04	-5.91E+04	2.92E+04	-4.08E+04	1.35E+04	1.64E+03	8.79E+04
5	100con 60base	-4.06E+04	3.17E+04	-6.01E+04	3.11E+04	-4.19E+04	1.44E+04	1.71E+03	8.99E+04
6	100con 50base	-4.22E+04	3.38E+04	-6.15E+04	3.37E+04	-4.34E+04	1.56E+04	1.79E+03	9.26E+04
7	100con 40base	-4.39E+04	3.60E+04	-6.29E+04	3.64E+04	-4.51E+04	1.70E+04	1.86E+03	9.56E+04
8	100con 30base	-4.65E+04	3.93E+04	-6.53E+04	4.02E+04	-4.76E+04	1.91E+04	1.96E+03	1.00E+05
9	100con 20base	-5.07E+04	4.43E+04	-6.92E+04	4.59E+04	-5.18E+04	2.28E+04	1.95E+03	1.08E+05
10	100con 10base	-5.99E+04	5.46E+04	-7.79E+04	5.70E+04	-6.09E+04	3.11E+04	1.84E+03	1.25E+05

concrete

		S11		S22		S12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11	75con 100base	-3.08E+04	2.11E+04	-5.24E+04	2.09E+04	-3.25E+04	8.75E+03	1.21E+03	7.38E+04
12	75con 90base	-3.14E+04	2.20E+04	-5.31E+04	2.21E+04	-3.31E+04	9.17E+03	1.31E+03	7.49E+04
13	75con 80base	-3.21E+04	2.30E+04	-5.38E+04	2.35E+04	-3.38E+04	9.67E+03	1.41E+03	7.62E+04
14	75con 70base	-3.30E+04	2.41E+04	-5.46E+04	2.50E+04	-3.46E+04	1.03E+04	1.47E+03	7.78E+04
15	75con 60base	-3.40E+04	2.55E+04	5.56E+04	2.69E+04	-3.56E+04	1.10E+04	1.53E+03	7.96E+04
16	75con 50base	-3.54E+04	2.74E+04	-5.69E+04	2.93E+04	-3.70E+04	1.21E+04	1.61E+03	8.21E+04
17	75con 40base	-3.69E+04	2.93E+04	-5.84E+04	3.18E+04	-3.85E+04	1.32E+04	1.69E+03	8.49E+04
18	75con 30base	-3.92E+04	3.22E+04	-6.07E+04	3.55E+04	-4.08E+04	1.51E+04	1.80E+03	8.92E+04
19	75con 20base	-4.29E+04	3.66E+04	-6.45E+04	4.10E+04	-4.45E+04	1.83E+04	1.80E+03	9.62E+04
20	75con 10base	-5.09E+04	4.56E+04	-7.30E+04	5.17E+04	-5.27E+04	2.56E+04	1.63E+03	4.56E+04

concrete

		S11		S22		S12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21	50con 100base	-2.38E+04	1.50E+04	-4.61E+04	1.58E+04	-2.55E+04	5.52E+03	8.26E+02	6.17E+04
22	50con 90base	-2.43E+04	1.57E+04	-4.67E+04	1.68E+04	-2.60E+04	5.83E+03	9.28E+02	6.27E+04
23	50con 80base	-2.48E+04	1.64E+04	-4.74E+04	1.80E+04	-2.66E+04	6.20E+03	1.05E+03	6.38E+04
24	50con 70base	-2.55E+04	1.73E+04	-4.82E+04	1.94E+04	-2.73E+04	6.65E+03	1.11E+03	6.52E+04
25	50con 60base	-2.63E+04	1.84E+04	-4.91E+04	2.10E+04	-2.82E+04	7.22E+03	1.18E+03	6.68E+04
26	50con 50base	-2.74E+04	1.99E+04	-5.04E+04	2.32E+04	-2.93E+04	8.04E+03	1.29E+03	6.90E+04
27	50con 40base	-2.87E+04	2.14E+04	-5.18E+04	2.54E+04	-3.06E+04	8.96E+03	1.42E+03	7.14E+04
28	50con 30base	-3.05E+04	2.38E+04	-5.40E+04	2.88E+04	-3.25E+04	1.06E+04	1.65E+03	7.52E+04
29	50con 20base	-3.35E+04	2.74E+04	-5.76E+04	3.38E+04	-3.56E+04	1.30E+04	1.66E+03	8.13E+04
30	50con 10base	-4.01E+04	3.47E+04	-6.53E+04	4.38E+04	-4.24E+04	1.89E+04	1.43E+03	9.46E+04

b.) Strain Summary

concrete

		E11		E22		E12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1	100con 100base	-4.620E-04	3.307E-04	-7.125E-04	3.084E-04	-4.799E-04	1.468E-04	1.848E-05	1.046E-03
2	100con 90base	-4.710E-04	3.439E-04	-7.200E-04	3.250E-04	-4.885E-04	1.530E-04	1.910E-05	1.061E-03
3	100con 80base	-4.813E-04	3.588E-04	-7.286E-04	3.436E-04	-4.963E-04	1.603E-04	1.979E-05	1.078E-03
4	100con 70base	-4.932E-04	3.758E-04	-7.388E-04	3.647E-04	-5.098E-04	1.691E-04	2.054E-05	1.099E-03
5	100con 60base	-5.076E-04	3.958E-04	-7.510E-04	3.892E-04	-5.235E-04	1.798E-04	2.136E-05	1.123E-03
6	100con 50base	-5.274E-04	4.225E-04	-7.681E-04	4.216E-04	-5.427E-04	1.952E-04	2.236E-05	1.158E-03
7	100con 40base	-5.485E-04	4.501E-04	-7.867E-04	4.545E-04	-5.632E-04	2.121E-04	2.329E-05	1.195E-03
8	100con 30base	-5.811E-04	4.911E-04	-8.161E-04	5.022E-04	-5.951E-04	2.392E-04	2.446E-05	1.253E-03
9	100con 20base	-6.338E-04	5.539E-04	-8.647E-04	5.732E-04	-6.470E-04	2.846E-04	2.434E-05	1.349E-03
10	100con 10base	-7.491E-04	6.823E-04	-9.741E-04	7.123E-04	-7.615E-04	3.889E-04	2.299E-05	1.562E-03

concrete

		E11		E22		E12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11	75con 100base	-3.851E-04	2.633E-04	-6.556E-04	2.610E-04	-4.061E-04	1.094E-04	1.506E-05	9.226E-04
12	75con 90base	-3.929E-04	2.745E-04	-6.632E-04	2.762E-04	-4.138E-04	1.146E-04	1.643E-05	9.368E-04
13	75con 80base	-4.018E-04	2.871E-04	-6.719E-04	2.934E-04	-4.227E-04	1.208E-04	1.765E-05	9.530E-04
14	75con 70base	-4.123E-04	3.017E-04	-6.821E-04	3.131E-04	-4.330E-04	1.283E-04	1.833E-05	9.720E-04
15	75con 60base	-4.249E-04	3.189E-04	6.944E-04	3.360E-04	-4.455E-04	1.375E-04	1.911E-05	9.949E-04
16	75con 50base	-4.423E-04	3.421E-04	-7.115E-04	3.666E-04	-4.627E-04	1.508E-04	2.014E-05	1.027E-03
17	75con 40base	-4.609E-04	3.661E-04	-7.299E-04	3.979E-04	-4.812E-04	1.655E-04	2.111E-05	1.061E-03
18	75con 30base	-4.896E-04	4.020E-04	-7.589E-04	4.437E-04	-5.100E-04	1.890E-04	2.244E-05	1.115E-03
19	75con 20base	-5.360E-04	4.572E-04	-8.064E-04	5.123E-04	-5.566E-04	2.288E-04	2.250E-05	1.203E-03
20	75con 10base	-6.366E-04	5.696E-04	-9.119E-04	6.465E-04	-6.587E-04	3.199E-04	2.041E-05	5.704E-04

concrete

		E11		E22		E12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21	50con 100base	-2.970E-04	1.872E-04	-5.765E-04	1.975E-04	-3.190E-04	6.904E-05	1.033E-05	7.711E-04
22	50con 90base	-3.032E-04	1.957E-04	-5.839E-04	2.104E-04	-3.255E-04	7.291E-05	1.160E-05	7.835E-04
23	50con 80base	-3.104E-04	2.055E-04	-5.923E-04	2.251E-04	-3.329E-04	7.754E-05	1.318E-05	7.977E-04
24	50con 70base	-3.188E-04	2.168E-04	-6.021E-04	2.422E-04	-3.415E-04	8.318E-05	1.386E-05	8.144E-04
25	50con 60base	-3.290E-04	2.303E-04	-6.138E-04	2.623E-04	-3.520E-04	9.025E-05	1.473E-05	8.345E-04
26	50con 50base	-3.430E-04	2.487E-04	-6.302E-04	2.896E-04	-3.665E-04	1.005E-04	1.609E-05	8.625E-04
27	50con 40base	-3.582E-04	2.68[illegible]E-04	-6.4[illegible]7E-04	3.179E-04	-3.821E-04	1.120E-04	1.774E-05	8.925E-04
28	50con 30base	-3.815E-04	2.97[illegible]E-04	-6.750E-04	3.597E-04	-4.063E-04	1.307E-04	2.068E-05	9.394E-04
29	50con 20base	-4.193E-04	3.419E-04	-7.195E-04	4.229E-04	-4.455E-04	1.625E-04	2.069E-05	1.016E-03
30	50con 10base	-5.006E-04	4.334E-04	-8.168E-04	5.471E-04	-5.306E-04	2.359E-04	1.786E-05	1.183E-03

a.) Stress Summary

		base							
		S11		S22		S12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1	100con 100base	-1.57E+03	7.61E+03	-6.19E+00	-1.26E+02	-3.36E+03	1.65E+03	9.49E+01	1.23E+04
2	100con 90base	-1.59E+03	7.14E+03	-5.85E+03	-1.27E+02	-3.16E+03	1.58E+03	9.03E+01	1.17E+04
3	100con 80base	-1.60E+03	6.63E+03	-5.67E+03	-1.27E+02	-2.95E+03	1.50E+03	8.66E+01	1.11E+04
4	100con 70base	-1.60E+03	6.06E+03	-5.47E+03	-1.26E+02	-2.72E+03	1.40E+03	8.37E+01	1.04E+04
5	100con 60base	-1.59E+03	5.45E+03	-5.23E+03	-1.26E+02	-2.48E+03	1.30E+03	8.17E+01	9.62E+03
6	100con 50base	-1.57E+03	4.70E+03	-4.94E+03	-1.25E+02	-2.18E+03	1.18E+03	8.01E+01	8.68E+03
7	100con 40base	-1.53E+03	4.03E+03	-4.66E+03	-1.24E+02	-1.91E+03	1.07E+03	7.89E+01	7.81E+03
8	100con 30base	-1.47E+03	3.19E+03	-4.29E+03	-1.21E+02	-1.58E+03	9.29E+02	7.77E+01	6.72E+03
9	100con 20base	-1.37E+03	2.24E+03	3.83E+03	-1.16E+02	-1.20E+03	7.49E+02	7.11E+01	5.45E+03
10	100con 10base	-1.20E+03	1.13E+03	-3.18E+03	-1.08E+02	-7.49E+02	5.12E+02	6.27E+01	3.86E+03

		base							
		S11		S22		S12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11	75con 100base	-1.48E+03	7.27E+03	-5.97E+03	-1.28E+02	-3.38E+03	1.48E+03	9.67E+01	1.18E+04
12	75con 90base	-1.51E+03	6.85E+03	-5.83E+03	-1.28E+02	-3.20E+03	1.43E+03	9.30E+01	1.13E+04
13	75con 80base	-1.54E+03	6.40E+03	-5.67E+03	-1.28E+02	-3.00E+03	1.37E+03	9.02E+01	1.08E+04
14	75con 70base	-1.55E+03	5.90E+03	-5.49E+03	-1.29E+02	-2.78E+03	1.30E+03	8.81E+01	1.02E+04
15	75con 60base	-1.56E+03	5.34E+03	-5.28E+03	-1.28E+02	-2.54E+03	1.22E+03	8.67E+01	9.52E+03
16	75con 50base	-1.56E+03	4.65E+03	-5.01E+03	-1.28E+02	-2.25E+03	1.11E+03	8.56E+01	8.66E+03
17	75con 40base	-1.54E+03	4.02E+03	-4.75E+03	-1.27E+02	-1.98E+03	1.00E+03	8.47E+01	7.86E+03
18	75con 30base	-1.49E+03	3.23E+03	-4.41E+03	-1.24E+02	-1.65E+03	8.76E+02	8.28E+01	6.83E+03
19	75con 20base	-1.41E+03	2.30E+03	-3.96E+03	-1.19E+02	-1.27E+03	7.27E+02	7.63E+01	5.60E+03
20	75con 10base	-1.24E+03	1.20E+03	-3.31E+03	-1.07E+02	-8.00E+02	5.14E+02	6.47E+01	4.02E+03

		base							
		S11		S22		S12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21	50con 100base	-1.31E+03	6.60E+03	-5.83E+03	-1.32E+02	-3.38E+03	1.19E+03	9.80E+01	1.10E+04
22	50con 90base	-1.36E+03	6.27E+03	-5.72E+03	-1.32E+02	-3.21E+03	1.17E+03	9.57E+01	1.06E+04
23	50con 80base	-1.41E+03	5.91E+03	-5.60E+03	-1.33E+02	-3.02E+03	1.14E+03	9.40E+01	1.02E+04
24	50con 70base	-1.46E+03	5.50E+03	-5.46E+03	-1.33E+02	-2.82E+03	1.10E+03	9.30E+01	9.73E+03
25	50con 60base	-1.50E+03	5.04E+03	-5.29E+03	-1.34E+02	-2.60E+03	1.05E+03	9.25E+01	9.18E+03
26	50con 50base	-1.52E+03	4.46E+03	-5.06E+03	-1.34E+02	-2.32E+03	9.82E+02	9.22E+01	8.47E+03
27	50con 40base	-1.53E+03	3.91E+03	-4.84E+03	-1.33E+02	-2.06E+03	9.09E+02	9.18E+01	7.78E+03
28	50con 30base	-1.51E+03	3.19E+03	-4.53E+03	-1.31E+02	-1.74E+03	8.03E+02	9.04E+01	6.87E+03
29	50con 20base	-1.45E+03	2.34E+03	-4.11E+03	-1.26E+02	-1.35E+03	6.65E+02	8.42E+01	5.74E+03
30	50con 10base	-1.30E+03	1.26E+03	-3.47E+03	-1.12E+02	-8.68E+02	5.02E+02	7.05E+01	4.21E+03

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		base							
		E11		E22		E12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1	100con 100base	-3.930E-04	1.904E-03	-1.548E-06	-3.160E-05	-8.395E-04	4.130E-04	2.374E-05	3.066E-03
2	100con 90base	-3.970E-04	1.785E-03	-1.464E-03	-3.163E-05	-7.905E-04	3.948E-04	2.259E-05	2.924E-03
3	100con 80base	-3.993E-04	1.656E-03	-1.418E-03	-3.163E-05	-7.378E-04	3.743E-04	2.165E-05	2.767E-03
4	100con 70base	-3.995E-04	1.516E-03	-1.366E-03	-3.160E-05	-6.810E-04	3.510E-04	2.093E-05	2.595E-03
5	100con 60base	-3.973E-04	1.363E-03	-1.308E-03	-3.145E-05	-6.193E-04	3.245E-04	2.042E-05	2.405E-03
6	100con 50base	-3.913E-04	1.176E-03	-1.235E-03	-3.125E-05	-5.448E-04	2.948E-04	2.002E-05	2.170E-03
7	100con 40base	-3.823E-04	1.007E-03	-1.165E-03	-3.090E-05	-4.775E-04	2.680E-04	1.973E-05	1.953E-03
8	100con 30base	-3.670E-04	7.973E-04	-1.073E-03	-3.025E-05	-3.945E-04	2.322E-04	1.925E-05	1.681E-03
9	100con 20base	-3.425E-04	5.603E-04	9.578E-04	-2.903E-05	-3.000E-04	1.873E-04	1.777E-05	1.362E-03
10	100con 10base	-2.995E-04	2.830E-04	-7.945E-04	-2.700E-05	-1.873E-04	1.280E-04	1.566E-05	9.648E-04

		base							
		E11		E22		E12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11	75con 100base	-3.690E-04	1.917E-03	-1.492E-03	-3.198E-05	-8.453E-04	3.708E-04	2.416E-05	2.959E-03
12	75con 90base	-3.773E-04	1.713E-03	-1.457E-03	-3.205E-05	-7.990E-04	3.580E-04	2.325E-05	2.837E-03
13	75con 80base	-3.840E-04	1.600E-03	-1.417E-03	-3.210E-05	-7.488E-04	3.428E-04	2.254E-05	2.701E-03
14	75con 70base	-3.885E-04	1.474E-03	-1.372E-03	-3.213E-05	-6.943E-04	3.250E-04	2.202E-05	2.550E-03
15	75con 60base	-3.908E-04	1.335E-03	-1.320E-03	-3.208E-05	-6.345E-04	3.043E-04	2.167E-05	2.379E-03
16	75con 50base	-3.895E-04	1.164E-03	-1.253E-03	-3.193E-05	-5.618E-04	2.770E-04	2.140E-05	2.166E-03
17	75con 40base	-3.845E-04	1.005E-03	-1.189E-03	-3.163E-05	-4.953E-04	2.503E-04	2.118E-05	1.966E-03
18	75con 30base	-3.730E-04	8.065E-04	-1.101E-03	-3.098E-05	-4.125E-04	2.191E-04	2.071E-05	1.708E-03
19	75con 20base	-3.518E-04	5.760E-04	-9.893E-04	-2.963E-05	-3.165E-04	1.819E-04	1.907E-05	1.400E-03
20	75con 10base	-3.105E-04	2.993E-04	-8.263E-04	-2.675E-05	-1.999E-04	1.285E-04	1.616E-05	1.006E-03

		base							
		E11		E22		E12		MISES	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21	50con 100base	-3.265E-04	1.649E-03	-1.456E-03	-3.290E-05	-8.440E-04	2.965E-04	2.450E-05	2.749E-03
22	50con 90base	-3.405E-04	1.568E-03	-1.430E-03	-3.305E-05	-8.015E-04	2.915E-04	2.391E-05	2.657E-03
23	50con 80base	-3.535E-04	1.477E-03	-1.400E-03	-3.320E-05	-7.555E-04	2.845E-04	2.350E-05	2.552E-03
24	50con 70base	-3.648E-04	1.375E-03	-1.364E-03	-3.333E-05	-7.048E-04	2.753E-04	2.325E-05	2.432E-03
25	50con 60base	-3.738E-04	1.260E-03	-1.322E-03	-3.340E-05	-6.488E-04	2.630E-04	2.312E-05	2.294E-03
26	50con 50base	-3.800E-04	1.114E-03	-1.266E-03	-3.338E-05	-5.795E-04	2.456E-04	2.305E-05	2.117E-03
27	50con 40base	-3.813E-04	9.763E-04	-1.210E-03	-3.320E-05	-5.155E-04	2.272E-04	2.296E-05	1.945E-03
28	50con 30base	-3.765E-04	7.983E-04	-1.132E-03	-3.270E-05	-4.340E-04	2.008E-04	2.261E-05	1.717E-03
29	50con 20base	-3.615E-04	5.845E-04	-1.027E-03	-3.143E-05	-3.378E-04	1.663E-04	2.105E-05	1.434E-03
30	50con 10base	-3.248E-04	3.158E-04	-8.675E-04	-2.798E-05	-2.170E-04	1.255E-04	1.763E-05	1.053E-03

a.) Stress Summary

subgrade

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-6.10E+02	1.45E+02	-2.54E+03	7.96E+01	-6.84E+02	1.14E+03	1.22E+03	2.20E+03
2 100con 90base	-6.37E+02	1.22E+02	-2.55E+03	8.36E+01	-6.85E+02	1.15E+03	1.23E+03	2.20E+03
3 100con 80base	-6.69E+02	9.33E+01	-2.55E+03	8.80E+01	-6.85E+02	1.17E+03	1.23E+03	2.19E+03
4 100con 70base	-7.08E+02	5.76E+01	-2.56E+03	9.35E+01	-6.82E+02	1.19E+03	1.23E+03	2.19E+03
5 100con 60base	-7.57E+02	1.25E+01	-2.56E+03	1.01E+02	-6.76E+02	1.22E+03	1.23E+03	2.26E+03
6 100con 50base	-8.32E+02	-3.68E+01	-2.56E+03	1.11E+02	-6.64E+02	1.28E+03	1.23E+03	2.37E+03
7 100con 40base	-9.20E+02	-6.68E+01	-2.56E+03	1.23E+02	-6.48E+02	1.34E+03	1.23E+03	2.51E+03
8 100con 30base	-1.07E+03	-1.14E+02	-2.53E+03	1.43E+02	-6.17E+02	1.46E+03	1.22E+03	2.76E+03
9 100con 20base	-1.37E+03	-1.83E+02	-2.48E+03	1.78E+02	-5.64E+02	1.69E+03	1.21E+03	3.25E+03
10 100con 10base	-2.18E+03	-3.82E+02	-2.34E+03	2.61E+02	-4.58E+02	2.33E+03	1.10E+03	4.59E+03

subgrade

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-4.61E+02	1.65E+02	-2.59E+03	4.22E+01	-7.13E+02	8.48E+02	1.23E+03	2.26E+03
12 75con 90base	-4.65E+02	1.43E+02	-2.60E+03	4.49E+01	-7.15E+02	8.55E+02	1.23E+03	2.26E+03
13 75con 80base	-4.70E+02	1.14E+02	-2.61E+03	4.82E+01	-7.15E+02	8.66E+02	1.24E+03	2.26E+03
14 75con 70base	-4.76E+02	7.79E+01	-2.62E+03	5.23E+01	-7.13E+02	8.79E+02	1.24E+03	2.25E+03
15 75con 60base	-4.83E+02	3.21E+01	-2.63E+03	5.76E+01	-7.09E+02	8.99E+02	1.24E+03	2.24E+03
16 75con 50base	-4.93E+02	-1.64E+01	-2.64E+03	6.56E+01	-6.98E+02	9.32E+02	1.24E+03	2.21E+03
17 75con 40base	-5.28E+02	-4.67E+01	-2.62E+03	7.50E+01	-6.83E+02	9.75E+02	1.24E+03	1.96E+03
18 75con 30base	-6.40E+02	-9.44E+01	-2.61E+03	9.11E+01	-6.54E+02	1.06E+03	1.23E+03	2.11E+03
19 75con 20base	-8.60E+02	-1.66E+02	-1.39E+03	1.20E+02	-3.96E+02	1.23E+03	1.22E+03	2.31E+03
20 75con 10base	-1.49E+03	-2.63E+02	-2.42E+03	1.92E+02	-4.94E+02	1.75E+03	1.13E+03	3.39E+03

subgrade

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-4.84E+02	1.92E+02	-2.66E+03	2.78E+00	-7.48E+02	6.47E+02	9.72E+02	2.35E+03
22 50con 90base	-4.89E+02	1.70E+02	-2.67E+03	4.38E+00	-7.51E+02	6.48E+02	9.75E+02	2.35E+03
23 50con 80base	-4.93E+02	1.41E+02	-2.69E+03	6.36E+00	-7.53E+02	6.49E+02	9.80E+02	2.35E+03
24 50con 70base	-4.99E+02	1.05E+02	-2.70E+03	8.86E+00	-7.53E+02	6.47E+02	9.88E+02	2.34E+03
25 50con 60base	-5.06E+02	5.84E+01	-2.71E+03	1.22E+01	-7.50E+02	6.43E+02	1.00E+03	2.33E+03
26 50con 50base	-5.15E+02	1.21E+01	-2.71E+03	1.74E+01	-7.42E+02	6.33E+02	1.03E+03	2.31E+03
27 50con 40base	-5.25E+02	-1.84E+01	-2.71E+03	2.37E+01	-7.28E+02	6.09E+02	1.07E+03	2.07E+03
28 50con 30base	-5.41E+02	-6.70E+01	-2.70E+03	3.50E+01	-7.01E+02	6.52E+02	1.16E+03	2.21E+03
29 50con 20base	-5.67E+02	-1.41E+02	-2.66E+03	5.69E+01	-6.51E+02	7.56E+02	1.23E+03	2.10E+03
30 50con 10base	-7.84E+02	-2.46E+02	-2.53E+03	1.14E+02	-5.43E+02	1.11E+03	1.16E+03	2.09E+03

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subgrade

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-2.440E-04	5.792E-05	-1.014E-03	3.191E-05	-2.737E-04	4.540E-04	4.892E-04	8.784E-04
2 100con 90base	-2.548E-04	4.872E-05	-1.018E-03	3.342E-05	-2.741E-04	4.596E-04	4.904E-04	8.780E-04
3 100con 80base	-2.676E-04	3.732E-05	-1.021E-03	3.521E-05	-2.739E-04	4.668E-04	4.916E-04	8.764E-04
4 100con 70base	-2.831E-04	2.302E-05	-1.024E-03	3.741E-05	-2.729E-04	4.764E-04	4.924E-04	8.752E-04
5 100con 60base	-3.028E-04	4.984E-06	-1.026E-03	4.020E-05	-2.705E-04	4.896E-04	4.928E-04	9.032E-04
6 100con 50base	-3.326E-04	-1.473E-05	-1.025E-03	4.432E-05	-2.657E-04	5.100E-04	4.928E-04	9.476E-04
7 100con 40base	-3.678E-04	-2.673E-05	-1.022E-03	4.904E-05	-2.591E-04	5.360E-04	4.916E-04	1.002E-03
8 100con 30base	-4.296E-04	-4.540E-05	-1.013E-03	5.700E-05	-2.469E-04	5.832E-04	4.888E-04	1.102E-03
9 100con 20base	-5.480E-04	-7.316E-05	-9.924E-04	7.112E-05	-2.255E-04	6.768E-04	4.820E-04	1.298E-03
10 100con 10base	-8.700E-04	-1.528E-04	-9.364E-04	1.044E-04	-1.833E-04	9.328E-04	4.400E-04	1.837E-03

subgrade

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-1.843E-04	6.616E-05	-1.036E-03	1.686E-05	-2.850E-04	3.391E-04	4.916E-04	9.040E-04
12 75con 90base	-1.860E-04	5.704E-05	-1.040E-03	1.796E-05	-2.858E-04	3.422E-04	4.928E-04	9.040E-04
13 75con 80base	-1.880E-04	4.560E-05	-1.044E-03	1.928E-05	-2.860E-04	3.462E-04	4.940E-04	9.028E-04
14 75con 70base	-1.902E-04	3.118E-05	-1.047E-03	2.092E-05	-2.854E-04	3.518E-04	4.948E-04	8.996E-04
15 75con 60base	-1.930E-04	1.285E-05	-1.050E-03	2.304E-05	-2.835E-04	3.596E-04	4.956E-04	8.940E-04
16 75con 50base	-1.971E-04	-6.548E-06	-1.055E-03	2.623E-05	-2.793E-04	3.728E-04	4.956E-04	8.836E-04
17 75con 40base	-2.110E-04	-1.868E-05	-1.049E-03	2.998E-05	-2.731E-04	3.902E-04	4.948E-04	7.840E-04
18 75con 30base	-2.560E-04	-3.775E-05	-1.042E-03	3.643E-05	-2.614E-04	4.236E-04	4.924E-04	8.440E-04
19 75con 20base	-3.438E-04	-6.640E-05	-5.576E-04	4.816E-05	-1.586E-04	4.932E-04	4.864E-04	9.256E-04
20 75con 10base	-5.948E-04	-1.052E-04	-9.680E-04	7.688E-05	-1.974E-04	7.004E-04	4.508E-04	1.356E-03

subgrade

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-1.937E-04	7.696E-05	-1.064E-03	1.110E-06	-2.993E-04	2.586E-04	3.888E-04	9.392E-04
22 50con 90base	-1.954E-04	6.796E-05	-1.069E-03	1.754E-06	-3.005E-04	2.593E-04	3.898E-04	9.400E-04
23 50con 80base	-1.974E-04	5.652E-05	-1.074E-03	2.543E-06	-3.012E-04	2.594E-04	3.918E-04	9.392E-04
24 50con 70base	-1.996E-04	4.200E-05	-1.079E-03	3.544E-06	-3.012E-04	2.588E-04	3.952E-04	9.368E-04
25 50con 60base	-2.022E-04	2.337E-05	-1.082E-03	4.868E-06	-3.000E-04	2.570E-04	4.008E-04	9.320E-04
26 50con 50base	-2.069E-04	4.836E-06	-1.085E-03	6.940E-06	-2.966E-04	2.532E-04	4.120E-04	9.224E-04
27 50con 40base	-2.099E-04	-7.368E-06	-1.085E-03	9.472E-06	-2.912E-04	2.436E-04	4.284E-04	8.276E-04
28 50con 30base	-2.164E-04	-2.679E-05	-1.080E-03	1.402E-05	-2.805E-04	2.610E-04	4.636E-04	8.840E-04
29 50con 20base	-2.267E-04	-5.644E-05	-1.064E-03	2.274E-05	-2.602E-04	3.023E-04	4.904E-04	8.408E-04
30 50con 10base	-3.135E-04	-9.840E-05	-1.012E-03	4.544E-05	-2.172E-04	4.444E-04	4.652E-04	8.356E-04

A.I Stress Summary

dowel

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-1.34E+05	6.84E+04	-1.10E+05	9.17E+04	-1.80E+05	1.35E+05	6.34E+03	3.66E+05
2 100con 90base	-1.36E+05	7.39E+04	-1.14E+05	9.59E+04	-1.86E+05	1.39E+05	5.83E+03	3.77E+05
3 100con 80base	-1.39E+05	8.01E+04	-1.18E+05	1.01E+05	-1.92E+05	1.44E+05	5.30E+03	3.91E+05
4 100con 70base	-1.42E+05	8.72E+04	-1.23E+05	1.06E+05	-2.00E+05	1.50E+05	4.76E+03	4.06E+05
5 100con 60base	-1.46E+05	9.54E+04	-1.29E+05	1.13E+05	-2.09E+05	1.57E+05	4.22E+03	4.24E+05
6 100con 50base	-1.52E+05	1.06E+05	-1.37E+05	1.22E+05	-2.21E+05	1.67E+05	3.64E+03	4.49E+05
7 100con 40base	-1.58E+05	1.18E+05	-1.45E+05	1.31E+05	-2.34E+05	1.77E+05	3.25E+03	4.75E+05
8 100con 30base	-1.69E+05	1.34E+05	-1.58E+05	1.45E+05	-2.54E+05	1.93E+05	2.98E+03	5.15E+05
9 100con 20base	-1.87E+05	1.59E+05	-1.79E+05	1.67E+05	-2.81E+05	2.17E+05	2.81E+03	5.80E+05
10 100con 10base	-2.28E+05	2.10E+05	-2.24E+05	2.14E+05	-3.51E+05	2.68E+05	3.10E+03	7.17E+05

dowel

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-1.27E+05	6.13E+04	-1.03E+05	8.51E+04	-1.69E+05	1.31E+05	6.75E+03	3.43E+05
12 75con 90base	-1.29E+05	6.67E+04	-1.06E+05	8.92E+04	-1.74E+05	1.36E+05	6.26E+03	3.55E+05
13 75con 80base	-1.32E+05	7.28E+04	-1.11E+05	9.40E+04	-1.81E+05	1.41E+05	5.76E+03	3.68E+05
14 75con 70base	-1.35E+05	7.98E+04	-1.16E+05	9.95E+04	-1.89E+05	1.47E+05	5.26E+03	3.83E+05
15 75con 60base	-1.39E+05	8.80E+04	-1.21E+05	1.06E+05	-1.98E+05	1.55E+05	4.77E+03	4.02E+05
16 75con 50base	-1.46E+05	9.91E+04	-1.30E+05	1.15E+05	-2.10E+05	1.65E+05	4.29E+03	4.27E+05
17 75con 40base	-1.52E+05	1.10E+05	-1.38E+05	1.25E+05	-2.24E+05	1.76E+05	3.99E+03	4.54E+05
18 75con 30base	-1.63E+05	1.27E+05	-1.52E+05	1.39E+05	-2.44E+05	1.92E+05	3.83E+03	4.95E+05
19 75con 20base	-1.82E+05	1.53E+05	-1.73E+05	1.62E+05	-2.76E+05	2.18E+05	3.61E+03	5.61E+05
20 75con 10base	-2.24E+05	2.06E+05	-2.19E+05	2.10E+05	-3.44E+05	2.72E+05	3.59E+03	7.02E+05

dowel

	S11		S22		S12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-1.16E+05	5.17E+04	-9.22E+04	7.57E+04	-1.52E+05	1.24E+05	7.36E+03	3.11E+05
22 50con 90base	-1.19E+05	5.68E+04	-9.58E+04	7.96E+04	-1.58E+05	1.29E+05	6.95E+03	3.22E+05
23 50con 80base	-1.21E+05	6.26E+04	-9.99E+04	8.41E+04	-1.65E+05	1.34E+05	6.54E+03	3.34E+05
24 50con 70base	-1.25E+05	6.93E+04	-1.05E+05	8.94E+04	-1.72E+05	1.41E+05	6.15E+03	3.50E+05
25 50con 60base	-1.29E+05	7.73E+04	-1.11E+05	9.58E+04	-1.81E+05	1.10E+05	5.80E+03	3.68E+05
26 50con 50base	-1.12E+05	8.81E+04	-1.19E+05	1.05E+05	-1.94E+05	1.59E+05	5.51E+03	3.93E+05
27 50con 40base	-1.42E+05	9.94E+04	-1.28E+05	1.14E+05	-2.07E+05	1.70E+05	5.39E+03	4.20E+05
28 50con 30base	-1.53E+05	1.16E+05	-1.41E+05	1.29E+05	-2.28E+05	1.87E+05	5.42E+03	4.62E+05
29 50con 20base	-1.72E+05	1.42E+05	-1.63E+05	1.52E+05	-2.60E+05	2.15E+05	5.15E+03	5.29E+05
30 50con 10base	-2.15E+05	1.95E+05	-2.10E+05	2.00E+05	-3.30E+05	2.72E+05	5.11E+03	6.73E+05

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dowel

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
1 100con 100base	-2.670E-04	1.368E-04	-2.204E-04	1.834E-04	-3.596E-04	2.696E-04	1.268E-05	7.319E-04
2 100con 90base	-2.717E-04	1.478E-04	-2.277E-04	1.919E-04	-3.712E-04	2.786E-04	1.166E-05	7.549E-04
3 100con 80base	-2.772E-04	1.602E-04	-2.360E-04	2.014E-04	-3.844E-04	2.889E-04	1.061E-05	7.811E-04
4 100con 70base	-2.838E-04	1.744E-04	-2.457E-04	2.125E-04	-3.997E-04	3.009E-04	9.522E-06	8.117E-04
5 100con 60base	-2.921E-04	1.908E-04	-2.573E-04	2.256E-04	-4.178E-04	3.150E-04	8.432E-06	8.480E-04
6 100con 50base	-3.038E-04	2.128E-04	-2.732E-04	2.435E-04	-4.425E-04	3.342E-04	7.288E-06	8.978E-04
7 100con 40base	-3.169E-04	2.353E-04	-2.901E-04	2.622E-04	-4.684E-04	3.545E-04	6.496E-06	9.505E-04
8 100con 30base	-3.379E-04	2.685E-04	-3.160E-04	2.904E-04	-5.078E-04	3.851E-04	5.958E-06	1.031E-03
9 100con 20base	-3.736E-04	3.189E-04	-3.577E-04	3.348E-04	-5.610E-04	4.335E-04	5.610E-06	1.159E-03
10 100con 10base	-4.560E-04	4.205E-04	-4.478E-04	4.287E-04	-7.026E-04	5.364E-04	6.206E-06	1.434E-03

dowel

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
11 75con 100base	-2.531E-04	1.227E-04	-2.056E-04	1.702E-04	-3.372E-04	2.625E-04	1.351E-05	6.864E-04
12 75con 90base	-2.579E-04	1.335E-04	-2.129E-04	1.785E-04	-3.488E-04	2.718E-04	1.253E-05	7.094E-04
13 75con 80base	-2.636E-04	1.456E-04	-2.213E-04	1.879E-04	-3.620E-04	2.825E-04	1.153E-05	7.358E-04
14 75con 70base	-2.704E-04	1.596E-04	-2.311E-04	1.989E-04	-3.774E-04	2.949E-04	1.052E-05	7.666E-04
15 75con 60base	-2.789E-04	1.761E-04	-2.429E-04	2.121E-04	-3.958E-04	3.097E-04	9.542E-06	8.034E-04
16 75con 50base	-2.912E-04	1.982E-04	-2.592E-04	2.301E-04	-4.210E-04	3.300E-04	8.580E-06	8.542E-04
17 75con 40base	-3.047E-04	2.210E-04	-2.766E-04	2.490E-04	-4.476E-04	3.514E-04	7.982E-06	9.082E-04
18 75con 30base	-3.265E-04	2.548E-04	-3.034E-04	2.779E-04	-4.881E-04	3.839E-04	7.666E-06	9.909E-04
19 75con 20base	-3.633E-04	3.063E-04	-3.462E-04	3.233E-04	-5.522E-04	4.354E-04	7.210E-06	1.123E-03
20 75con 10base	-4.477E-04	4.103E-04	-4.387E-04	4.193E-04	-6.881E-04	5.443E-04	7.176E-06	1.405E-03

dowel

	E11		E22		E12		MISES	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
21 50con 100base	-2.324E-04	1.034E-04	-1.845E-04	1.513E-04	-3.050E-04	2.488E-04	1.472E-05	6.210E-04
22 50con 90base	-2.371E-04	1.136E-04	-1.916E-04	1.591E-04	-3.162E-04	2.581E-04	1.389E-05	6.432E-04
23 50con 80base	-2.428E-04	1.252E-04	-1.998E-04	1.682E-04	-3.291E-04	2.689E-04	1.307E-05	6.688E-04
24 50con 70base	-2.497E-04	1.386E-04	-2.095E-04	1.788E-04	-3.442E-04	2.816E-04	1.229E-05	6.990E-04
25 50con 60base	-2.583E-04	1.545E-04	-2.212E-04	1.916E-04	-3.624E-04	2.196E-04	1.160E-05	7.355E-04
26 50con 50base	-2.244E-04	1.761E-04	-2.376E-04	2.093E-04	-3.879E-04	3.179E-04	1.102E-05	7.863E-04
27 50con 40base	-2.845E-04	1.988E-04	-2.551E-04	2.281E-04	-4.144E-04	3.403E-04	1.078E-05	8.406E-04
28 50con 30base	-3.068E-04	2.326E-04	-2.823E-04	2.571E-04	-4.555E-04	3.747E-04	1.085E-05	9.244E-04
29 50con 20base	-3.444E-04	2.848E-04	-3.261E-04	3.032E-04	-5.209E-04	4.294E-04	1.031E-05	1.059E-03
30 50con 10base	-4.302E-04	3.905E-04	-4.202E-04	4.006E-04	-6.595E-04	5.449E-04	1.022E-05	1.346E-03

APPENDIX C

Von Mises Failure Criterion

2-D FEM Analysis of Concrete Stresses

For this study, three levels of concrete strength were used for simulation of stress changes occuring within a rigid pavement system over time

Values of f'c in psi: =====> translated to Young's Modulus in psf
E = 59,000 * SQRT (f'c)

psi	psi	psf			
3750.0	3.61E+06	5.2E+08	1	"new"	100%
2125.0	2.72E+06	3.92E+08	0.752773	"service"	75%
950.0	1.82E+06	2.62E+08	0.503322	"old"	50%

Evaluation of concrete performance completed using J(2), or Mises Failure criteria
Criteria calculates mises stress, a measure of shear, and compares to a "k" value.
k value is specified failure level. In this case, k = f'c
When the mises stress is equal to or greater than k, failure occurs.

<u>without a dowel bar</u>

1	100con 100base	3.15E+04	5.40E+05	0.058294	5.83%
2	100con 90base	3.13E+04	5.40E+05	0.057881	5.79%
3	100con 80base	3.10E+04	5.40E+05	0.057341	5.73%
4	100con 70base	3.06E+04	5.40E+05	0.056626	5.66%
5	100con 60base	3.01E+04	5.40E+05	0.055678	5.57%
6	100con 50base	2.93E+04	5.40E+05	0.054259	5.43%
7	100con 40base	2.84E+04	5.40E+05	0.052676	5.27%
8	100con 30base	2.71E+04	5.40E+05	0.050241	5.02%
9	100con 20base	2.52E+04	5.40E+05	0.046646	4.66%
10	100con 10base	2.21E+04	5.40E+05	0.040931	4.09%
11	75con 100base	3.02E+04	3.06E+05	0.098817	9.88%
12	75con 90base	3.01E+04	3.06E+05	0.098431	9.84%
13	75con 80base	2.99E+04	3.06E+05	0.097873	9.79%
14	75con 70base	2.97E+04	3.06E+05	0.097078	9.71%
15	75con 60base	2.94E+04	3.06E+05	0.095951	9.60%
16	75con 50base	2.88E+04	3.06E+05	0.094144	9.41%
17	75con 40base	2.82E+04	3.06E+05	0.09201	9.20%
18	75con 30base	2.71E+04	3.06E+05	0.088536	8.85%
19	75con 20base	2.54E+04	3.06E+05	0.083065	8.31%
20	75con 10base	2.25E+04	3.06E+05	0.073549	7.35%
21	50con 100base	2.84E+04	1.37E+05	0.207405	20.74%
22	50con 90base	2.84E+04	1.37E+05	0.207368	20.74%
23	50con 80base	2.83E+04	1.37E+05	0.207142	20.71%
24	50con 70base	2.81E+04	1.37E+05	0.205154	20.52%
25	50con 60base	2.81E+04	1.37E+05	0.205621	20.56%
26	50con 50base	2.79E+04	1.37E+05	0.203889	20.39%
27	50con 40base	2.75E+04	1.37E+05	0.200943	20.09%
28	50con 30base	2.68E+04	1.37E+05	0.195914	19.59%
29	50con 20base	2.56E+04	1.37E+05	0.186908	18.69%
30	50con 10base	2.20E+04	1.37E+05	0.160819	16.08%

2-D FEM Analysis of Concrete Stresses

For this study, three levels of concrete strength were used for simulation of stress changes occuring within a rigid pavement system over time.

Values of f'c in psi: =====> translated to Young's Modulus in psi
E = 59,000 * SQRT (f'c)

psi	psi	psf			
3750.0	3.61E+06	5.2E+08	1	"new"	100%
2125.0	2.72E+06	3.92E+08	0.752773	"service"	75%
950.0	1.82E+06	2.62E+08	0.503322	"old"	50%

Evaluation of concrete performance completed using J(2), or Mises Failure criteria
Criteria calculates mises stress, a measure of shear, and compares to a "k" value.
k value is specified failure level. In this case, k = f'c
When the mises stress is equal to or greater than k, failure occurs.

with a dowel bar

	model	MISES	k value	stress ratio	% toward failure
1	100con 100base	8.36E+04	5.40E+05	0.154896	15.49%
2	100con 90base	8.49E+04	5.40E+05	0.15715	15.72%
3	100con 80base	8.63E+04	5.40E+05	0.159737	15.97%
4	100con 70base	8.79E+04	5.40E+05	0.162772	16.28%
5	100con 60base	8.99E+04	5.40E+05	0.166428	16.64%
6	100con 50base	9.26E+04	5.40E+05	0.171526	17.15%
7	100con 40base	9.56E+04	5.40E+05	0.177028	17.70%
8	100con 30base	1.00E+05	5.40E+05	0.185648	18.56%
9	100con 20base	1.08E+05	5.40E+05	0.199796	19.98%
10	100con 10base	1.25E+05	5.40E+05	0.23137	23.14%
11	75con 100base	7.38E+04	3.06E+05	0.241209	24.12%
12	75con 90base	7.49E+04	3.06E+05	0.244905	24.49%
13	75con 80base	7.62E+04	3.06E+05	0.249147	24.91%
14	75con 70base	7.78E+04	3.06E+05	0.254121	25.41%
15	75con 60base	7.96E+04	3.06E+05	0.260108	26.01%
16	75con 50base	8.21E+04	3.06E+05	0.268441	26.84%
17	75con 40base	8.49E+04	3.06E+05	0.277425	27.74%
18	75con 30base	8.92E+04	3.06E+05	0.291448	29.14%
19	75con 20base	9.62E+04	3.06E+05	0.314386	31.44%
20	75con 10base	1.06E+05	3.06E+05	0.345199	34.52%
21	50con 100base	6.17E+04	1.37E+05	0.450906	45.09%
22	50con 90base	6.27E+04	1.37E+05	0.458165	45.82%
23	50con 80base	6.38E+04	1.37E+05	0.466499	46.65%
24	50con 70base	6.52E+04	1.37E+05	0.476257	47.63%
25	50con 60base	6.68E+04	1.37E+05	0.488012	48.80%
26	50con 50base	6.90E+04	1.37E+05	0.504364	50.44%
27	50con 40base	7.14E+04	1.37E+05	0.521959	52.20%
28	50con 30base	7.52E+04	1.37E+05	0.549364	54.94%
29	50con 20base	8.13E+04	1.37E+05	0.593984	59.40%
30	50con 10base	9.46E+04	1.37E+05	0.691645	69.16%