

1. Report No. 0-1831-2	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle CRCP-9: IMPROVED COMPUTER PROGRAM FOR MECHANISTIC ANALYSIS OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS		5. Report Date February 2001	
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		8. Performing Organization Report No. Research Report 1831-2	
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. Project 0-1831	
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Section/Construction Division P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Research Report (9/99-8/00)	
		14. Sponsoring Agency Code	
15. Supplementary Notes Project conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration, and the Texas Department of Transportation.			
16. Abstract  A new version of the CRCP computer program, CRCP-9, has been developed in this study. The numerical model of the CRC pavements was developed using finite element theories, the crack spacing prediction model was developed using the Monte Carlo method, and the failure prediction model was developed using probability theories. CRCP-9 uses two-dimensional numerical methods to calculate stresses and strains, which is a totally different approach compared with the previous computer program CRCP-8 that uses one-dimensional analytical methods to calculate them. The major characteristics of CRCP-9 that differ from CRCP-8 include consideration of nonlinear variations in temperature and drying shrinkage through the depth of the concrete slab, nonlinear bond-slip relationship between concrete and steel bars, viscoelastic effect of concrete, curling and warping effects, and the ability of changing locations of the longitudinal steel bars. Details of the theoretical background of mechanistic modeling have been presented in this report. The descriptions of the computer program and input and output procedures have also been explained. Sample analysis results from CRCP-9 have been shown and comparisons of the results between CRCP-9 and CRCP-8 have been made.			
17. Key Words Continuously reinforced concrete pavement, finite element, crack spacing, punchout, bond-slip		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 116	22. Price



**CRCP-9: IMPROVED COMPUTER PROGRAM FOR MECHANISTIC ANALYSIS  
OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS**

*by*

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Research Report No. 1831-2

Research Project 0-1831

Project Title: *Improvement of Concrete Pavement Performance Model*

Conducted for the

**TEXAS DEPARTMENT OF TRANSPORTATION**

in cooperation with the

**U.S. DEPARTMENT OF TRANSPORTATION**

**Federal Highway Administration**

by the

**CENTER FOR TRANSPORTATION RESEARCH**

Bureau of Engineering Research

**THE UNIVERSITY OF TEXAS AT AUSTIN**

February 2001



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## **ACKNOWLEDGMENTS**

The researchers would like to acknowledge the expert assistance and guidance provided by the TxDOT project monitoring committee, which included G. Lantz (CSTC), G. Graham (CST-PAV), G. Lankes (CSTM), J. Kosel (CSTC), and Moon C. Won (CSTM).

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.



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## CHAPTER 1. INTRODUCTION

### 1.1 BACKGROUND AND OBJECTIVE

The first mechanistic model of continuously reinforced concrete pavement (CRCP), called CRCP-1, was developed in the mid-1970s under a study sponsored by the National Cooperative Highway Research Program (NCHRP) (Ref 1). This computer program evaluated the effect of such design variables as layer thicknesses and properties, concrete strength, and steel reinforcement, together with environmental and traffic loads, such as temperature variation, drying shrinkage, wheel loads, tire pressures, etc. In 1991, Won et al. developed an improvement to the CRCP program, CRCP-5, that simulates material variance to concrete tensile strength and includes fatigue failure models (Ref 2). The normalized curing curves were determined for different coarse aggregates commonly used in Texas pavements (Ref 3), and these curves and the calibrated failure prediction model were included in CRCP-7 (Ref 4). In 1995, previous versions of the CRCP programs were integrated into one program, CRCP-8, with simplification of the user input process (Ref 5). Although CRCP-8 has permitted pavement engineers to develop designs of the CRC pavements, there are some limitations owing to the simplified assumptions of the one-dimensional analysis. In 1996, Texas Department of Transportation (TxDOT) Project 0-1758 was conducted to expand the ability of the mechanistic model by incorporating the variations in temperature and moisture changes through the depth of concrete slab. As a result of the project, a two-dimensional finite element model was developed (Refs 6, 7). In 1998, TxDOT decided to extend the project to complete the development of a new mechanistic model, CRCP-9. CRCP-9 uses two-dimensional finite element theories to reduce the cost of computation, but in order to increase the accuracy of the 2-D model, three-dimensional analyses were performed first using a commercial finite element analysis program, ABAQUS (Ref 8), and the differences between 2-D and 3-D analysis results were investigated (Refs 9, 10).

The first version of the CRCP-9 computer program has recently been developed. The analysis engine of this mechanistic model was developed using finite element theories, the crack spacing prediction model using the Monte Carlo method, and the failure prediction model using probability theories. The previous computer program, CRCP-8, uses one-dimensional analytical methods to calculate stresses and strains, but CRCP-9 uses totally different two-dimensional numerical methods to calculate them. The major characteristics of CRCP-9 that differ from CRCP-8 include consideration of nonlinear variations in temperature and drying shrinkage through the depth of the concrete slab, nonlinear bond-slip relationship between concrete and steel bars, viscoelastic effect of concrete, curling and warping effects, and the ability to investigate the effect of placing the longitudinal steel bars at different depths. The objective of this report is to describe the details of the CRCP-9 development.

## **1.2 ORGANIZATION**

This report consists of six chapters and four appendices. The background and objective of this study are presented in Chapter 1. The finite element model of CRC pavements and the material characteristics are explained in Chapter 2. In Chapter 3, crack spacing and fatigue failure prediction models are presented. Chapter 4 describes the computer program; input and output guides are also included. Sample analysis results obtained by CRCP-9 are presented in Chapter 5, while Chapter 6 includes summary, conclusions, and recommendations. Sample input and output files and the source code of the CRCP-9 computer program are listed in the appendices.

## CHAPTER 2. NUMERICAL MODELING OF CRCP

### 2.1 FINITE ELEMENT MODEL OF CRCP

The configuration of the continuously reinforced concrete (CRC) pavement system is shown in Figure 2.1. There are longitudinal and transverse steel bars in the system. The major purpose of the use of longitudinal steel bars is to hold cracks tightly to provide structural continuities at the cracks. These steel bars are normally placed at the mid-depth of the concrete slab. The transverse steel bars are used mainly to keep the longitudinal steel bars in the proper places and to keep the longitudinal cracks in case they occur.

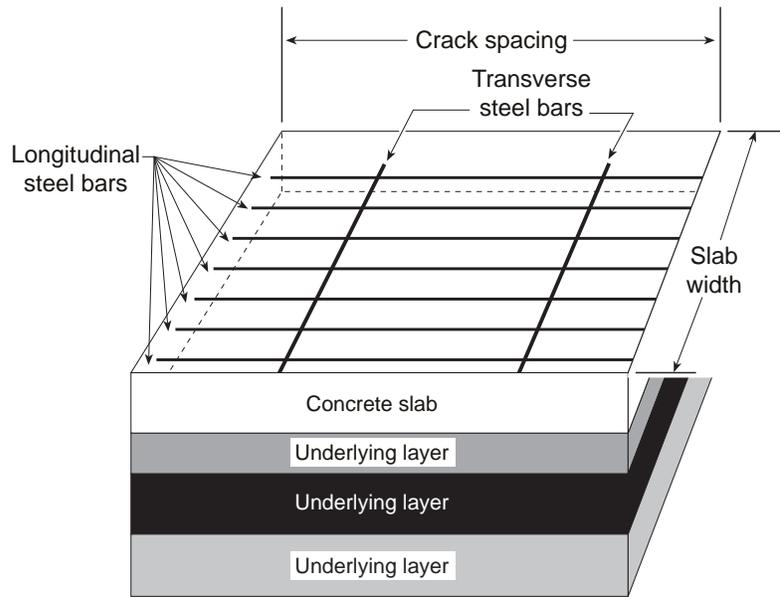


Figure 2.1. Configuration of CRC pavement

The finite element method has been used to model the CRC pavement systems. The concrete slab has been discretized using two-dimensional plane elements with the thickness of the element as the longitudinal steel bar spacing that is the distance between two longitudinal steel bars. The shape functions for a four-noded bilinear rectangular element, which has  $\xi$  and  $\eta$  coordinates of  $(-1, 1)$ ,  $(-1, -1)$ ,  $(1, 1)$ , and  $(1, -1)$  at nodes 1, 2, 3, and 4, respectively, can be written as

$$f_i = \frac{1}{4}(1 + \xi\xi_i)(1 + \eta\eta_i) \quad (2.1)$$

where  $\xi_i$  and  $\eta_i$  are the coordinates at node  $i$ . The displacements  $u$  and  $v$  in the two principal directions can be written as

$$\begin{Bmatrix} u \\ v \end{Bmatrix} = \begin{bmatrix} f_1 & 0 & f_2 & 0 & f_3 & 0 & f_4 & 0 \\ 0 & f_1 & 0 & f_2 & 0 & f_3 & 0 & f_4 \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ u_3 \\ v_3 \\ u_4 \\ v_4 \end{Bmatrix} = \mathbf{N}^T \mathbf{U} \quad (2.2)$$

For a rectangular element with the side lengths of  $a$  and  $b$  in the  $\xi$  and  $\eta$  directions, respectively, strains can be determined by

$$\begin{Bmatrix} \varepsilon_\xi \\ \varepsilon_\eta \\ \gamma_{\xi\eta} \end{Bmatrix} = \begin{bmatrix} \frac{2}{a} \frac{\partial f_1}{\partial \xi} & 0 & \frac{2}{a} \frac{\partial f_2}{\partial \xi} & 0 & \frac{2}{a} \frac{\partial f_3}{\partial \xi} & 0 & \frac{2}{a} \frac{\partial f_4}{\partial \xi} & 0 \\ 0 & \frac{2}{b} \frac{\partial f_1}{\partial \eta} & 0 & \frac{2}{b} \frac{\partial f_2}{\partial \eta} & 0 & \frac{2}{b} \frac{\partial f_3}{\partial \eta} & 0 & \frac{2}{b} \frac{\partial f_4}{\partial \eta} \\ \frac{2}{b} \frac{\partial f_1}{\partial \eta} & \frac{2}{a} \frac{\partial f_1}{\partial \xi} & \frac{2}{b} \frac{\partial f_2}{\partial \eta} & \frac{2}{a} \frac{\partial f_2}{\partial \xi} & \frac{2}{b} \frac{\partial f_3}{\partial \eta} & \frac{2}{a} \frac{\partial f_3}{\partial \xi} & \frac{2}{b} \frac{\partial f_4}{\partial \eta} & \frac{2}{a} \frac{\partial f_4}{\partial \xi} \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ u_3 \\ v_3 \\ u_4 \\ v_4 \end{Bmatrix} = \mathbf{B} \mathbf{U} \quad (2.3)$$

The element stiffness matrix can be obtained by

$$\mathbf{K} = \frac{ab}{4} t_w \int_{-1}^1 \int_{-1}^1 \mathbf{B}^T \mathbf{D} \mathbf{B} d\xi d\eta \quad (2.4)$$

where  $t_w$  is the thickness of the plane element, which is the distance between longitudinal steel bars (longitudinal steel bar spacing), and  $\mathbf{D}$  is a material property matrix. For an isotropic material, if the problem is plane strain,  $\mathbf{D}$  can be written as

$$\mathbf{D} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \quad (2.5)$$

where  $E$  is Young's modulus of elasticity and  $\nu$  is Poisson's ratio. For a plane stress problem,  $\mathbf{D}$  can be obtained by

$$\mathbf{D} = \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \quad (2.6)$$

The longitudinal steel bar has been discretized using frame elements. Assume that an element with a length of  $a$  has a constant cross-sectional area ( $A$ ), moment of inertia ( $I$ ), and modulus of elasticity ( $E$ ) within the element. Node 1 has degrees of freedom of  $u_1$  in the principal direction,  $w_1$  in the direction perpendicular to  $u_1$ ,  $\theta_1$  in the counterclockwise direction, and node 2 has  $u_2$ ,  $w_2$ ,  $\theta_2$  in the same directions as  $u_1$ ,  $w_1$ ,  $\theta_1$ , respectively, then the shape functions can be written as

$$\begin{aligned} f_1 &= 1 - \frac{\xi}{a} \\ f_2 &= 1 - \frac{3\xi^2}{a^2} + \frac{2\xi^3}{a^3} \\ f_3 &= \xi - \frac{2\xi^2}{a} + \frac{\xi^3}{a^2} \\ f_4 &= \frac{\xi}{a} \\ f_5 &= \frac{3\xi^2}{a^2} - \frac{2\xi^3}{a^3} \\ f_6 &= -\frac{\xi^2}{a} + \frac{\xi^3}{a^2} \end{aligned} \quad (2.7)$$

The displacements can be written as

$$\{u\} = [f_1 \quad f_2 \quad f_3 \quad f_4 \quad f_5 \quad f_6] \begin{Bmatrix} u_1 \\ w_1 \\ \theta_1 \\ u_2 \\ w_2 \\ \theta_2 \end{Bmatrix} = \mathbf{N}^T \mathbf{U} \quad (2.8)$$

The strain and the curvature can then be obtained by

$$\begin{Bmatrix} \varepsilon_{\xi} \\ \kappa \end{Bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial \xi} & 0 & 0 & \frac{\partial f_4}{\partial \xi} & 0 & 0 \\ 0 & \frac{\partial^2 f_2}{\partial \xi^2} & \frac{\partial^2 f_3}{\partial \xi^2} & 0 & \frac{\partial^2 f_5}{\partial \xi^2} & \frac{\partial^2 f_6}{\partial \xi^2} \end{bmatrix} \begin{Bmatrix} u_1 \\ w_1 \\ \theta_1 \\ u_2 \\ w_2 \\ \theta_2 \end{Bmatrix} = \mathbf{BU} \quad (2.9)$$

The element stiffness matrix can be obtained by

$$\mathbf{K} = \int_0^a \mathbf{B}^T \mathbf{D} \mathbf{B} d\xi = \frac{E}{a^3} \begin{bmatrix} Aa^2 & 0 & 0 & -Aa^2 & 0 & 0 \\ 0 & 12I & 6aI & 0 & -12I & 6aI \\ 0 & 6aI & 4a^2I & 0 & -6aI & 2a^2I \\ -Aa^2 & 0 & 0 & Aa^2 & 0 & 0 \\ 0 & -12I & -6aI & 0 & 12I & -6aI \\ 0 & 6aI & 2a^2I & 0 & -6aI & 4a^2I \end{bmatrix} \quad (2.10)$$

The element stiffness matrices should be assembled to create a total stiffness matrix of the system.

When there are initial strains without any other loads, the equilibrium equation can be written as

$$\int_V \mathbf{B}^T \mathbf{D} \mathbf{B} dV \mathbf{U} = \int_V \mathbf{B}^T \mathbf{D} \varepsilon_0 dV \quad (2.11)$$

where

$V$  = volume of element,

$\varepsilon_0$  = initial concrete strain vector due to temperature and drying shrinkage changes.

The right-side term of the above equation is the load vector that makes the displacements. The initial strain vector resulting from temperature change and drying shrinkage for the plane strain problem can be written as

$$\begin{Bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \end{Bmatrix} = (1 + \nu) \begin{Bmatrix} \alpha \Delta T + \varepsilon_{sh} \\ \alpha \Delta T + \varepsilon_{sh} \\ 0 \end{Bmatrix} \quad (2.12)$$

where  $\alpha$  is the coefficient of thermal expansion,  $\Delta T$  is the change in temperature from the reference temperature, and  $\varepsilon_{sh}$  is the drying shrinkage strain (negative sign for shrinkage). For the plane stress problem, the initial strain vector can be obtained by

$$\begin{Bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \end{Bmatrix} = \begin{Bmatrix} \alpha \Delta T + \varepsilon_{sh} \\ \alpha \Delta T + \varepsilon_{sh} \\ 0 \end{Bmatrix} \quad (2.13)$$

Finally, the stresses can be obtained by

$$\sigma = \mathbf{D}(\mathbf{B}\mathbf{U} - \varepsilon_0) \quad (2.14)$$

The stresses are calculated at the integration points and the average values are used for each element.

The bond-slip between concrete and longitudinal steel bar has been modeled using spring elements between the nodes at contact positions with the active degree of freedom in the longitudinal direction. The stiffness of the spring element can be obtained by

$$K = k_{bond} A_{contact} \quad (2.15)$$

where  $k_{bond}$  is the bond stiffness per unit area, which is a slope of the curve representing the relationship between bond stress and slip. The contact area,  $A_{contact}$ , between concrete and steel is defined by

$$A_{contact} = \pi d \left( \frac{a_L}{2} + \frac{a_R}{2} \right) \quad (2.16)$$

where  $d$  is a diameter of steel bar, and  $a_L$  and  $a_R$  are horizontal lengths of the elements on the left and right sides of a contact node, respectively. In this study, the bond-slip relationship can be defined as several different approaches such as linear, bilinear, linear with ultimate slip, and bilinear with ultimate slip. As shown in Figure 2.2 in the linear bond-slip model, it is assumed that the bond stress increases with increasing the relative movement. In the linear bond-slip model with an ultimate slip, there will be no connection between concrete and steel bar after the ultimate slip. In the bilinear bond-slip model, the stiffness of bond stress decreases after a certain value of relative movement, which is a yield slip. The bilinear bond-slip model with an ultimate slip model is also considered.

The frictional bond-slip that occurs at the interface between concrete and base layer has also been modeled using spring elements. The spring stiffness can also be obtained by Eq. 2.15 with the contact area as

$$A_{contact} = t_w \left( \frac{a_L}{2} + \frac{a_R}{2} \right) \quad (2.17)$$

where  $t_w$  is the thickness of the plane element. The relationship between bond stress and slip is assumed to be linear. The effect of the nonlinear bond-slip model was investigated in previous research (Ref 10) and it was found that the nonlinear modeling of this frictional bond-slip affected the analysis results very little. Therefore, the frictional bond-slip between concrete and base has been assumed to be linear in this study. The frictional bond-slip between concrete and base (or subbase if there is no base) depends on base layer types. Five different subbase types of flexible, asphalt-stabilized, cement-stabilized, lime-treated clay, and untreated clay subbases are used in the computer program, and the typical values of bond-slip stiffness have been defined as listed in Table 2.1 (Ref 5).

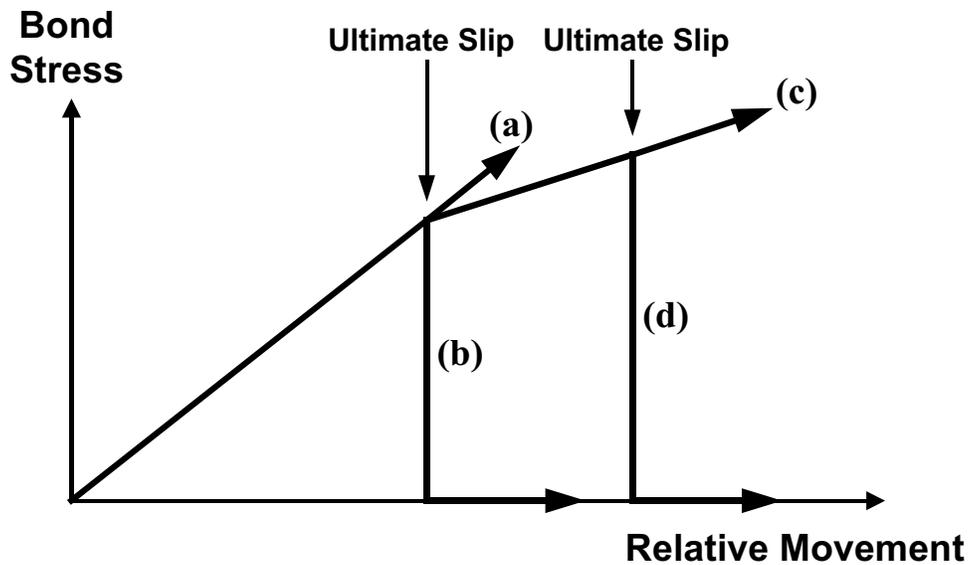


Figure 2.2. Bond-slip relationships: (a) linear; (b) linear with ultimate slip; (c) bilinear; (d) bilinear with ultimate slip

Table 2.1. Bond-slip stiffness for various subbase types

Subbase Types	Bond-Slip Stiffness / Unit Area (pci)
Flexible	145.5
Asphalt-Stabilized	55.9
Cement-Stabilized	15400
Lime-Treated Clay	154.5
Untreated Clay	22

The underlying layers have been modeled using vertical spring elements. If any side of the concrete slab curls up, there can be a gap between the slab and the base layer. To properly model this curling effect, tensionless vertical springs that can sustain only the compressive forces have been developed. In the computer program, all vertical springs are first assumed to have connections with a concrete slab and the pavement system is analyzed. After the analysis, the stresses in the vertical springs are investigated. If there is any vertical spring in tension, that spring is removed from the system and another analysis is performed with a new system. This procedure continues until there is no vertical spring in tension. It is noted that the curling effect in the CRC pavement is significant when the transverse crack spacing is long and the temperature variation between the top and bottom of the concrete slab is large (Ref 10). The stiffness of the vertical spring under the bottom of the concrete slab can be obtained by multiplying the vertical stiffness of underlying layers per unit area by the contact area defined in Eq. 2.17.

The boundary conditions of the finite element model should be correctly defined to obtain viable results. In this model, it is assumed that at cracks, there are no restraints for concrete and no longitudinal and rotational displacements for longitudinal steel bars. At the center of the two transverse cracks, it is assumed that vertical degrees of freedom exist and the longitudinal and rotational displacements are restrained. Figure 1 shows the finite element model developed in this research. To find the optimal size of the finite element, the convergence test has been performed and the element size has been selected as 38.1 mm (1.5 in.) for each side. Figure 2.2 shows the finite element model developed in this study.

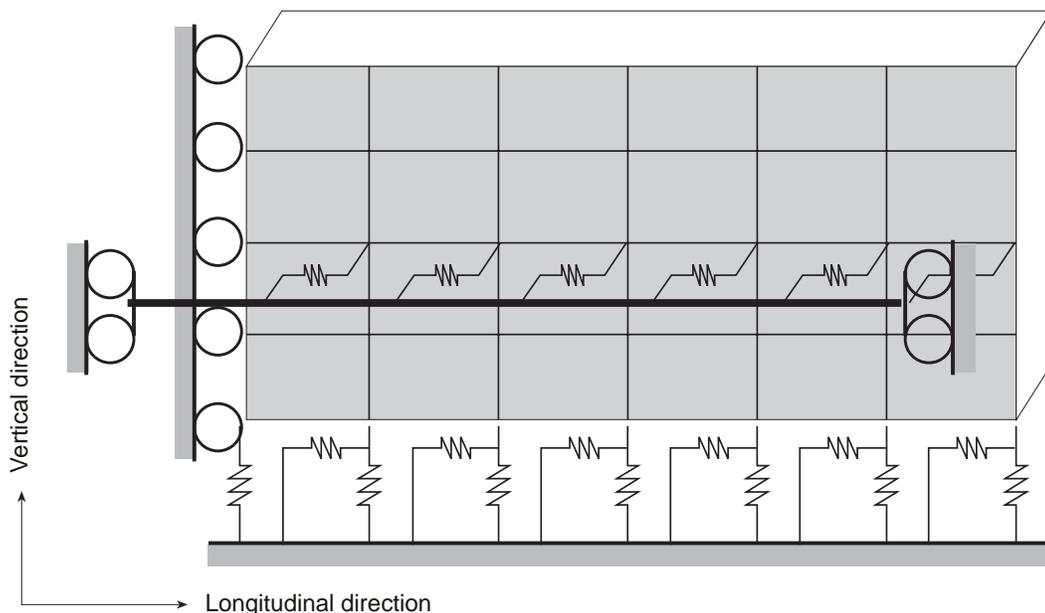


Figure 2.3. Finite element model of CRCP

The accuracy of the two-dimensional finite element model has been investigated by comparison with the three-dimensional model (Ref 10). It is noted that the stresses are slightly overestimated if the plane strain elements are used and are slightly underestimated with the plane stress elements compared with the 3-D analysis results. The differences between the stresses from 2-D and 3-D models are negligible with the plane stress elements. In the 3-D models, however, the stresses tend to increase near the edge or longitudinal joint on the transverse steel bar locations within about 10 inches (25 cm). This phenomenon becomes clearer when the bond between concrete and transverse steel bars is strong. Except in those regions, the 2-D models have predicted the results from 3-D models quite well (Ref 11).

## 2.2 WHEEL LOAD STRESS CALCULATION

If the external load is applied to any finite element node, this load will act as a line load because the finite element model developed in this study is two-dimensional. Therefore, the stresses due to the wheel load applications have been obtained using Westergaard equations in the interior of a slab (Ref 12) as

$$\sigma = \frac{3(1+\nu)P}{2\pi h^2} \left( \ln \frac{l}{b} + 0.6159 \right) \quad (2.18)$$

where  $h$  is the thickness of the slab (inches),  $\nu$  is Poisson's ratio, and  $P$  is the magnitude of the load (lbs). The radius of relative stiffness  $l$  is defined by

$$l = \left[ \frac{Eh^3}{12(1-\nu^2)k} \right]^{0.25} \quad (2.19)$$

where  $E$  is the modulus of elasticity and  $k$  is the modulus of subgrade reaction. In Eq. 2.18,  $b$  is defined by

$$b = a \quad \text{when } a \geq 1.724h \quad (2.20)$$

$$b = \sqrt{1.6a^2 + h^2} - 0.675h \quad \text{when } a < 1.724h \quad (2.21)$$

where  $a$  is the radius of the circular loaded area.

The stresses caused by the environmental loads are calculated by using the finite element model, the stresses caused by the external wheel loads are calculated by the above Westergaard equations, and those stresses are added to obtain the concrete stresses due to the combined effects in the slab. Figure 2.4 shows concrete stresses through the depth of the concrete slab for various temperature conditions. As shown in the figure, the maximum

stress can occur at the bottom, not always at the surface, and can occur when the temperature increases, not always when the temperature drops. In this case, a new crack will be initiated from the bottom. In order to include this phenomenon, the daily maximum temperature information is also needed in addition to the daily minimum temperature information. It is noted that further studies are being conducted to obtain more realistic wheel load stresses including effects of discontinuities at cracks and multiple wheel loads.

### 2.3 MATERIAL PROPERTIES

The changes in temperature and drying shrinkage occur slowly. Because of these slow changes in environmental loads, the creep of strain and the relaxation of stress in concrete may occur. There are a number of concepts used to analyze the creep effect for concrete (Ref 13). In this study, the creep effect has been considered using the effective modulus method (Ref 14). In this method, the creep of concrete is accounted for by reducing the elastic modulus of concrete (effective modulus or reduced modulus) as

$$E_{eff}(t) = \frac{E(t_0)}{1 + \phi(t, t_0)} \quad (2.22)$$

where

$t$  = time of consideration,  
 $t_0$  = time at first application of load,  
 $E(t_0)$  = modulus of elasticity at time  $t_0$ , and  
 $\phi(t, t_0)$  = creep coefficient at time  $t$  for concrete loaded at time  $t_0$ , and defined in this study by

$$\phi(t, t_0) = \phi_{max} [1 - (1 - \phi_x)^{\frac{t}{t_x}}] \quad (2.23)$$

where

$\phi_{max}$  = maximum creep ratio to instantaneous elastic strain,  
 $\phi_x$  = ratio to  $\phi_{max}$  to define a point on creep curve, and  
 $t_x$  = time corresponding to  $\phi_x$ .

The effects of variables in Eq. 2.23 on the analysis results have been investigated in previous research (Ref 6).

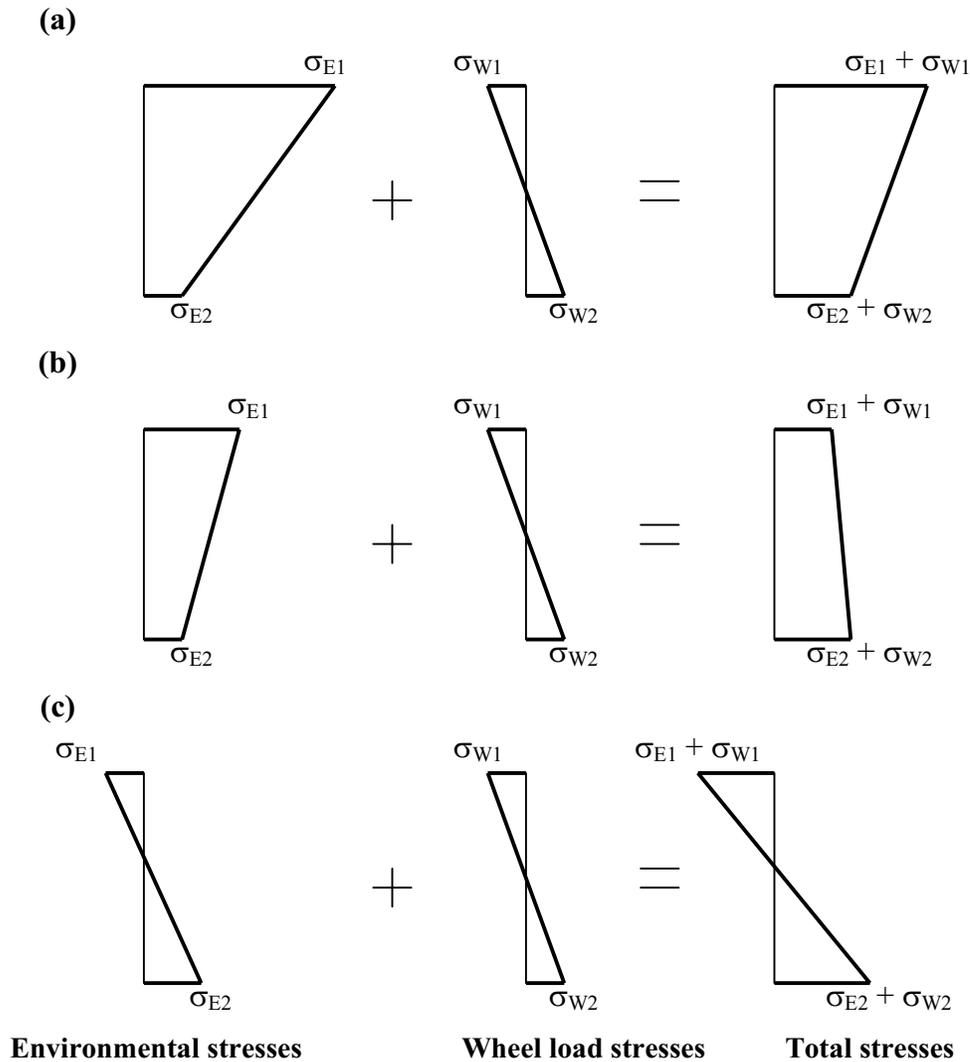


Figure 2.4. Stress distribution through depth: (a) when temperature drops and maximum total stress occurs at surface; (b) when temperature drops and maximum total stress occurs at bottom; (c) when temperature increases and maximum total stress occurs at bottom

Concrete material properties such as elastic modulus, tensile strength, compressive strength, and drying shrinkage change with time. The equations for variations of these material properties with time were developed for concrete with various coarse aggregate types in previous research (Ref 3) and are written by

$$F(t) = A(2 - e^{-Bt} - e^{-Ct}) \quad (2.24)$$

where

$t$  = time of curing (days),

$e$  = base of natural log,

$F(t)$  = concrete properties such as elastic modulus, tensile and compressive strengths, and drying shrinkage at time  $t$ , and

A, B, and C = coefficients of curvature specific to a given aggregate.

The above equation is used to determine absolute values for material properties. In order to estimate the material properties at a curing time  $t$  relative to a chosen final curing time  $t_f$ , a normalized model is required. Using a final curing time of 28 days for elastic modulus, tensile strength, and compressive strength, and a final curing time of 256 days for drying shrinkage, normalized models could be developed from the above equation by dividing the A coefficient by the value of the respective material properties at a final curing time  $t_f$ .

$$F_N(t) = N_{28}(2 - e^{-Bt} - e^{-Ct}) \quad (2.25)$$

$$Z_N(t) = N_{256}(2 - e^{-Bt} - e^{-Ct}) \quad (2.26)$$

where

$F_N(t)$  = normalized concrete properties of elastic modulus, tensile strength, and compressive strength at time  $t$ ,

$Z_N(t)$  = normalized drying shrinkage at time  $t$ ,

$N_{28}$ ,  $N_{256}$ , B, and C = coefficients of curvature specific to each aggregate.

In the computer program, eight different coarse aggregate types of limestone, siliceous river gravel (SRG), granite, dolomite, Vega, Bridgeport, western tascosa, and Ferris are used. The coefficients of A, B, C,  $N_{28}$ , and  $N_{256}$ , and the thermal expansion coefficients for concrete with different coarse aggregates are listed in Table 2.2. The coefficient of thermal expansion of concrete depends on coarse aggregate types and the typical value is used for each aggregate type as listed in Table 2.2.

Table 2.2. Coefficients for Equations 2.25 and 2.26

		Aggregate Types							
		Granite	Dolomite	Vega	Bridge-port / Tin Top	Western Tascosa	Ferris	Limestone	Siliceous River Gravel
<b>Coefficient of thermal expansion (/F)</b>		5.74E-6	5.9E-6	6.5E-6	4.84E-6	6.15E-6	5.44E-6	6.29E-6	8.18E-6
<b>Elastic modulus (psi)</b>	A	1678000	2324000	1882000	1992000	1803000	1979000	1802000	2282000
	B	0.78	0.485	0.301	0.688	0.405	0.738	0.535	0.574
	C	1.65E14	3.537	1.574	2.00	97.056	2.67E12	110.46	61755.1
	N <sub>28</sub>	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
<b>Tensile strength (psi)</b>	A	266.46	247.06	221.08	221.85	216.01	241.94	217.83	231.07
	B	0.15	0.261	0.302	0.332	0.198	0.137	0.177	0.267
	C	1.05	1.094	0.3014	0.723	2.505	2.479	1.068	0.468
	N <sub>28</sub>	0.504	0.5	0.5	0.5	0.501	0.505	0.502	0.5
<b>Compres. strength (psi)</b>	A	2570.8	2236.7	1995.3	2038.2	2068.5	2000.1	2550.57	2445.25
	B	0.096	0.231	0.367	0.582	0.214	0.206	0.115	0.182
	C	0.623	0.562	0.367	0.220	0.647	0.801	0.490	0.473
	N <sub>28</sub>	0.5176	0.5009	0.4978	0.4980	0.4998	0.5014	0.5102	0.5020
<b>Drying shrinkage</b>	A	3.2123 E-4	2.5206 E-4	2.3519 E-4	3.4362 E-4	3.58456 E-4	3.2723 E-4	2.291 E-4	1.9839 E-4
	B	0.0851	0.04062	0.03948	0.0328	0.03109	0.0745	0.0398	0.0619
	C	0.001	0.00155	0.01255	0.00069	0.00072	0.00119	0.00754	0.005
	Z <sub>256</sub>	0.8112	0.7569	0.5146	0.8582	0.8600	0.7828	0.5403	0.5636

## CHAPTER 3. CRACK SPACING AND PUNCHOUT PREDICTION MODELS

### 3.1 CRACK SPACING PREDICTION

A crack will occur when and where the concrete stress exceeds the tensile strength of concrete. If the concrete slab is assumed to be homogeneous, the new crack will occur at the center of the two previously formed transverse cracks because the maximum concrete stress occurs at the center. However, because the tensile strength of concrete is governed by the weakest element in it, there exists variation in concrete tensile strength from location to location. The concrete tensile strength depends largely on the bond characteristics between cement paste and the aggregate surface, which depends on local conditions, such as aggregate surface shape, texture, and the existence of voids between cement paste and the aggregate surface.

To include the effect of the variation of the tensile strength along the pavement length in the model, the concrete tensile strength at each finite element is selected randomly using a normal distribution because the concrete tensile strength distribution along the pavement length is reported to be sufficiently close to the normal distribution (Refs 2, 15). Once the tensile strength at each finite element is determined and the stresses are calculated from the model, the difference between the tensile strength and the concrete stress is obtained at each finite element. Where the concrete stress exceeds the tensile strength and the difference between them is the largest, a new crack will occur. With the obtained new crack spacings, the program calculates again the concrete tensile stresses and compares these with the tensile strength. If the concrete stresses exceed the concrete tensile strength, then another new crack will occur at the point where the largest difference between the stress and the strength exists. The program repeats the same procedure until the concrete stresses are smaller than the concrete tensile strength. This methodology is known as the Monte Carlo method (Ref 2) and Figure 3.1 shows this approach. As for initial lengths of the slab for the analysis, several different spacings were evaluated for their effects on the analysis results.

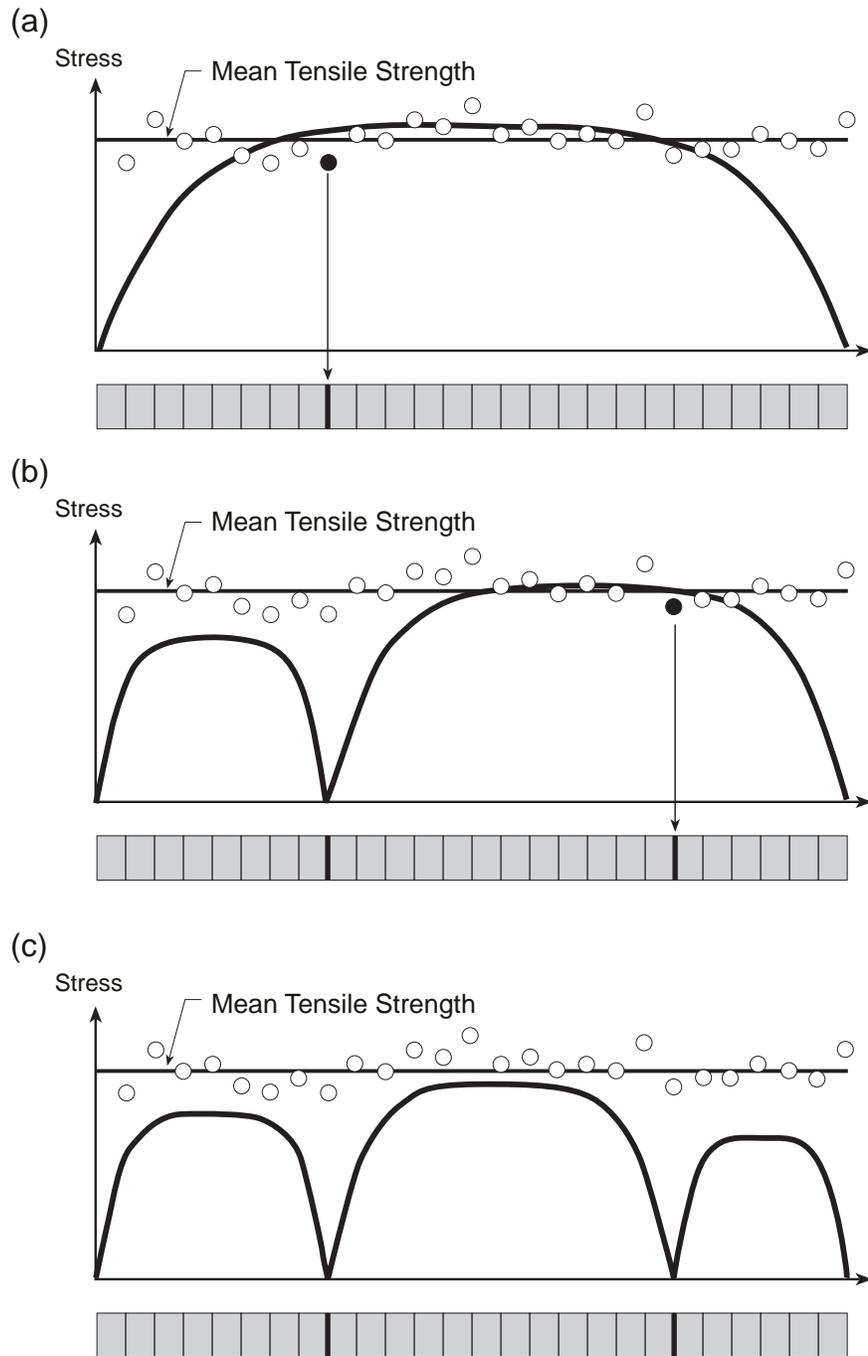


Figure 3.1. Methodology of crack spacing prediction

### 3.2 PUNCHOUT PREDICTION

There are structural failures and functional failures in the pavement systems (Ref 16). The structural failures lead to functional failures in continuously reinforced concrete (CRC) pavements and the major failure manifestation is the punchout (Ref 17). The punchout is a structural failure in which a small segment of pavement is loosened from the main body and displaced downward under traffic. As shown in Figure 3.2, the punchout occurs when a new longitudinal crack forms near a previous longitudinal crack or near the edge of the pavement so that the segment bounded by two closely spaced transverse cracks, a longitudinal crack, and the pavement edge or a previously formed longitudinal crack is loosened from the main body of the pavement. Even though the punchout development mechanism is complicated, it is assumed that the longitudinal crack is the most significant contributing factor in the punchout development. Therefore, it is assumed that longitudinal cracks result in punchouts. Once the crack spacings along the pavement length are obtained from the analysis, the transverse stresses are calculated for each crack spacing (Ref 2) by

$$s = e^{9.8474} D^{-1.8143} X^{-0.4477} \quad (3.1)$$

where

$s$  = stress in transverse direction for 9000 lb single wheel load (psi),  
 $e$  = base of natural log,  
 $D$  = slab thickness (in.), and  
 $X$  = crack spacing (ft).

The most widely used form of the fatigue failure equation is

$$N = C_1 \left(\frac{f}{s}\right)^{C_2} \quad (3.2)$$

where

$N$  = number of load applications,  
 $f$  = flexural strength,  
 $s$  = flexural stress from Eq. 3.1, and  
 $C_1$  and  $C_2$  = coefficients

Using the above equation, the number of load applications corresponding to various probabilities of fatigue failure is calculated. After the relationship between the fatigue failure (or punchouts) and load applications has been obtained for each crack spacing, the final fatigue failure versus load application curve can be obtained by adding each curve from each crack spacing. The appropriate coefficients of  $C_1$  and  $C_2$  in Eq. 3.2 for CRC pavements have been found by Suh et al. (Ref 4). The widely used value of  $C_2$  is 4. These values change with the percentage of reliability and the swelling conditions of subgrade soil as listed in Table 3.1.

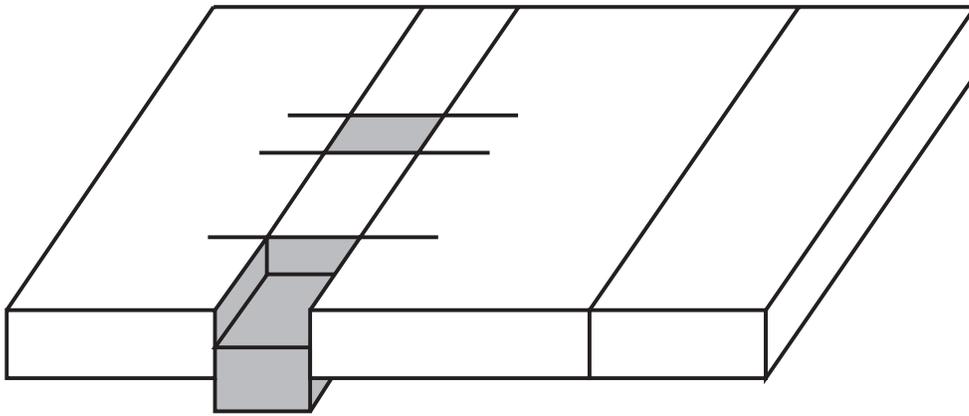


Figure 3.2. Configuration of punchouts

Table 3.1. Coefficient  $C_1$  values in Eq. 3.2. (Unit: Millions, CV: 30 %)

	Coarse Agg. Type	SRG		Limestone	
	Swelling Condition	Yes	No	Yes	No
Reliability	95 %	1.4	2.0	1.8	2.6
	75 %	2.4	3.1	2.5	3.7
	50 %	3.1	4.2	3.1	4.8

## CHAPTER 4. DESCRIPTION OF COMPUTER PROGRAM

### 4.1 MAIN PROGRAM

The CRCP-9 computer program has been written in Fortran language. CRCP-9 consists of a main program and subroutine programs. The main program is divided into several distinct parts. The dimensions of arrays are defined first, input values are read, and basic variables are defined. The output format of `crpfor.sum`, which is a summary file of the analysis, for input values is defined next. Then, the analysis is performed with calling subroutine programs. A number of output files are created during the analysis to communicate with a Windows-based, user-friendly interface program and to inform users of the progress of the analysis. When the analysis is completed, these output files are deleted automatically by the user-friendly interface program. Finally, analysis results are written in output files of `crpfor.out` and `crpfor.sum`. The descriptions of subroutine programs and input and output guides are explained in the following sections.

The dimensions of arrays should be larger than the required dimensions. However, using very large dimensions can lead to hardware memory problems. The subroutine CHMEMO checks the dimensions of arrays, and if more dimensions are needed for any array, a notice is given and the program stops. The required dimensions of the arrays used in the program are as follows.

ALOAD(ITNOD1)	DISP(ITNOD1)
SK(ITNOD1,MBAND)	BNSL(NUMELX)
TEMLD(ITNOD1)	STRINI(NUMELY,4)
TLOAD(NUMELY,8)	INOD(INODDIM,8)
SS(KS)	IMAX(NUMELX)
IMAXC(NUMELX)	TEMPR1(NUMELY+1)
TEMPR(29,NUMELY+1)	TEMPRA(29,NUMELY+1)
DRYSH(29,NUMELY+1)	STRSS(NUMELX)
STRSSF(NUMELX*2)	TSTARR(NUMELX*2)
DISTRB(NUMELX*2)	

where

$$\begin{aligned} \text{ITNOD1} &= 2 * (\text{NUMELX} + 1) * (\text{NUMELY} + 2) \\ \text{MBAND} &= (\text{NUMELY} + 3) * 2 + 4 \\ \text{KS} &= \text{ITNOD1} * \text{MBAND} \\ \text{INODDIM} &= (\text{NUMELY} + 1) * \text{NUMELX} \end{aligned}$$

and, NUMELX and NUMELY are the numbers of plane elements in the longitudinal and vertical directions, respectively. In the program, NUMELY is selected to be 10, and the maximum NUMELX is 200 because half of the first primary crack spacing is selected to be

300 inches and the length of a finite element in the longitudinal direction is 1.5 inches. Users can change the number of finite elements in the vertical direction by modifying NUMELY, and in the longitudinal direction, by modifying A (the length of a finite element in the longitudinal direction) and CRSPC(IPCS,1) (primary crack spacing). The maximum NUMELX is calculated by dividing half of CRSPC(1,1) into A.

## 4.2 SUBROUTINE PROGRAMS

There are a number of subroutine programs used in the CRCP-9 computer code and the descriptions are as follows:

### ***STRDIST***

This subroutine is used to impose random coefficients to each finite element in the longitudinal direction of the pavement. These coefficients are multiplied by the mean concrete tensile strength to define variations of concrete tensile strengths. The distribution of the concrete tensile strength is assumed to be a normal distribution. The random values are distributed within the coefficient of variation in concrete tensile strength.

### ***CHMEMO***

This subroutine is used to check the required dimensions of the arrays. If a required dimension of an array is larger than the current dimension of the array, a notice that a larger dimension of the array is needed is given and the program stops. Users must revise the dimensions of the arrays that need more dimensions. The arrays that need to be revised are informed by the program.

### ***CONCPRO***

The concrete material properties such as elastic modulus, tensile strength, compressive strength, and drying shrinkage at each given day are calculated in this subroutine. Eq. 2.24 and Table 2.2 are used to define these values.

### ***CREEP***

To account for creep of strain in concrete, the reduced elastic modulus of concrete is calculated using the effective modulus method. The creep coefficient curve is defined in this subroutine.

### ***LINREC4***

This is used to find the element stiffness matrix using four-noded bilinear isoparametric or rectangular elements for the concrete slab. The material property matrix **D** is defined here according to the type of plane element (plane stress or plane strain).

### ***MATPRO***

This subroutine is used to multiply matrices.

### ***FRAME***

The longitudinal steel bar is discretized using frame elements. The element stiffness matrix of the frame element, which includes horizontal, vertical, and rotational degrees of freedom, is defined in this subroutine.

***SHRINK***

The equivalent temperature variations owing to drying shrinkage strains are calculated here. A positive value of drying shrinkage makes a negative value of the equivalent temperature.

***TEMPRT***

This subroutine calculates the initial stresses and equivalent nodal loads due to changes in temperature and drying shrinkage. We can use an average temperature from the nodal temperatures for an entire element or interpolated temperatures from the nodal temperatures at integration points. To use an average temperature in the subroutine, select INDEX=0, and to use interpolated temperatures, select INDEX=1. The differences in the results are negligible when there are a sufficient number of elements (Ref 6).

***ASSEM***

The element stiffness matrices and nodal load vectors are assembled to create the global stiffness matrix and load vector. The half-bandwidth is used for the global stiffness matrix.

***BOUND***

The boundary conditions of the finite element model are defined in this subroutine. To model the restraints, spring elements with a very large stiffness value are used.

***BNSLIP***

The bond-slip relationship between concrete and steel bar is defined here. The linear, linear with an ultimate slip, bilinear, and bilinear with an ultimate slip cases can be considered by controlling input values. For example, if we have the same bond-slip stiffness values for the primary and secondary stiffness values, we can model the linear bond-slip relationship. Also, if we have a very large yield slip value so that the relative movement between concrete and steel cannot reach the value, we can model the linear bond-slip relationship.

***FRSLIP***

The frictional bond-slip relationship at the interface between the bottom of the concrete slab and the base layer is defined here. The linear bond-slip relationship is used for this frictional bond-slip.

***CURL***

The underlying layers are modeled using a Winkler type elastic foundation. To account for the curling and warping effects, the spring elements for the elastic foundation sustain only the compressive forces. In other words, the tensionless springs are used for the foundation.

***DWEIGHT***

The body forces (dead weights) of concrete steel are calculated in this subroutine and added to the load vector.

***SOLVE***

To solve the equilibrium equations developed in the program, the one-dimensional compacted array of banded stiffness matrix and Gaussian elimination are used (Ref 18).

**CHSLIP**

This subroutine is used to determine if the relative movement between concrete and steel exceeds the limit values such as yield slip and ultimate slip.

**CHCURL**

This is used to check if any vertical spring for the underlying layers is in tension. If there is any spring in tension, this spring will be removed from the system and a new analysis will be performed with a new system.

**COMPST**

This subroutine compares the stresses when the temperature is high and when the temperature is low at a given day to find the maximum tensile stress. Because the wheel load stresses are added to obtain the final stresses in the system, the maximum tensile stress does not always occur when the temperature is low. An explanation about this fact is presented in Chapter 2.

**TSTRTH**

The tensile strength distribution along the pavement is defined here. It is assumed that the tensile strength is constant along the depth of the concrete slab and the variation exists only in the longitudinal direction.

**STRESS**

The stress at each integration point is calculated in this subroutine. For any finite element, an average value of the stresses at integration points is used for the stress at that finite element.

**WHEEL**

The stresses in the concrete slab due to the wheel load applications are calculated here by using the Westergaard equation.

**PUNCHOUT**

The relationships between the number of punchouts and the wheel load applications are predicted in this subroutine.

### 4.3 INPUT GUIDE

The required inputs in this program are explained. The format for input values is free form, such that only a space is needed between input values. Sample input is shown in Appendix A.

**LINE 1**

TITLECRCP: This is used in conjunction with a Windows-based, user-friendly interface program.

**LINE 2**

TITLEINP: Title of analysis

**LINE 3**

TOTD: Thickness of concrete slab (unit: in.)

IELTYPE: Index for plane element type (1: plane stress, other: plane strain)  
NUMPCS: Number of different primary crack spacings  
(Maximum = 10, cannot be 3, 6, 7, 9)  
If more than 10 primary crack spacings are considered, the dimensions of the arrays of CRSPC, CRWID, STLSTR, ICRLOC, and INDCR should be changed according to the maximum number of different primary crack spacings.

**LINE 4**

POIS1: Poisson's ratio of concrete  
ALPC: Coefficient of thermal expansion of concrete (unit: /F)  
WEIGHT: Specific weight of concrete (unit: pcf)  
CV: Coefficient of variation in concrete tensile strength (unit: %)  
STRAT: Percent reinforcement (steel ratio) (unit: %)

**LINE 5**

IAGG: Index for coarse aggregate type  
(1: Granite, 2: Dolomite, 3: Vega, 4: Bridgeport/Tin Top,  
5: Western Tascosa, 6: Ferris, 7: Limestone,  
8: Siliceous river gravel)  
IDEFAULT Index whether or not using default values (0: use default values)

**LINE 6**

CSTR28: 28-day concrete compressive strength (put 0 to use a default value)  
TSTR28: 28-day concrete tensile strength (put 0 to use a default value)  
ECONC28: 28-day concrete elastic modulus (put 0 to use a default value)  
ZSH256: 256-day concrete drying shrinkage (put 0 to use a default value)

**LINE 7**

STLOC: Steel bar location from surface (unit: in.)  
ESTL: Young's modulus of elasticity of steel  
DIASTL: Diameter of longitudinal steel bar  
ALPS: Coefficient of thermal expansion of steel (unit: /F)  
STWEI: Specific weight of steel (unit: pcf)

**LINE 8**

IBONDCS: Index for bond-slip relationship between concrete and steel (It is used in conjunction with a Windows-based user interface; 0 to 12; 12: user-defined input values)  
AKBUA: Primary bond-slip stiffness per unit area between concrete and steel (unit: pci)  
AKBUA2: Secondary bond-slip stiffness per unit area between concrete and steel (unit: pci)  
YLSLIP: Yield slip between concrete and steel (unit: in.)

ULSLIP: Ultimate slip between concrete and steel (unit: in.)

**LINE 9**

BOTKV: Vertical stiffness per unit area of underlying layers (unit: pci)  
INDSPR: Index for tensionless springs for underlying layers (1: no tensionless)

**LINE 10**

INDFR: Index for subbase type for friction  
(1: Flexible (145.5 pci), 2: Asphalt-stabilized (55.9 pci),  
3: Cement-stabilized (15400 pci), 4: Lime-treated clay (154.5 pci),  
5: Untreated clay (22 pci))  
AKFRUA: Bond-slip stiffness per unit area between concrete and base (unit: pci)

**LINE 11**

WHLOAD: Wheel load (unit: lbs)  
WHRAD: Radius of loaded area (unit: in.)  
WHDAY: Days before wheel load applied

**LINE 12**

ICREEP: Index for creep analysis (1: creep analysis)  
PHIMAX: Maximum creep ratio to instantaneous elastic strain  
PERCEN: Consideration percent to maximum creep (unit: %)  
DAYPC: Corresponding day to PERCEN  
TIME: Loading duration (unit: hour)

**LINE 13**

IFATPRO: Index for reliability of punchout prediction  
(1: 95%, 2: 75%, 3: 50%)  
ISWELL: Index for swelling condition (1: swelling = yes)  
ITEMIND: Index for temperature variation through concrete depth  
(0: uniform, 1: linear, 2: nonlinear)  
IDRYIND: Index for drying shrinkage variation through concrete depth  
(0: uniform, 1: linear, 2: nonlinear)

**LINE 14**

TEMF: Reference (curing) temperature

**LINE 15**

IDAY2: Second day for temperature and drying shrinkage input  
IDAY3: Third day for temperature and drying shrinkage input  
IDAY4: Fourth day for temperature and drying shrinkage input  
IFDAY: Final day for temperature and drying shrinkage input

**LINE 16 –LINE 334**

DO I=1, 29: From day 1 to 28, and another day for the minimum yearly temperature  
DAYCON(I): Consideration day after concrete placement  
DO J=1, 11: At each finite element node, temperature and drying shrinkage are defined. Because the number of elements in the vertical direction is 10, the number of finite element nodes is 11.  
TEMPR(I,J): Minimum daily temperatures at each finite element node from surface on day I (unit: F)  
TEMPRA(I,J): Maximum daily temperatures at each finite element node from surface on day I (unit: F)  
DRYSH(I,J): Daily drying shrinkage ratio at each finite element node from surface on day I (range from 0 to 1)  
ENDDO  
ENDDO

**4.4 OUTPUT GUIDE**

Two output files are created after performing the analysis. One is named *crpfor.out*, and the other, *crpfor.sum*. The file *crpfor.out* is used to provide output values to a Windows-based, user-friendly interface program developed using MS Visual Basic. The file *crpfor.sum* summarizes input values and analysis results. Sample output files of *crpfor.out* and *crpfor.sum* are shown in Appendices B and C. The output format can be modified in the main program.



## CHAPTER 5. SAMPLE ANALYSIS RESULTS

The analysis results from the CRCP-9 computer program include time histories of mean crack spacing, mean crack width, and mean steel stress until 28 days after placement of concrete and at the final day of the analysis, which is generally selected to be the day when the minimum yearly temperature occurs. The crack spacing distribution and cumulative values are also obtained at the final of the analysis. For example, to obtain the crack spacing distribution at 60 days after placement, the final day of the analysis has to be selected to be sixty in the input process. The standard deviation of the crack spacing at each day is also provided. If the standard deviations of the crack width and the steel stress are needed, users can modify the program. The number of punchouts per mile is predicted for a given wheel load application. In this program, the number of punchouts can be estimated up to 100 million ESALs.

### 5.1 CRACK SPACING

First, the variations in mean crack spacings for the first 28 days are investigated for different longitudinal steel ratios as shown in Figure 5.1. The large decrease in the crack spacing is observed within the first several days. As the amount of steel increases, the smaller crack spacings are obtained.

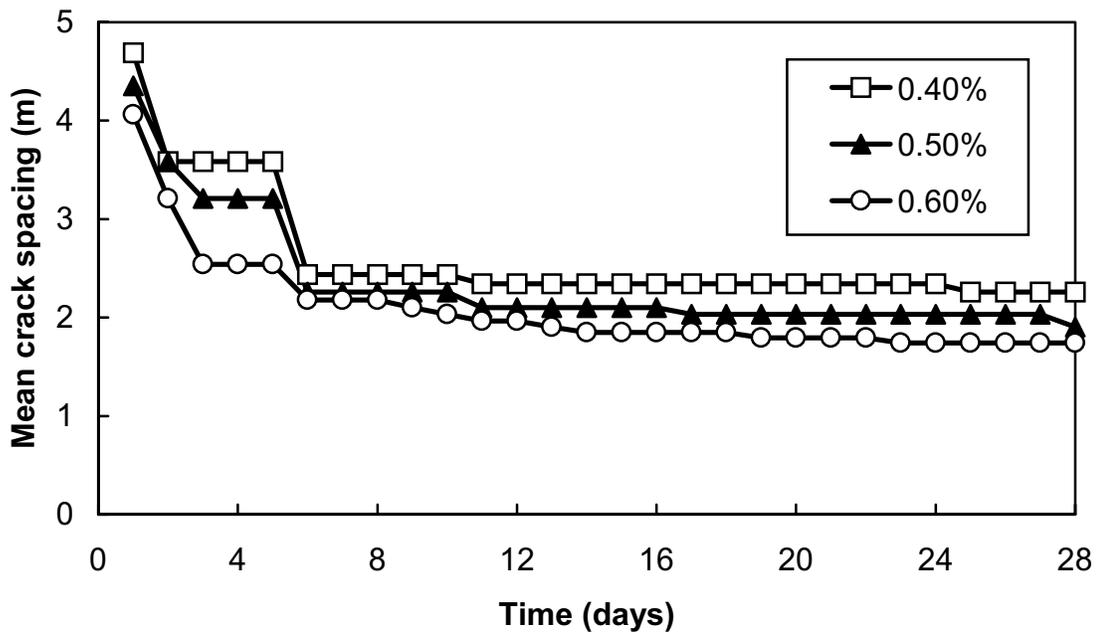


Figure 5.1. Time histories of mean crack spacing for various steel ratios (1 m = 3.28 ft)

The bond-slip relationship between concrete and steel is reported to have significant effects on the behavior of the continuously reinforced concrete (CRC) pavements (Refs 9, 10). To examine this bond-slip relationship, the time histories of mean crack spacing have been compared between linear and nonlinear models (in this study, we use a bilinear with an ultimate slip model for the nonlinear bond-slip model) for three different coarse aggregates of granite, limestone, and siliceous river gravel (SRG) as shown in Figure 5.2. If we have the same linear or nonlinear bond-slip model for different coarse aggregates, the mean crack spacings are the largest with the granite pavement and the smallest with the SRG pavement at a given day. However, the limestone pavement with a nonlinear bond-slip model shows larger mean crack spacings than the granite pavement with a linear bond-slip model after 14 days of placement. The same results can be observed between the SRG pavement with a nonlinear bond-slip model and the limestone pavement with a linear bond-slip model. This implies that more reasonable bond-slip input values should be obtained by experiments to improve the accuracy of the analysis results.

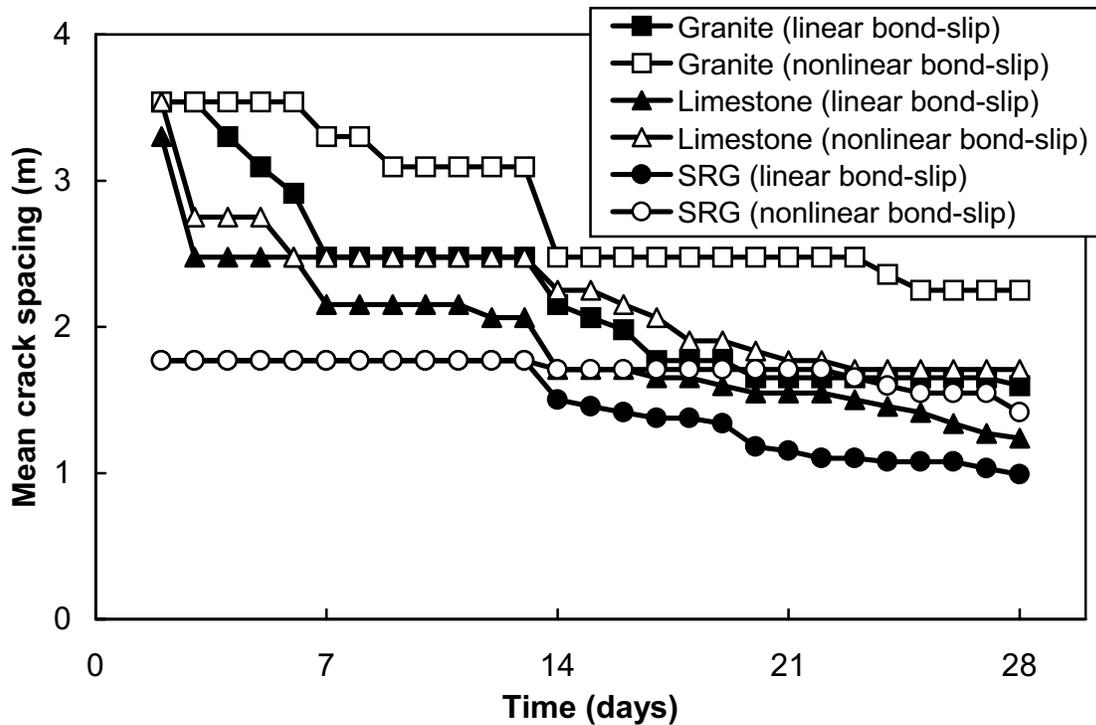


Figure 5.2. Effect of bond-slip types on mean crack spacing (1 m = 3.28 ft)

Figure 5.3 shows the time histories of mean crack spacing for pavements with three different aggregate types of granite, limestone, and SRG. Figures 5.3(a) and (b) show the results with a linear and a nonlinear bond-slip relationship, respectively. The pavement with granite has the largest crack spacings and the pavement with SRG has the smallest. The mean crack spacings are larger with a nonlinear bond-slip model because the predicted concrete stresses are smaller with the nonlinear bond-slip model.

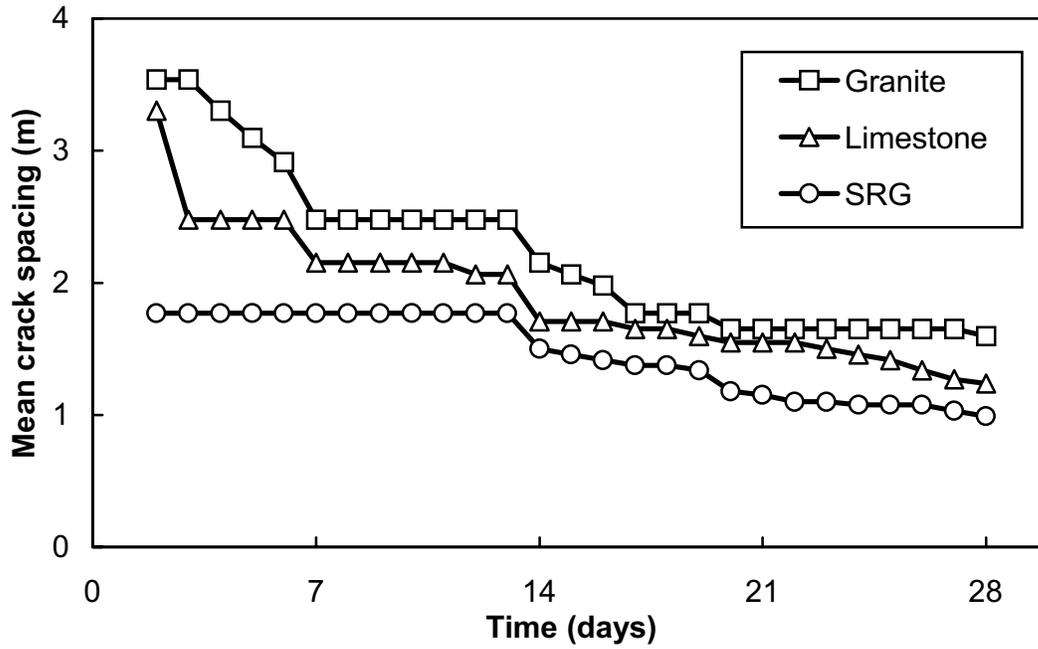
Figure 5.4(a) shows the crack spacing distributions at 28 days after concrete placement for three different aggregate types. The pavement with SRG shows high frequencies of crack spacings at smaller values and the pavement with granite has high frequencies at larger values. Figure 5.4(b) shows the cumulative crack spacing distributions from the results shown in Figure 5.4(a).

Figure 5.5 shows the cumulative crack spacing distributions for different values of the coefficient of variation (CV) in concrete tensile strength. The crack spacings tend to decrease when CV values increase. This means that the material variability should be well controlled to prevent very narrow crack spacings.

## **5.2 CRACK WIDTH AND STEEL STRESS**

The time histories of mean crack width are investigated as shown in Figure 5.6. The pavement with granite tends to have larger crack widths and the pavement with limestone has smaller crack widths. The time histories of mean steel stress at crack are also investigated as shown in Figure 5.7. The results are very similar to the time histories of mean crack width.

(a)



(b)

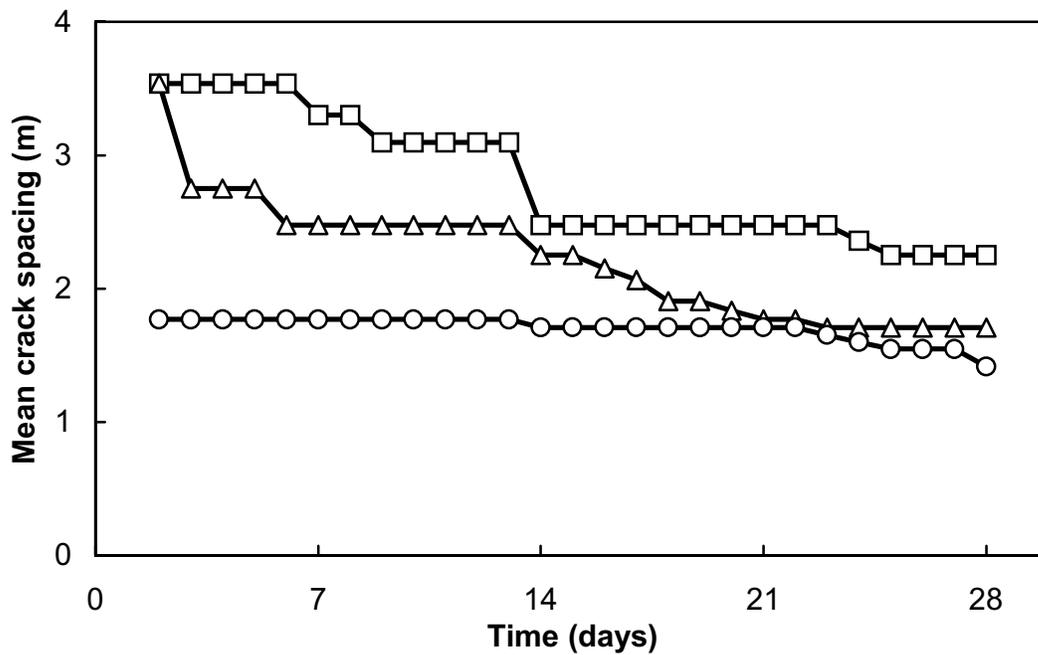


Figure 5.3. Time histories of mean crack spacing for various coarse aggregate types: (a) with linear bond-slip model; (b) with nonlinear bond-slip model (1 m = 3.28 ft)

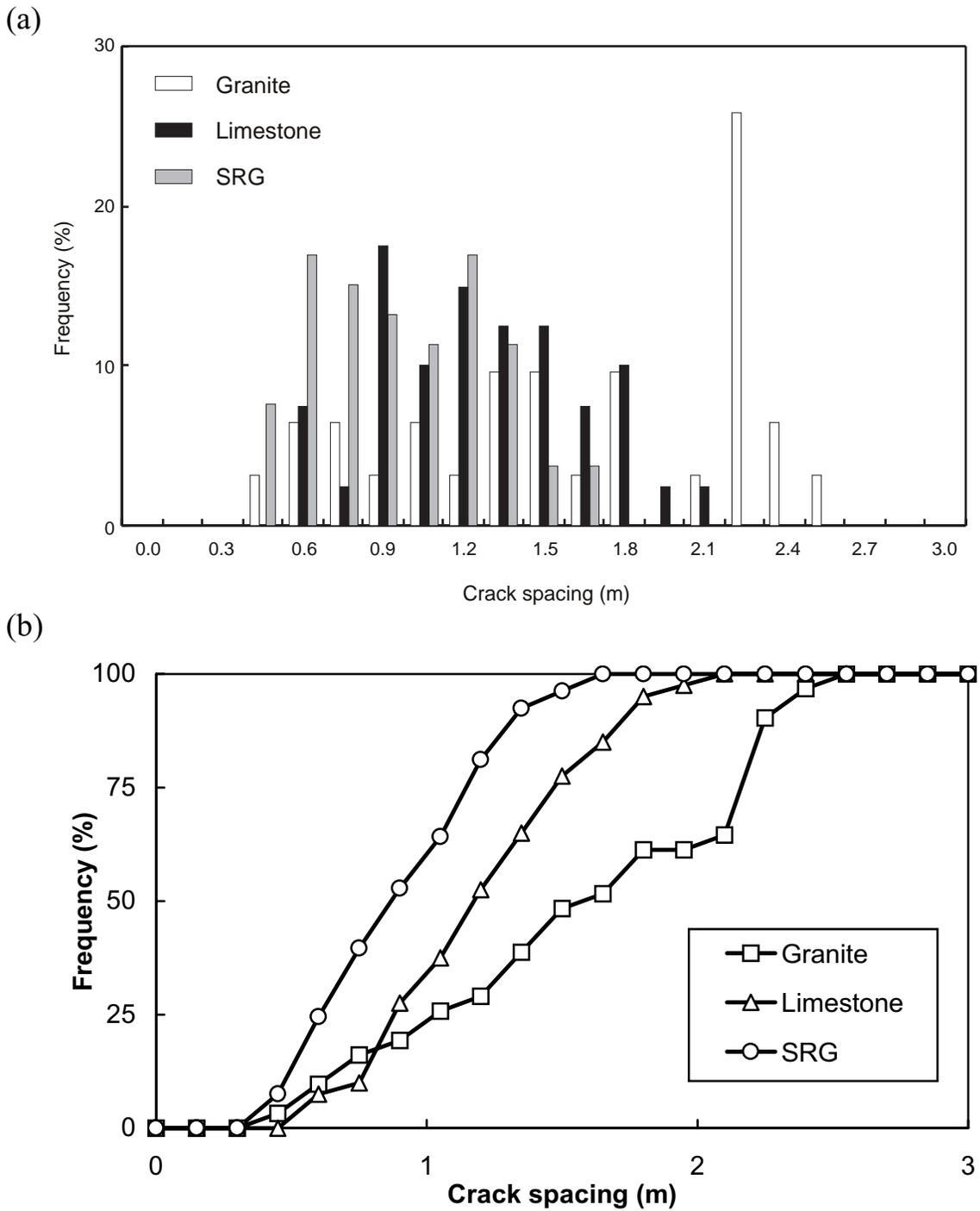


Figure 5.4 Crack spacing distribution at 28 days after concrete placement: (a) crack spacing distribution, (b) cumulative crack spacing distribution (1 m = 3.28 ft)

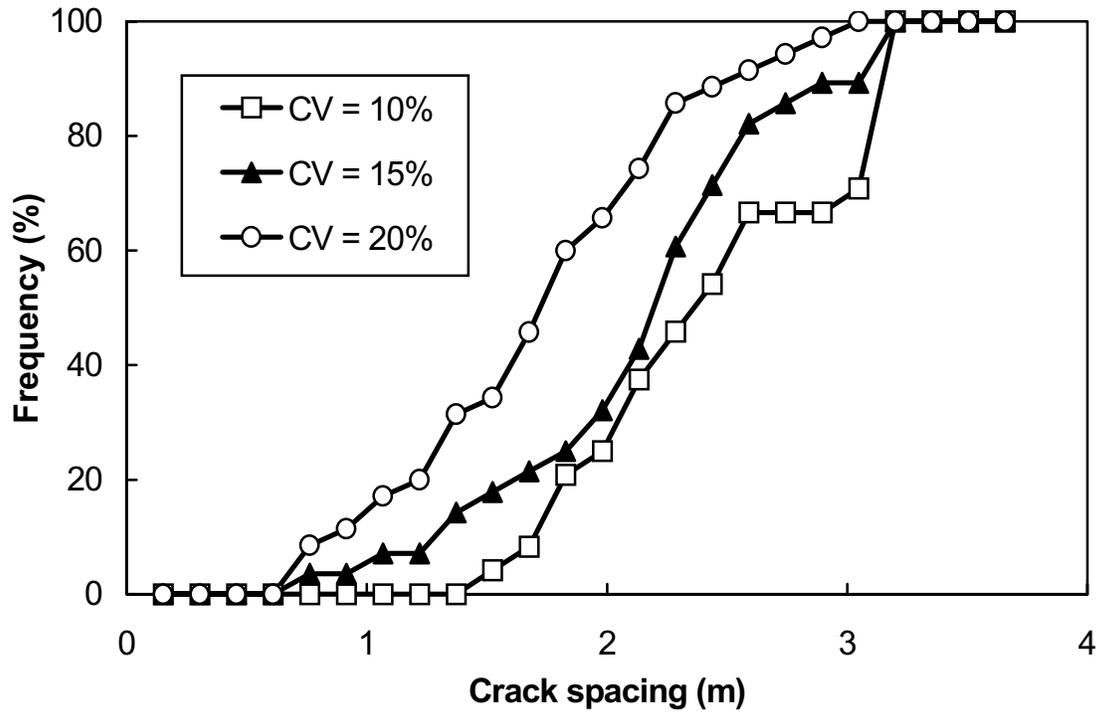
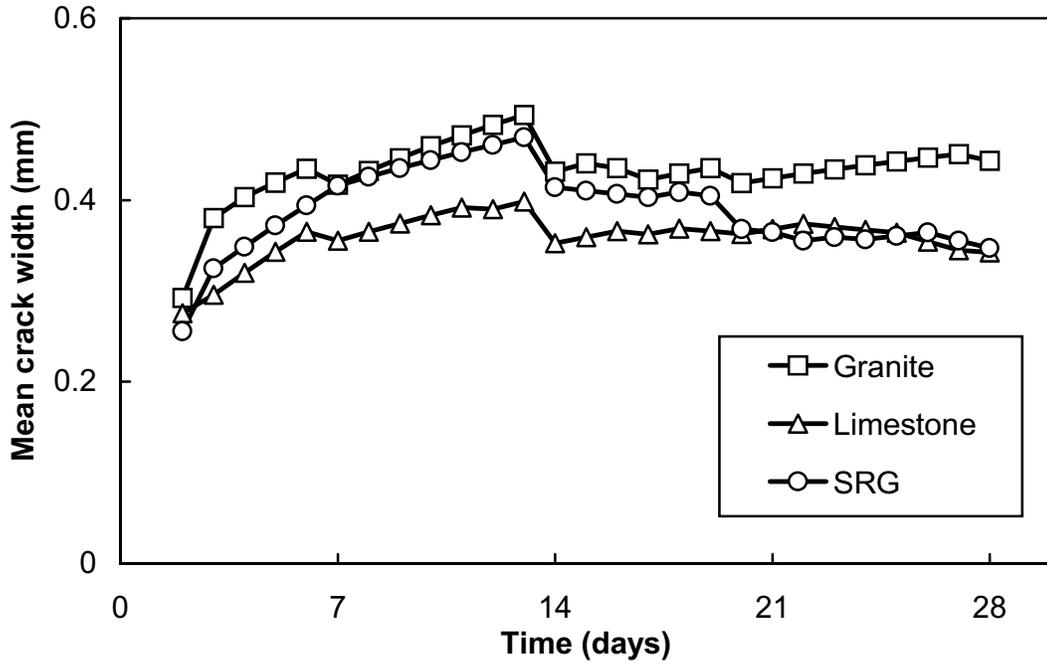


Figure 5.5. Cumulative crack spacing distribution for various CV values (1 m = 3.28 ft)

(a)



(b)

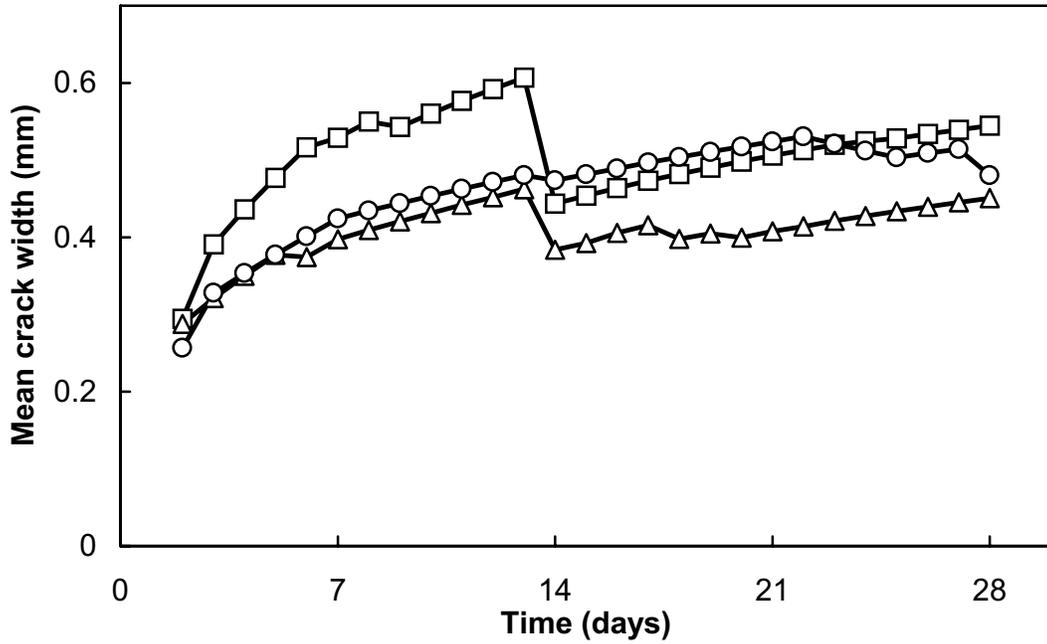
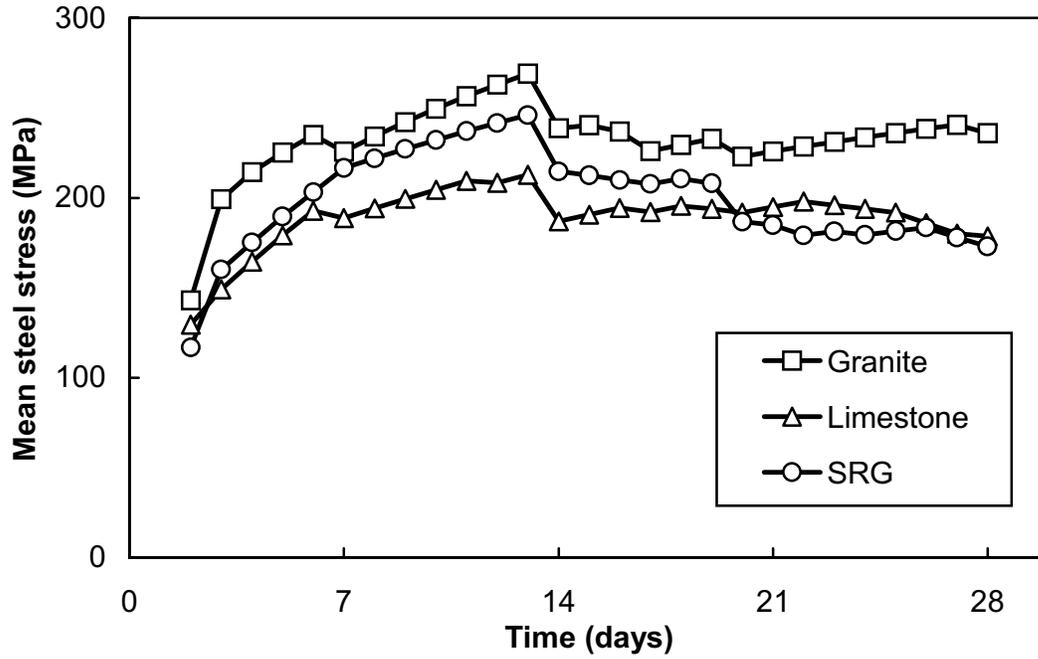


Figure 5.6. Time histories of mean crack width: (a) with linear bond-slip model; (b) with nonlinear bond-slip model (1 mm = 0.0394 in.)

(a)



(b)

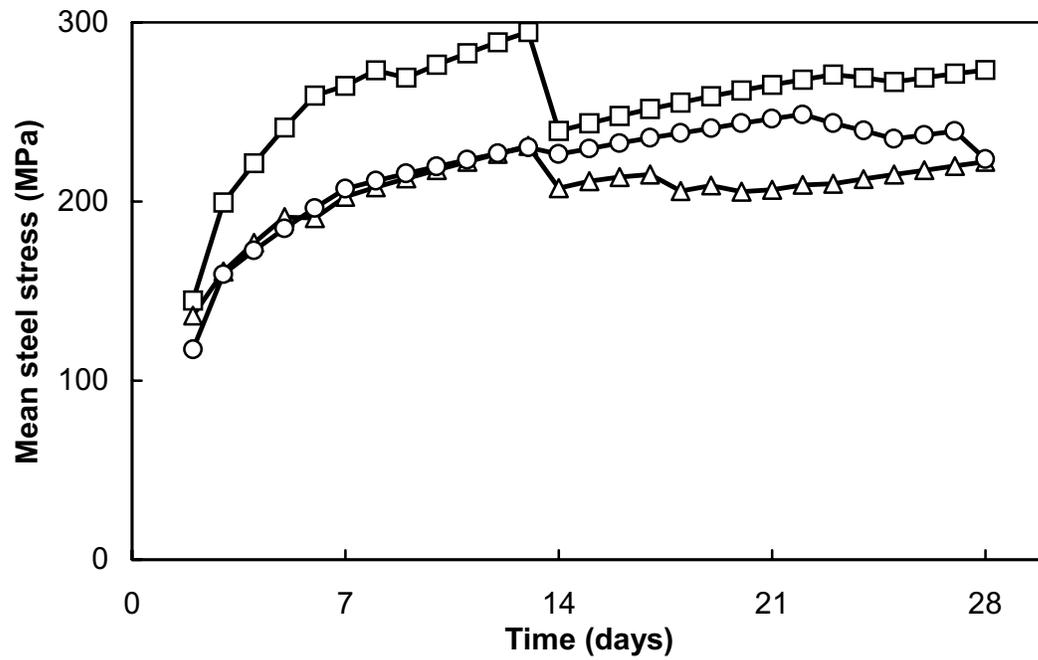


Figure 5.7. Time histories of mean steel stress at crack: (a) with linear bond-slip model; (b) with nonlinear bond-slip model (1MPa = 145.14 psi)

### 5.3 PUNCHOUTS

Figure 5.8 shows the number of punchouts per kilometer according to the wheel load applications for various coefficients of variation (CV) values in the concrete tensile strength. As the CV value increases, the frequency of punchouts increases. This is partly because of the shorter crack spacings with larger CV values, as already investigated in Figure 5.5. The punchout failures are closely related to the transverse crack spacings partly because the transverse stresses that cause longitudinal cracks depend on the transverse crack spacing among other factors such as load transfer and base conditions. The shorter the transverse crack spacings, the higher the transverse stresses obtained.

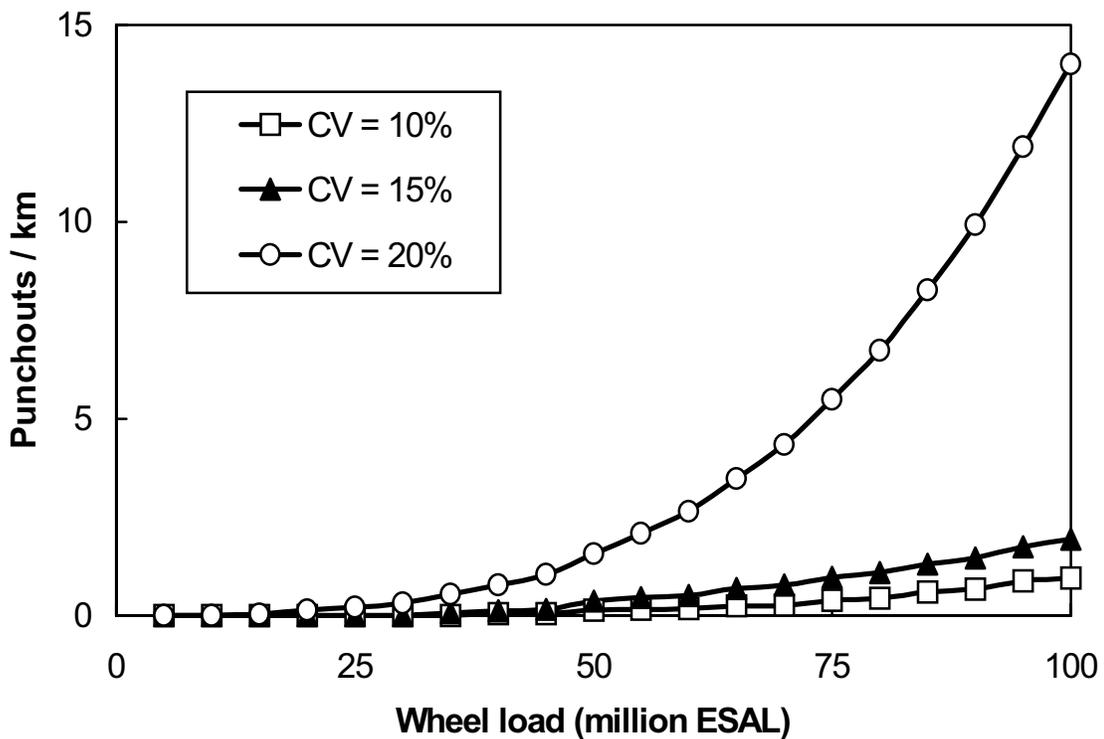
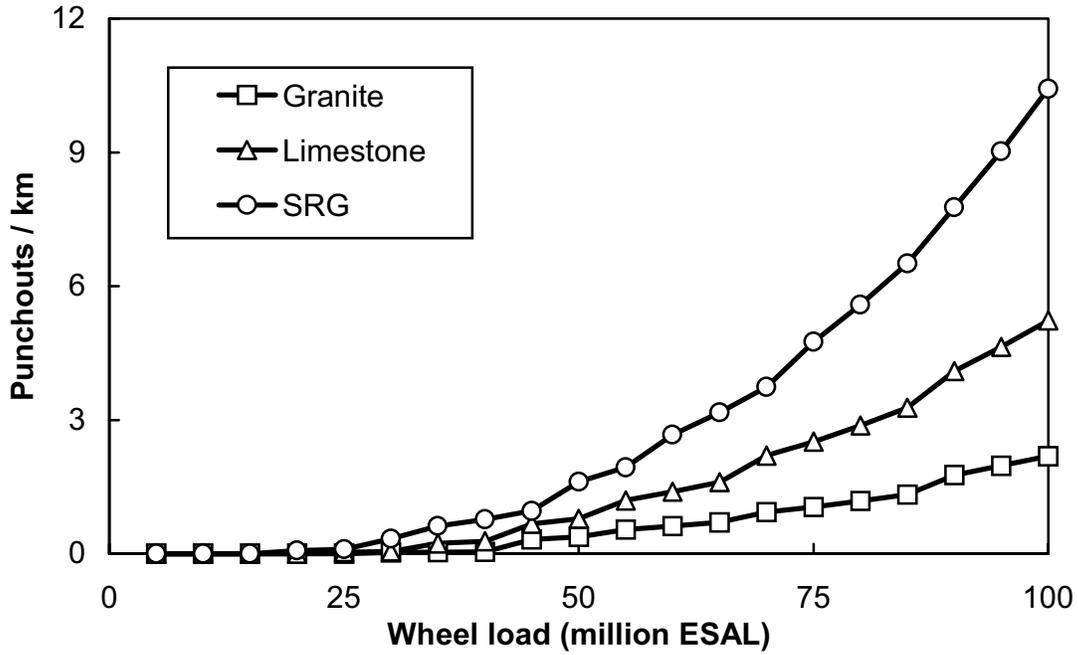


Figure 5.8. Punchout frequency curve for various CV values (1 km = 0.63 miles)

Figure 5.9 shows punchout frequencies for three different coarse aggregate types under the identical base conditions and load transfer characteristics except for concrete strength variability. The pavement with SRG shows higher frequencies of punchouts and the pavement with granite shows lower frequencies of punchouts. Those are because of shorter crack spacings for the pavement with SRG and larger crack spacings for the pavement with granite, as already investigated in Figures 5.3 and 5.4.

(a)



(b)

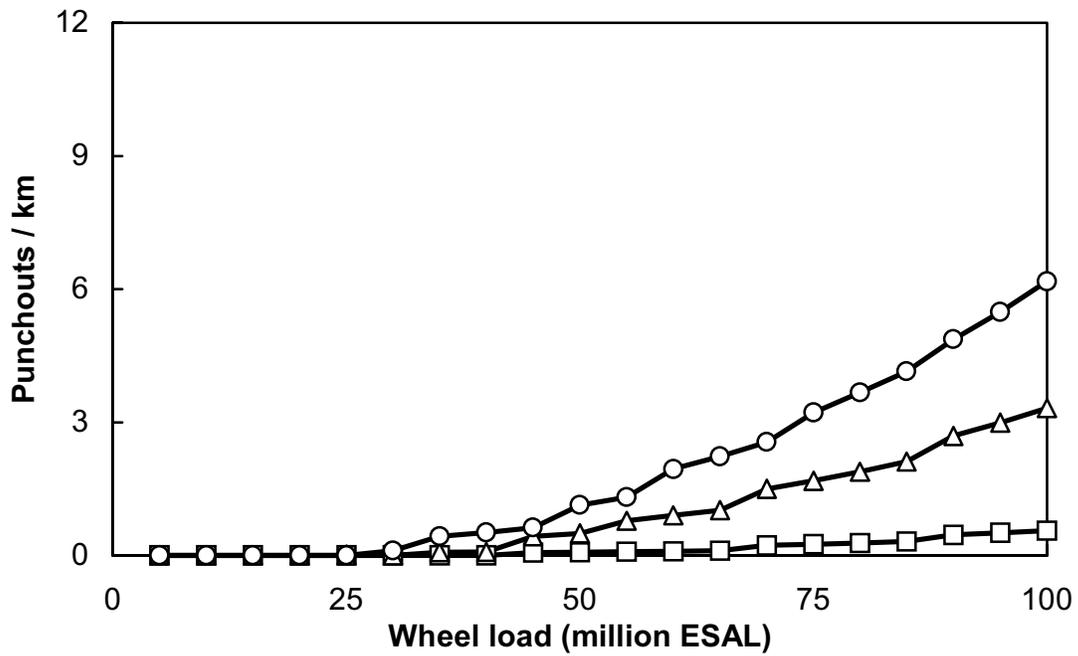


Figure 5.9. Punchout frequency curves: (a) with linear bond-slip model; (b) with nonlinear bond-slip model (1 km = 0.63 miles)

## 5.4 COMPARISON WITH CRCP-8

The results from CRCP-8 and CRCP-9 have been compared as shown in Figure 5.10 to investigate how much difference exists in the results between the two programs. Because the input parameters in those two computer programs are not the same, efforts have been made to have close input values for the two programs. The crack spacing, crack width, and steel stress are compared for different values of the coefficient of variation (CV) in concrete tensile strength. The crack spacings from CRCP-8 are larger than those from CRCP-9 when CV values are small and are very close with CV values of 20 and larger as shown in Figure 5.10(a). The crack widths are larger and the steel stresses are smaller in the results from CRCP-9 compared with CRCP-8 (Figures 5.10[b] and [c]). It should be noted that the analysis results from CRCP-9 are very sensitive to the bond-slip relationship between concrete and steel bars. Because CRCP-8 and CRCP-9 use different algorithms for the stress transfer from steel to concrete, further experimental studies should be conducted to have more reasonable input values for the bond-slip relationship.

CRCP-9 includes all the input parameters required in CRCP-8. There are additional input parameters in CRCP-9 as listed below.

- The variations of temperature and drying shrinkage through the depth of the concrete slab can be considered.
- The location of the longitudinal steel bar can be changed.
- The specific weights of concrete and steel are included for the calculation of the curling and warping effects.
- The stiffness of the bond-slip between concrete and steel is included.
- The parameters for the creep effects are included.
- The type of the plane element can be selected (plane stress or plane strain).

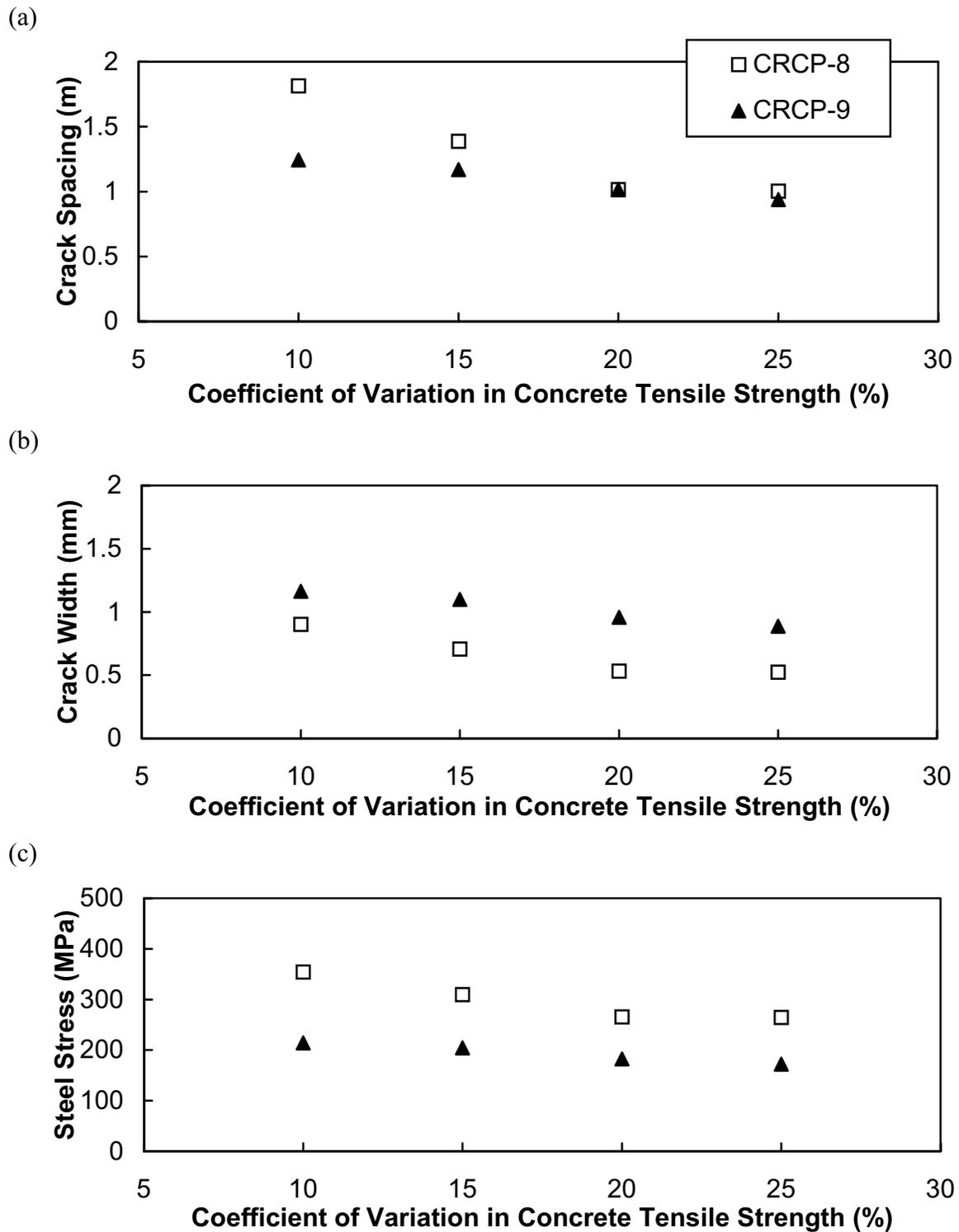


Figure 5.10. Results from CRCP-8 and CRCP-9: (a) mean crack spacing; (b) crack width; (c) steel stress at crack (1MPa = 145.14 psi, 1 mm = 0.0394 in., 1 m = 3.28 ft)

## CHAPTER 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

### 6.1 SUMMARY

A new version of the CRCP computer program, CRCP-9, has been developed in this study. The numerical model of the continuously reinforced concrete (CRC) pavements was developed using finite element theories, the crack spacing prediction model using the Monte Carlo method, and the failure prediction model using probability theories. CRCP-9 uses two-dimensional numerical methods to calculate stresses and strains, which is a totally different approach compared with the previous version of the program, which used one-dimensional analytical methods to calculate them. The major characteristics of CRCP-9 that differ from CRCP-8 include consideration of nonlinear variations in temperature and drying shrinkage through the depth of the concrete slab, nonlinear bond-slip relationship between concrete and steel bars, viscoelastic effect of concrete, curling and warping effects, and the ability of changing locations of the longitudinal steel bars. Details of the theoretical background of mechanistic modeling have been presented. The descriptions of the computer program and input and output procedures have also been explained. Sample analysis results from CRCP-9 and comparisons of the results between CRCP-9 and CRCP-8 are presented.

### 6.2 CONCLUSIONS

This study to develop a new mechanistic model of the CRC pavements, CRCP-9, points to the following conclusions:

1. CRCP-9 considers the variations of temperature and drying shrinkage through the depth of the concrete slab, which cause stresses due to curling and warping of the concrete slab.
2. The bond-slip relationships between concrete and steel have been considered with various models. The various bond-slip models and their input values significantly affect the analysis results.
3. The time histories of mean crack spacing, crack width, and steel stress at crack can be predicted by using CRCP-9.
4. CRCP-9 provides the crack spacing distribution and its cumulative values at a given day.
5. CRCP-9 also estimates the number of punchouts per mile according to the wheel load applications from the predicted crack spacing distribution
6. CRCP-9 can be used for various purposes. It can be used, for instance, to determine the optimum longitudinal steel design, such as amount of steel, bar diameter, and location of the steel bar for given pavement structure, material properties, and environmental conditions.

### **6.3 RECOMMENDATIONS**

Efforts have been made to develop a more realistic mechanistic model that predicts behavior and performance of the CRC pavement systems. To improve the accuracy of the program, it is needed that the calibration of the program with field data should be further performed to obtain more reasonable ranges of input values and analysis results. As investigated, the bond-slip relationship between concrete and steel significantly affects the analysis results. Further investigations with experimental studies to identify reasonable input values for the bond-slip relationship should be undertaken. The wheel load stresses in CRCP-9 are obtained simply by using Westergaard equations. A study needs to be performed to find more realistic wheel load stresses with considerations of discontinuities at cracks and edges of the pavement and effects of multiple wheel loads.

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**APPENDIX A:**

**SAMPLE INPUT FILE OF CRCPPFOR.INP**



This is an input file of CRCP-9

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1	145.5			
9000	6	14		
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110				
2	3	7	180	
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98	102	0.5		
99	101	0.5		
100	100	0.5		
3				
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40	58	0.5
42	57	0.5
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46	55	0.5
48	54	0.5
50	53	0.5
52	52	0.5

**APPENDIX B:**

**SAMPLE OUTPUT FILE OF CRCPFOR.OUT**



This is an output file of CRCP-9

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2.000000000000000	
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20425.4129763802	
3.000000000000000	
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21112.3148521433	
4.000000000000000	
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1.228242724288305E-002	
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25345.6321460105	
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80.7692307692308	26.4288707117915
1.417949902580445E-002	
27819.7574763242	
10.000000000000000	
80.7692307692308	26.4288707117915
1.452038371574588E-002	
28525.3890353521	
11.000000000000000	
80.7692307692308	26.4288707117915
1.485247384102198E-002	
29209.8075832916	
12.000000000000000	
80.7692307692308	26.4288707117915
1.517614075732510E-002	
29876.2543598551	
13.000000000000000	
80.7692307692308	26.4288707117915
1.549166129568539E-002	
30526.9290479329	
14.000000000000000	
70.000000000000000	26.3969695230343
1.416315452452465E-002	

27730.2406346326	
15.00000000000000	
70.00000000000000	26.3969695230343
1.443331017666517E-002	
28278.7753974233	
16.00000000000000	
70.00000000000000	26.3969695230343
1.469831841800895E-002	
28815.5291340378	
17.00000000000000	
65.62500000000000	26.6830353408303
1.420776467140416E-002	
27769.8555372361	
18.00000000000000	
65.62500000000000	26.6830353408303
1.444957980321882E-002	
28255.5849882840	
19.00000000000000	
58.33333333333333	23.2856655954306
1.349902243096111E-002	
26238.7677836583	
20.00000000000000	
55.2631578947368	22.0307013177978
1.317075882281815E-002	
25519.6896929872	
21.00000000000000	
55.2631578947368	22.0307013177978
1.337223197074354E-002	
25916.8489342125	
22.00000000000000	
55.2631578947368	22.0307013177978
1.357024456247735E-002	
26306.7406833351	
23.00000000000000	
52.50000000000000	20.2027225887998
1.326216301606916E-002	
25624.7372746929	
24.00000000000000	
52.50000000000000	20.2027225887998
1.344622140958038E-002	
25985.1871916674	
25.00000000000000	
52.50000000000000	20.2027225887998
1.362704571186657E-002	
26339.6452422606	
26.00000000000000	
52.50000000000000	20.2027225887998
1.380445745711014E-002	
26688.5673180314	
27.00000000000000	
47.7272727272727	17.0405447474327
1.302059168987639E-002	
24989.9745971601	
28.00000000000000	
47.7272727272727	17.0405447474327
1.318078925935605E-002	
25300.6001175648	



0.0000000000000000E+000	100.00000000000000

**APPENDIX C:**

**SAMPLE OUTPUT FILE OF CRCPFOR.SUM**



CRCP-9

=====  
crcpfor  
=====

\*\*\*\*\*INPUT VALUES\*\*\*\*\*

CONCRETE PROPERTIES

=====

Pavement Thickness (in.) = 12.0000000000000  
Poisson Ratio of Concrete = 0.150000000000000  
Specific Weight of Concrete (pcf) = 145.0000000000000  
Coefficient of Variation for Concrete Tensile Strength (%) =  
10.0000000000000  
Coarse Aggregate Type = Limestone  
Thermal Coefficient (/F) = 6.289999873843044E-006  
Elastic Modulus at 28 days (psi) = 3604000  
Tensile Strength at 28 days (psi) = 434  
Compressive Strength at 28 days (psi) = 5000  
Drying Shrinkage at 256 days = 0.000425

STEEL PROPERTIES

=====

Elastic Modulus of Steel Bar (psi) = 29000000.0000000  
Steel Bar Diameter (in.) = 0.750000000000000  
Thermal Coefficient of Steel (/F) = 5.000000000000000E-006  
Specific Weight of Steel (pcf) = 490.0000000000000  
Percent Reinforcement (Steel Ratio) (%) = 0.600000000000000  
Steel Location from Surface (in.) = 6.000000000000000

BOND-SLIP RELATIONSHIP

=====

1. Bond Between Concrete and Steel Reinforcement  
Type of Bond-Slip = User Defined  
Bond-Slip Stiffness / Unit Area (psi/in) = 250000.000000000  
Secondary B-S Stiffness / Unit Area (psi/in) = 250000.000000000  
Yield Slip (in.) = 100.0100000000000  
Ultimate Slip (in.) = 100.0500000000000  
2. Bond Between Concrete and Base Layers  
Vertical Stiffness of Subgrade (psi/in) = 400.0000000000000  
Subbase Type = Flexible  
Bond-Slip Stiffness / Unit Area (psi/in) = 145.5000000000000

LOADS

=====

1. External Load  
Wheel Load (lbs) = 9000.0000000000000  
Wheel Base Radius (in.) = 6.000000000000000  
Days After Concrete Sets Before Wheel Load Applied = 14.0000000000000  
2. Environmental Load  
Curing Temperature (F) = 110.0000000000000  
Days Before Minimum Temperature = 180  
Type of Temperature Variation through Depth = Linear  
Type of Drying Shrinkage Variation through Depth = Uniform

TEMPERATURE AND DRYING SHRINKAGE

=====

Depth ( in )	Min. Temp. ( F )	Max. Temp. ( F )	Drying Shrinkage Ratio
DAY =			
		1	
0.00	100.000	110.000	0.500
1.20	101.000	109.000	0.500

2.40	102.000	108.000	0.500
3.60	103.000	107.000	0.500
4.80	104.000	106.000	0.500
6.00	105.000	105.000	0.500
7.20	106.000	104.000	0.500
8.40	107.000	103.000	0.500
9.60	108.000	102.000	0.500
10.80	109.000	101.000	0.500
12.00	110.000	100.000	0.500
DAY =		2	
0.00	90.000	110.000	0.500
1.20	91.000	109.000	0.500
2.40	92.000	108.000	0.500
3.60	93.000	107.000	0.500
4.80	94.000	106.000	0.500
6.00	95.000	105.000	0.500
7.20	96.000	104.000	0.500
8.40	97.000	103.000	0.500
9.60	98.000	102.000	0.500
10.80	99.000	101.000	0.500
12.00	100.000	100.000	0.500
DAY =		3	
0.00	85.000	105.000	0.500
1.20	86.000	104.000	0.500
2.40	87.000	103.000	0.500
3.60	88.000	102.000	0.500
4.80	89.000	101.000	0.500
6.00	90.000	100.000	0.500
7.20	91.000	99.000	0.500
8.40	92.000	98.000	0.500
9.60	93.000	97.000	0.500
10.80	94.000	96.000	0.500
12.00	95.000	95.000	0.500
DAY =		7	
0.00	80.000	100.000	0.500
1.20	81.000	99.000	0.500
2.40	82.000	98.000	0.500
3.60	83.000	97.000	0.500
4.80	84.000	96.000	0.500
6.00	85.000	95.000	0.500
7.20	86.000	94.000	0.500
8.40	87.000	93.000	0.500
9.60	88.000	92.000	0.500
10.80	89.000	91.000	0.500
12.00	90.000	90.000	0.500
DAY =		180	
0.00	32.000	62.000	0.500
1.20	34.000	61.000	0.500
2.40	36.000	60.000	0.500
3.60	38.000	59.000	0.500
4.80	40.000	58.000	0.500
6.00	42.000	57.000	0.500
7.20	44.000	56.000	0.500
8.40	46.000	55.000	0.500
9.60	48.000	54.000	0.500
10.80	50.000	53.000	0.500
12.00	52.000	52.000	0.500

ADVANCED INPUTS

=====

Number of Different Primary Crack Spacings =  
 Finite Element Type = Plane Stress  
 Consideration of Viscoelasticity = Yes

2

Max. Creep Ratio to Instantaneous Strain = 2.0000000000000000  
 Percent Ratio to Max. Creep = 99.0000000000000000  
 Corresponding Day to Above Ratio = 30.0000000000000000  
 Duration of Temperature Drop = 12.0000000000000000  
 Use of Tensionless Springs for Curling Effect = Yes  
 Punchout Prediction Parameters  
 Swelling Condition = No  
 Reliability = 50 %

\*\*\*\*\*ANALYSIS RESULTS\*\*\*\*\*

Day	Crack Sp. ( ft )	Std. Dev. ( ft )	Crack Width ( in )	Steel Stress ( psi )
1.	29.167	15.342	0.000917	8317.91
2.	12.500	0.856	0.011671	20425.41
3.	7.955	3.076	0.011341	21112.31
4.	7.955	3.076	0.012282	23297.16
5.	7.955	3.076	0.013167	25345.63
6.	7.955	3.076	0.014014	27303.83
7.	6.731	2.202	0.013461	26328.28
8.	6.731	2.202	0.013827	27089.76
9.	6.731	2.202	0.014179	27819.76
10.	6.731	2.202	0.014520	28525.39
11.	6.731	2.202	0.014852	29209.81
12.	6.731	2.202	0.015176	29876.25
13.	6.731	2.202	0.015492	30526.93
14.	5.833	2.200	0.014163	27730.24
15.	5.833	2.200	0.014433	28278.78
16.	5.833	2.200	0.014698	28815.53
17.	5.469	2.224	0.014208	27769.86
18.	5.469	2.224	0.014450	28255.58
19.	4.861	1.940	0.013499	26238.77
20.	4.605	1.836	0.013171	25519.69
21.	4.605	1.836	0.013372	25916.85
22.	4.605	1.836	0.013570	26306.74
23.	4.375	1.684	0.013262	25624.74
24.	4.375	1.684	0.013446	25985.19
25.	4.375	1.684	0.013627	26339.65
26.	4.375	1.684	0.013804	26688.57
27.	3.977	1.420	0.013021	24989.97
28.	3.977	1.420	0.013181	25300.60
180.	2.303	0.689	0.017873	33234.24

PREDICTED PUNCHOUTS / MILE

=====

Million ESALS	Number of Punchouts / Mile
5	0.000
10	0.000
15	0.000
20	0.000
25	0.000
30	0.000
35	0.197
40	0.238
45	0.637
50	0.747
55	1.181
60	1.365
65	1.557
70	2.329
75	2.626
80	2.962

85	3.330
90	4.234
95	4.731
100	5.268

CRACK SPACING DISTRIBUTION

=====

Range of Crack Sp. ( + 0.25 ft )	Crack Sp. Dist. ( % )	Cumulative Value ( % )
0.00	0.000	0.000
0.50	0.000	0.000
1.00	0.000	0.000
1.50	15.789	15.789
2.00	28.947	44.737
2.50	23.684	68.421
3.00	23.684	92.105
3.50	2.632	94.737
4.00	2.632	97.368
4.50	2.632	100.000
5.00	0.000	100.000
5.50	0.000	100.000
6.00	0.000	100.000
6.50	0.000	100.000
7.00	0.000	100.000
7.50	0.000	100.000
8.00	0.000	100.000
8.50	0.000	100.000
9.00	0.000	100.000
9.50	0.000	100.000
10.00	0.000	100.000
10.50	0.000	100.000
11.00	0.000	100.000
11.50	0.000	100.000
12.00	0.000	100.000
12.50	0.000	100.000
13.00	0.000	100.000
13.50	0.000	100.000
14.00	0.000	100.000
14.50	0.000	100.000
15.00	0.000	100.000
15.50	0.000	100.000
16.00	0.000	100.000
16.50	0.000	100.000
17.00	0.000	100.000
17.50	0.000	100.000
18.00	0.000	100.000
18.50	0.000	100.000
19.00	0.000	100.000
19.50	0.000	100.000
20.00	0.000	100.000

**APPENDIX D:**

**LIST OF PROGRAM CRCP-9**



```

PROGRAM CRCP9
C
C   Version 1.0
C   Computer program to analyze the behavior of CRC pavements
C
C   Developed by Seong-Min Kim, Moon C. Won, and B. Frank McCullough
C
C   Center for Transportation Research, University of Texas at Austin
C   &
C   Texas Department of Transportation
C
C   August 2000
C
C   IMPLICIT REAL*8 (A-H,O-Z)
C   CHARACTER*40 TITLECRCP
C   CHARACTER*60 TITLEINP
C   DIMENSION ALOAD(8844), DISP(8844), AKS(2,2), AKSB(4,4), DRYSH(29,21)
C   DIMENSION SK(8844,50), AK(8,8), D(3,3), BNSL(200), TEMPR(29,21)
C   DIMENSION TEMLD(8844), STRINI(20,4), TLOAD(20,8), TEMPR1(21)
C   DIMENSION INOD(4200,8), SS(442200), IMAX(200), IMAXC(200)
C   DIMENSION TEMPRA(29,21), DAYCON(29), CRWTH(29), STLSS(29)
C   DIMENSION CRSPC(10,4095), CRWID(10,4095), STLSTR(10,4095)
C   DIMENSION STRSS(200), STRSSF(400), TSTARR(400), DISTRB(400)
C   DIMENSION ICRLOC(10,29), INDCR(10,4095), CRSPAVG(29), CRWDAVG(29)
C   DIMENSION CRSPSDD(29), SSTRAVG(29), CRSPDIST(41)
C   COMMON NUMELX, NUMELY, A, B, E1, POIS1, THICK, ITNOD1, MBAND
C
C   minimum memory requirements
C
C   ALOAD(ITNOD1), DISP(ITNOD1), SK(ITNOD1, MBAND), BNSL(NUMELX)
C   TEMLD(ITNOD1), STRINI(NUMELY, 4), TLOAD(NUMELY, 8)
C   INOD(INODDIM, 8), SS(KS), IMAX(NUMELX), IMAXC(NUMELX)
C   TEMPR1(NUMELY+1), TEMPR(29, NUMELY+1), TEMPRA(29, NUMELY+1)
C   DRYSH(29, NUMELY+1), STRSS(NUMELX), STRSSF(NUMELX*2)
C   TSTARR(NUMELX*2), DISTRB(NUMELX*2)
C
C   open input and output files
C
C   OPEN (5, FILE='crcpfor.inp', STATUS='OLD')
C   OPEN (6, FILE='crcpfor.out', STATUS='UNKNOWN')
C   OPEN (9, FILE='crcpfor.sum', STATUS='UNKNOWN')
C
C   read input data
C
C   READ(5, *) TITLECRCP
C   READ(5, *) TITLEINP
C   READ(5, *) TOTD, IELTYPE, NUMPCS
C   READ(5, *) POIS1, ALPC, WEIGHT, CV, STRAT
C   READ(5, *) IAGG, IDEFAULT
C   READ(5, *) CSTR28, TSTR28, ECONC28, ZSH256
C   READ(5, *) STLOC, ESTL, DIASTL, ALPS, STWEI
C   READ(5, *) IBONDCS, AKBUA, AKBUA2, YLSLIP, ULSLIP
C   READ(5, *) BOTKV, INDSPR
C   READ(5, *) INDFR, AKFRUA
C   READ(5, *) WHLOAD, WHRAD, WHDAY
C   READ(5, *) ICREEP, PHIMAX, PERCEN, DAYPC, TIME
C   READ(5, *) IFATPRO, ISWELL, ITEMIND, IDRYIND
C   READ(5, *) TEMF
C   READ(5, *) IDAY2, IDAY3, IDAY4, IFDAY
C   DO I=1,29
C     READ(5, *) DAYCON(I)
C     DO J=1,11

```

```

                READ(5,*) TEMPR(I,J),TEMPRA(I,J),DRYSH(I,J)
ENDDO
ENDDO
C
C
C   WHERE,
C   TOD = thickness of concrete slab (pavement thickness)
C   IELTYPE = index for element type (1:plane stress, other:plane strain)
C   NUMPCS = no. of different primary crack spacing
C             (max. = 10, cannot be 3,6,7,9)
C   POIS1 = Poisson's ratio of concrete
C   WEIGHT = specific weight of concrete (pcf)
C   ALPC,ALPS = coefficient of thermal expansion for concrete and steel
C   CV = coefficient of variation for concrete tensile strength (%)
C   STRAT = percent reinforcement (%), steel ratio
C   IAGG = index for aggregate type
C           1 = Granite
C           2 = Dolomite
C           3 = Vega
C           4 = Bridgeport/Tin Top
C           5 = Western Tascosa
C           6 = Ferris
C           7 = Limestone
C           8 = Siliceous River Gravel
C   IDEFAULT = Index for using default values (0=default values)
C   CSTR28 = 28 day concrete compressive strength (put 0 for default)
C   TSTR28 = 28 day concrete tensile strength (put 0 for default)
C   ECONC28 = 28 day concrete elastic modulus (put 0 for default)
C   ZSH256 = 256 day concrete drying shrinkage (put 0 for default)
C   DAYCON(I) = consideration day after placement of concrete
C   STLOC = steel location from surface
C   ESTL,DIASTL = modulus and diameter of longitudinal steel
C   STWEI = specific weight of steel bar (pcf)
C   IBONDCS = Index for B-S (0 to 12) (12: user defined)
C   AKBUA,AKBUA2 = primary and secondary bond-slip stiffness per unit area
C   YLSLIP,ULSLIP = yield and ultimate slips
C   BOTKV = vertical stiffness per unit area of the base layer
C   INDSPR = index for tensionless sprs for foundation (1=no tensionless)
C   INDFR = index for subbase friction (subbase type for friction)
C           1 = Flexible (145.5 pci)
C           2 = Asphalt-Stabilized (55.9)
C           3 = Cement-Stabilized (15400)
C           4 = Lime-Treated Clay (154.5)
C           5 = Untreated Clay (22)
C   AKFRUA = bond-slip stiffness per unit area between concrete and base
C   WHLOAD = wheel load (lbs)
C   WHRAD = radius of loaded area (in.)
C   WHDAY = days before wheel load applied
C   ICREEP = index for creep analysis (1=creep analysis)
C   PHIMAX = maximum creep ratio to instantaneous strain
C   PERCEN = consideration percent to maximum creep
C   DAYPC = corresponding day to PERCEN
C   TIME = loading duration (hr)
C   IFATPRO = Index for reliability of punchout prediction
C             (1:95%, 2:75%, 3:50%)
C   ISWELL = Index for swelling condition (1:swelling=yes)
C   ITEMIND = Index for temp. variation (0:uniform,1:linear,2:nonlinear)
C   IDRYIND = Index for drying shrinkage(" ")
C   IDAY2, IDAY3, IDAY4, IFDAY = Days for temp. and drying shrinkage input
C   TEMF = reference temperature
C   TEMPR(I,J) = minimum temperatures at each node from surface on I day
C   TEMPRA(I,J) = maximum temperatures at each node from surface on I day
C   DRYSH(I,J) = drying shrinkage ratio at each node from the surface
C

```

```

C   define basic variables
C
C   WRITE(6,*) 'This is an output file of CRCP-9'
C
C   NUMELY=10
C   FULLDAY=28
C   IHIST=FULLDAY+1
C
C   DO I=1,IHIST
C       CRWTH(I)=0.
C       STLSS(I)=0.
C   ENDDO
C
C   A=1.5
C   B=TOTD/FLOAT(NUMELY)
C   ASTL=(DIASSTL/2.)*(DIASSTL/2.)*3.141592654
C   THICK=ASTL*100./(TOTD*STRAT)
C   LSTLOC=STLOC/B+1
C   IF(LSTLOC.EQ.1) THEN
C       WRITE(*,*) 'Steel location from surface must be larger than 0'
C       GO TO 1000
C   ENDIF
C   IF(ALPC.EQ.0.) THEN
C       IF(IAGG.EQ.1) ALPC=0.00000574
C       IF(IAGG.EQ.2) ALPC=0.0000059
C       IF(IAGG.EQ.3) ALPC=0.0000065
C       IF(IAGG.EQ.4) ALPC=0.00000484
C       IF(IAGG.EQ.5) ALPC=0.00000615
C       IF(IAGG.EQ.6) ALPC=0.00000544
C       IF(IAGG.EQ.7) ALPC=0.00000629
C       IF(IAGG.EQ.8) ALPC=0.00000818
C   ENDIF
C   AKSTL=ESTL*ASTL/A
C   BNAREA=A*3.141592654*DIASSTL
C   AKBOND=AKBUA*BNAREA
C   AKBOND2=AKBUA2*BNAREA
C   BNFORCE=YLSLIP*BNAREA*(AKBUA-AKBUA2)
C   IF(INDFR.EQ.1) AKFRUA=145.5           ! Flexible
C   IF(INDFR.EQ.2) AKFRUA=55.9           ! Asphalt-Stabilized
C   IF(INDFR.EQ.3) AKFRUA=15400          ! Cement-Stabilized
C   IF(INDFR.EQ.4) AKFRUA=154.5          ! Lime-Treated Clay
C   IF(INDFR.EQ.5) AKFRUA=22.0           ! Untreated Clay
C   FRAREA=A*THICK
C   AKFR=AKFRUA*FRAREA
C   BOTK=BOTKV*A*THICK
C   MBAND=(NUMELY+3)*2+4
C   ELWEI=WEIGHT*A*B*THICK/1728.
C   ELSTWEI=STWEI*A*3.141592*DIASSTL**2/(4.*1728.)
C   SEED=10000001.
C   IF(NUMPCS.EQ.(3.OR.6.OR.7.OR.9)) NUMPCS=NUMPCS+1
C   DELPCS=600./FLOAT(2*NUMPCS)
C
C   WRITE(9,*) 'CRCP-9'
C   WRITE(9,*) '===== '
C   WRITE(9,*) '           ',TITLEINP
C   WRITE(9,*) '===== '
C   WRITE(9,*) ' '
C   WRITE(9,*) '*****INPUT VALUES*****'
C   WRITE(9,*) ' '
C   WRITE(9,*) 'CONCRETE PROPERTIES'
C   WRITE(9,*) '===== '
C   WRITE(9,*) 'Pavement Thickness (in.) = ',TOTD
C   WRITE(9,*) 'Poisson Ratio of Concrete = ',POIS1

```

```

WRITE(9,*) 'Specific Weight of Concrete (pcf) = ',WEIGHT
WRITE(9,*) 'Coefficient of Variation for Concrete Tensile ',
1 'Strength (%) = ',CV
IF(IAGG.EQ.1) WRITE(9,*) 'Coarse Aggregate Type = Granite'
IF(IAGG.EQ.2) WRITE(9,*) 'Coarse Aggregate Type = Dolomite'
IF(IAGG.EQ.3) WRITE(9,*) 'Coarse Aggregate Type = Vega'
IF(IAGG.EQ.4) WRITE(9,*) 'Coarse Aggregate Type = ',
1 'Bridgeport/Tin Top'
IF(IAGG.EQ.5) WRITE(9,*) 'Coarse Aggregate Type = Western Tascosa'
IF(IAGG.EQ.6) WRITE(9,*) 'Coarse Aggregate Type = Ferris'
IF(IAGG.EQ.7) WRITE(9,*) 'Coarse Aggregate Type = Limestone'
IF(IAGG.EQ.8) WRITE(9,*) 'Coarse Aggregate Type = ',
1 'Siliceous River Gravel'
WRITE(9,*) 'Thermal Coefficient (/F) = ',ALPC
IF(IDEFAULT.EQ.1) THEN
  WRITE(9,*) 'Elastic Modulus at 28 days (psi) = ',ECONC28
  WRITE(9,*) 'Tensile Strength at 28 days (psi) = ',TSTR28
  WRITE(9,*) 'Compressive Strength at 28 days (psi) = ',CSTR28
  WRITE(9,*) 'Drying Shrinkage at 256 days = ',ZSH256
ELSE
  IF(IAGG.EQ.1) THEN
    WRITE(9,*) 'Elastic Modulus at 28 days (psi) = 3356000'
    WRITE(9,*) 'Tensile Strength at 28 days (psi) = 529'
    WRITE(9,*) 'Compressive Strength at 28 days (psi) = 4967'
    WRITE(9,*) 'Drying Shrinkage at 256 days = 0.000394'
  ENDIF
  IF(IAGG.EQ.2) THEN
    WRITE(9,*) 'Elastic Modulus at 28 days (psi) = 4648000'
    WRITE(9,*) 'Tensile Strength at 28 days (psi) = 494'
    WRITE(9,*) 'Compressive Strength at 28 days (psi) = 4470'
    WRITE(9,*) 'Drying Shrinkage at 256 days = 0.000335'
  ENDIF
  IF(IAGG.EQ.3) THEN
    WRITE(9,*) 'Elastic Modulus at 28 days (psi) = 3764000'
    WRITE(9,*) 'Tensile Strength at 28 days (psi) = 442'
    WRITE(9,*) 'Compressive Strength at 28 days (psi) = 3990'
    WRITE(9,*) 'Drying Shrinkage at 256 days = 0.000461'
  ENDIF
  IF(IAGG.EQ.4) THEN
    WRITE(9,*) 'Elastic Modulus at 28 days (psi) = 3984000'
    WRITE(9,*) 'Tensile Strength at 28 days (psi) = 444'
    WRITE(9,*) 'Compressive Strength at 28 days (psi) = 4072'
    WRITE(9,*) 'Drying Shrinkage at 256 days = 0.000399'
  ENDIF
  IF(IAGG.EQ.5) THEN
    WRITE(9,*) 'Elastic Modulus at 28 days (psi) = 3606000'
    WRITE(9,*) 'Tensile Strength at 28 days (psi) = 431'
    WRITE(9,*) 'Compressive Strength at 28 days (psi) = 4132'
    WRITE(9,*) 'Drying Shrinkage at 256 days = 0.000418'
  ENDIF
  IF(IAGG.EQ.6) THEN
    WRITE(9,*) 'Elastic Modulus at 28 days (psi) = 3958000'
    WRITE(9,*) 'Tensile Strength at 28 days (psi) = 479'
    WRITE(9,*) 'Compressive Strength at 28 days (psi) = 3994'
    WRITE(9,*) 'Drying Shrinkage at 256 days = 0.000413'
  ENDIF
  IF(IAGG.EQ.7) THEN
    WRITE(9,*) 'Elastic Modulus at 28 days (psi) = 3604000'
    WRITE(9,*) 'Tensile Strength at 28 days (psi) = 434'
    WRITE(9,*) 'Compressive Strength at 28 days (psi) = 5000'
    WRITE(9,*) 'Drying Shrinkage at 256 days = 0.000425'
  ENDIF
  IF(IAGG.EQ.8) THEN

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        WRITE(9,*) 'Elastic Modulus at 28 days (psi) = 4564000'
        WRITE(9,*) 'Tensile Strength at 28 days (psi) = 462'
        WRITE(9,*) 'Compressive Strength at 28 days (psi) = 4876'
        WRITE(9,*) 'Drying Shrinkage at 256 days = 0.000342'
    ENDIF
ENDIF
WRITE(9,*) ' '
WRITE(9,*) 'STEEL PROPERTIES'
WRITE(9,*) '=====
WRITE(9,*) 'Elastic Modulus of Steel Bar (psi) = ',ESTL
WRITE(9,*) 'Steel Bar Diameter (in.) = ',DIASL
WRITE(9,*) 'Thermal Coefficient of Steel (/F) = ',ALPS
WRITE(9,*) 'Specific Weight of Steel (pcf) = ',STWEI
WRITE(9,*) 'Percent Reinforcement (Steel Ratio) (%) = ',STRAT
WRITE(9,*) 'Steel Location from Surface (in.) = ',STLOC
WRITE(9,*) ' '
WRITE(9,*) 'BOND-SLIP RELATIONSHIP'
WRITE(9,*) '=====
WRITE(9,*) '1. Bond Between Concrete and Steel Reinforcement'
IF(IBONDCE.EQ.0) THEN
    WRITE(9,*) 'Type of Bond-Slip = Strong Linear'
    WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
ENDIF
IF(IBONDCE.EQ.1) THEN
    WRITE(9,*) 'Type of Bond-Slip = Moderate Linear'
    WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
ENDIF
IF(IBONDCE.EQ.2) THEN
    WRITE(9,*) 'Type of Bond-Slip = Weak Linear'
    WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
ENDIF
IF(IBONDCE.EQ.3) THEN
    WRITE(9,*) 'Type of Bond-Slip = ',
1    'Strong Linear with Ultimate Slip'
    WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
    WRITE(9,*) 'Ultimate Slip (in.) = ',ULSLIP
ENDIF
IF(IBONDCE.EQ.4) THEN
    WRITE(9,*) 'Type of Bond-Slip = ',
1    'Moderate Linear with Ultimate Slip'
    WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
    WRITE(9,*) 'Ultimate Slip (in.) = ',ULSLIP
ENDIF
IF(IBONDCE.EQ.5) THEN
    WRITE(9,*) 'Type of Bond-Slip = Weak Linear with Ultimate Slip'
    WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
    WRITE(9,*) 'Ultimate Slip (in.) = ',ULSLIP
ENDIF
IF(IBONDCE.EQ.6) THEN
    WRITE(9,*) 'Type of Bond-Slip = Strong Bilinear'
    WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
    WRITE(9,*) 'Secondary B-S Stiffness / Unit Area (psi/in) = ',
1    AKBUA2
    WRITE(9,*) 'Yield Slip (in.) = ',YLSLIP
ENDIF
IF(IBONDCE.EQ.7) THEN
    WRITE(9,*) 'Type of Bond-Slip = Moderate Bilinear'
    WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
    WRITE(9,*) 'Secondary B-S Stiffness / Unit Area (psi/in) = ',
1    AKBUA2
    WRITE(9,*) 'Yield Slip (in.) = ',YLSLIP
ENDIF
IF(IBONDCE.EQ.8) THEN

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WRITE(9,*) 'Type of Bond-Slip = Weak Bilinear'
WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
WRITE(9,*) 'Secondary B-S Stiffness / Unit Area (psi/in) = ',
1      AKBUA2
WRITE(9,*) 'Yield Slip (in.) = ',YLSLIP
ENDIF
IF(IBONDCS.EQ.9) THEN
WRITE(9,*) 'Type of Bond-Slip = ',
1      'Strong Bilinear with Ultimate Slip'
WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
WRITE(9,*) 'Secondary B-S Stiffness / Unit Area (psi/in) = ',
1      AKBUA2
WRITE(9,*) 'Yield Slip (in.) = ',YLSLIP
WRITE(9,*) 'Ultimate Slip (in.) = ',ULSLIP
ENDIF
IF(IBONDCS.EQ.10) THEN
WRITE(9,*) 'Type of Bond-Slip = ',
1      'Moderate Bilinear with Ultimate Slip'
WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
WRITE(9,*) 'Secondary B-S Stiffness / Unit Area (psi/in) = ',
1      AKBUA2
WRITE(9,*) 'Yield Slip (in.) = ',YLSLIP
WRITE(9,*) 'Ultimate Slip (in.) = ',ULSLIP
ENDIF
IF(IBONDCS.EQ.11) THEN
WRITE(9,*) 'Type of Bond-Slip = ',
1      'Weak Bilinear with Ultimate Slip'
WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
WRITE(9,*) 'Secondary B-S Stiffness / Unit Area (psi/in) = ',
1      AKBUA2
WRITE(9,*) 'Yield Slip (in.) = ',YLSLIP
WRITE(9,*) 'Ultimate Slip (in.) = ',ULSLIP
ENDIF
IF(IBONDCS.EQ.12) THEN
WRITE(9,*) 'Type of Bond-Slip = User Defined'
WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKBUA
WRITE(9,*) 'Secondary B-S Stiffness / Unit Area (psi/in) = ',
1      AKBUA2
WRITE(9,*) 'Yield Slip (in.) = ',YLSLIP
WRITE(9,*) 'Ultimate Slip (in.) = ',ULSLIP
ENDIF
WRITE(9,*) '2. Bond Between Concrete and Base Layers'
WRITE(9,*) 'Vertical Stiffness of Subgrade (psi/in) = ',BOTKV
IF(INDFR.EQ.1) WRITE(9,*) 'Subbase Type = Flexible'
IF(INDFR.EQ.2) WRITE(9,*) 'Subbase Type = Asphalt-Stabilized'
IF(INDFR.EQ.3) WRITE(9,*) 'Subbase Type = Cement-Stabilized'
IF(INDFR.EQ.4) WRITE(9,*) 'Subbase Type = Lime-Treated Clay'
IF(INDFR.EQ.5) WRITE(9,*) 'Subbase Type = Untreated Clay'
IF(INDFR.EQ.0) WRITE(9,*) 'Subbase Type = User Defined'
WRITE(9,*) 'Bond-Slip Stiffness / Unit Area (psi/in) = ',AKFRUA
WRITE(9,*) ' '
WRITE(9,*) 'LOADS'
WRITE(9,*) '====='
WRITE(9,*) '1. External Load'
WRITE(9,*) 'Wheel Load (lbs) = ',WHLOAD
WRITE(9,*) 'Wheel Base Radius (in.) = ',WHRAD
WRITE(9,*) 'Days After Concrete Sets Before Wheel Load Applied',
1      ' = ',WHDAY
WRITE(9,*) '2. Environmental Load'
WRITE(9,*) 'Curing Temperature (F) = ',TEMPF
WRITE(9,*) 'Days Before Minimum Temperature = ',IFDAY
IF(ITEMIND.EQ.0) WRITE(9,*) 'Type of Temperature Variation ',
1      'through Depth = Uniform'

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IF(ITEMIND.EQ.1) WRITE(9,*) 'Type of Temperature Variation ',
1 'through Depth = Linear'
IF(ITEMIND.EQ.2) WRITE(9,*) 'Type of Temperature Variation ',
1 'through Depth = Nonlinear'
IF(IDRYIND.EQ.0) WRITE(9,*) 'Type of Drying Shrinkage Variation ',
1 'through Depth = Uniform'
IF(IDRYIND.EQ.1) WRITE(9,*) 'Type of Drying Shrinkage Variation ',
1 'through Depth = Linear'
IF(IDRYIND.EQ.2) WRITE(9,*) 'Type of Drying Shrinkage Variation ',
1 'through Depth = Nonlinear'
WRITE(9,*) ' '
WRITE(9,*) 'TEMPERATURE AND DRYING SHRINKAGE'
WRITE(9,*) '===== '
DO I=1,29
  IF(I.EQ.1) THEN
    WRITE(9,*) 'Depth',' Min. Temp.',' Max. Temp.',
1 ' Drying Shrinkage Ratio'
    WRITE(9,*) '( in )',' ( F )',' ( F )'
    WRITE(9,*) 'DAY = ',I
    DO J=1,11
      DEPPR=FLOAT(J-1)*TOTD/10.
      WRITE(9,9010) DEPPR,TEMPR(I,J),TEMPRA(I,J),DRYSH(I,J)
    ENDDO
  ENDIF
  IF(I.EQ.IDAY2) THEN
    WRITE(9,*) 'DAY = ',I
    DO J=1,11
      DEPPR=FLOAT(J-1)*TOTD/10.
      WRITE(9,9010) DEPPR,TEMPR(I,J),TEMPRA(I,J),DRYSH(I,J)
    ENDDO
  ENDIF
  IF(I.EQ.IDAY3) THEN
    WRITE(9,*) 'DAY = ',I
    DO J=1,11
      DEPPR=FLOAT(J-1)*TOTD/10.
      WRITE(9,9010) DEPPR,TEMPR(I,J),TEMPRA(I,J),DRYSH(I,J)
    ENDDO
  ENDIF
  IF(I.EQ.IDAY4) THEN
    WRITE(9,*) 'DAY = ',I
    DO J=1,11
      DEPPR=FLOAT(J-1)*TOTD/10.
      WRITE(9,9010) DEPPR,TEMPR(I,J),TEMPRA(I,J),DRYSH(I,J)
    ENDDO
  ENDIF
  IF(I.EQ.29) THEN
    WRITE(9,*) 'DAY = ',IFDAY
    DO J=1,11
      DEPPR=FLOAT(J-1)*TOTD/10.
      WRITE(9,9010) DEPPR,TEMPR(I,J),TEMPRA(I,J),DRYSH(I,J)
    ENDDO
  ENDIF
ENDDO
9010 FORMAT(F6.2,3x,F7.3,5x,F7.3,8x,F7.3)
WRITE(9,*) ' '
WRITE(9,*) 'ADVANCED INPUTS'
WRITE(9,*) '===== '
WRITE(9,*) 'Number of Different Primary Crack Spacings = ',NUMPCS
IF(IELTYPE.EQ.1) THEN
  WRITE(9,*) 'Finite Element Type = Plane Stress'
ELSE
  WRITE(9,*) 'Finite Element Type = Plane Strain'
ENDIF

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IF(ICREEP.EQ.1) THEN
  WRITE(9,*) 'Consideration of Viscoelasticity = Yes'
  WRITE(9,*) 'Max. Creep Ratio to Instantaneous Strain = ',PHIMAX
  WRITE(9,*) 'Percent Ratio to Max. Creep = ',PERCEN
  WRITE(9,*) 'Corresponding Day to Above Ratio = ',DAYPC
  WRITE(9,*) 'Duration of Temperature Drop = ',TIME
ELSE
  WRITE(9,*) 'Consideration of Viscoelasticity = No'
ENDIF
IF(INDSPR.EQ.0) THEN
  WRITE(9,*) 'Use of Tensionless Springs for Curling Effect = Yes'
ELSE
  WRITE(9,*) 'Use of Tensionless Springs for Curling Effect = No'
ENDIF
WRITE(9,*) 'Punchout Prediction Parameters'
IF(ISWELL.EQ.1) THEN
  WRITE(9,*) 'Swelling Condition = Yes'
ELSE
  WRITE(9,*) 'Swelling Condition = No'
ENDIF
IF(IFATPRO.EQ.1) WRITE(9,*) 'Reliability = 95 %'
IF(IFATPRO.EQ.2) WRITE(9,*) 'Reliability = 75 %'
IF(IFATPRO.EQ.3) WRITE(9,*) 'Reliability = 50 %'
C
WRITE(9,*) ' '
WRITE(9,*) ' '
WRITE(9,*) '*****ANALYSIS RESULTS*****'
WRITE(9,*) ' '
WRITE(9,*) 'Day      Crack Sp. Std. Dev.  Crack Width  Steel Stress'
WRITE(9,*) '          ( ft )      ( ft )      ( in )      ( psi )'
C
C
DO 3333 IPCS=1,NUMPCS
C
CRSPC(IPCS,1)=600.-FLOAT(IPCS-1)*DELPCS
INDCR(IPCS,1)=1
DO I=2,4095
  INDCR(IPCS,I)=0
ENDDO
C
SEED=SEED+3000.
CALL STRDIST(SEED,DISTRB,CV,CRSPC,IPCS,A)
C
ICRACK=1
C
DO 2222 IDAY=1,IHIST
C
ECONDAY=DAYCON(IDAY)
C
150 CONTINUE
C
WRITE(*,*) 'CRACK =',ICRACK
C
JCRACK1=2**(ICRACK-1)
JCRACK2=2**ICRACK-1
C
DO 4444 JCRACK=JCRACK1,JCRACK2
C
IF(CRSPC(IPCS,JCRACK).EQ.0.) THEN
  II=JCRACK*2
  CRSPC(IPCS,II)=0.
  CRSPC(IPCS,II+1)=0.
  GO TO 333
ENDIF

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IF (INDCR (IPCS, JCRACK) .EQ. 0) THEN
    II=JCRACK*2
    CRSPC (IPCS, II) =CRSPC (IPCS, JCRACK)
    CRSPC (IPCS, II+1) =0.
    CRWID (IPCS, JCRACK) =CRWID (IPCS, JCRACK/2)
    STLSTR (IPCS, JCRACK) =STLSTR (IPCS, JCRACK/2)
    GO TO 333
ENDIF
NA=1
JOO=1
C
    TOTL=CRSPC (IPCS, JCRACK) /2.
    NUMELX=TOTL/A
    NUM2=NUMELX*2
C
180 CONTINUE
190 CONTINUE
C
    DO I=1, NUMELX
        IMAXC (I) =0
    ENDDO
    MIN=1
170 CONTINUE
C
    ITNOD= (NUMELX+1) * (NUMELY+1)
    ITNOD1=ITNOD*2+ (NUMELX+1) *2
    KS=ITNOD1*MBAND
    INODDIM= (NUMELY+1) *NUMELX
    IF (JOO.EQ.1) THEN
        DELT=TEMPR (IDAY, LSTLOC) -TEMF
        DO I=1, NUMELY+1
            TEMPR1 (I) =TEMPR (IDAY, I)
        ENDDO
    ELSE
        DELT=TEMPRA (IDAY, LSTLOC) -TEMF
        DO I=1, NUMELY+1
            TEMPR1 (I) =TEMPRA (IDAY, I)
        ENDDO
    ENDIF
C
    CALL CHMEMO (KS, INODDIM, ICHMEMO)
C
This program can take up to 200 by 20 elements
C
    IF (ICHMEMO.EQ.1) GO TO 1000
C
    CALL CONCPRO (IAGG, CSTR28, TSTR28, ECONC28, ZSH256,
+                ECONDAY, CSTR, TSTRNG, ECONC, ZSH)
    IF (ECONDAY.LE.28.) ACSTR28=CSTR
C
    IF (ICREEP.EQ.1) THEN
        CALL CREEP (TIME, ECONC, E1, PHIMAX, PERCEN, DAYPC)
    ELSE
        E1=ECONC
    ENDIF
C
    CALL LINREC4 (AK, D, IELTYPE)
C
    CALL FRAME (A, ESTL, DIASTL, AKSTL, AKS, AKSB)
C
    CALL SHRINK (DRYSH, TEMPR1, ALPC, IDAY, ZSH)
C
    CALL TEMPRT (TEMPR1, TEMF, ALPC, TLOAD, STRINI, D, IELTYPE)
C

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      KIM=1
      IULSLP=0
      DO I=1,NUMELX
        IMAX(I)=0
      ENDDO
C
100 CONTINUE
C
      DO I=1,ITNOD1
        ALOAD(I)=0.
      ENDDO
C
      CALL ASSEM(AK,SK,INOD,LSTLOC,AKS,TLOAD,TEMLD,AKSB)
C
      CALL BOUND(SK,LSTLOC)
C
      CALL BNSLIP(SK,AKBOND,AKBOND2,LSTLOC,KIM,ALOAD,IMAX,BNFORCE,
+        BNSLMAXS,BNSL,ULSLIP)
C
      CALL FRSLIP(SK,AKFR,MIN,IMAXC)
C
      CALL CURL(SK,BOTK,MIN,IMAXC)
C
      DO 101 I=1,ITNOD1
      DO 102 J=1,MBAND
        K=(J-1)*ITNOD1+I
        SS(K)=SK(I,J)
102 CONTINUE
        ALOAD(I)=ALOAD(I)+TEMLD(I)
101 CONTINUE
C
      CALL DWEIGHT(ALOAD,ELWEI,ELSTWEI,LSTLOC)
C
      CALL SOLVE(ITNOD1,MBAND,ALOAD,SS,KS)
C
      DO I=1,ITNOD1
        DISP(I)=ALOAD(I)
      ENDDO
C
      CALL CHSLIP(DISP,IMAX,KIM,BNSL,BNSLMAX,BNSLMAXS,LSTLOC,YLSLIP,
+        IULSL,ULSLIP)
C
      IF(IMAX(KIM).EQ.1) GO TO 555
C
      IF(BNSLMAX.GT.YLSLIP) THEN
        KIM=KIM+1
        IULSLP=IULSL
        GO TO 100
      ENDIF
C
      IF(IULSL.NE.IULSLP) THEN
C
        write(*,*) 'IULSLP and IULSL',IULSLP,IULSL
        IULSLP=IULSL
        GO TO 100
      ENDIF
C
555 continue
C
      IF(INDSPR.EQ.1) GO TO 105
C
      CALL CHCURL(DISP,MIN,IMAXC,INDCURL)
C
      IF(INDCURL.EQ.1) GO TO 170

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C
105 CONTINUE
C
INDST=0
IF (NA.EQ.1) THEN
  CALL COMPST (STRINI, INOD, LSTLOC, ESTL, ALPS, JOO, NA, INDMA,
+             DELT, DISP, D, CHSTRES, INDST, CSTR1, SSTR1, WHDAY,
+             TOD, WHRAD, WHLOAD, ECONC, BOTKV, ECONDAY)
  IF (INDMA.EQ.1) GO TO 190
  IF (INDMA.EQ.2) GO TO 180
ENDIF
C
IWIDTH=ITNOD1-2*(NUMELY+2)+1
CRWID (IPCS, JCRACK)=DABS (2.*DISP (IWIDTH))
C
CALL TSTRTH (CRSPC, IPCS, JCRACK, JCRACK1, DISTRB, TSTRNG, A,
+           NUM2, TSTARR)
C
DO III=1, NUMELX
  STRSS (III)=0.
  DO 400 JSTR=1, NUMELY+1
    IF (JSTR.EQ.LSTLOC) GO TO 400
    IF (JSTR.EQ.LSTLOC-1) GO TO 400
    IF (JSTR.EQ.LSTLOC+1) GO TO 400
    IELINP=(III-1)*(NUMELY+1)+JSTR
    CALL STRESS (IELINP, STRINI, INOD, LSTLOC, ESTL, ALPS, DELT, DISP,
+             D, CHSTRES, INDST, CSTR1, SSTR1)
    IF (ECONDAY.GE.WHDAY) THEN
      CALL WHEEL (TOD, WHRAD, WHLOAD, ECONC, BOTKV, WHSTR)
      IF (JSTR.LT.LSTLOC) THEN
        CHWHSTR=WHSTR*(FLOAT (2*JSTR-1)/FLOAT (NUMELY)-1.)
      ELSE
        CHWHSTR=WHSTR*(FLOAT (2*JSTR-3)/FLOAT (NUMELY)-1.)
      ENDIF
      CHSTRES=CHSTRES+CHWHSTR
    ENDIF
    IF (CHSTRES.GT.STRSS (III)) STRSS (III)=CHSTRES
400 CONTINUE
ENDDO
C
DO I=1, NUMELX
  J=NUMELX+I
  K=NUMELX+1-I
  STRSSF (J)=STRSS (I)
  STRSSF (K)=STRSS (I)
c write (6,*) i, ' ', strss(i)
ENDDO
C
DIFMAX=0.
DO I=1, NUM2
  DIFE=STRSSF (I)-TSTARR (I)
  IF (DIFE.GT.DIFMAX) THEN
    DIFMAX=DIFE
    IDIFLOC=I
  ENDIF
ENDDO
II=JCRACK*2
IF (DIFMAX.EQ.0.) THEN
  CRSPC (IPCS, II)=CRSPC (IPCS, JCRACK)
  CRSPC (IPCS, II+1)=0.
ELSE
  J=IDIFLOC/2
  IDIFLOC=J*2

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        IF (IDIFLOC.EQ.0.) THEN
            CRSPC (IPCS, II)=CRSPC (IPCS, JCRACK)
            CRSPC (IPCS, II+1)=0.
        ELSE
            CRSPC (IPCS, II)=A*FLOAT (IDIFLOC)
            CRSPC (IPCS, II+1)=FLOAT (NUM2) *A-CRSPC (IPCS, II)
            INDCR (IPCS, II)=1
            INDCR (IPCS, II+1)=1
        ENDIF
    ENDIF
C
    INDST=2
    CALL STRESS (IELINP, STRINI, INOD, LSTLOC, ESTL, ALPS, DELT, DISP, D,
+             CHSTRES, INDST, CSTR1, SSTR1)
    STLSTR (IPCS, JCRACK)=SSTR1
C
333 CONTINUE
C
    IF (JCRACK.EQ.JCRACK2) THEN
C
    do n=jcrack1,jcrack2
C
    write(6,*) n, ' ', crspc (ipcs, n), ' ', CRWID (IPCS, N), ' ',
C
+             INDCR (IPCS, N)
C
    enddo
        DO M=JCRACK1, JCRACK2
            MM=M*2+1
            IF (CRSPC (IPCS, MM) .NE.0.) THEN
C
                IF (ICRACK.EQ.11) THEN
                    WRITE (6, *) ECONDAY, ' ', IPCS, ' ', ICRACK
                    GO TO 4444
                ELSE
                    ICRACK=ICRACK+1
                    GO TO 150
                ENDIF
            ENDIF
        ENDDO
    ENDIF
C
4444 CONTINUE
C
    ICRLOC (IPCS, IDAY)=ICRACK
    DO I=JCRACK1, JCRACK2
        INDCR (IPCS, I)=1
        CRWTH (IDAY)=CRWTH (IDAY)+CRWID (IPCS, I)
        STLSS (IDAY)=STLSS (IDAY)+STLSTR (IPCS, I)
    ENDDO
C
    IF (IDAY.EQ.4) THEN
        IF (IPCS.EQ.1) THEN
            OPEN (8, FILE='crcp01.out', STATUS='UNKNOWN')
            CLOSE (8)
        ENDIF
        IF (IPCS.EQ.2) THEN
            OPEN (8, FILE='crcp07.out', STATUS='UNKNOWN')
            CLOSE (8)
        ENDIF
        IF (IPCS.EQ.3) THEN
            OPEN (8, FILE='crcp13.out', STATUS='UNKNOWN')
            CLOSE (8)
        ENDIF
        IF (IPCS.EQ.4) THEN
            OPEN (8, FILE='crcp19.out', STATUS='UNKNOWN')
            CLOSE (8)
        ENDIF
    ENDIF

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IF(IPCS.EQ.5) THEN
    OPEN (8,FILE='crcp25.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.6) THEN
    OPEN (8,FILE='crcp31.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.7) THEN
    OPEN (8,FILE='crcp37.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.8) THEN
    OPEN (8,FILE='crcp43.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
ENDIF

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C

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IF(IDAY.EQ.9) THEN
IF(IPCS.EQ.1) THEN
    OPEN (8,FILE='crcp02.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.2) THEN
    OPEN (8,FILE='crcp08.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.3) THEN
    OPEN (8,FILE='crcp14.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.4) THEN
    OPEN (8,FILE='crcp20.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.5) THEN
    OPEN (8,FILE='crcp26.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.6) THEN
    OPEN (8,FILE='crcp32.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.7) THEN
    OPEN (8,FILE='crcp38.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.8) THEN
    OPEN (8,FILE='crcp44.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
ENDIF

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C

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IF(IDAY.EQ.14) THEN
IF(IPCS.EQ.1) THEN
    OPEN (8,FILE='crcp03.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.2) THEN
    OPEN (8,FILE='crcp09.out',STATUS='UNKNOWN')
    CLOSE(8)
ENDIF
IF(IPCS.EQ.3) THEN

```

```

        OPEN (8, FILE='crcp15.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.4) THEN
        OPEN (8, FILE='crcp21.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.5) THEN
        OPEN (8, FILE='crcp27.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.6) THEN
        OPEN (8, FILE='crcp33.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.7) THEN
        OPEN (8, FILE='crcp39.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.8) THEN
        OPEN (8, FILE='crcp45.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
ENDIF

```

C

```

IF (IDAY.EQ.19) THEN
    IF (IPCS.EQ.1) THEN
        OPEN (8, FILE='crcp04.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.2) THEN
        OPEN (8, FILE='crcp10.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.3) THEN
        OPEN (8, FILE='crcp16.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.4) THEN
        OPEN (8, FILE='crcp22.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.5) THEN
        OPEN (8, FILE='crcp28.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.6) THEN
        OPEN (8, FILE='crcp34.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.7) THEN
        OPEN (8, FILE='crcp40.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.8) THEN
        OPEN (8, FILE='crcp46.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
ENDIF

```

C

```

IF (IDAY.EQ.24) THEN
    IF (IPCS.EQ.1) THEN
        OPEN (8, FILE='crcp05.out', STATUS='UNKNOWN')
    
```

```

        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.2) THEN
        OPEN (8, FILE='crcp11.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.3) THEN
        OPEN (8, FILE='crcp17.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.4) THEN
        OPEN (8, FILE='crcp23.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.5) THEN
        OPEN (8, FILE='crcp29.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.6) THEN
        OPEN (8, FILE='crcp35.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.7) THEN
        OPEN (8, FILE='crcp41.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.8) THEN
        OPEN (8, FILE='crcp47.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
ENDIF

```

C

```

IF (IDAY.EQ.IHIST) THEN
    IF (IPCS.EQ.1) THEN
        OPEN (8, FILE='crcp06.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.2) THEN
        OPEN (8, FILE='crcp12.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.3) THEN
        OPEN (8, FILE='crcp18.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.4) THEN
        OPEN (8, FILE='crcp24.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.5) THEN
        OPEN (8, FILE='crcp30.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.6) THEN
        OPEN (8, FILE='crcp36.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.7) THEN
        OPEN (8, FILE='crcp42.out', STATUS='UNKNOWN')
        CLOSE (8)
    ENDIF
    IF (IPCS.EQ.8) THEN
        OPEN (8, FILE='crcp48.out', STATUS='UNKNOWN')

```

```

                CLOSE (8)
            ENDIF
        ENDIF
C
2222 CONTINUE
C
3333 CONTINUE
C
        DO I=1,IHIST
            ISUM=0
            CRSPSUM=0.
            CRSPSUM2=0.
            DO J=1,NUMPCS
                K1=2** (ICRLOC (J,I) -1)
                K2=2**ICRLOC (J,I) -1
                DO K=K1,K2
                    IF (CRSPC (J,K) .NE.0.) THEN
                        ISUM=ISUM+1
                        CRSPSUM=CRSPSUM+CRSPC (J,K)
C
                        if(i.eq.ihist) write(6,*) crspc(j,k)
                        CRSPSUM2=CRSPSUM2+CRSPC (J,K) *CRSPC (J,K)
                    ENDIF
                ENDDO
            ENDDO
C
            if(i.eq.ihist) write(6,*) 'ISUM',isum
C
                CRSPAVG (I)=CRSPSUM/FLOAT (ISUM)
                CRWDAVG (I)=CRWTH (I) /FLOAT (ISUM)
                SSTRAVG (I)=STLSS (I) /FLOAT (ISUM)
                CRSPSDD (I)=DSQRT ( (CRSPSUM2-FLOAT (ISUM) *CRSPAVG (I) *
+                CRSPAVG (I) ) /FLOAT (ISUM) )
                WRITE (6,*) DAYCON (I)
                WRITE (6,*) CRSPAVG (I) ,CRSPSDD (I)
                WRITE (6,*) CRWDAVG (I)
                WRITE (6,*) SSTRAVG (I)
                WRITE (9,9001) DAYCON (I) ,CRSPAVG (I) /12. ,CRSPSDD (I) /12. ,
+                CRWDAVG (I) ,SSTRAVG (I)
9001    FORMAT (1x,F4.0,3x,F6.3,4x,F6.3,4x,F10.6,4x,F10.2)
            ENDDO
C
        CALL PUNCHOUT (CRSPC,TOTD,IAGG,ISWELL,ACSTR28,ICRLOC,
+                IFATPRO,IHIST,NUMPCS)
C
        DO I=1,41
            CRSPDIST (I)=0.
        ENDDO
C
        IF (INDDAY.EQ.1) THEN
C
            I=28
C
        ELSE
            I=IHIST
C
        ENDIF
C
        ISUM1=0
C
        DO J=1,NUMPCS
            K1=2** (ICRLOC (J,I) -1)
            K2=2**ICRLOC (J,I) -1
            DO K=K1,K2
                IF (CRSPC (J,K) .NE.0.) THEN
                    ISUM1=ISUM1+1
                    POS=(CRSPC (J,K) /12.-0.25) /0.5+2.
                    IPOS=POS
                ENDIF
            ENDDO
        ENDDO
    ENDIF
END

```

```

                                IF (IPOS.GT.22) IPOS=22
                                CRSPDIST (IPOS)=CRSPDIST (IPOS)+1.
                                ENDIF
                                ENDDO
                                ENDDO
C
CUM=0.
WRITE (9,*) ' '
WRITE (9,*) 'CRACK SPACING DISTRIBUTION'
WRITE (9,*) '===== '
WRITE (9,*) 'Range of Crack Sp.   Crack Sp. Dist. Cumulative Value'
WRITE (9,*) ' ( +- 0.25 ft )           ( % )           ( % )'
DO I=1,41
    CRSPDIST (I)=CRSPDIST (I)/FLOAT (ISUM1)*100.
    AI=FLOAT (I)*0.5-0.5
    CUM=CUM+CRSPDIST (I)
    WRITE (6,*) CRSPDIST (I),CUM
    WRITE (9,9002) AI,CRSPDIST (I),CUM
9002    FORMAT (4x,F6.2,14x,F7.3,10x,F7.3)
ENDDO
C
1000 CONTINUE
OPEN (7,FILE='crcpend.out',STATUS='UNKNOWN')
CLOSE (7)
STOP
END
C*****
SUBROUTINE STRDIST (SEED,DISTRB,CV,CRSPC,IPCS,A)
C
C    to impose random coefficients to each element of the pavement
C    for variation of concrete tensile strength
C
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION DISTRB (400),CRSPC (10,4095)
C
J=CRSPC (IPCS,1)/A
DO I=1,J
    DISTRB (I)=GGNQF ()
ENDDO
DO I=1,J
    DISTRB (I)=DISTRB (I)*CV/100.+1.
    IF (DISTRB (I).LT.0.) DISTRB (I)=0.
ENDDO
C
RETURN
END
C
FUNCTION GGNQF ()
C
REAL*4 X1,T,RANVAL
C
10 CALL RANDOM (RANVAL)
IF (RANVAL.EQ.0) GOTO 10
C
X1=SQRT (-2.*LOG (RANVAL))
C
20 CALL RANDOM (RANVAL)
IF (RANVAL.EQ.0) GOTO 20
C
T=6.2831853072*RANVAL
C
GGNQF = (X1*COS (T))
C

```

```

        RETURN
        END
C*****
        SUBROUTINE TSTRTH(CRSPC,IPCS,JCRACK,JCRACK1,DISTRB,TSTRNG,A,
+           NUM2,TSTARR)
C
C   to calculate tensile strength distribution at each element
C   of the pavement
C
        IMPLICIT REAL*8 (A-H, O-Z)
        DIMENSION DISTRB(400),CRSPC(10,4095),TSTARR(400)
C
        DO I=1,NUM2
            TSTARR(I)=0.
        ENDDO
C
        IF(JCRACK.EQ.JCRACK1) THEN
            DO I=1,NUM2
                TSTARR(I)=DISTRB(I)*TSTRNG
            ENDDO
        ELSE
            SP1=0.
            DO I=JCRACK1,JCRACK-1
                SP1=SP1+CRSPC(IPCS,I)
            ENDDO
            N1=SP1/A
            DO I=1,NUM2
                TSTARR(I)=DISTRB(N1+I)*TSTRNG
            ENDDO
        ENDIF
C
        RETURN
        END
C*****
        SUBROUTINE CHMEMO(KS,INODDIM,ICHMEMO)
C
C   to check required dimensions of the arrays
C
C   minimum memory requirements
C   ALOAD(ITNOD1),DISP(ITNOD1),SK(ITNOD1,MBAND),BNSL(NUMELX)
C   TEMLD(ITNOD1),STRINI(NUMELY,4),TLOAD(NUMELY,8)
C   INOD(INODDIM,8),SS(KS),IMAX(NUMELX),IMAXF(NUMELX)
C
C   where
C   ITNOD1=(NUMELY+1)*(NUMELX+1)*2+(NUMELX+1)*2
C   MBAND=(NUMELY+3)*2+4
C   KS=ITNOD1*MBAND
C   INODDIM=(NUMELY+1)*NUMELX
C
        IMPLICIT REAL*8 (A-H, O-Z)
        COMMON NUMELX,NUMELY,SKIP(5),ITNOD1,MBAND
C
C   the following values should be changed to fit current computer memory
C
C   ITNOD1C=9664
C   MBANDC=70
C   NUMELXC=150
C   NUMELYC=30
C   KSC=676480
C   INODC=4650
C
        ITNOD1C=8844
        MBANDC=50

```

```

NUMELXC=200
NUMELYC=20
KSC=442200
INODC=4200
C
ICHMEMO=0
IF(ITNOD1.GT.ITNOD1C) THEN
  WRITE(*,*) 'memory fault: check dimensions of following arrays'
  WRITE(*,*) 'ALOAD, DISP, TEMPLD, SK'
  ICHMEMO=1
ENDIF
IF(MBAND.GT.MBANDC) THEN
  WRITE(*,*) 'memory fault: check dimension of SK array'
  ICHMEMO=1
ENDIF
IF(NUMELX.GT.NUMELXC) THEN
  WRITE(*,*) 'memory fault: check dimensions of following arrays'
  WRITE(*,*) 'BNSL, IMAX, IMAXF'
  ICHMEMO=1
ENDIF
IF(NUMELY.GT.NUMELYC) THEN
  WRITE(*,*) 'memory fault: check dimensions of STRINI and TLOAD'
  ICHMEMO=1
ENDIF
IF(KS.GT.KSC) THEN
  WRITE(*,*) 'memory fault: check dimension of SS array'
  ICHMEMO=1
ENDIF
IF(INODDIM.GT.INODC) THEN
  WRITE(*,*) 'memory fault: check dimension of INOD array'
  ICHMEMO=1
ENDIF
C
RETURN
END
C*****
SUBROUTINE CONCPRO(IAGG,CSTR28,TSTR28,ECONC28,ZSH256,
+                 ECONDAY,CSTR,TSTR,ECONC,ZSH)
C
C   to calculate concrete properties at a consideration day
C
C   IMPLICIT REAL*8 (A-H, O-Z)
C
C   DIMENSION AC(10),BC(10),CC(10),AN28C(10)
C   DIMENSION AT(10),BT(10),CT(10),AN28T(10)
C   DIMENSION AE(10),BE(10),CE(10),AN28E(10)
C   DIMENSION AD(10),BD(10),CD(10),AN256D(10)
C
C   IAGG
C   Granite = 1,           Dolomite = 2
C   Vega = 3,             Bridgeport/Tin Top = 4
C   Western Tascosa = 5,  Ferris = 6
C   Limestone = 7,       Siliceous River Gravel = 8
C
C   Define coefficients
C
C   COMPRESSIVE STRENGTH
C   Granite
C   AC(1)=2570.8
C   BC(1)=0.096
C   CC(1)=0.623
C   AN28C(1)=0.5176
C   Dolomite

```

AC (2)=2236.7  
 BC (2)=0.231  
 CC (2)=0.562  
 AN28C (2)=0.5009  
 C Vega  
 AC (3)=1995.3  
 BC (3)=0.367  
 CC (3)=0.367  
 AN28C (3)=0.4978  
 C Bridgeport/Tin Top  
 AC (4)=2038.2  
 BC (4)=0.582  
 CC (4)=0.220  
 AN28C (4)=0.4980  
 C Western Tascosa  
 AC (5)=2068.5  
 BC (5)=0.214  
 CC (5)=0.647  
 AN28C (5)=0.4998  
 C Ferris  
 AC (6)=2000.1  
 BC (6)=0.206  
 CC (6)=0.801  
 AN28C (6)=0.5014  
 C Limestone  
 AC (7)=2550.57  
 BC (7)=0.115  
 CC (7)=0.490  
 AN28C (7)=0.5102  
 C Siliceous River Gravel  
 AC (8)=2445.25  
 BC (8)=0.182  
 CC (8)=0.473  
 AN28C (8)=0.5020  
 C  
 C TENSILE STRENGTH  
 C Granite  
 AT (1)=266.46  
 BT (1)=0.15  
 CT (1)=1.05  
 AN28T (1)=0.504  
 C Dolomite  
 AT (2)=247.06  
 BT (2)=0.261  
 CT (2)=1.094  
 AN28T (2)=0.500  
 C Vega  
 AT (3)=221.08  
 BT (3)=0.302  
 CT (3)=0.3014  
 AN28T (3)=0.500  
 C Bridgeport/Tin Top  
 AT (4)=221.85  
 BT (4)=0.332  
 CT (4)=0.723  
 AN28T (4)=0.500  
 C Western Tascosa  
 AT (5)=216.01  
 BT (5)=0.198  
 CT (5)=2.505  
 AN28T (5)=0.501  
 C Ferris  
 AT (6)=241.94

BT(6)=0.137  
 CT(6)=2.479  
 AN28T(6)=0.505  
 C Limestone  
 AT(7)=217.83  
 BT(7)=0.177  
 CT(7)=1.068  
 AN28T(7)=0.502  
 C Siliceous River Gravel  
 AT(8)=231.07  
 BT(8)=0.267  
 CT(8)=0.468  
 AN28T(8)=0.500  
 C  
 C ELASTIC MODULUS  
 C Granite  
 AE(1)=1678000.  
 BE(1)=0.78  
 CE(1)=1.65E14  
 AN28E(1)=0.500  
 C Dolomite  
 AE(2)=2324000.  
 BE(2)=0.485  
 CE(2)=3.537  
 AN28E(2)=0.500  
 C Vega  
 AE(3)=1882000.  
 BE(3)=0.301  
 CE(3)=1.574  
 AN28E(3)=0.500  
 C Bridgeport/Tin Top  
 AE(4)=1992000  
 BE(4)=0.688  
 CE(4)=2.00  
 AN28E(4)=0.500  
 C Western Tascosa  
 AE(5)=1803000.  
 BE(5)=0.405  
 CE(5)=97.056  
 AN28E(5)=0.500  
 C Ferris  
 AE(6)=1979000.  
 BE(6)=0.738  
 CE(6)=2.668E12  
 AN28E(6)=0.500  
 C Limestone  
 AE(7)=1802000.  
 BE(7)=0.535  
 CE(7)=110.46  
 AN28E(7)=0.500  
 C Siliceous River Gravel  
 AE(8)=2282000.  
 BE(8)=0.574  
 CE(8)=61755.1  
 AN28E(8)=0.500  
 C  
 C DRYING SHRINKAGE  
 C Granite  
 AD(1)=0.00032123  
 BD(1)=0.0851  
 CD(1)=0.001  
 AN256D(1)=0.8112  
 C Dolomite

```

AD(2)=0.00025206
BD(2)=0.04062
CD(2)=0.00155
AN256D(2)=0.7569
C Vega
AD(3)=0.00023519
BD(3)=0.03948
CD(3)=0.01255
AN256D(3)=0.5146
C Bridgeport/Tin Top
AD(4)=0.00034362
BD(4)=0.0328
CD(4)=0.00069
AN256D(4)=0.8582
C Western Tascosa
AD(5)=0.000358456
BD(5)=0.03109
CD(5)=0.000715
AN256D(5)=0.8600
C Ferris
AD(6)=0.00032723
BD(6)=0.0745
CD(6)=0.00119
AN256D(6)=0.7828
C Limestone
AD(7)=0.0002291
BD(7)=0.0398
CD(7)=0.00754
AN256D(7)=0.5403
C Siliceous River Gravel
AD(8)=0.00019839
BD(8)=0.0619
CD(8)=0.005
AN256D(8)=0.5636
C
C Define concrete properties at a consideration day
C
ECOND1=ECONDAY
C
C DRYING SHRINKAGE
C
IF(ECONDAY.GE.256.) ECOND1=256.
CONST4=2.-DEXP(-1.*BD(IAGG)*ECOND1)-DEXP(-1.*CD(IAGG)*ECOND1)
IND4=ZSH256
IF(IND4.EQ.0) THEN
    ZSH=AD(IAGG)*CONST4
ELSE
    ZSH=ZSH256*AN256D(IAGG)*CONST4
ENDIF
C
C COMPRESSIVE STRENGTH
C
IF(ECONDAY.GE.28.) ECOND1=28.
CONST1=2.-DEXP(-1.*BC(IAGG)*ECOND1)-DEXP(-1.*CC(IAGG)*ECOND1)
IND1=CSTR28
IF(IND1.EQ.0) THEN
    CSTR=AC(IAGG)*CONST1
ELSE
    CSTR=CSTR28*AN28C(IAGG)*CONST1
ENDIF
C
C TENSILE STRENGTH
C

```

```

CONST2=2.-DEXP(-1.*BT(IAGG)*ECOND1)-DEXP(-1.*CT(IAGG)*ECOND1)
IND2=TSTR28
IF(IND2.EQ.0) THEN
  TSTR=AT(IAGG)*CONST2
ELSE
  TSTR=TSTR28*AN28T(IAGG)*CONST2
ENDIF
C
C ELASTIC MODULUS
C
CONST3=2.-DEXP(-1.*BE(IAGG)*ECOND1)-DEXP(-1.*CE(IAGG)*ECOND1)
IND3=ECONC28
IF(IND3.EQ.0) THEN
  ECONC=AE(IAGG)*CONST3
ELSE
  ECONC=ECONC28*AN28E(IAGG)*CONST3
ENDIF
C
C write(*,*) CSTR
C write(*,*) TSTR
C write(*,*) ECONC
C write(*,*) ZSH
C
C RETURN
C END
C*****
SUBROUTINE CREEP(TIME,ECONC,E1,PHIMAX,PERCEN,DAYPC)
C
C to find the reduced modulus using Effective Modulus Method
C
IMPLICIT REAL*8 (A-H, O-Z)
C
IF(PERCEN.EQ.100.) THEN
  WRITE(*,*) 'PUT LESS THAN 100 FOR PERCEN'
  WRITE(*,*) 'CREEP ANALYSIS WAS NOT PERFORMED'
  GO TO 806
ENDIF
CONST=(1./(1.-PERCEN/100.))**(TIME/(DAYPC*24.))
PHI=PHIMAX*(1.-1./CONST)
E1=ECONC/(1.+PHI)
C
806 RETURN
C END
C*****
SUBROUTINE LINREC4(AK,D,IELTYPE)
C
C to find the element stiffness matrix using 4-node isoparametric
C element (or 4-node bi-linear rectangular element)
C
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION AK(8,8),XI(4),ETA(4),XINT(2),YINT(2),WX(2),WY(2)
DIMENSION D(3,3),BMAT(3,8),BT(8,3),F(4),FPXI(4),FPET(4),AUX(8,8)
DIMENSION AJAC(2)
COMMON NUMELX,NUMELY,A,B,E1,POIS1,THICK
DATA XI/-1.,-1.,1.,1./,ETA/1.,-1.,1.,-1./
DATA XINT/-0.57735027,0.57735027/,YINT/-0.57735027,0.57735027/
DATA WX/1.,1./,WY/1.,1./
C
C initialize matrices
C
DO 1 I=1,3
DO 3 J=1,3

```

```

3 D(I,J)=0.
1 CONTINUE
  DO 4 I=1,8
  DO 5 J=1,8
5 AK(I,J)=0.
4 CONTINUE

C
  IF(IELTYPE.EQ.1) THEN
C
  define D matrix (plane stress)
  COND=E1/(1.-POIS1*POIS1)
  D(1,1)=COND
  D(1,2)=D(1,1)*POIS1
  D(2,1)=D(1,2)
  D(2,2)=D(1,1)
  D(3,3)=E1/(2.+2.*POIS1)
  ELSE
C
  define D matrix (plane strain)
  COND=E1/((1.+POIS1)*(1.-2.*POIS1))
  D(1,1)=COND*(1.-POIS1)
  D(1,2)=COND*POIS1
  D(2,1)=D(1,2)
  D(2,2)=D(1,1)
  D(3,3)=COND*(1.-2.*POIS1)/2.
  ENDIF

C
C number of integration points in x and y directions
C
NPX=2
NPY=2

C
DO 100 IX=1,NPX
DO 101 IY=1,NPY

C
FACT=A*B*WX(IX)*WY(IY)*THICK/4.
X=XINT(IX)
Y=YINT(IY)

C
C find derivatives of shape functions at integration points
C
DO 10 I=1,4
  F(I)=(1.+X*XI(I))*(1.+Y*ETA(I))/4.
  FPXI(I)=XI(I)*(1.+Y*ETA(I))/4.
  FPET(I)=ETA(I)*(1.+X*XI(I))/4.
10 CONTINUE

C
C define B matrix and transpose of B
C
DO I=1,3
DO J=1,8
BMAT(I,J)=0.
ENDDO
ENDDO
AJAC(1)=A/2.
AJAC(2)=B/2.
DO 20 I=1,4
  I1=2*I-1
  I2=I1+1
  BMAT(1,I1)=FPXI(I)/AJAC(1)
  BMAT(2,I2)=FPET(I)/AJAC(2)
  BMAT(3,I1)=BMAT(2,I2)
  BMAT(3,I2)=BMAT(1,I1)
20 CONTINUE
DO 21 I=1,3

```

```

      DO 22 J=1,8
        BT(J,I)=BMAT(I,J)
22 CONTINUE
21 CONTINUE
C
C   define element stiffness matrix
C
      CALL MATPRO(D,BMAT,AUX,3,3,8,3,3,8)
C
      DO 23 I=1,3
        DO 24 J=1,8
          BMAT(I,J)=AUX(I,J)
24 CONTINUE
23 CONTINUE
C
      CALL MATPRO(BT,BMAT,AUX,8,3,8,8,3,8)
C
      DO 25 I=1,8
        DO 26 J=1,8
          AK(I,J)=AK(I,J)+FACT*AUX(I,J)
26 CONTINUE
25 CONTINUE
C
101 CONTINUE
100 CONTINUE
      RETURN
      END
C*****
      SUBROUTINE MATPRO(AA,BB,CC,NA,NB,NC,M,N,L)
C
C   to multiply matrices
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION AA(NA,N),BB(NB,L),CC(NC,L)
      DO 56 I=1,M
        DO 57 J=1,L
          SUM=0.
          DO 58 K=1,N
            SUM=SUM+AA(I,K)*BB(K,J)
58 CONTINUE
          CC(I,J)=SUM
57 CONTINUE
56 CONTINUE
      RETURN
      END
C*****
      SUBROUTINE FRAME(A,ESTL,DIASSTL,AKSTL,AKS,AKSB)
C
C   to define element stiffness matrix for frame (truss and beam) elements
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION AKS(2,2),AKSB(4,4)
C
C   element stiffness matrix for truss element
C
      AKS(1,1)=AKSTL
      AKS(1,2)=-AKSTL
      AKS(2,2)=AKS(1,1)
C
      AMINER=3.141592654*(DIASSTL**4)/64.
      CONBE=ESTL*AMINER/(A**3)
C
C   element stiffness matrix for beam element

```

```

C
  AKSB(1,1)=12.*CONBE
  AKSB(1,2)=6.*A*CONBE
  AKSB(1,3)=-12.*CONBE
  AKSB(1,4)=6.*A*CONBE
  AKSB(2,2)=4.*A*A*CONBE
  AKSB(2,3)=-6.*A*CONBE
  AKSB(2,4)=2.*A*A*CONBE
  AKSB(3,3)=12.*CONBE
  AKSB(3,4)=-6.*A*CONBE
  AKSB(4,4)=4.*A*A*CONBE
C
  RETURN
  END
C*****
SUBROUTINE ASSEM(AK,SK,INOD,LSTLOC,AKS,TLOAD,TEMLD,AKSB)
C
C   to assemble element stiffness matrices and temperature load
C   vectors into global systems (using half-bandwidth for stiffness)
C
  IMPLICIT REAL*8 (A-H,O-Z)
  DIMENSION INOD(4200,8),SK(8844,50),AK(8,8),AKS(2,2),AKSB(4,4)
  DIMENSION TLOAD(20,8),TEMLD(8844)
  COMMON NUMELX,NUMELY,SKIP(5),ITNOD1,MBAND
C
C   initialize banded stiffness matrix and temperature load vector
C
  DO 30 I=1,ITNOD1
  DO 31 J=1,MBAND
    SK(I,J)=0.
31 CONTINUE
    TEMLD(I)=0.
30 CONTINUE
C
C   element numbering and connectivity with degrees of freedom
C
  DO 32 KX=1,NUMELX
  DO 33 KY=1,NUMELY
    IF(KY.LT.LSTLOC) THEN
      IEL=(KX-1)*(NUMELY+1)+KY
      INOD( IEL, 1)=IEL*2+2*KX-3
      INOD( IEL, 2)=INOD( IEL, 1)+1
      INOD( IEL, 3)=INOD( IEL, 1)+2
      INOD( IEL, 4)=INOD( IEL, 1)+3
      INOD( IEL, 5)=INOD( IEL, 1)+(NUMELY+2)*2
      INOD( IEL, 6)=INOD( IEL, 5)+1
      INOD( IEL, 7)=INOD( IEL, 5)+2
      INOD( IEL, 8)=INOD( IEL, 5)+3
    ELSE
      IEL=(KX-1)*NUMELY+KX+KY
      IF(KY.EQ.LSTLOC) THEN
        INOD( IEL, 1)=IEL*2+2*KX-5
        INOD( IEL, 2)=INOD( IEL, 1)+1
        INOD( IEL, 3)=INOD( IEL, 1)+4
        INOD( IEL, 4)=INOD( IEL, 1)+5
        INOD( IEL, 5)=INOD( IEL, 1)+(NUMELY+2)*2
        INOD( IEL, 6)=INOD( IEL, 5)+1
        INOD( IEL, 7)=INOD( IEL, 5)+4
        INOD( IEL, 8)=INOD( IEL, 5)+5
      ELSE
        INOD( IEL, 1)=IEL*2+2*KX-3
        INOD( IEL, 2)=INOD( IEL, 1)+1
        INOD( IEL, 3)=INOD( IEL, 1)+2

```

```

        INOD ( IEL, 4) = INOD ( IEL, 1) + 3
        INOD ( IEL, 5) = INOD ( IEL, 1) + ( NUMELY + 2) * 2
        INOD ( IEL, 6) = INOD ( IEL, 5) + 1
        INOD ( IEL, 7) = INOD ( IEL, 5) + 2
        INOD ( IEL, 8) = INOD ( IEL, 5) + 3
    ENDIF
ENDIF
C
C   assemble element stiffness matrix and load vector into global system
C
    DO 35 I=1,8
    DO 36 J=I,8
        SK ( INOD ( IEL, I) , INOD ( IEL, J) - INOD ( IEL, I) + 1) =
+
36      SK ( INOD ( IEL, I) , INOD ( IEL, J) - INOD ( IEL, I) + 1) + AK ( I, J)
        TEMLD ( INOD ( IEL, I) ) = TEMLD ( INOD ( IEL, I) ) + TLOAD ( KY, I)
35      CONTINUE
C
33 CONTINUE
32 CONTINUE
C
C   element and d.o.f. numbering for frame elements
C
    DO 37 KX=1, NUMELX
        IEL = LSTLOC + ( KX - 1) * ( NUMELY + 1)
        INOD ( IEL, 1) = IEL * 2 + 2 * KX - 2
        INOD ( IEL, 2) = INOD ( IEL, 1) + 1
        INOD ( IEL, 3) = INOD ( IEL, 1) + ( NUMELY + 2) * 2
        INOD ( IEL, 4) = INOD ( IEL, 3) + 1
        INOD ( IEL, 5) = IEL * 2 + 2 * KX
        INOD ( IEL, 6) = INOD ( IEL, 5) + ( NUMELY + 2) * 2
C
C   assemble element stiffness matrix for beam elements
C
    DO 41 I=1,4
    DO 42 J=I,4
        SK ( INOD ( IEL, I) , INOD ( IEL, J) - INOD ( IEL, I) + 1) =
+
42      SK ( INOD ( IEL, I) , INOD ( IEL, J) - INOD ( IEL, I) + 1) + AKSB ( I, J)
41 CONTINUE
C
C   assemble element stiffness matrix for truss elements
C
    DO 38 I=5,6
    DO 39 J=I,6
        SK ( INOD ( IEL, I) , INOD ( IEL, J) - INOD ( IEL, I) + 1) =
+
39      SK ( INOD ( IEL, I) , INOD ( IEL, J) - INOD ( IEL, I) + 1) + AKS ( I - 4, J - 4)
38 CONTINUE
37 CONTINUE
C
    RETURN
    END
C*****
SUBROUTINE TEMPRT ( TEMPR1, TEMF, ALPC, TLOAD, STRINI, D, IELTYPE)
C
C   to calculate initial stresses and applied loads due to
C   temperature variations.
C
    IMPLICIT REAL*8 ( A-H, O-Z)
    DIMENSION D ( 3, 3) , XI ( 4) , ETA ( 4) , XINT ( 2) , YINT ( 2) , WX ( 2) , WY ( 2)
    DIMENSION STRINI ( 20, 4) , AJAC ( 2) , BMAT ( 3, 8) , BT ( 8, 3) , TEMPR1 ( 21)
    DIMENSION TLOAD ( 20, 8) , F ( 4) , FPXI ( 4) , FPET ( 4) , TEMPL ( 4)

```

```

COMMON NUMELX, NUMELY, A, B, E1, POIS1, THICK
DATA XI/-1., -1., 1., 1./, ETA/1., -1., 1., -1./
DATA XINT/-0.57735027, 0.57735027/, YINT/-0.57735027, 0.57735027/
DATA WX/1., 1./, WY/1., 1./
C
DO I=1, NUMELY
DO J=1, 8
  TLOAD(I, J)=0.
ENDDO
ENDDO
C
C number of integration points in x and y directions
C
NPX=2
NPY=2
C
  TEMDIF=TEM DN-TEMUP
  TEMINC=TEM DIF/FLOAT(NUMELY)
C
DO 500 ITEMP=1, NUMELY
C
  TEMUPL=TEMUP+TEMINC*FLOAT(ITEMP-1)
  TEMDNL=TEMUPL+TEMINC
  TEMUPL=TEMPR1(ITEMP)
  TEMDNL=TEMPR1(ITEMP+1)
  TEMAV=(TEMUPL+TEMDNL)/2.
C
INDEX=0
C
if INDEX=0 : use of an average temperature for an element
if INDEX=1 : use of interpolated temperature from the nodes
              at each integration point
C
IF(INDEX.EQ.1) THEN
  TEML(1)=TEMUPL
  TEML(2)=TEMDNL
  TEML(3)=TEMUPL
  TEML(4)=TEMDNL
ELSE
  DO I=1, 4
    TEML(I)=TEMAV
  ENDDO
ENDIF
C
NUMIP=1
DO 301 IX=1, NPX
DO 302 IY=1, NPY
  FACT=A*B*WX(IX)*WY(IY)*THICK/4.
  X=XINT(IX)
  Y=YINT(IY)
  DO I=1, 4
    F(I)=(1.+X*XI(I))*(1.+Y*ETA(I))/4.
    FPXI(I)=XI(I)*(1.+Y*ETA(I))/4.
    FPET(I)=ETA(I)*(1.+X*XI(I))/4.
  ENDDO
  CONTEM=0.
  DO I=1, 4
    CONTEM=CONTEM+F(I)*TEML(I)
  ENDDO
C
IF(IELTYPE.EQ.1) THEN
C
  for plane stress:
  CONTEM=(CONTEM-TEMF)*ALPC

```

```

ELSE
C   for plane strain:
      CONTEM=(CONTEM-TEMF)*ALPC*(1.+POIS1)
ENDIF
C
      STRINI(ITEMP,NUMIP)=-1.*CONTEM*(D(1,1)+D(1,2))
C
C   define B matrix and transpose of B
C
DO I=1,3
DO J=1,8
BMAT(I,J)=0.
ENDDO
ENDDO
AJAC(1)=A/2.
AJAC(2)=B/2.
DO I=1,4
  I1=2*I-1
  I2=I1+1
  BMAT(1,I1)=FPXI(I)/AJAC(1)
  BMAT(2,I2)=FPET(I)/AJAC(2)
  BMAT(3,I1)=BMAT(2,I2)
  BMAT(3,I2)=BMAT(1,I1)
ENDDO
DO I=1,3
DO J=1,8
  BT(J,I)=BMAT(I,J)
ENDDO
ENDDO
C
DO I=1,8
  CONLO=-1.*(BT(I,1)+BT(I,2))*STRINI(ITEMP,NUMIP)*FACT
  TLOAD(ITEMP,I)=TLOAD(ITEMP,I)+CONLO
ENDDO
NUMIP=NUMIP+1
302 CONTINUE
301 CONTINUE
500 CONTINUE
C
RETURN
END
C*****
SUBROUTINE SHRINK(DRYSH,TEMPR1,ALPC,IDAY,ZSH)
C
C   to calculate equivalent temperatures due to variations of drying
C   shrinkage strains
C   (positive shrinkage strain represents negative strain)
C
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION DRYSH(29,21),TEMPR1(21)
COMMON NUMELX,NUMELY
C
C   DTUP=SHRUP/ALPC
C   DTDN=SHRDN/ALPC
C   TEMUP=TEMUP-DTUP
C   TEMDN=TEMDN-DTDN
DO I=1,NUMELY+1
  DTEM=DRYSH(IDAY,I)*ZSH/ALPC
  TEMPR1(I)=TEMPR1(I)-DTEM
ENDDO
C
RETURN
END

```

```

C*****
SUBROUTINE BOUND(SK,LSTLOC)
C
C   to apply boundary conditions (using big spring method)
C
  IMPLICIT REAL*8 (A-H, O-Z)
  DIMENSION SK(8844,50)
  COMMON NUMELX,NUMELY
C
  BIGK=1.0E15
C
C   boundary condition for left side (no d.o.f. in x-direction)
C
  LSTLOC1=LSTLOC+1
  DO I=1,NUMELY+2
    IF(I.LE.LSTLOC) THEN
      J=I*2-1
    ELSE
      IF(I.EQ.LSTLOC1) THEN
        J=I*2
      ELSE
        J=I*2-1
      ENDIF
    ENDIF
    SK(J,1)=SK(J,1)+BIGK
  ENDDO
C
C   boundary condition for left side of steel (no rotational d.o.f.)
C
  J=LSTLOC1*2-1
  SK(J,1)=SK(J,1)+BIGK
C
C   bound. cond. for right side of steel(no dof in x- and rot. direc.)
C
  NSTLL=( (NUMELY+2)*2)*NUMELX+LSTLOC*2+1
  SK(NSTLL,1)=SK(NSTLL,1)+BIGK
  SK(NSTLL+1,1)=SK(NSTLL+1,1)+BIGK
C
C   boundary condition for bottom
C
  NST1=(NUMELY+2)*2
  NST11=NST1+NST1*NUMELX
  SK(NST1,1)=SK(NST1,1)+BOTK/2.
  SK(NST11,1)=SK(NST11,1)+BOTK/2.
  DO I=2,NUMELX
    J1=NST1+NST1*(I-1)
    SK(J1,1)=SK(J1,1)+BOTK
  ENDDO
C
  RETURN
  END
C*****
SUBROUTINE BNSLIP(SK,AKBOND,AKBOND2,LSTLOC,KIM,ALOAD,IMAX,
+               BNFORCE,BNSLMAXS,BNSL,ULSLIP)
C
C   define bond-slip relation between concrete and steel bar
C
  IMPLICIT REAL*8 (A-H, O-Z)
  DIMENSION SK(8844,50),ALOAD(8844),IMAX(200),BNSL(200)
  COMMON NUMELX,NUMELY,SKIP(5),ITNOD1,MBAND
C
  NINC=(NUMELY+2)*2
  NST=LSTLOC*2-1+NINC

```

```

DO I=1,NUMELX
  J1=NST+(I-1)*NINC
  J2=J1+3
  IF(I.EQ.NUMELX) THEN
    SK(J1,1)=SK(J1,1)+AKBOND/2.
    SK(J1,4)=SK(J1,4)-AKBOND/2.
    SK(J2,1)=SK(J2,1)+AKBOND/2.
  ELSE
    SK(J1,1)=SK(J1,1)+AKBOND
    SK(J1,4)=SK(J1,4)-AKBOND
    SK(J2,1)=SK(J2,1)+AKBOND
  ENDIF
ENDDO
C
IF(KIM.EQ.1) GO TO 889
C
DO IKIM=1,KIM-1
  J1=NST+(IMAX(IKIM)-1)*NINC
  J2=J1+3
  IF(DABS(BNSL(IMAX(IKIM))) .LT.ULSLIP) THEN
    IF(IMAX(IKIM).EQ.NUMELX) THEN
      AKB=AKBOND2/2.-AKBOND/2.
      BNFOR=BNFORCE/2.
    ELSE
      AKB=AKBOND2-AKBOND
      BNFOR=BNFORCE
    ENDIF
  ELSE
    BNFOR=0.
    IF(IMAX(IKIM).EQ.NUMELX) THEN
      AKB=-AKBOND/2.
    ELSE
      AKB=-AKBOND
    ENDIF
  ENDIF
  SK(J1,1)=SK(J1,1)+AKB
  SK(J1,4)=SK(J1,4)-AKB
  SK(J2,1)=SK(J2,1)+AKB
  IF(BNSLMAXS.LT.0.) THEN
    ALOAD(J1)=ALOAD(J1)+BNFOR
    ALOAD(J2)=ALOAD(J2)-BNFOR
  ELSE
    ALOAD(J1)=ALOAD(J1)-BNFOR
    ALOAD(J2)=ALOAD(J2)+BNFOR
  ENDIF
ENDDO
C
889 RETURN
END
C*****
SUBROUTINE FRSLIP(SK,AKFR,MIN,IMAXC)
C
C define bond-slip relation between concrete and base
C
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION SK(8844,50),IMAXC(200)
COMMON NUMELX,NUMELY,SKIP(5),ITNOD1,MBAND
C
NINC=(NUMELY+2)*2
NSTFR=(NUMELY+2)*2-1+NINC
DO I=1,NUMELX
  J1=NSTFR+(I-1)*NINC
  IF(I.EQ.NUMELX) THEN

```

```

        SK(J1,1)=SK(J1,1)+AKFR/2.
    ELSE
        SK(J1,1)=SK(J1,1)+AKFR
    ENDIF
ENDDO
C
    IF(MIN.EQ.1) GO TO 689
C
    IMIN=MIN-1
    DO J=IMAXC(IMIN),NUMELX
        J1=NINC*(J+1)-1
        IF(J.EQ.NUMELX) THEN
            AKF=AKFR/2.
        ELSE
            AKF=AKFR
        ENDIF
        SK(J1,1)=SK(J1,1)-AKF
    ENDDO
C
689 RETURN
END
C*****
SUBROUTINE CURL(SK,BOTK,MIN,IMAXC)
C
C    to define the elastic foundation for underlying layers
C
    IMPLICIT REAL*8 (A-H, O-Z)
    DIMENSION SK(8844,50),IMAXC(200)
    COMMON NUMELX,NUMELY
C
    NINC=(NUMELY+2)*2
    NINCE=NINC*(NUMELX+1)
    SK(NINC,1)=SK(NINC,1)+BOTK/2.
    SK(NINCE,1)=SK(NINCE,1)+BOTK/2.
    DO I=2,NUMELX
        J1=NINC*I
        SK(J1,1)=SK(J1,1)+BOTK
    ENDDO
C
    IF(MIN.EQ.1) GO TO 579
C
    IMIN=MIN-1
    DO J=IMAXC(IMIN),NUMELX
        J1=NINC*(J+1)
        IF(J.EQ.NUMELX) THEN
            AKC=BOTK/2.
        ELSE
            AKC=BOTK
        ENDIF
        SK(J1,1)=SK(J1,1)-AKC
    ENDDO
C
579 RETURN
END
C*****
SUBROUTINE DWEIGHT(ALOAD,ELWEI,ELSTWEI,LSTLOC)
C
C    to add the dead weight (body force) of concrete and steel
C
    IMPLICIT REAL*8 (A-H, O-Z)
    DIMENSION ALOAD(8844)
    COMMON NUMELX,NUMELY
C

```

```

NXL=NUMELX+1
NYL=NUMELY+1
C
DO I=1,NYL
  IF (I.LT.LSTLOC) THEN
    IF (I.EQ.1) THEN
      DO J=1,NXL
        K=2*I+(NUMELY+2)*2*(J-1)
        IF ((J.EQ.1).OR.(J.EQ.NXL)) THEN
          ALOAD(K)=ALOAD(K)-ELWEI/4.
        ELSE
          ALOAD(K)=ALOAD(K)-ELWEI/2.
        ENDIF
      ENDDO
    ELSE
      DO J=1,NXL
        K=2*I+(NUMELY+2)*2*(J-1)
        IF ((J.EQ.1).OR.(J.EQ.NXL)) THEN
          ALOAD(K)=ALOAD(K)-ELWEI/2.
        ELSE
          ALOAD(K)=ALOAD(K)-ELWEI
        ENDIF
      ENDDO
    ENDIF
  ELSE
    IF (I.EQ.LSTLOC) THEN
      DO J=1,NXL
        K=2*I+(NUMELY+2)*2*(J-1)
        IF ((J.EQ.1).OR.(J.EQ.NXL)) THEN
          IF (I.EQ.1) THEN
            ALOAD(K)=ALOAD(K)-ELWEI/4.-ELSTWEI/2.
          ELSE
            ALOAD(K)=ALOAD(K)-ELWEI/2.-ELSTWEI/2.
          ENDIF
        ELSE
          IF (I.EQ.1) THEN
            ALOAD(K)=ALOAD(K)-ELWEI/2.-ELSTWEI
          ELSE
            ALOAD(K)=ALOAD(K)-ELWEI-ELSTWEI
          ENDIF
        ENDIF
      ENDDO
    ELSE
      IF (I.EQ.NYL) THEN
        DO J=1,NXL
          K=2*I+(NUMELY+2)*2*(J-1)+2
          IF ((J.EQ.1).OR.(J.EQ.NXL)) THEN
            ALOAD(K)=ALOAD(K)-ELWEI/4.
          ELSE
            ALOAD(K)=ALOAD(K)-ELWEI/2.
          ENDIF
        ENDDO
      ELSE
        DO J=1,NXL
          K=2*I+(NUMELY+2)*2*(J-1)+2
          IF ((J.EQ.1).OR.(J.EQ.NXL)) THEN
            ALOAD(K)=ALOAD(K)-ELWEI/2.
          ELSE
            ALOAD(K)=ALOAD(K)-ELWEI
          ENDIF
        ENDDO
      ENDIF
    ENDIF
  ENDIF
ENDIF

```

```

        ENDIF
    ENDDO
C
    RETURN
    END
C*****
SUBROUTINE SOLVE (NEQ,MBAND,R,SS,KS)
C
C    to solve equilibrium equations using 1-D compacted array of
C    banded stiffness matrix and Gaussian eliminations
C
C    NEQ  = number of equations
C    MBAND = half-bandwidth
C    R    = constant vector (load vector)
C    SS   = 1-D array of coefficient matrix (banded stiffness matrix)
C    KS   = NEQ*MBAND
C
    IMPLICIT REAL*8 (A-H, O-Z)
    DIMENSION R(NEQ),SS(KS)
C
C    forward reduction of 1-D array of banded coefficient matrix
C
    DO 790 N=1,NEQ
    DO 780 L=2,MBAND
    KK1=(L-1)*NEQ+N
    IF(SS(KK1).EQ.0.) GO TO 780
    I=N+L-1
    C=SS(KK1)/SS(N)
    J=0
    DO 750 K=L,MBAND
    J=J+1
750 SS((J-1)*NEQ+I)=SS((J-1)*NEQ+I)-C*SS((K-1)*NEQ+N)
    SS(KK1)=C
780 CONTINUE
790 CONTINUE
C
C    forward reduction of the vector of constants
C
    DO 830 N=1,NEQ
    DO 820 L=2,MBAND
    IF(SS((L-1)*NEQ+N).EQ.0.) GO TO 820
    I=N+L-1
    R(I)=R(I)-SS((L-1)*NEQ+N)*R(N)
820 CONTINUE
830 R(N)=R(N)/SS(N)
C
C    solve for unknowns by back-substitution
C
    DO 860 M=2,NEQ
    N=NEQ+1-M
    DO 850 L=2,MBAND
    IF(SS((L-1)*NEQ+N).EQ.0.) GO TO 850
    K=N+L-1
    R(N)=R(N)-SS((L-1)*NEQ+N)*R(K)
850 CONTINUE
860 CONTINUE
    RETURN
    END
C*****
SUBROUTINE CHSLIP (DISP,IMAX,KIM,BNSL,BNSLMAX,BNSLMAXS,LSTLOC,
+                YLSLIP,IULSL,ULSLIP)
C
C    to check if the slip exceeds the limit value

```

```

C
  IMPLICIT REAL*8 (A-H, O-Z)
  DIMENSION BNSL(200), DISP(8844), IMAX(200)
  COMMON NUMELX, NUMELY
C
  DO I=1, NUMELX
    BNSL(I)=0.
  ENDDO
  NINC=(NUMELY+2)*2
  NST=LSTLOC*2-1+NINC
  DO I=1, NUMELX
    J1=NST+(I-1)*NINC
    J2=J1+3
    BNSL(I)=DISP(J1)-DISP(J2)
  ENDDO
C
  BNSLMAX=0.
  DO 881 I=1, NUMELX
    IF(KIM.EQ.1) GO TO 883
    DO K=1, KIM-1
      IF(I.EQ.IMAX(K)) GO TO 888
    ENDDO
883  ABNSL=DABS(BNSL(I))
    IF(ABNSL.GE.BNSLMAX) THEN
      BNSLMAX=ABNSL
      IMAX(KIM)=I
      BNSLMAXS=BNSL(I)
    ENDIF
888  CONTINUE
881  CONTINUE
C
  IULSL=0
  DO I=1, KIM
    IF(DABS(BNSL(IMAX(I)))>.ULSLIP) THEN
      IULSL=IULSL+1
    ENDIF
  ENDDO
C
  write(*,*) 'Concrete-Steel Bond-Slip =', KIM, IMAX(KIM),
C
  1      BNSL(IMAX(KIM))
C
  RETURN
  END
C*****
  SUBROUTINE CHCURL(DISP, MIN, IMAXC, INDCURL)
C
  to check if any vertical spring is in tension
C
  IMPLICIT REAL*8 (A-H, O-Z)
  DIMENSION DISP(8844), IMAXC(200)
  COMMON NUMELX, NUMELY
C
  NINC=(NUMELY+2)*2
  DO I=1, NUMELX
    J1=NINC*(I+1)
    IF(DISP(J1)>.0) THEN
      IMAXC(MIN)=I
      GO TO 578
    ENDIF
C
  write(*,*) I, DISP(J1)
  ENDDO
  IMAXC(MIN)=NUMELX+1
578  CONTINUE
C

```

```

IF (MIN.EQ.1) THEN
  IF (IMAXC (MIN) .GT.NUMELX) THEN
    INDCURL=0
  ELSE
    INDCURL=1
  ENDIF
ELSE
  MIN1=MIN-1
  IF ((IMAXC (MIN1) -IMAXC (MIN)) .GT.0) THEN
    INDCURL=1
  ELSE
    INDCURL=0
  ENDIF
ENDIF

C
C   write(*,*) 'Curling index (MIN) = ',MIN,IMAXC (MIN)
C   MIN=MIN+1
C
C   RETURN
C   END
C*****
SUBROUTINE COMPST (STRINI, INOD, LSTLOC, ESTL, ALPS, JOO, NA, INDMA,
+                 DELT, DISP, D, CHSTRES, INDST, CSTR1, SSTR1, WHDAY,
+                 TOTD, WHRAD, WHLOAD, ECONC, BOTKV, ECONDAY)
C
C   to compare stresses at morning and afternoon
C
C   IMPLICIT REAL*8 (A-H, O-Z)
C   DIMENSION STRINI (20,4), INOD (4200,8), DISP (8844), D (3,3)
C   COMMON NUMELX, NUMELY, A, B, E1, POIS1, THICK, ITNOD1, MBAND
C
  IF (JOO.EQ.1) THEN
    STMAX1=0.
    DO 401 I=1, NUMELY+1
      IF (I.EQ.LSTLOC) GO TO 401
      CALL STRESS (I, STRINI, INOD, LSTLOC, ESTL, ALPS, DELT, DISP,
+               D, CHSTRES, INDST, CSTR1, SSTR1)
      IF (ECONDAY.GE.WHDAY) THEN
        CALL WHEEL (TOTD, WHRAD, WHLOAD, ECONC, BOTKV, WHSTR)
        IF (I.LT.LSTLOC) THEN
          CHWHSTR=WHSTR* (FLOAT (2*I-1) /FLOAT (NUMELY) -1.)
        ELSE
          CHWHSTR=WHSTR* (FLOAT (2*I-3) /FLOAT (NUMELY) -1.)
        ENDIF
        CHSTRES=CHSTRES+CHWHSTR
      ENDIF
      IF (CHSTRES.GT.STMAX1) STMAX1=CHSTRES
401    CONTINUE
      JOO=2
      INDMA=1
      GO TO 404
    ELSE
      STMAX2=0.
      DO 403 I=1, NUMELY+1
        IF (I.EQ.LSTLOC) GO TO 403
        CALL STRESS (I, STRINI, INOD, LSTLOC, ESTL, ALPS, DELT, DISP,
+               D, CHSTRES, INDST, CSTR1, SSTR1)
        IF (ECONDAY.GE.WHDAY) THEN
          CALL WHEEL (TOTD, WHRAD, WHLOAD, ECONC, BOTKV, WHSTR)
          IF (I.LT.LSTLOC) THEN
            CHWHSTR=WHSTR* (FLOAT (2*I-1) /FLOAT (NUMELY) -1.)
          ELSE
            CHWHSTR=WHSTR* (FLOAT (2*I-3) /FLOAT (NUMELY) -1.)
          ENDIF
        ENDIF
      ENDIF
    ENDIF
  ENDIF

```

```

                ENDIF
                CHSTRES=CHSTRES+CHWHSTR
            ENDIF
            IF (CHSTRES.GT.STMAX2) STMAX2=CHSTRES
403     CONTINUE
        ENDIF
C
        IF (STMAX1.GE.STMAX2) THEN
            JOO=1
        ELSE
            JOO=2
        ENDIF
C
        NA=2
        INDMA=2
C
404 CONTINUE
C
        RETURN
        END
C*****
SUBROUTINE STRESS (IELINP, STRINI, INOD, LSTLOC, ESTL, ALPS,
+                DELT, DISP, D, CHSTRES, INDST, CSTR1, SSTR1)
C
C    to find stresses for concrete and steel bar
C
        IMPLICIT REAL*8 (A-H, O-Z)
        DIMENSION STR(4,3), AJAC(2), STRINI(20,4), INOD(4200,8)
        DIMENSION XI(4), ETA(4), XINT(2), YINT(2), DISP(8844)
        DIMENSION D(3,3), BMAT(3,8), FPXI(4), FPET(4), AUX(8,8), UL(8)
        COMMON NUMELX, NUMELY, A, B, E1, POIS1, THICK, ITNOD1, MBAND
        DATA XI/-1.,-1.,1.,1./,ETA/1.,-1.,1.,-1./
        DATA XINT/-0.57735027,0.57735027/,YINT/-0.57735027,0.57735027/
C
C    number of integration points in x and y directions
C
        NPX=2
        NPY=2
C
        ITNUMEL=NUMELX*(NUMELY+1)
        MINUS=-1*(NUMELY+1)
        DO LOC=ITNUMEL,0,MINUS
            IF(LOC.LT.IELINP) GO TO 77
        ENDDO
77     ILOC1=IELINP-LOC
        IF (ILOC1.LT.LSTLOC) THEN
            ILOC=ILOC1
        ELSE
            ILOC=ILOC1-1
        ENDIF
C
        DO I=1,8
            J=INOD(IELINP,I)
            UL(I)=DISP(J)
        ENDDO
C
        NUMIP=1
C
        DO 200 IX=1,NPX
        DO 201 IY=1,NPY
C
            X=XINT(IX)
            Y=YINT(IY)

```

```

C
C   find derivatives of shape functions at integration points
C
DO 20 I=1,4
  FPXI(I)=XI(I)*(1.+Y*ETA(I))/4.
  FPET(I)=ETA(I)*(1.+X*XI(I))/4.
20 CONTINUE
C
C   define B matrix and transpose of B
C
DO I=1,3
DO J=1,8
  BMAT(I,J)=0.
ENDDO
ENDDO
AJAC(1)=A/2.
AJAC(2)=B/2.
DO 21 I=1,4
  I1=2*I-1
  I2=I1+1
  BMAT(1,I1)=FPXI(I)/AJAC(1)
  BMAT(2,I2)=FPET(I)/AJAC(2)
  BMAT(3,I1)=BMAT(2,I2)
  BMAT(3,I2)=BMAT(1,I1)
21 CONTINUE
C
C   calculate element stresses at integration points
C
CALL MATPRO(D,BMAT,AUX,3,3,8,3,3,8)
DO 23 I=1,3
  STRTEMP=0.
  DO 24 J=1,8
    STRTEMP=STRTEMP+AUX(I,J)*UL(J)
24 CONTINUE
  STR(NUMIP,I)=STRTEMP
23 CONTINUE
  NUMIP=NUMIP+1
C
201 CONTINUE
200 CONTINUE
C
DO I=1,4
DO J=1,2
  STR(I,J)=STR(I,J)+STRINI(ILOC,I)
ENDDO
ENDDO
C
CHSTRES=(STR(1,1)+STR(2,1)+STR(3,1)+STR(4,1))/4.
C
IF(INDST.EQ.1) THEN
C   WRITE(6,*) 'CONCRETE STRESS'
  STROUT1=0.
  STROUT2=0.
  STROUT3=0.
  DO I=1,4
    STROUT1=STR(I,1)+STROUT1
    STROUT2=STR(I,2)+STROUT2
    STROUT3=STR(I,3)+STROUT3
  ENDDO
  STROUT1=STROUT1/4.
  STROUT2=STROUT2/4.
  STROUT3=STROUT3/4.
C

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C      to print element numbers and stresses, use below
C      WRITE(6,205) IELINP,STROUT1
C 205  FORMAT(I5,10X,F12.4)
C      to print only the stresses, use below
C      WRITE(6,205) STROUT1
C 205  FORMAT(F12.4)
C      CSTR1=STROUT1
C
C      ENDIF
C      IF(INDST.EQ.2) THEN
C          WRITE(6,*) 'STRESS IN STEEL BAR'
C          THERMAL=-ESTL*ALPS*DELT
C          WRITE(6,*) 'Initial thermal stress'
C          WRITE(6,833) THERMAL
C 833  FORMAT(F12.4)
C          WRITE(6,*) 'Maximum stress in steel bar'
C          DO I=1,NUMELX
C              J=LSTLOC+(I-1)*(NUMELY+1)
C              SIGST=ESTL*(DISP(INOD(J,6))-DISP(INOD(J,5)))/A+THERMAL
C              WRITE(6,207) SIGST
C 207  FORMAT(F15.4)
C          ENDDO
C          JJ=LSTLOC+(NUMELX-1)*(NUMELY+1)
C          SIGST=ESTL*(DISP(INOD(JJ,6))-DISP(INOD(JJ,5)))/A+THERMAL
C          WRITE(6,207) SIGST
C 207  FORMAT(F15.4)
C          SSTR1=SIGST
C      ENDIF
C
C      RETURN
C      END
C*****
C      SUBROUTINE WHEEL(TOTD,WHRAD,WHLOAD,ECONC,BOTKV,WHSTR)
C
C      to calculate wheel load stress by Westergaard equation
C
C      IMPLICIT REAL*8 (A-H, O-Z)
C      COMMON NUMELX,NUMELY,A,B,E1,POIS1,THICK,ITNOD1,MBAND
C
C      BBIND=1.724*TOTD
C      IF(WHRAD.GE.BBIND) THEN
C          BBB=WHRAD
C      ELSE
C          BBB=DSQRT(1.6*WHRAD*WHRAD+TOTD*TOTD)-0.675*TOTD
C      ENDIF
C
C      calculate radius of relative stiffness
C      ALC1=ECONC*TOTD*TOTD*TOTD/(12.*(1.-POIS1*POIS1)*BOTKV)
C      AL1=DSQRT(DSQRT(ALC1))
C
C      calculate wheel load stress
C      C1=3.*(1.+POIS1)*WHLOAD/(2.*3.141592*TOTD*TOTD)
C      C2=DLOG(AL1/BBB)+0.6159
C      WHSTR=C1*C2
C
C      RETURN
C      END
C*****
C      SUBROUTINE PUNCHOUT(CRSPC,TOTD,IAGG,ISWELL,ACSTR28,
C      +                    ICRLOC,IFATPRO,IHIST,NUMPCS)
C
C      to calculate punchout prediction
C

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IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION CRSPC(10,4095),FPM(20),ICRLOC(10,29),XNOR(30)
C
C Define probability of standardized normal distribution
C XNOR(1)=probability of minus infinity to 0.1
C XNOR(25)=prob. of minus infinity to 2.5, and so on
C
XNOR(1)=0.5398
XNOR(2)=0.5793
XNOR(3)=0.6179
XNOR(4)=0.6554
XNOR(5)=0.6915
XNOR(6)=0.7257
XNOR(7)=0.7580
XNOR(8)=0.7881
XNOR(9)=0.8159
XNOR(10)=0.8413
XNOR(11)=0.8643
XNOR(12)=0.8849
XNOR(13)=0.9032
XNOR(14)=0.9192
XNOR(15)=0.9332
XNOR(16)=0.9452
XNOR(17)=0.9554
XNOR(18)=0.9641
XNOR(19)=0.9713
XNOR(20)=0.9772
XNOR(21)=0.9821
XNOR(22)=0.9861
XNOR(23)=0.9893
XNOR(24)=0.9918
XNOR(25)=0.9938
XNOR(26)=0.9953
XNOR(27)=0.9965
XNOR(28)=0.9974
XNOR(29)=0.9981
XNOR(30)=0.9987
C
C Define coefficients of fatigue equation
C Unit=million, COEFVA=0.3
C
C A value          SRG(IAGG=8)          Limestone and others
C swelling        Yes          No          Yes          No
C          95%          1.4          2.0          1.8          2.6
C          75%          2.4          3.1          2.5          3.7
C          50%          3.1          4.2          3.1          4.8
C
C if ISWELL=1, swelling=yes
C IFATPRO=1;95%, 2;75%, 3;50%
C
IF(IAGG.EQ.8) THEN
  IF(ISWELL.EQ.1) THEN
    IF(IFATPRO.EQ.1) FATA=1400000.
    IF(IFATPRO.EQ.2) FATA=2400000.
    IF(IFATPRO.EQ.3) FATA=3100000.
  ELSE
    IF(IFATPRO.EQ.1) FATA=2000000.
    IF(IFATPRO.EQ.2) FATA=3100000.
    IF(IFATPRO.EQ.3) FATA=4200000.
  ENDIF
ELSE
  IF(ISWELL.EQ.1) THEN
    IF(IFATPRO.EQ.1) FATA=1800000.

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                IF(IFATPRO.EQ.2) FATA=2500000.
                IF(IFATPRO.EQ.3) FATA=3100000.
ELSE
                IF(IFATPRO.EQ.1) FATA=2600000.
                IF(IFATPRO.EQ.2) FATA=3700000.
                IF(IFATPRO.EQ.3) FATA=4800000.
ENDIF
ENDIF
C
FATB=4.
COEFVA=0.3
FSTR=7.5*DSQRT(ACSTR28)
C write(6,*) 'Flexural strength ',fstr
TPAVL=0.
DO I=1,NUMPCS
    TPAVL=TPAVL+CRSPC(I,1)
ENDDO
C i mile = 5280ft = 63360in.
AMUL=63360/TPAVL
C
DO I=1,20
    FPM(I)=0.
ENDDO
C
DO I=1,NUMPCS
C IF(INDDAY.EQ.1) THEN
    ICR=ICRLOC(I,IHIST)
C ELSE
C ICR=ICRLOC(I,1)
C ENDIF
    ICR1=2**(ICR-1)
    ICR2=2**ICR-1
    DO J=ICR1,ICR2
        CRSPA=CRSPC(I,J)
        IF(CRSPA.EQ.0.) GO TO 765
        TST1=EXP(9.8474)*TOTD**(-1.8143)*(CRSPA/12.)**(-0.4477)
        ANUMLOAD=FATA*(FSTR/TST1)**FATB
        STDD=COEFVA*ANUMLOAD
        DO K=1,20
            AESAL=5000000.*FLOAT(K)
            Z=(AESAL-ANUMLOAD)/STDD
            ZZ=DABS(Z)
            IF(ZZ.GE.3.) THEN
                PHYZ=1.
                GO TO 764
            ENDIF
            IF(ZZ.LT.0.1) THEN
                DEL=0.0398*ZZ*10.
                PHYZ=0.5+DEL
                GO TO 764
            ENDIF
            IZ=ZZ*10.
            DIF=XNOR(IZ+1)-XNOR(IZ)
            DEL=DIF*(ZZ*10.-FLOAT(IZ))
            PHYZ=XNOR(IZ)+DEL
764 CONTINUE
            IF(Z.LT.0.) THEN
                PRFTG=1.-PHYZ
            ELSE
                PRFTG=PHYZ
            ENDIF
            FPM(K)=AMUL*PRFTG+FPM(K)
        ENDDO
    ENDDO

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765 CONTINUE
      ENDDO
      ENDDO
      WRITE (9,*) ' '
      WRITE (9,*) 'PREDICTED PUNCHOUTS / MILE'
      WRITE (9,*) '===== '
      WRITE (9,*) ' Million ESALS      Number of Punchouts / Mile'
      do i=1,20
      write (6,*) fpm(i)
      WRITE (9,9011) I*5,FPM(I)
9011 FORMAT(I10,13x,F10.3)
      enddo
C
      RETURN
      END
C*****

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