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16. Abstract

Continuously reinforced concrete pavement (CRCP) performance depends primarily on early-age cracks that result from changes in temperature and drying shrinkage. This report presents the findings of a study of the early-age behavior of CRCP in response to temperature change using a three-dimensional finite element model. The nonlinear effects of the bond slip between concrete and steel and between concrete and base have been studied. The modeling for the curling effect and the viscoelastic material characteristics have also been considered. The test results from the two-dimensional and three-dimensional models have been compared to verify the possibility of using a two-dimensional model. From this project it has been found that the crack width and the concrete stress are dependent in the transverse steel arrangement near the edge (longitudinal joint), but almost independent in the interior of the slab. The tensile stress occurring at the top of the edge on the transverse steel location can be higher than that occurring at the top of the slab center. This observation represents the possibility of forming a transverse crack from the edge on the transverse steel location. The two-dimensional model with the plane stress element gives results very close to those of the three-dimensional model except near the edge.

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THREE-DIMENSIONAL NONLINEAR FINITE ELEMENT ANALYSIS OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

by

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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 OBJECTIVES

The performance of continuously reinforced concrete pavement (CRCP) depends, to a large extent, on the early-age cracking caused by changes in temperature and drying shrinkage. To minimize the early-age cracking, the Texas Department of Transportation (TxDOT) has sponsored several research projects to model CRCP behavior and to improve CRCP design and construction practices. The first mechanistic model of CRCP was developed at the Center for Transportation Research of The University of Texas at Austin in 1975 (Ref 1). The computer program, called CRCP-1, 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. Using these data, the mechanistic equations were applied to predict early-age cracking. This mechanistic model has been modified several times to improve its accuracy. For TxDOT project 0-1169, researchers worked to develop an improved mechanistic model for CRCP, taking into account material variability (Ref 2). Previous versions of the CRCP programs predicted only the mean crack spacing; but by predicting frequency distributions for crack spacings, it was possible to estimate probabilities of failure development for each crack spacing predicted. Thus, a predicted curve for failures versus traffic for any given design could be developed. The resulting computer program, dubbed CRCP-8, also includes the aggregate-related concrete material properties. Also, a considerable effort has been made to calibrate and validate the CRCP programs (Ref 3). Although the model has permitted pavement engineers to develop designs of the CRCP, there are some limitations owing to simplified assumptions, including one-dimensional analysis.

In 1996, TxDOT initiated a research project to expand the ability of the mechanistic model by incorporating the variations in temperature and moisture changes through the depth of concrete slab, and, as a result of the project, a two-dimensional finite element model was developed (Refs 4, 5). In 1998, TxDOT, encouraged by the improvement, decided to extend the project to complete the development of a new mechanistic model of CRCP. The new model will continue to use the two-dimensional finite element theories to reduce the cost of computation. However, in order to increase the accuracy of the 2D model and to evaluate the significant factors to be included in the model, three-dimensional analyses have also been performed using a finite element analysis program, ABAQUS (Ref 6). The results from the three-dimensional analysis have been helpful in achieving an improved understanding of the CRCP behavior. The objective of this report is to present the three-dimensional linear and nonlinear analysis results along with a comparison between 2-D and 3-D analyses. The new computer program that will be developed within the next fiscal year will include the significant nonlinear effects found in this research and will use the most appropriate 2-D finite elements selected by the comparison with the 3-D analysis.

1.2 ORGANIZATION

This report consists of six chapters and four appendices. The background and objectives are presented in Chapter 1. The 2-D and 3-D finite element models and material characteristics are explained in Chapter 2. The behaviors of CRCP obtained using linear finite element models are presented in Chapter 3. In Chapter 4, the significance of each nonlinear factor such as bond slip, curling, and creep is evaluated. The responses of CRCP to the temperature change obtained using nonlinear finite element models are presented in Chapter 5. Chapter 6 includes the summary, conclusions of the research, and researchers' recommendations for further research. The sample inputs for the 2-D and 3-D linear and nonlinear finite element analyses using ABAQUS are provided in the appendices.

CHAPTER 2. FINITE ELEMENT MODELING

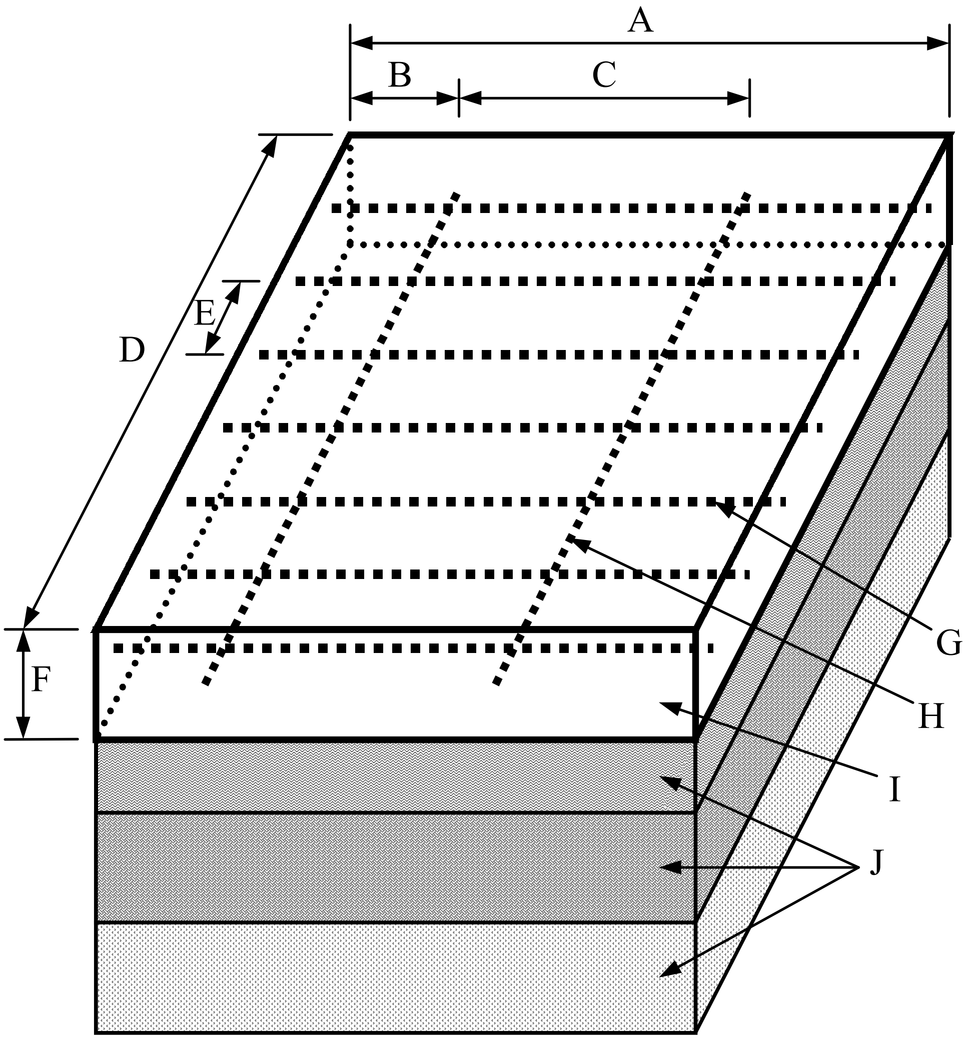
2.1 INTRODUCTION

This chapter details the 2-D and 3-D finite element models of CRCP. Because there are a number of publications related to the finite element method, the theoretical aspects of the finite element modeling refer to those publications (Refs 4, 7, 8). In Project 0-1831, a commercial finite element analysis computer program, ABAQUS, has been used (Ref 6).

2.2 THREE-DIMENSIONAL MODEL OF CRCP

The configuration of CRCP is shown in Figure 2.1. The distance from a transverse crack to the nearest transverse steel is denoted by B in this study. The geometry and material properties used in this project are listed in Table 2.1. Figure 2.2 shows a part of the finite element model used in this project. The concrete slab is discretized using three-dimensional brick elements; reinforcing steels are modeled using frame elements; and the bond slip between concrete and the steel bars for both longitudinal and transverse directions is modeled using horizontal springs, respectively. The underlying layers are modeled using vertical springs, and the frictional resistance at the interface between concrete and base is modeled using horizontal springs. The effects of the different types of bond-slip relations between concrete and steel and between concrete and base have been investigated in a previous study (Refs 4, 5), and in this study the relations have been assumed to be nonlinear as shown in Figure 2.3. After performing a sensitivity study, the size of an element has been selected to be 1.5 in. (3.81 cm) in the longitudinal and the vertical directions and 3 in. (7.62 cm) in the transverse direction.

The boundary conditions of the finite element model (i.e., cracks, edges, joints, etc.) must be correctly defined to obtain viable results. At cracks, there are no restraints for concrete and no longitudinal and rotational displacements for the longitudinal steels. At longitudinal joints, there are no restraints for concrete and no transverse and rotational displacements for the transverse steels. The stress-producing mechanism considered in this project is the temperature variation throughout the depth of the concrete slab, and this variation is assumed to be linear. Because the response of the CRC pavement system owing to environmental loading is symmetric with respect to the centerline along the longitudinal direction, half of the slab width has been considered for modeling. In this case, at the symmetric face, there are no transverse displacements for concrete and no transverse and rotational displacements for the transverse steels.

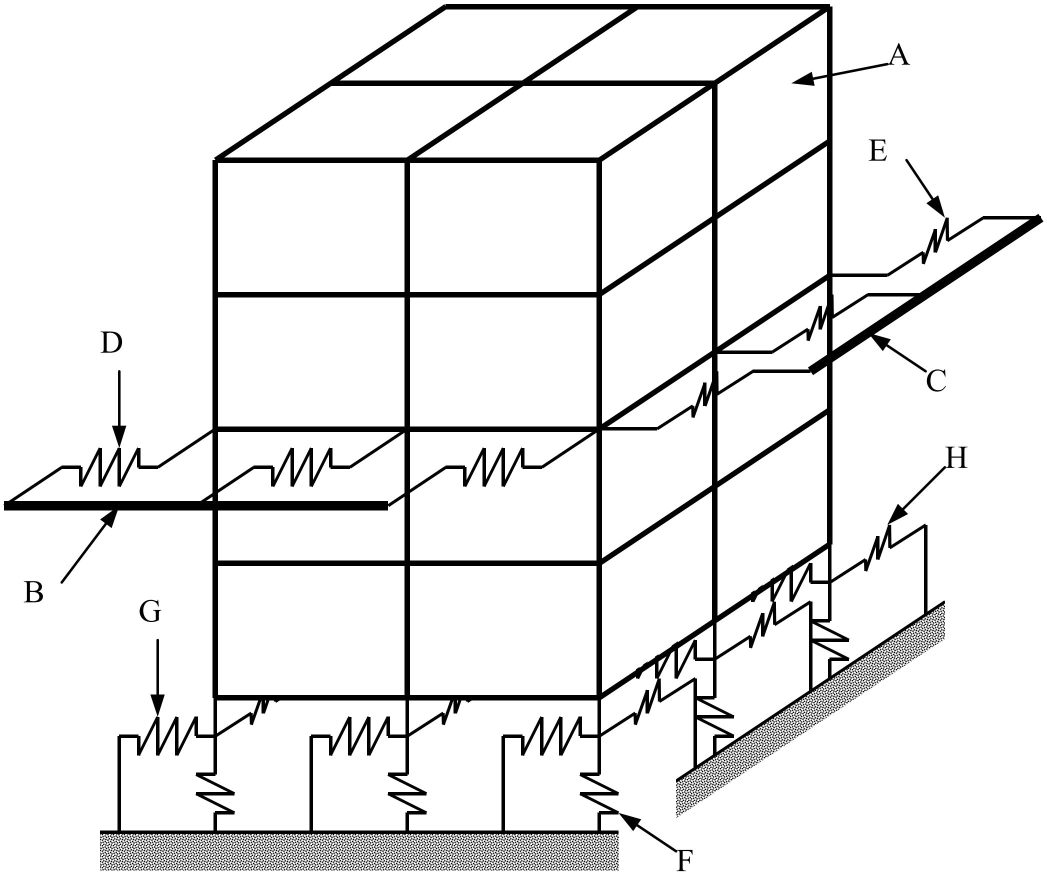


A: Crack spacing
B: Distance to transverse steel
C: Transverse steel spacing
D: Slab width
E: Longitudinal steel spacing
F: Slab thickness
G: Longitudinal steel
H: Transverse steel
I: Concrete slab
J: Underlying layers

Figure 2.1. Continuously reinforced concrete pavement (CRCP)

Table 2.1. Geometry and material properties of CRCP model

Crack spacing	5 ft (1.524 m)	Expansion of coefficient of steel	0.000005/°F (0.000009/°C)
Longitudinal steel spacing	6 in. (15.24 cm)	Surface temperature	85°F (29.4°C)
Transverse steel spacing	3 ft (91.44 cm)	Bottom temperature	100°F (37.8°C)
Concrete slab thickness	12 in. (30.48 cm)	Reference temperature	120°F (48.9°C)
Steel location from surface	6 in. (15.24 cm)	Vertical stiffness of underlying layers	400 psi/in. (0.1085 MPa/mm)
Concrete modulus of elasticity	2,000,000 psi (13,780 MPa)	Bond-slip stiffness between concrete and steel	700,000 psi/in. (190 MPa/mm)
Poisson's ratio	0.15	Bond-slip stiffness between concrete and base	150 psi/in. (0.0407 MPa/mm)
Diameter of longitudinal steel	0.75 in. (19.05 mm)	Load duration	12 hr.
Diameter of transverse steel	0.625 in. (15.875 mm)	Modulus ratio in Prony series	0.45
Expansion coefficient of concrete	0.000006/°F (0.0000108/°C)	Relaxation time in Prony series	48 hr.



A: 3-D brick element for concrete slab
B: Frame element for longitudinal steel
C: Frame element for transverse steel
D: Spring for bond slip between concrete and longitudinal steel
E: Spring for bond slip between concrete and transverse steel
F: Vertical spring for underlying layers
G: Spring for frictional bond slip in longitudinal direction
H: Spring for frictional bond slip in transverse direction

Figure 2.2. Three-dimensional finite element model of CRCP

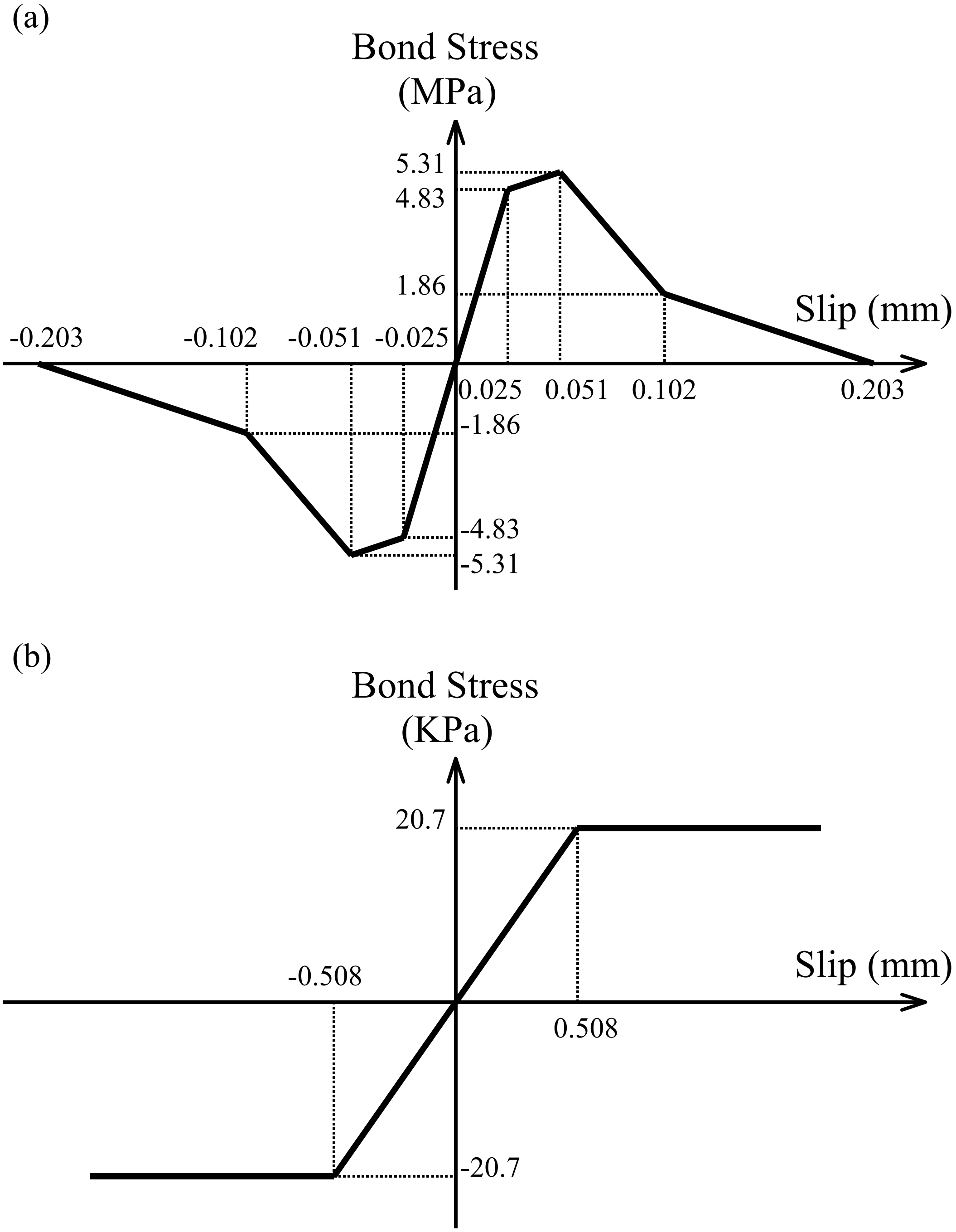


Figure 2.3. Bond stress-slip relation: (a) between concrete and steel; (b) between concrete and base (1 mm = 0.0394 in., 1 MPa = 145 psi)

2.3 TWO-DIMENSIONAL MODEL OF CRCP

Two-dimensional finite element models have also been created to compare the results with those from the three-dimensional models. When 2-D models are used, modeling in the transverse direction (out of plane direction in 2-D models) cannot be considered. Therefore, the transverse steels and the bond slip in the transverse direction cannot be modeled using 2-D models. The concrete slab is modeled using plane stress or plane strain elements, and the longitudinal steel bars are modeled using frame elements. The thickness of the 2-D plane stress or strain element is the longitudinal steel spacing. The bond slip between concrete and steel and between concrete and base is modeled using horizontal spring elements. The underlying layers are modeled using vertical springs. All the material behavior and properties are assumed to be the same as those used in the 3-D models.

The boundary conditions of the 2-D model also have to be defined properly. The geometric symmetry is used because the model and the environmental loading are symmetric with respect to the center of two cracks. At the center of two cracks, there are no horizontal displacements for the concrete slab and the longitudinal steel bar and no rotational displacements for the longitudinal steel bar. At cracks, there are no horizontal and rotational displacements for the longitudinal steel bar. Figure 2.4 shows the 2-D finite element model (including boundary conditions).

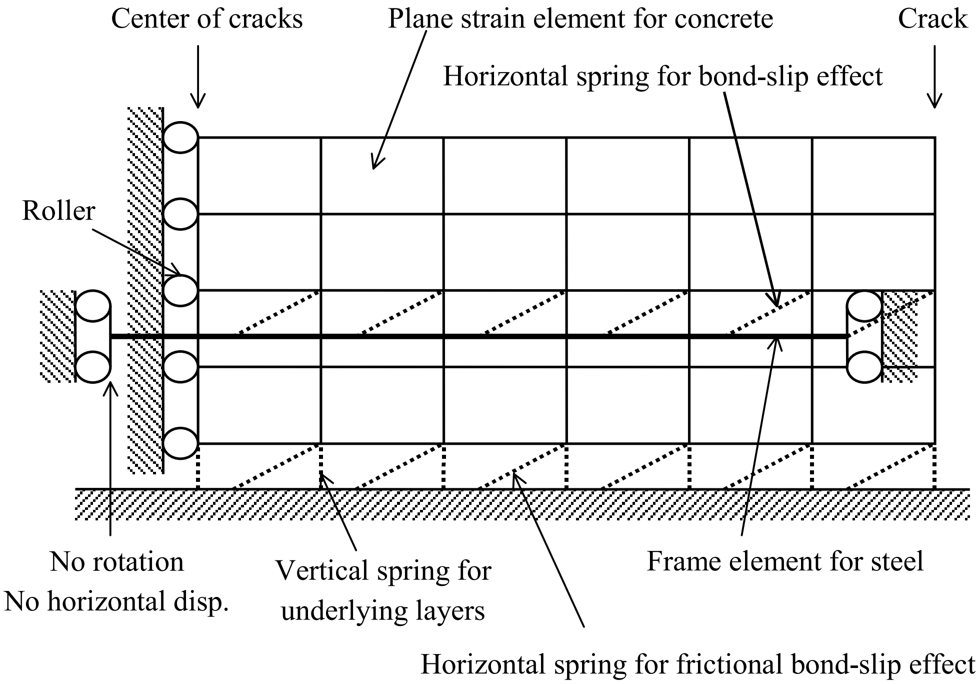


Figure 2.4. Two-dimensional finite element model

CHAPTER 3. LINEAR SYSTEM OF CRCP

3.1 INTRODUCTION

The behavior of CRCP has been investigated using the finite element model (described in the previous chapter) with linear material properties. The bond-slip relationships between concrete and steel and between concrete and base are assumed to be linear elastic in this case. The vertical springs used to model the underlying layers are assumed to sustain tensile forces as well as compressive forces. The sample inputs for 2-D and 3-D linear analyses are listed in Appendices A and C, respectively.

3.2 CRACK WIDTH DISTRIBUTION

Figure 3.1 shows the top view of CRCP. Because the crack width is the sum of relative displacements of two slabs at the surface and the locations of the transverse steel bars are not always symmetric with respect to the crack, two slabs with different locations of transverse steels should be analyzed to obtain the crack widths. In the figure, both Slab A and Slab B have to be analyzed to find the relative displacements along the crack. Figure 3.2 shows the relative displacements along the crack for the two slabs when B is 1.5 in. (0.038 m). The crack width can now be obtained as the sum of relative displacements as shown in the figure.

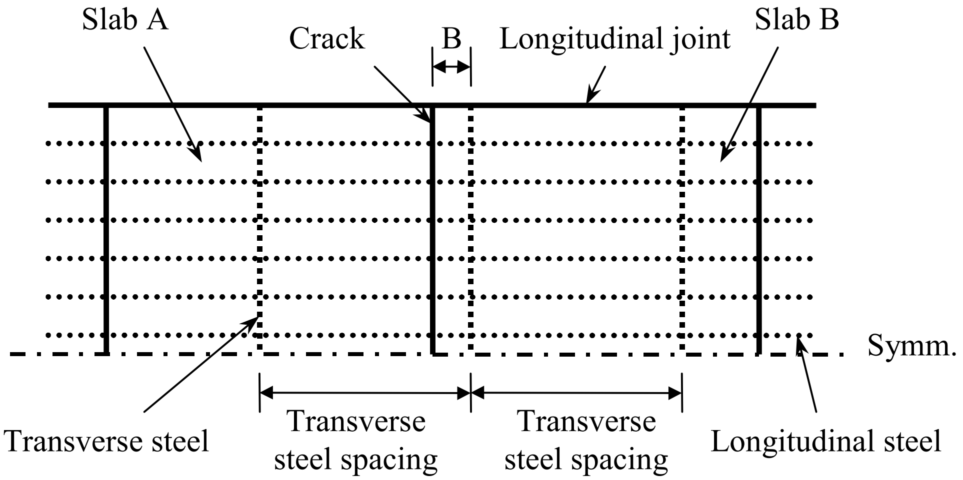


Figure 3.1. Top view of CRCP

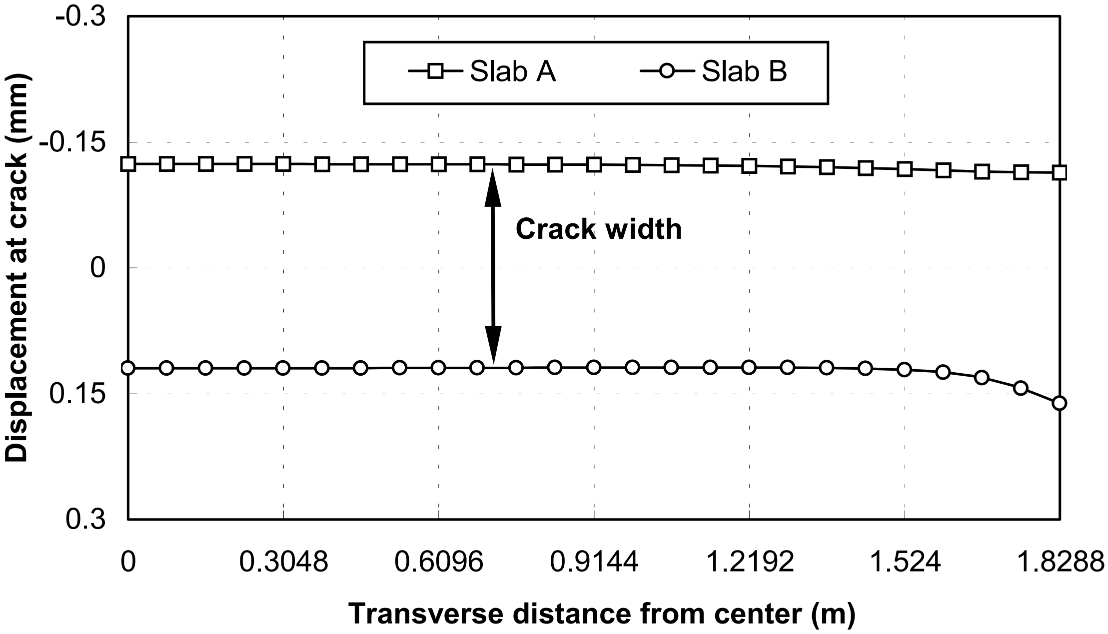


Figure 3.2. Relative displacements at crack when B is 0.038 m (1.5 in.)
(1 m = 39.4 in., 1 mm = 0.0394 in.)

Figure 3.3 shows the variation of the crack width along the transverse crack with different transverse steel bar locations. In the figure, B = 3 in. (0.076 m) represents the fact that there are two transverse steel bars in one slab with distances of 3 and 39 in. (0.076 and 0.99 m) from the crack where the width is measured, because the transverse steel spacing selected for this study is 36 in. (0.914 m) and there is another steel bar in the opposite side slab with a distance of 33 in. (0.838 m) from the crack. As shown in the figure, large variations in the crack width may be observed near the edge (longitudinal joint) of the slab, especially within 10 in. (25 cm) from the edge. Except in the region near the edge, the variations in the crack width can be negligible for each arrangement of transverse steel relative to the crack. If the number of transverse steel bars is the same, the crack width is almost the same in the interior of the slab, even though the locations of the steel bars are different. The differences in the crack width with respect to the number of transverse steel bars are relatively small (about 3 percent).

The 3-D analysis results of the crack width distribution are compared to those from the 2-D analysis. As shown in Figure 3.4, the 2-D analysis with the plane stress element underestimates the crack width from the 3-D analysis, and that with the plane strain element overestimates the crack width from the 3-D analysis. Also, the 2-D analysis cannot predict the variation of the crack width in the transverse direction.

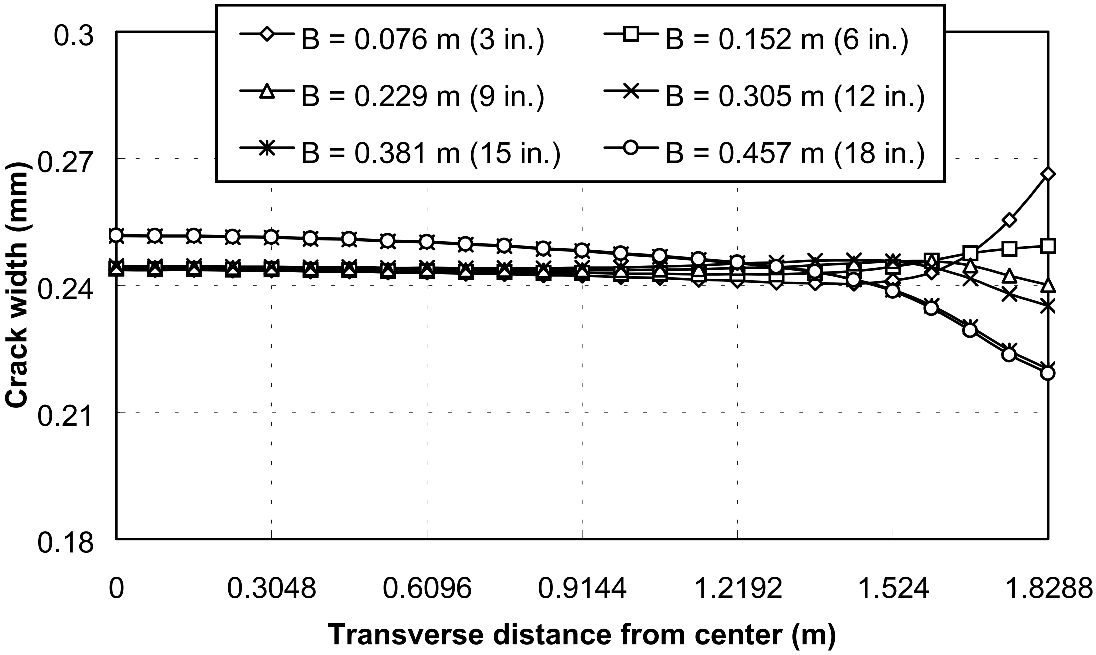


Figure 3.3. Crack width distribution for linear system
(1 m = 39.4 in., 1 mm = 0.0394 in.)

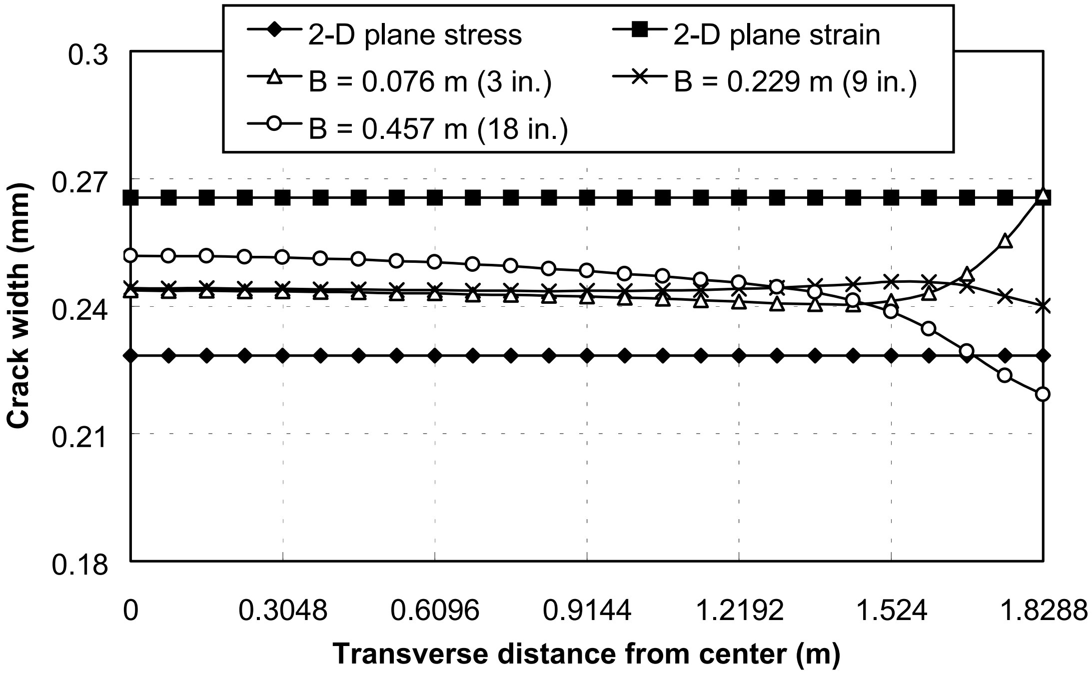


Figure 3.4. Comparison of crack width distribution between 2-D and 3-D linear analyses
(1 m = 39.4 in., 1 mm = 0.0394 in.)

3.3 CONCRETE STRESS DISTRIBUTION

The concrete stress distribution at the top of the slab along the longitudinal direction has been investigated. As shown in Figure 3.5(*a*), along the centerline of the slab, the stress distributions are almost the same regardless of the transverse steel arrangement. On the other hand, the stresses along the edge, shown in Figure 3.5(*b*), have the peak values at the locations of the transverse bars. When there are two transverse steel bars, the maximum stress occurs at the location of the transverse steel with the largest distance from the nearest crack. Figure 3.6 shows the stress distributions along the centerline and edge when B = 6 in. (0.152 m). The maximum stress occurs at the edge with a steel bar location of 42 in. (1.067 m). This observation implies a possibility of the formation of a new crack propagating from the edge at the transverse steel location. Figure 3.7 shows the concrete stress distribution along the transverse direction at the center of the slab. As the transverse distance increases, the difference in the stress between different transverse steel arrangements becomes larger. The variation of the stress is significant near the edge, especially within about 10 in. (25 cm).

The concrete stress distributions from the 2-D analysis are compared with those from the 3-D analysis. Figure 3.8(*a*) shows the stress distribution along the centerline. The 2-D analysis results with the plane stress elements are very close to those from the 3-D analysis. The 2-D analysis results with the plane strain elements, on the other hand, overestimate those from the 3-D analysis. For the stress along the edge, as shown in Figure 3.8(*b*), any 2-D analysis cannot predict the stress distribution of the 3-D model. Because the 2-D models cannot include the effect of the transverse steel, it is difficult to predict the stress distribution along the edge, which primarily depends on the transverse steel arrangement.

The concrete stress observed up to this point is the longitudinal stress (axial stress in the longitudinal direction) at the top of the slab. Because the slab width (12 ft or 3.66 m) is larger than the crack spacing (5 ft or 1.52 m) in this study, the transverse stress (axial stress in the transverse direction) also needs to be investigated. If the maximum transverse stress is larger than the maximum longitudinal stress, a new crack can occur along the longitudinal direction (longitudinal crack). Figure 3.9 shows longitudinal and transverse stresses at the center of the slab along the transverse direction for different transverse steel bar locations. As shown in the figure, the longitudinal stresses are still larger than the transverse stresses. When there are two transverse steel bars in the slab (Figure 3.9[*a*]), the maximum transverse stress is larger than that where there is only one transverse steel bar in the slab (Figure 3.9[*b*]). This finding implies that, as the transverse steel spacing decreases, the transverse stress becomes larger and can be larger than the longitudinal stress; a new longitudinal crack can be initiated in this case.

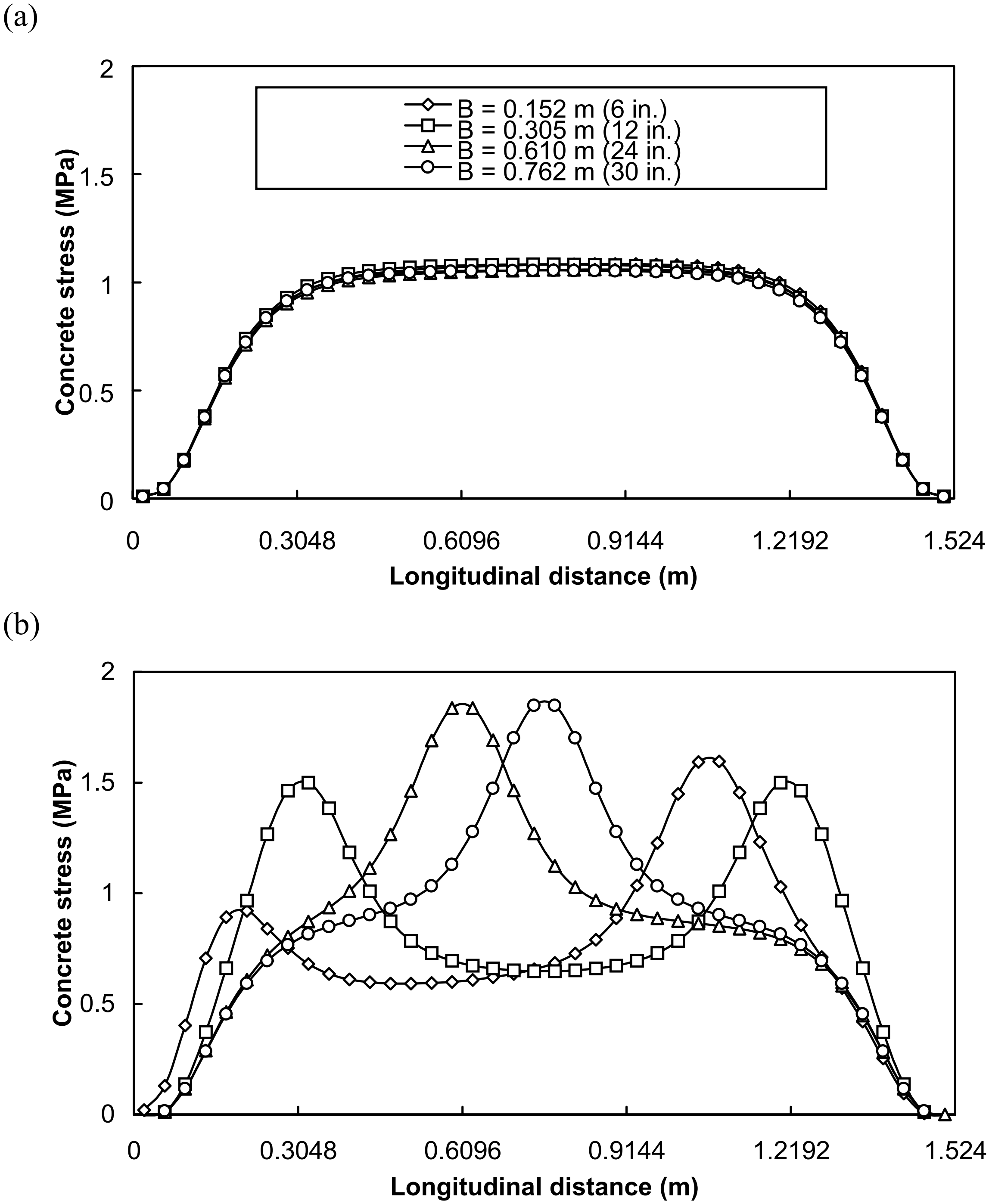


Figure 3.5. Concrete stress distribution for linear system: (a) along centerline; (b) along edge (1 MPa = 145 psi, 1 m = 39.4 in.)

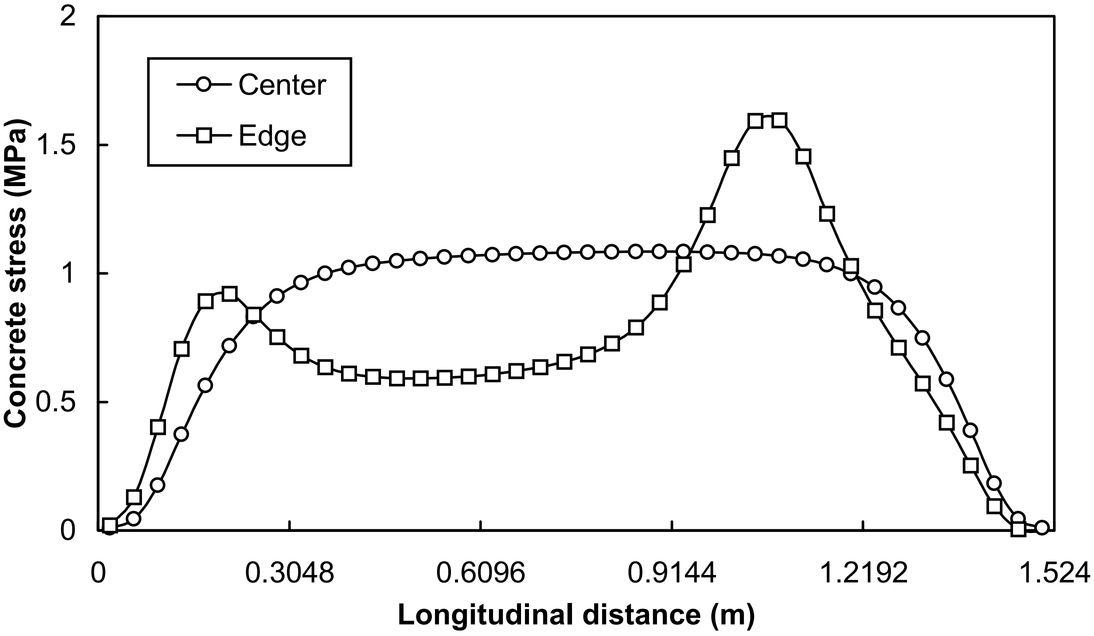


Figure 3.6. Comparison of concrete stresses when B is 0.152 m (6 in.)
(1 MPa = 145 psi, 1 m = 39.4 in.)

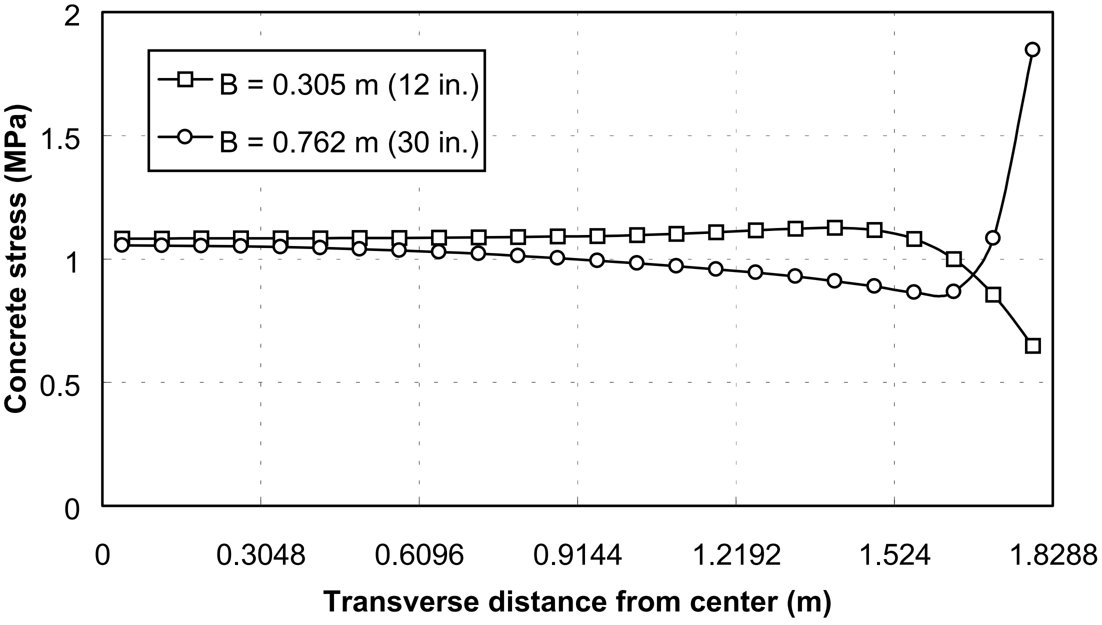


Figure 3.7. Concrete stress distribution along the transverse direction at slab center
(1 MPa = 145 psi, 1 m = 39.4 in.)

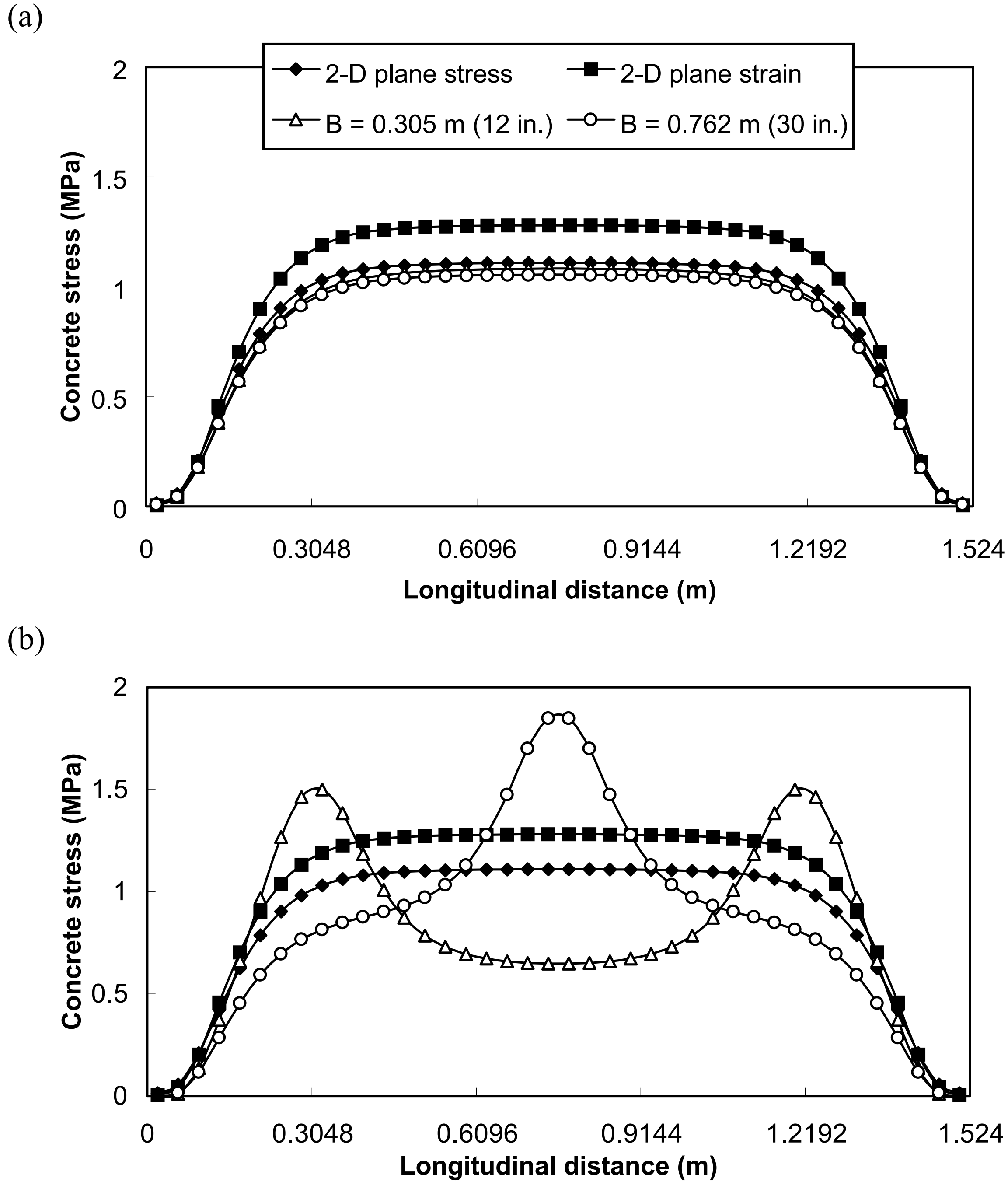


Figure 3.8. Comparison of concrete stress distribution between 2-D and 3-D linear analyses:
(a) along centerline; (b) along edge
(1 MPa = 145 psi, 1 m = 39.4 in.)

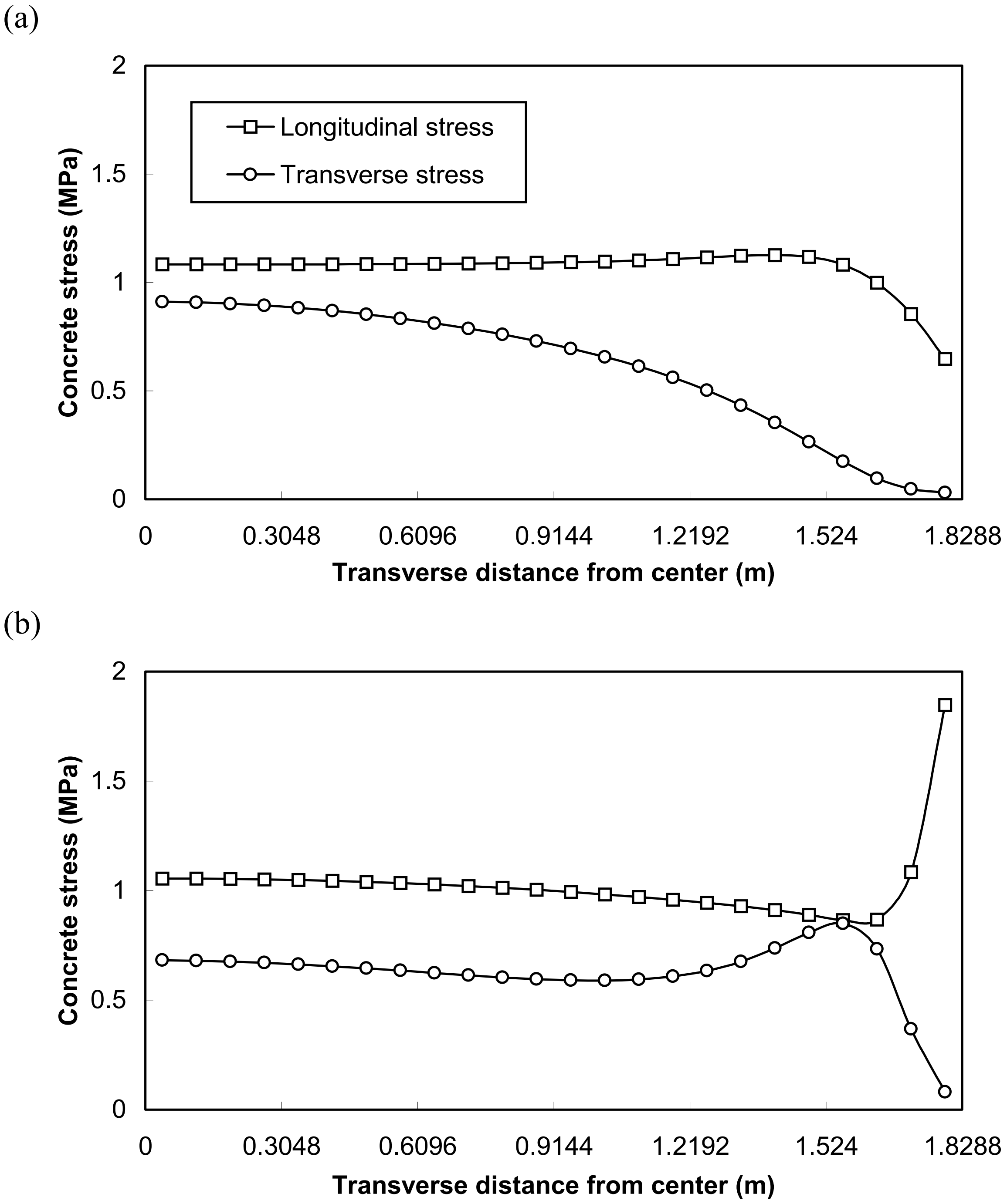


Figure 3.9. Comparison of stresses at slab center along transverse direction: (a) When B = 12 in. (0.305 m); (b) When B = 30 in. (0.762 m)
(1 MPa = 145 psi, 1 m = 39.4 in.)

CHAPTER 4. SIGNIFICANCE OF NONLINEAR MODELING

4.1 INTRODUCTION

The significance of the nonlinear modeling of CRCP has been investigated. When a selected variable is considered nonlinear in the modeling, all the other variables are assumed to be linear elastic in order to establish the significance of the nonlinear modeling of that variable. The variables considered in this study are bond slip between concrete and steel, bond slip between concrete and base, curling of the slab, and viscoelastic material behavior of concrete.

4.2 EFFECT OF NONLINEAR BOND SLIP

The effect of the nonlinear bond slip between concrete and steel was investigated first. Figure 4.1 shows the crack width distribution for different locations of the transverse steel bars when the nonlinear bond slip between concrete and steel shown in Figure 2.3(*a*) is assumed. As shown in the figure, the variations near the edge tend to decrease compared to those of the linear system shown in Figure 3.3. This finding is a result of the transverse steel bars losing their bond with concrete near the longitudinal joints in order for the bond development phenomenon to occur. Figure 4.2 shows the differences in the crack width distribution between the linear and nonlinear bond slip relations for different locations of the transverse steel bars. If the nonlinear bond slip is considered, the crack width increases about 2 percent. This increment is due to the loss of the bond slip and the decrease in the bond stiffness between concrete and longitudinal steel bars near the cracks.

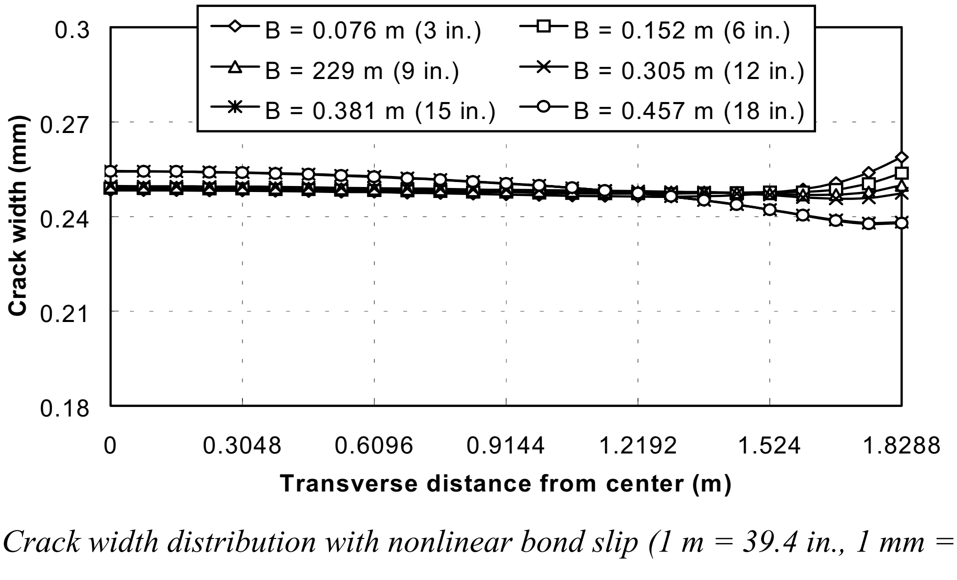


Figure 4.1. Crack width distribution with nonlinear bond slip (1 m = 39.4 in., 1 mm = 0.0394 in.)

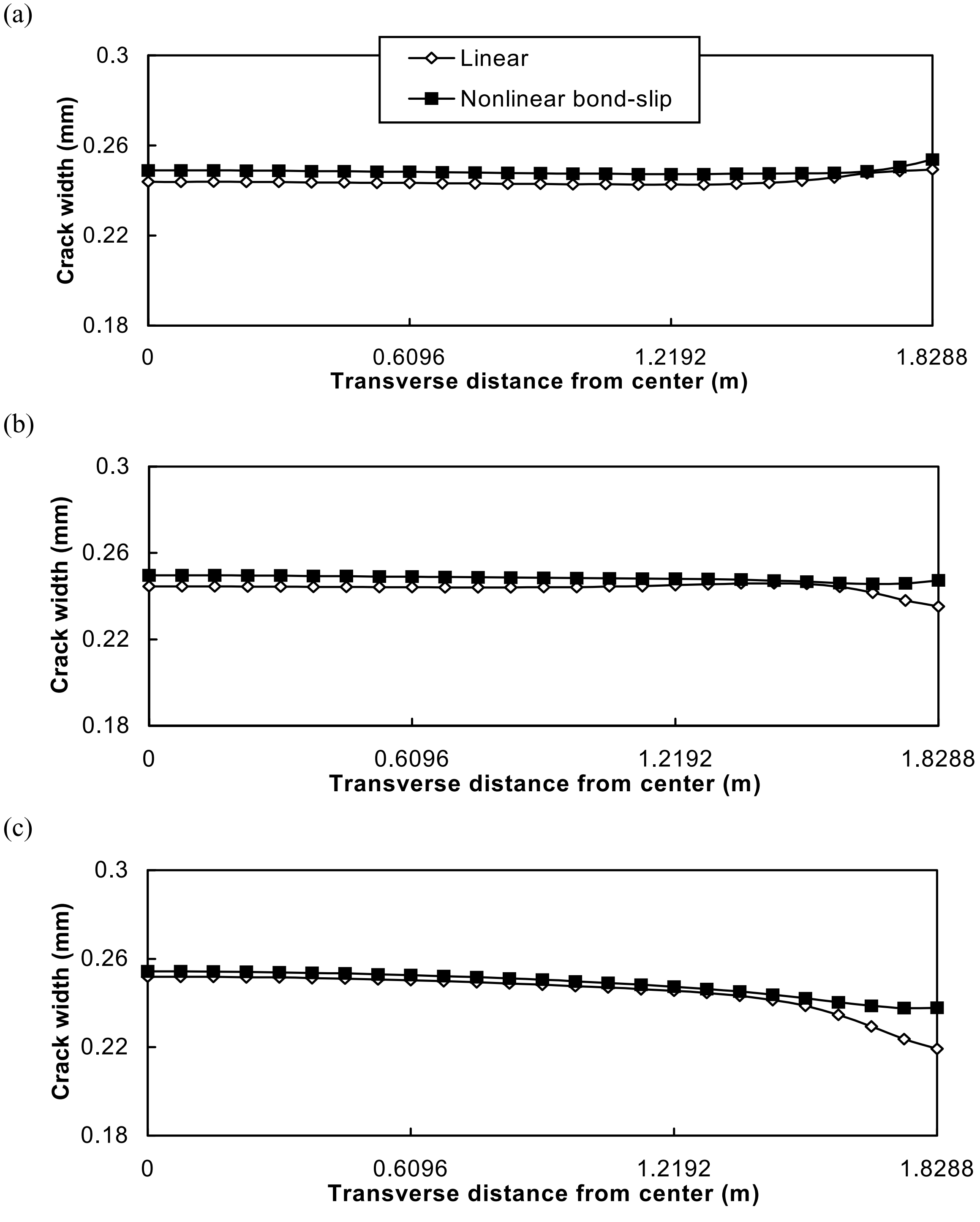


Figure 4.2. Effect of nonlinear bond slip on crack width distribution: (a) B=6 in. (0.152 m); (b) B=12 in. (0.305 m); (c) B=18 in. (0.457 m)

The crack width distributions from the 2-D and 3-D analyses have been compared when the nonlinear bond slip between concrete and steel is considered. As shown in Figure 4.3, the 3-D analysis results are between the 2-D analysis results with the plane stress and plane strain elements. The 2-D results with the plane strain elements greatly overestimate the 3-D results, and the 2-D results with the plane stress elements slightly underestimate the 3-D results.

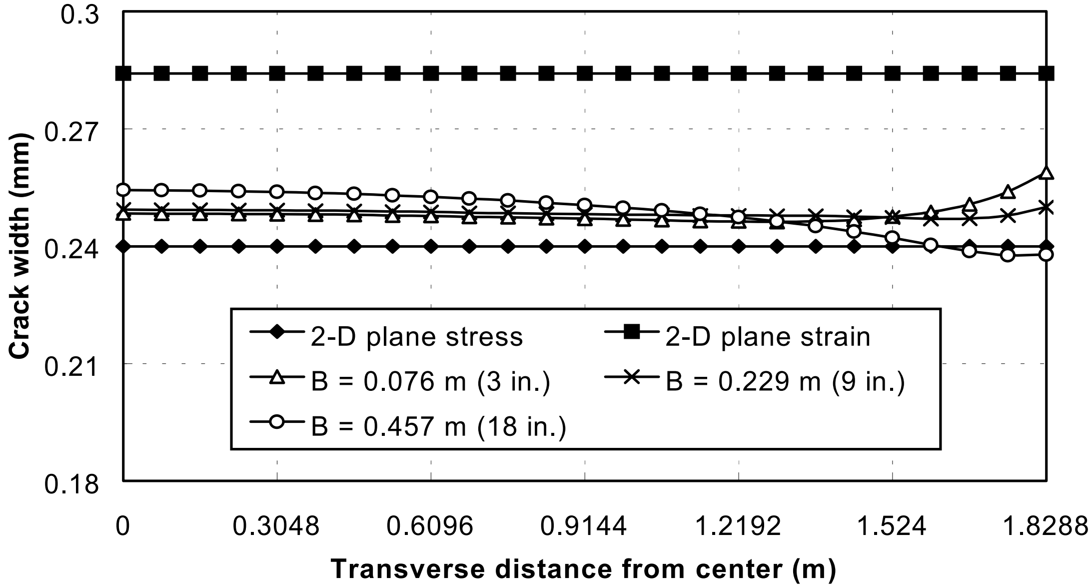


Figure 4.3. Comparison of crack width distribution between 2-D and 3-D analyses with nonlinear bond slip between concrete and steel (1 m = 39.4 in., 1 mm = 0.0394 in.)

The effect of the nonlinear bond slip on the concrete surface stress has also been investigated. Figure 4.4 shows the concrete stress distribution along the centerline and edge. The concrete stress distributions along the centerline are almost the same regardless of the transverse steel arrangement, as shown in Figure 4.4(*a*); these stress distributions are also clearer than those obtained in the linear system shown in Figure 3.5(*a*). This finding means that the stresses along the centerline are independent of the transverse steel arrangement. As in the linear system, the concrete stresses along the edge have their peak values at the locations of the transverse steel bars, as shown in Figure 4.4(*b*), but the peak values and the variations of the stresses tend to decrease compared to those from the linear analysis shown in Figure 3.5(*b*). To investigate the extent to which the nonlinear bond slip affects the results, the results are compared with those from the linear system, as shown in Figure 4.5. When the nonlinear bond slip is considered, the concrete stresses along the centerline decrease about 10 percent. For the concrete stresses along the edge, significant decrements can be observed near the locations of the transverse steels. This significant decrement is caused by the loss of the bond between concrete and transverse steel bars near the edge.

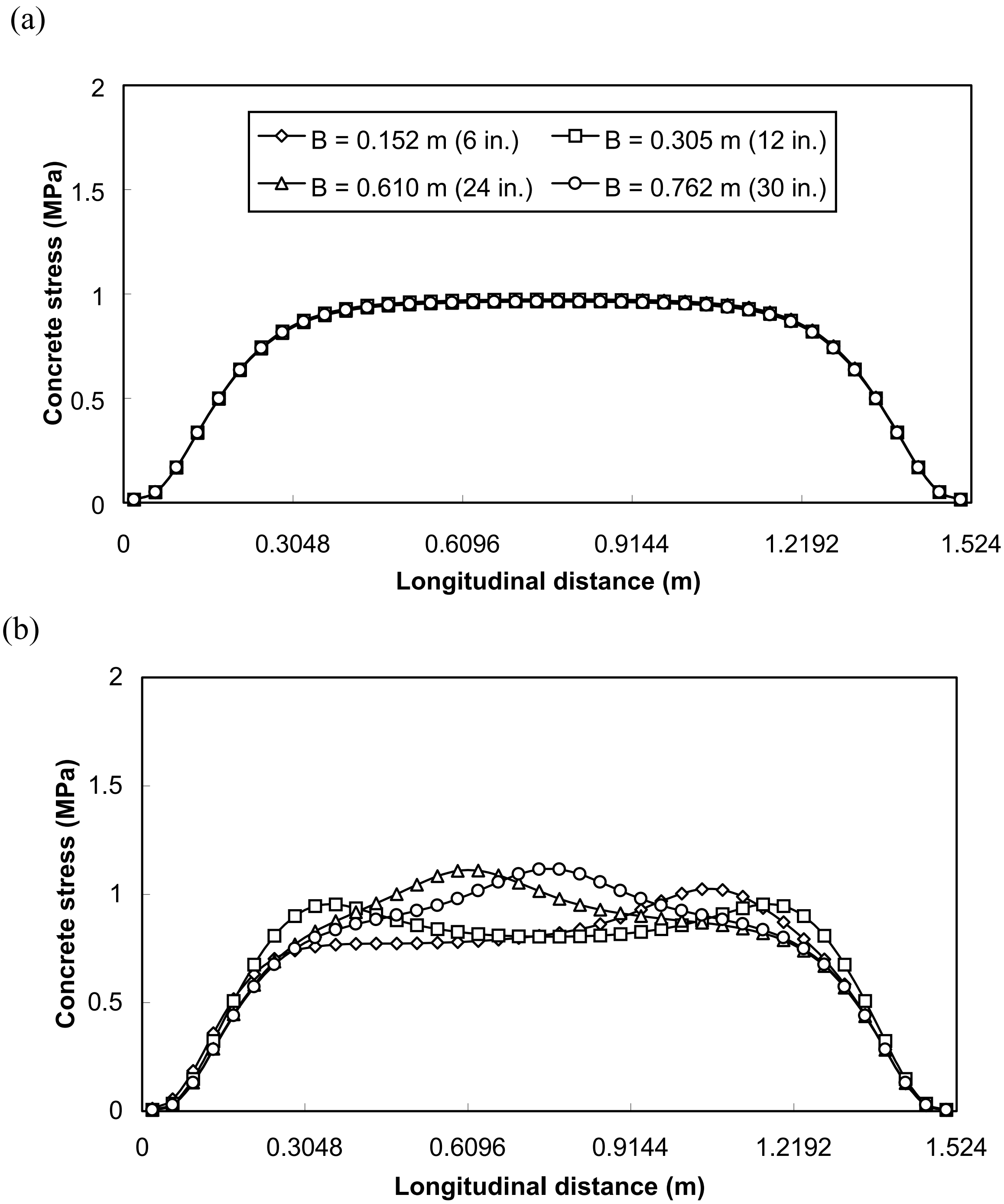


Figure 4.4. Concrete stress distribution with nonlinear bond slip between concrete and steel: (a) along centerline; (b) along edge

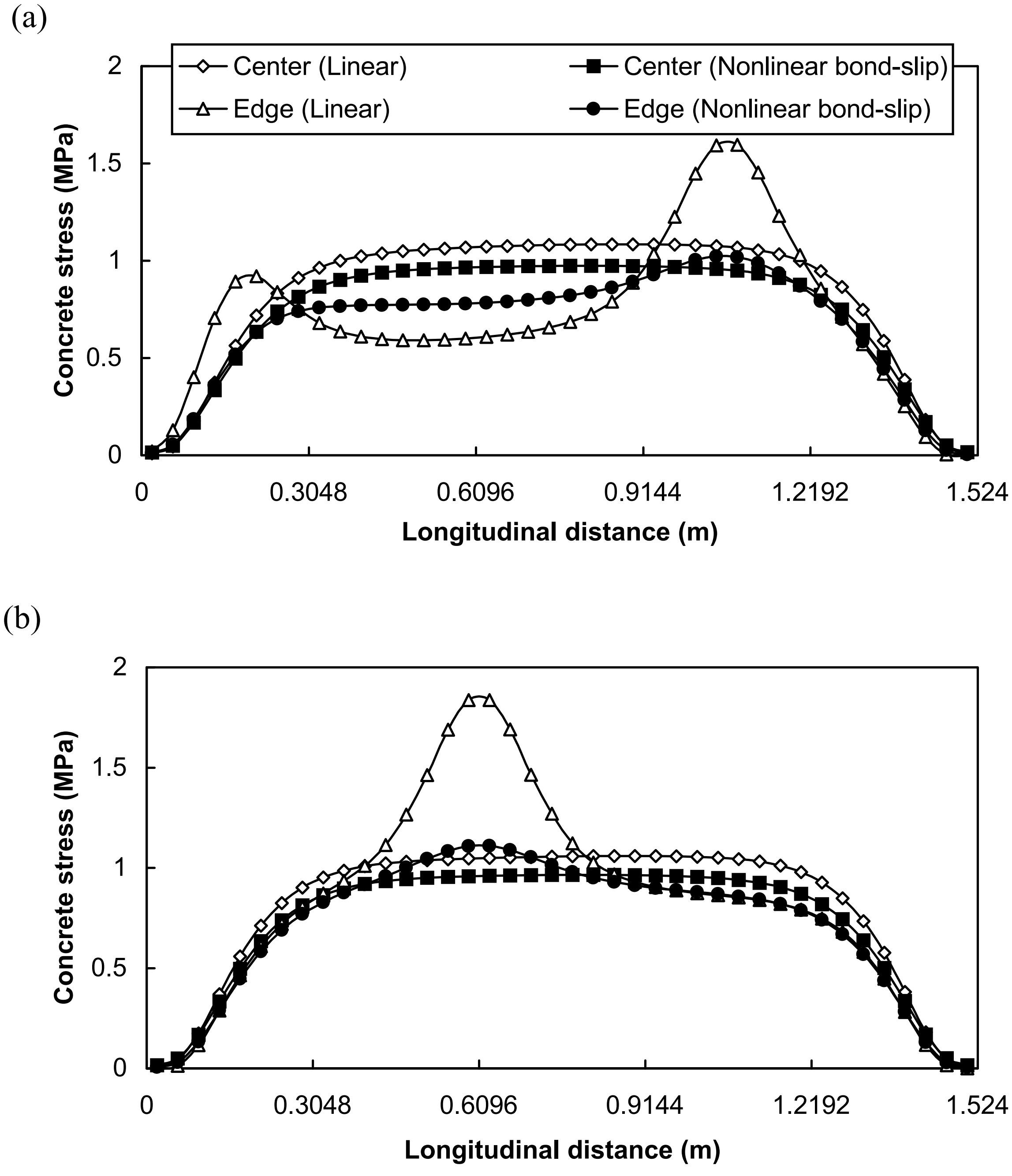


Figure 4.5. Effect of nonlinear bond slip on concrete stress distribution: (a) B=6 in. (0.152 m); (b) B=24 in. (0.610 m)

The concrete stresses from the 2-D and 3-D analyses are compared when the nonlinear bond slip between concrete and steel is considered. The 2-D model with the plane stress elements gives results very close to those obtained with the 3-D models for the stresses along the centerline, as shown in Figure 4.6(*a*). The 2-D results with the plane strain elements overestimate the 3-D results. For the stresses along the edge, the 2-D analysis results cannot predict the variations observed in the 3-D analysis results, as shown in Figure 4.6(*b*).

The effect of the nonlinear bond slip at the interface between concrete and base has also been investigated. For the CRCP model selected in this study, there were no differences in the crack width and the concrete stress between the linear system and the system with the nonlinear bond slip shown in Figure 2.3(*b*). To investigate the importance of the bond-slip modeling between concrete and base, the results from the system without the bond-slip modeling between concrete and base were compared with results from the system with the bond slip consideration. For the crack width, the maximum difference between the systems with and without the bond-slip modeling was about 1 percent. For the concrete stress, the maximum difference was about 0.3 percent. This finding implies that the modeling of the bond slip between concrete and base only slightly affects the analysis results.

4.3 CURLING EFFECT

The vertical springs used in the linear system to model the underlying layers are able to sustain both the tensile and compressive forces. However, if any side of a concrete slab curls up, there is a possibility of discontinuity developing between the concrete slab and the base layer. To properly model this situation, the tensionless vertical springs that can sustain only the compressive forces are used. The difference in the analysis results between the linear system and the system with the tensionless vertical springs has also been investigated. For the 3-D model used in this study, there was very little difference in the results. The differences in the crack widths and in the concrete stresses at their maximum values were about 0.5 percent. Figure 4.7 shows how much of the slab area loses contact with the base when the tensionless springs are used. If the number of the transverse steel bars is the same, the results are the same regardless of the location of the steel bars. If the number of the transverse steel bars differs, only slight differences in the contact area are observed, with such differences small enough to be negligible.

Because the curling effect depends on the slab length and the temperature gradient between the top and bottom of the slab, more investigation has been performed with 2-D models. As shown in Table 4.1, the jointed concrete pavement (JCP) and the CRCP are considered. When the slab is short and the temperature gradient is small, there is no difference in the results between the linear system and the system with the tensionless springs. As the slab length and the temperature gradient increase, the differences become significant for the concrete tensile stress. The effect of tensionless spring on concrete stress is more pronounced in JCP than in CRCP. This effect implies that when the stresses need to be evaluated for the JCP, it is better to use the tensionless springs in order to obtain more accurate analysis results.

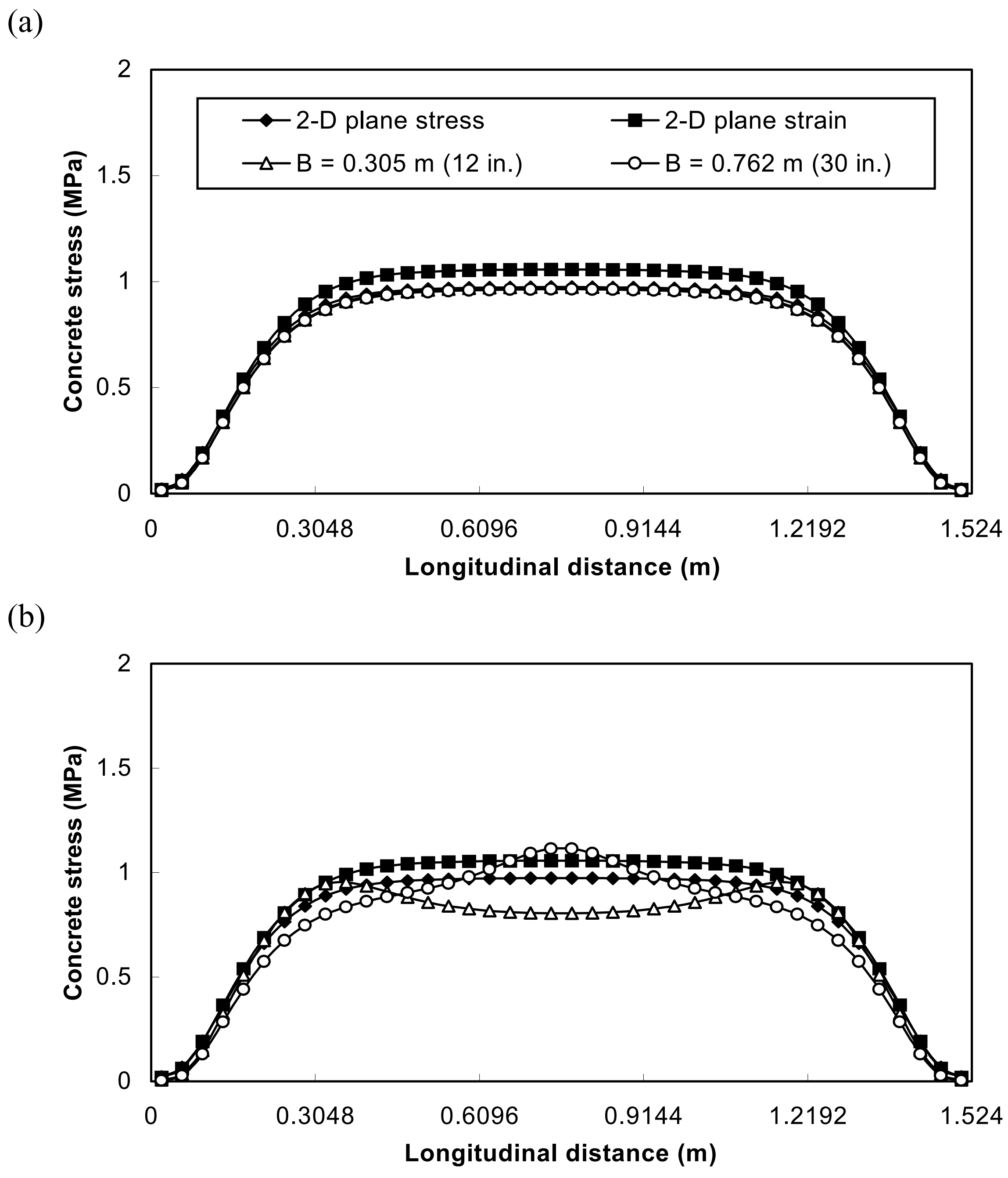


Figure 4.6. Comparison of concrete stress distribution between 2-D and 3-D analyses with nonlinear bond slip: (a) along centerline; (b) along edge

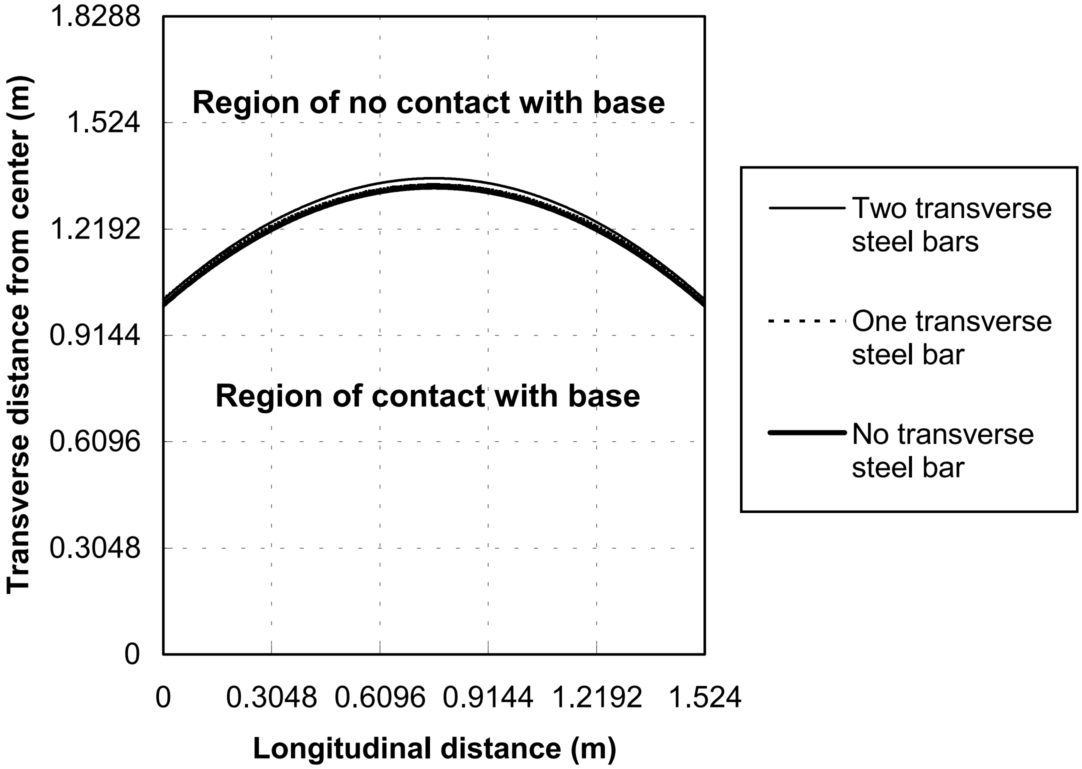


Figure 4.7. Region of contact with base when tensionless springs are used and the slab curls upward

4.4 CREEP EFFECT

As a result of slow changes in temperature and drying shrinkage, concrete in CRCP experiences creep and stress relaxation. A number of concepts come into play in analyzing these creep effects (Ref 9). In this study, instead of using a particular creep coefficient curve, the creep coefficient is assumed to be 0.11 after 12 hours, so that the ratio of the effective modulus can be 90 percent (Refs 4, 5). Because the duration of the temperature drop is relatively short (about 12 hours), the time history of the creep coefficient curve within that duration can be negligible. As shown in Figure 4.8, the crack width decreases when the creep effect is considered, and the maximum difference between the linear system and the system with the viscoelastic material modeling (creep modeling) is less than 1 percent. The concrete stress also decreases with the viscoelastic modeling, with the maximum difference less than 3 percent, as shown in Figure 4.9.

Table 4.1. Comparing curling effects of JCP and CRCP behavior with an elastic foundation (1 m = 39.4 in., 1 mm = 0.0394 in., 1 kPa = 0.145 psi, x ℃ = [x∗ 9/5 + 32] ℉)

Slab length (m)	Temp. grad. (°C)	Type of foundation	Plane strain model				Plane stress model			
			Max. stress (kPa)	Difference (%)	Crack width (mm)	Difference (%)	Max. stress (kPa)	Difference (%)	Crack width (mm)	Difference (%)
Jointed Concrete Pavement										
1.5	8.3	Linear	28.528	**0**	0.3656	**0**	29.325	**0**	0.3172	**0**
		Tensionless	28.528		0.3656		29.325		0.3172	
	15.6	Linear	62.747	**13.12**	0.4311	**0.15**	62.842	**7.10**	0.3735	**0.10**
		Tensionless	54.512		0.4317		58.383		0.3739	
3	8.3	Linear	287.82	**32.15**	0.6983	**2.12**	249.57	**24.97**	0.6059	**1.72**
		Tensionless	195.27		0.7131		187.27		0.6163	
	15.6	Linear	551.05	**52.66**	0.7986	**5.44**	477.36	**46.08**	0.6920	**4.95**
		Tensionless	260.89		0.8421		257.37		0.7263	
Continuously Reinforced Concrete Pavement										
1.5	8.3	Linear	1280.30	**0**	0.2655	**0**	1109.18	**0**	0.2284	**0**
		Tensionless	1280.30		0.2655		1109.18		0.2284	
	15.6	Linear	1322.73	**0.47**	0.3301	**0.15**	1149.54	**0.24**	0.2839	**0.08**
		Tensionless	1316.52		0.3306		1146.78		0.2841	
3	8.3	Linear	1996.86	**3.54**	0.3759	**3.02**	1716.72	**2.65**	0.3220	**2.36**
		Tensionless	1926.14		0.3872		1671.18		0.3296	
	15.6	Linear	2268.72	**11.19**	0.4738	**7.98**	1951.67	**9.72**	0.4060	**7.24**
		Tensionless	2014.80		0.5116		1761.92		0.4353	

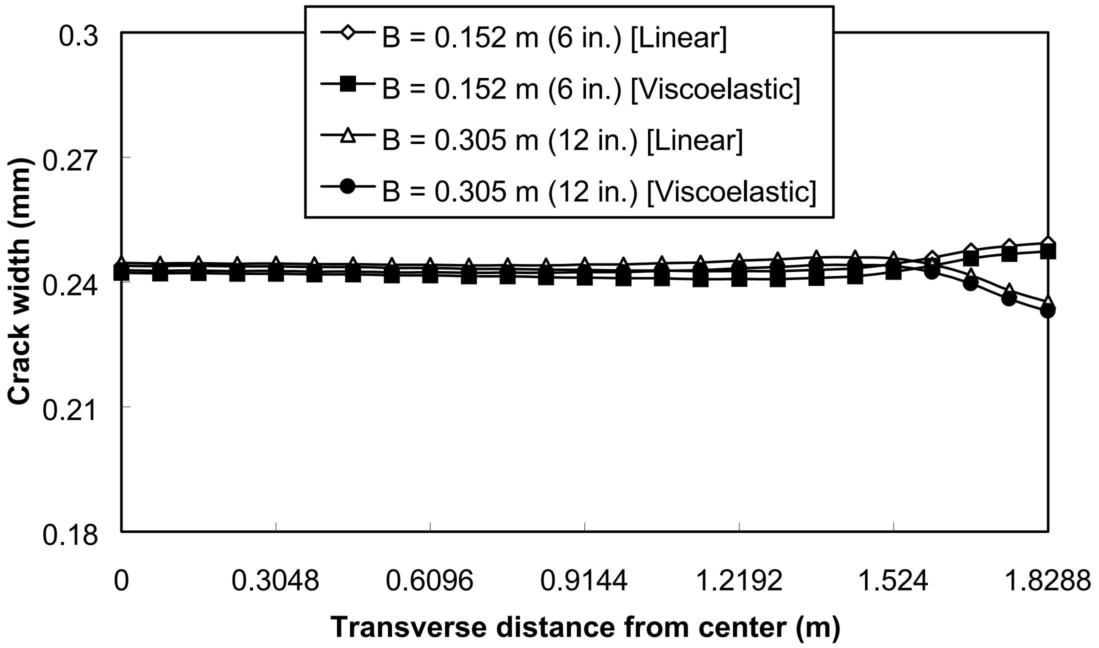


Figure 4.8. Effect of viscoelastic modeling on crack width distribution

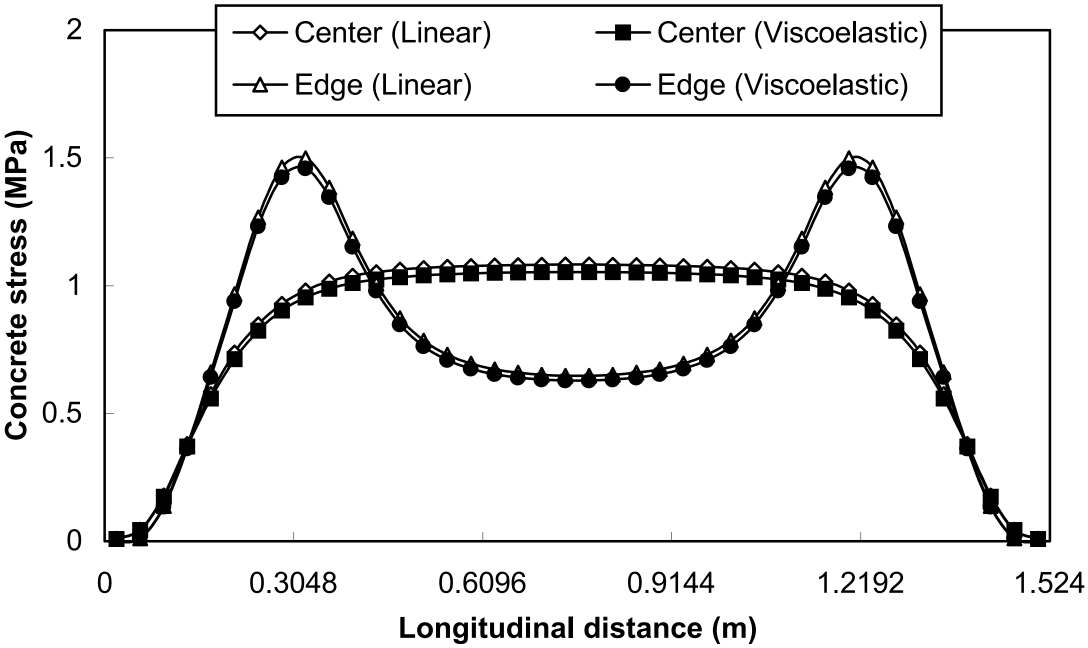


Figure 4.9. Effect of viscoelastic modeling on concrete stress distribution when B is 12 in. (0.305 m)

CHAPTER 5. NONLINEAR SYSTEM OF CRCP

5.1 INTRODUCTION

The behavior of the nonlinear CRCP system with all nonlinear factors, as explained in the previous chapter, has been investigated and compared with that of the linear system. The analysis results from the 2-D and 3-D nonlinear systems of CRCP have also been compared. The sample inputs for 2-D and 3-D nonlinear analyses are listed in Appendices B and D, respectively.

5.2 CRACK WIDTH DISTRIBUTION

Figure 5.1 shows the crack width distribution for the linear and nonlinear systems, as well as the different locations of the transverse steel bars. As shown in the figure, the crack widths are very similar except in the region within about 10 in. (25 cm) from the edge, regardless of the type of modeling system or the location of the transverse reinforcement. This finding appears to result from the net summation of the crack widths that increase with the nonlinear bond slip and the tensionless spring models and that decrease with the viscoelastic material model. The maximum differences in the crack width variation near the edge are about 4 percent and 0.9 percent for the linear and nonlinear systems, respectively.

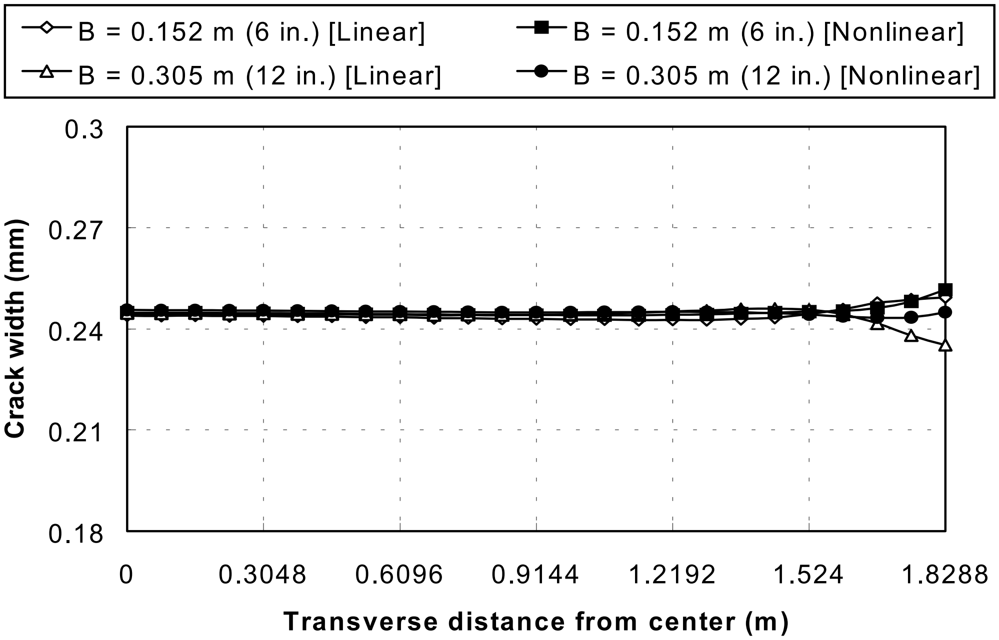


Figure 5.1. Crack width distribution for nonlinear system
(1 m = 39.4 in., 1 mm = 0.0394 in.)

The crack widths from the 2-D linear and nonlinear analyses are shown in Figure 5.2. As indicated in the figure, the crack widths increase with the nonlinear analysis, with the increment larger for the 2-D model with the plane strain elements. Specifically, the increments are 3.7 percent and 5.4 percent for the 2-D models with the plane stress and plane strain elements, respectively. For the 3-D analysis, the differences in the crack widths between the linear and nonlinear models are very small, as shown in Figure 5.1; for the 2-D analysis, the differences are more prominent. Figure 5.3 shows the crack widths from the 3-D models with different locations of the transverse steel bars and from the 2-D models with the plane stress and plane strain elements. The 2-D model with the plane stress element underestimates the crack width of the 3-D model by about 3 percent, and that with the plane strain element overestimates the crack width by about 14percent. For the linear system, the 2-D models with the plane stress and plane strain elements differ similarly from the 3-D model, as shown in Figure 3.4; but for the nonlinear system, the 2-D model with the plane stress elements differs only slightly from the 3-D model. Although the 2-D models cannot precisely predict the crack width of the 3-D model, the 2-D model with the plane stress element yields results very close to those of the 3-D model.

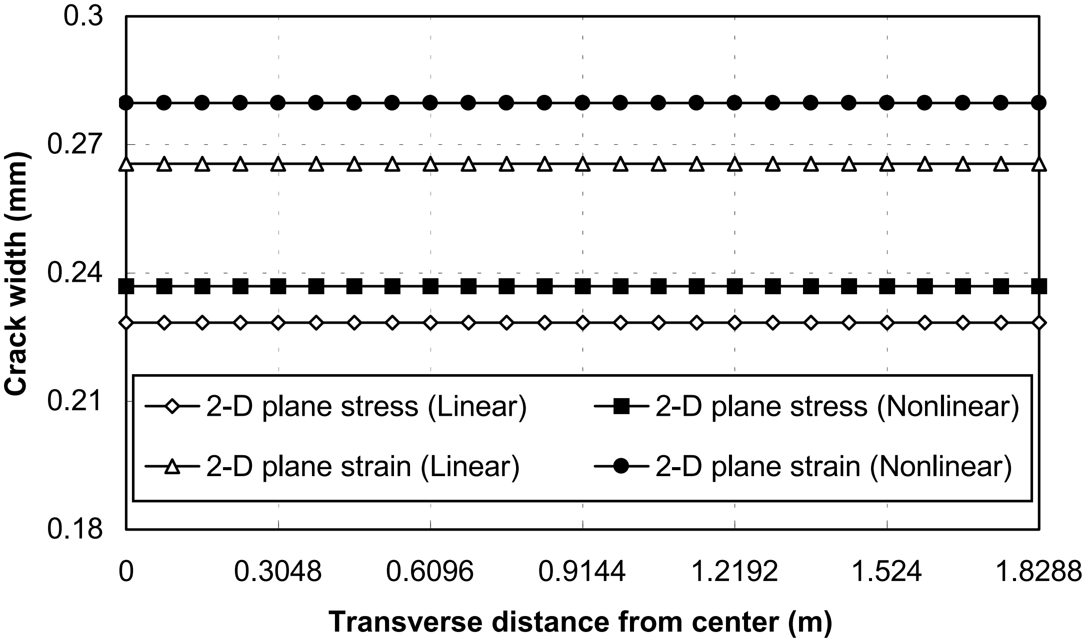


Figure 5.2. Crack widths from 2-D linear and nonlinear analyses (1 m = 39.4 in., 1 mm = 0.0394 in.)

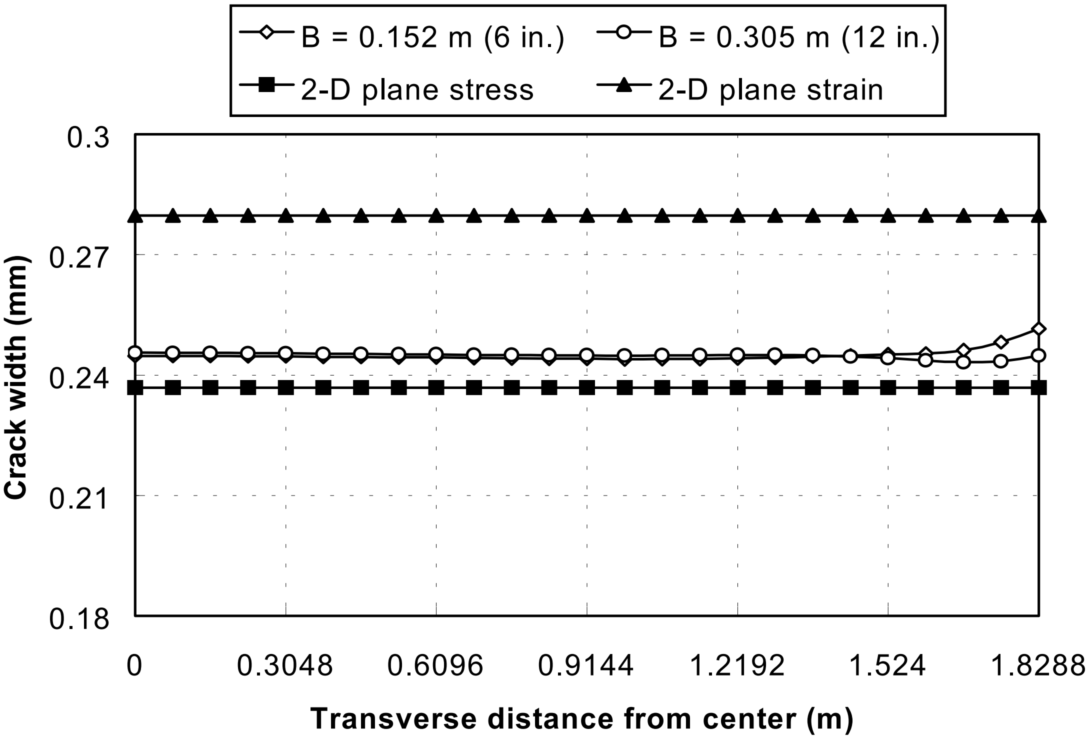


Figure 5.3. Comparison of crack widths between 2-D and 3-D nonlinear analyses (1 m = 39.4 in., 1 mm = 0.0394 in.)

5.3 CONCRETE STRESS DISTRIBUTION

Figure 5.4 presents the concrete stress distribution along the pavement centerline and along the edge for the linear and nonlinear systems. The concrete stress along the centerline decreases with the nonlinear system (about 12 percent at maximum value). Along the edge, the concrete stress decreases substantially at the locations of the transverse steel bars (about 40 percent) and increases between the two peaks, as compared with the results from the linear system. For the nonlinear system, the maximum stress that occurred on the edge at the transverse steel bar location is almost the same as (Figure 5.4[*a*]) or higher (Figure 5.4[*b*]) than that which occurred along the centerline. This implies that there is a possibility of crack occurrence initiated at the edge near the location of the transverse reinforcement. Field studies of crack location occurrence made in connection with previous research (Ref 10) revealed a high probability of occurrence on the edge at the transverse steel bar location. In addition, it appeared that the cracks initiated at the pavement edge.

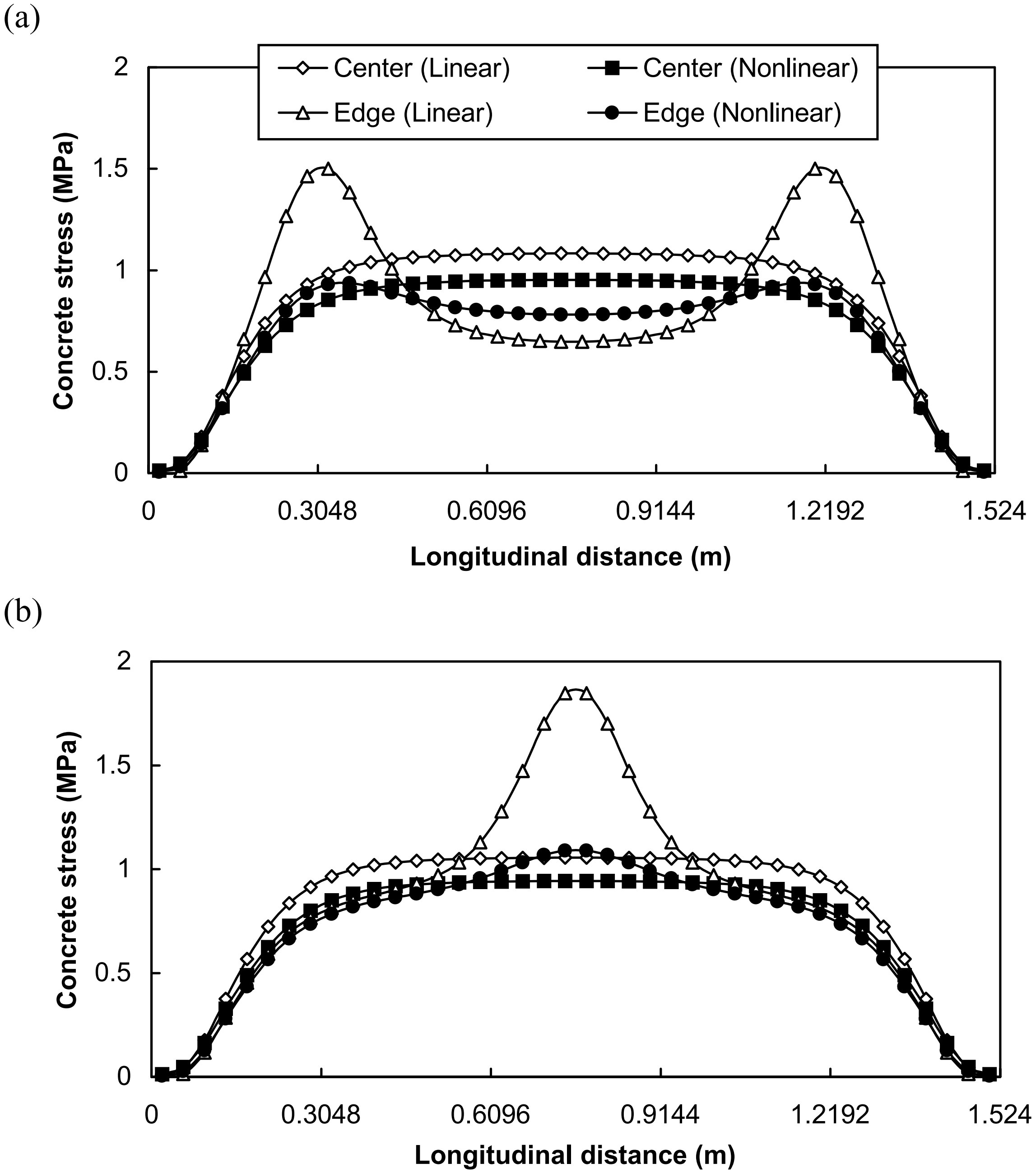


Figure 5.4. Concrete stress distribution for linear and nonlinear systems: (a) B = 0.305 m (12 in.); (b) B = 0.762 m (30 in.) (1 MPa = 145 psi, 1 m = 39.4 in.)

The 2-D analysis results for the concrete stresses between linear and nonlinear systems have been compared. As shown in Figure 5.5, the concrete stress decreases with the nonlinear system. The decrements at the center are about 14 percent and 18 percent for the 2-D models with the plane stress and plane strain elements, respectively. The concrete stress distributions with the 2-D and 3-D models are shown in Figure 5.6. For the concrete stress along the centerline (Figure 5.6[a]), the 2-D model with the plane stress element matches very closely the stress of the 3-D model, while the 2-D model with the plane strain element overestimates the stress by about 10 percent. For the stress along the edge (Figure 5.6[b]), the 2-D models cannot accurately predict the stress of the 3-D model, because the stress along the edge of the 3-D model depends on the transverse steel bar locations that cannot be modeled in the 2-D models. It is noted that the variation of the concrete stress distribution along the transverse direction at a given position in the longitudinal direction is observed within about 25 cm (10 in.) from the edge. Except in that region, the concrete stress along the transverse direction seems to be the same regardless of the transverse reinforcement arrangement. From this comparison, it is found that the 2-D model with the plane stress element gives very good results. Because the CRCP has longitudinal joints and the connections to an adjacent slab are provided by the tie bars as part of the transverse steel design, the concrete stresses in the transverse direction are much smaller than those in the longitudinal direction, and the concrete slab is allowed to move in the transverse direction. For this reason, the 2-D model with the plane stress element gives results closer to those of the 3-D model. The 2-D model with the plane strain element yields different results because the plane strain element does not allow any strain or displacement in the transverse direction, which causes very high transverse stresses in concrete.

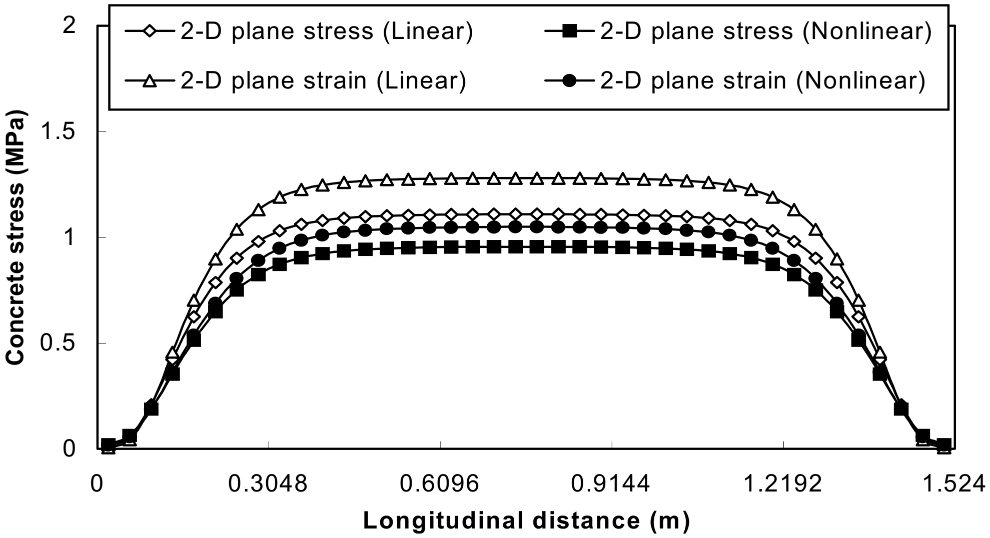


Figure 5.5. Concrete stresses from 2-D linear and nonlinear analyses (1 MPa = 145 psi, 1 m = 39.4 in.)

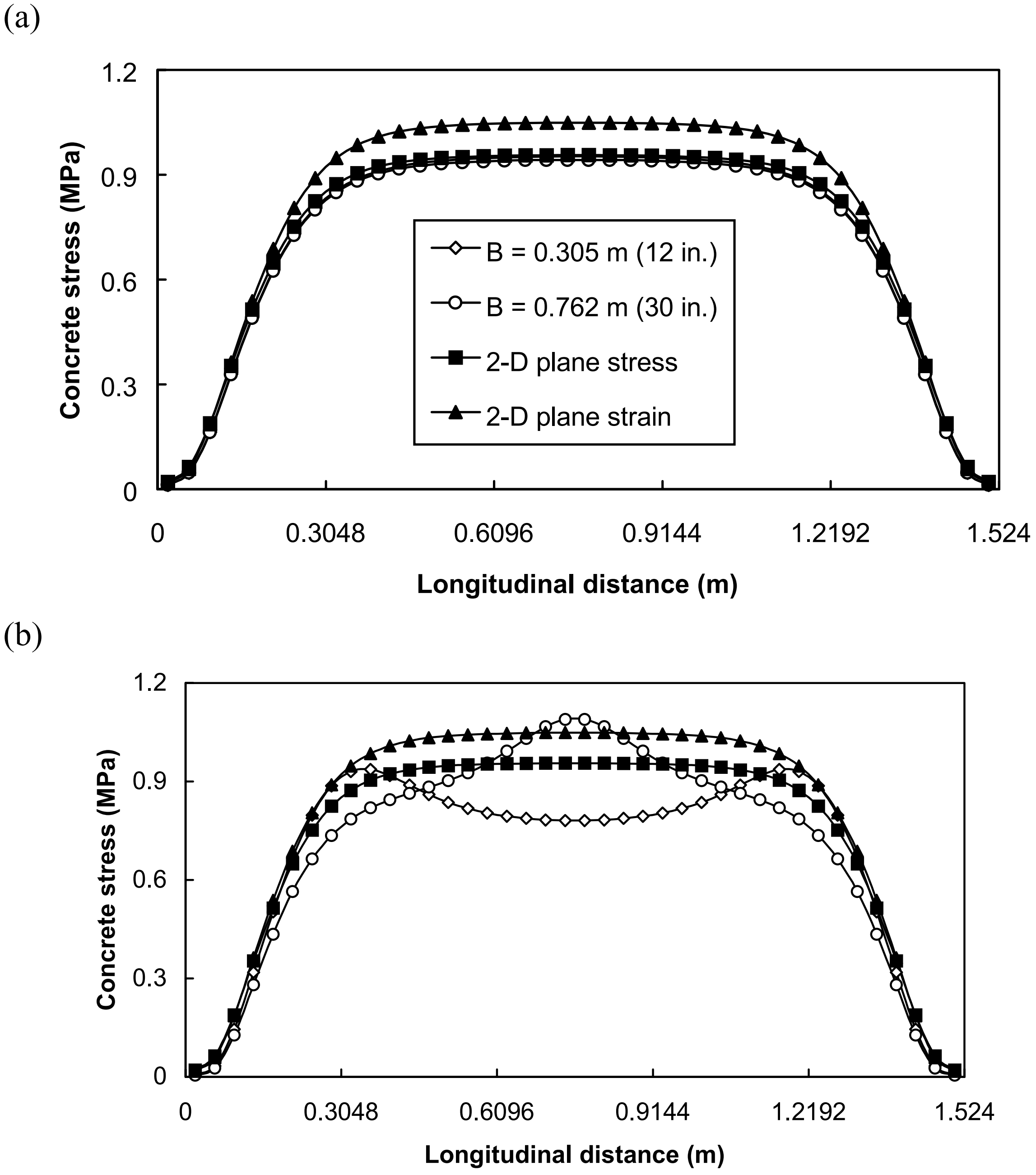


Figure 5.6. Comparison of concrete stress distribution between 2-D and 3-D nonlinear analyses: (a) along centerline; (b) along edge (1 MPa = 145 psi, 1 m = 39.4 in.)

CHAPTER 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

The behavior of CRCP in response to temperature change was studied using a three-dimensional finite element model. The concrete slab was discretized using three-dimensional brick elements; the longitudinal and transverse steels were modeled using frame elements; the bond slip between concrete and steel was modeled using spring elements; the underlying layers were modeled using vertical springs; and the frictional bond slip between concrete and base was modeled using horizontal springs. The nonlinear modeling was performed for the bond slip between concrete and steel and between concrete and base for the curling effect and for the viscoelastic material characteristics. The importance of the nonlinear modeling and the differences between the linear and nonlinear analyses were investigated. The results obtained from the two-dimensional and three-dimensional models were also compared. The important nonlinear factors obtained by the 3-D analysis will be included in the new computer program that will be developed within the second year of this project using two-dimensional finite element modeling.

6.2 CONCLUSIONS

This three-dimensional finite element analysis of the CRCP points to the following conclusions:

1. The crack width is affected by the location and the number of transverse steel bars within about 10 in. (25 cm) from the edge (longitudinal joint) and is independent of the transverse steel arrangement in the other regions.
2. With the linear system, the maximum concrete stress in the longitudinal direction occurs at the edge on the transverse steel bar farthest from the crack. In the nonlinear system, the maximum stress occurs either at the center of the slab or at the edge of the slab where the transverse steel bar is located farthest from the crack. This finding corresponds to the high probability of a transverse crack occurring near a transverse steel bar location, which has been observed previously on experimental projects.
3. The effect of the nonlinear bond-slip relationship between concrete and steel on the concrete stress was found to be very significant.
4. The frictional bond-slip relationship at the interface between the concrete slab and the base has a minor effect on the behavior of the CRCP.
5. The use of tensionless springs to model the underlying layers should be considered when the temperature variation along the depth and the crack spacing is large. This issue is more significant when jointed concrete pavements (JCP) are analyzed.

6. The two-dimensional CRCP model with the plane stress element approximates the results of the three-dimensional model except in the regions within about 10 in. (25 cm) from the edge.

6.3 RECOMMENDATIONS

Efforts have been made to analyze the behavior of CRCP with realistic three-dimensional models. As expected, the behavior of CRCP depends on the bond slip between concrete and steel and on viscoelastic material characteristics. In order to use reasonable input values for those variables, further experimental investigations need to be undertaken. This study has concentrated on the response to environmental loading represented by temperature change. The response to tire loading needs to be investigated with the 2-D and 3-D models, with the relationship between the models used in the new CRCP program.

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APPENDIX A:

SAMPLE INPUT FOR 2-D LINEAR CRCP MODEL

```
*heading
CRCP2DLIN
*****************************
**slab length=5ft
*****************************
*preprint, echo=no
**restart,write
*********************************************
**Discretize concrete slab using plain stress elements
*********************************************
*node
1,0.,0.
21,30.,0.
801,0.,12.
821,30.,12.
*ngen,nset=bottom
1,21
*ngen,nset=top
801,821
*nfill,nset=side
bottom,top,8,100
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1,1,2,102,101
*elgen,elset=conc
1,20,1,1,8,100,100
*solid section,elset=conc,material=concrete
6.
*material,name=concrete
*elastic
2.e6,0.15
*expansion
0.000006
*******************************************
** Discretize steel bar using beam elements
*******************************************
*node
1001,0.,6.
1021,30.,6.
*ngen, nset=nsteel
1001,1021
*element, type=b21, elset=stbar
1001,1001,1002
*elgen, elset=stbar
1001,20,1,1
*beam section, elset=stbar, material=steel, section=circ
0.375
*material, name=steel
*elastic
2.9e7
*expansion
0.000005
**When stresses in steel are not wanted to plot, use the
below lines
***beam general section, elset=stbar, section=circ
**0.375
**
**2.9e7,,0.000005
*****************************************
**Connect steel and concrete by springs
*****************************************
*element, type=spring2, elset=bondsp
2001,401,1001
*elgen, elset=bondsp
2001,20,1,1
*spring, elset=bondsp
1,1
2474000.
*element, type=spring2, elset=bondsp1
2021,421,1021
*spring, elset=bondsp1
1,1
1237000.
*********************************************
**Modeling of underlying layer using elastic foundation
*********************************************
*elset, elset=botel, gen
1,20,1
*foundation
botel,f1,400.
********************************************
**Modeling of frictional bond
**between conc and base using springs
********************************************
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4002,2
*elgen, elset=horisp
4002,19,1,1
*spring, elset=horisp
1
1350.
*element, type=spring1, elset=horisp1
4001,1
*spring, elset=horisp1
1
675.
*element, type=spring1, elset=horisp2
4021,21
*spring, elset=horisp2
1
675.
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**Modeling of vertical compatibility
**between steel and conc.
*********************************************
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*elgen, elset=rigid
5001,21,1,1
*spring, elset=rigid
2,2
10000000000.
****************************
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1,801,100
*nset, nset=right, gen
21,821,100
*nset, nset=top2, gen
701,721
```

```
*nset, nset=top3, gen
601,621
*nset, nset=top4, gen
501,521
*nset, nset=mid, gen
401,421
*nset, nset=bot4, gen
301,321
*nset, nset=bot3, gen
201,221
*nset, nset=bot2, gen
101,121
*elset, elset=surf, gen
701,720
*boundary
left,1
1001,1
1001,6
1021,1
1021,6
*initial conditions, type=temperature
side,120.
nsteel,120.
********************
*step
*static
*temperature
top,85.
top2,86.875
top3,88.75
top4,90.625
mid,92.5
bot4,94.375
bot3,96.25
bot2,98.125
bottom,100.
nsteel,92.5
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S11
*el print, elset=stbar
S11
*node print, nset=right
u1
*end step
```

APPENDIX B:

SAMPLE INPUT FOR 2-D NONLINEAR CRCP MODEL

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*heading
CRCP2DNON
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**slab length=5ft
**Nonlinear system
********************************
*preprint, echo=no
**restart,write
************************************************
**Discretize concrete slab using plain stress elements
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21,30.,0.
801,0.,12.
821,30.,12.
*ngen,nset=bottom
1,21
*ngen,nset=top
801,821
*nfill,nset=side
bottom,top,8,100
*element,type=cps4,elset=conc
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*elgen,elset=conc
1,20,1,1,8,100,100
*solid section,elset=conc,material=concrete
6.
*material,name=concrete
*elastic
2.e6,0.15
*expansion
0.000006
*viscoelastic, time=prony
0.45,0.45,48.
************************************************
** Discretize steel bar using beam elements
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1021,30.,6.
*ngen, nset=nsteel
1001,1021
*element, type=b21, elset=stbar
1001,1001,1002
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1001,20,1,1
*beam section, elset=stbar, material=steel, section=circ
0.375
*material, name=steel
*elastic
2.9e7
*expansion
0.000005
**When stresses in steel are not wanted to plot,
**use the below lines
***beam general section, elset=stbar, section=circ
**0.375
**
**2.9e7,,0.000005
*********************************************
**Connect steel and concrete by springs
*********************************************
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*elgen, elset=bondsp
2001,20,1,1
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2721.4,0.002
954.3,0.004
0.,0.008
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***spring, elset=bondsp1
*spring, elset=bondsp1, nonlinear
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477.15,0.004
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*spring, elset=vertsp1, nonlinear
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0.,0.
*element, type=spring1, elset=vertsp2
3021,21
```

```
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*spring, elset=vertsp2, nonlinear
2
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-3600.,-2.
0.,0.
************************************************
**Modeling of frictional bond
**between concrete and base using springs
************************************************
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*elgen, elset=horisp
4002,19,1,1
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1
1350.
*element, type=spring1, elset=horisp1
4001,1
*spring, elset=horisp1
1
675.
*element, type=spring1, elset=horisp2
4021,21
*spring, elset=horisp2
1
675.
************************************************
**Modeling of vertical compatibility
**between steel and conc.
************************************************
*element, type=spring2, elset=rigid
5001,401,1001
*elgen, elset=rigid
5001,21,1,1
*spring, elset=rigid
2,2
10000000000.
**********************************
*nset, nset=left, gen
1,801,100
*nset, nset=right, gen
21,821,100
*nset, nset=top2, gen
701,721
*nset, nset=top3, gen
601,621
*nset, nset=top4, gen
501,521
*nset, nset=mid, gen
401,421
*nset, nset=bot4, gen
301,321
*nset, nset=bot3, gen
201,221
*nset, nset=bot2, gen
101,121
*elset, elset=surf, gen
701,720
*boundary
left,1
1001,1
1001,6
1021,1
1021,6
*initial conditions, type=temperature
side,0.
nsteel,0.
*amplitude, name=tem
0.,0.,12.,1.
***********************
*step
***static
*visco
4.,12.,0.5
*temperature, amplitude=tem
top,-35.
top2,-33.125
top3,-31.25
top4,-29.375
mid,-27.5
bot4,-25.625
bot3,-23.75
bot2,-21.875
bottom,-20.
nsteel,-27.5
***temperature
**top,85.
**top2,86.875
**top3,88.75
**top4,90.625
**mid,92.5
**bot4,94.375
**bot3,96.25
**bot2,98.125
**bottom,100.
**nsteel,92.5
*dload
conc,by,-0.084
stbar,py,-0.125275
*el print, elset=surf
S11
*el print, elset=stbar
S11
*node print, nset=right
u1
*end step
```

APPENDIX C:

SAMPLE INPUT FOR 3-D LINEAR CRCP MODEL

```
*heading
CRCP3DLIN
************************************************
**Slab length=5ft
**Base friction in longi. & transv. direc. considered
**Dead load of concrete and steel considered
**Spring elements for underlying layers
**Springs are defined line by line for easy modifying
**Transverse reinforcement is considered (spacing=3ft)
**Two transverse steel bars (B=6 in.)
************************************************
*preprint, echo=no
**restart,write
************************************************
**Discretize concrete slab using 3D brick elements
************************************************
*node
1,0.,0.,0.
41,60.,0.,0.
801,0.,12.,0.
841,60.,12.,0.
240001,0.,0.,72.
240041,60.,0.,72.
240801,0.,12.,72.
240841,60.,12.,72.
*ngen,nset=bottom1
1,41
*ngen,nset=bottom2
240001,240041
*ngen,nset=top1
801,841
*ngen,nset=top2
240801,240841
*nfill,nset=front
bottom1,top1,8,100
*nfill,nset=back
bottom2,top2,8,100
*nfill,nset=allnodes
front,back,24,10000
*element,type=c3d8,elset=conc
1,1,2,102,101,10001,10002,10102,10101
*elgen,elset=conc
1,40,1,1,8,100,100,24,10000,10000
*solid section,elset=conc,material=concrete
*material,name=concrete
*elastic
2.e6,0.15
*expansion
0.000006
************************************************
** Discretize longitudinal steel bar using beam elements
************************************************
*node
11001,0.,6.,3.
11041,60.,6.,3.
231001,0.,6.,69.
231041,60.,6.,69.
*ngen, nset=nsteel1
11001,11041
*ngen, nset=nsteel12
231001,231041
*nfill, nset=allsteel
nsteel1,nsteel12,11,20000
*element, type=b31, elset=stb1
11001,11001,11002
*elgen, elset=stb1
11001,40,1,1
*elcopy,old set=stb1,new set=stb2,element
shift=20000,shift nodes=20000
*elcopy,old set=stb2,new set=stb3,element
shift=20000,shift nodes=20000
*elcopy,old set=stb3,new set=stb4,element
shift=20000,shift nodes=20000
*elcopy,old set=stb4,new set=stb5,element
shift=20000,shift nodes=20000
*elcopy,old set=stb5,new set=stb6,element
shift=20000,shift nodes=20000
*elcopy,old set=stb6,new set=stb7,element
shift=20000,shift nodes=20000
*elcopy,old set=stb7,new set=stb8,element
shift=20000,shift nodes=20000
*elcopy,old set=stb8,new set=stb9,element
shift=20000,shift nodes=20000
*elcopy,old set=stb9,new set=stb10,element
shift=20000,shift nodes=20000
*elcopy,old set=stb10,new set=stb11,element
shift=20000,shift nodes=20000
*elcopy,old set=stb11,new set=stb12,element
shift=20000,shift nodes=20000
*elset, elset=stbar
stb1,stb2,stb3,stb4,stb5,stb6,stb7,stb8,stb9,stb10,stb11,st
b12
*beam section, elset=stbar, material=steel, section=circ
0.375
*material, name=steel
*elastic
2.9e7
*expansion
0.000005
**When stresses in steel are not wanted to plot, use the
below lines
***beam general section, elset=stbar, section=circ
**0.375
**
**2.9e7,,0.000005
*********************************************
**Connect longitudinal steel and concrete by springs
*********************************************
*element, type=spring2, elset=bsp1
12002,10402,11002
*elgen, elset=bsp1
12002,39,1,1
*elcopy,old set=bsp1,new set=bsp2,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp2,new set=bsp3,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp3,new set=bsp4,element
shift=20000,shift nodes=20000
```

```
*elcopy,old set=bsp4,new set=bsp5,element shift=20000,shift nodes=20000
*elcopy,old set=bsp5,new set=bsp6,element shift=20000,shift nodes=20000
*elcopy,old set=bsp6,new set=bsp7,element shift=20000,shift nodes=20000
*elcopy,old set=bsp7,new set=bsp8,element shift=20000,shift nodes=20000
*elcopy,old set=bsp8,new set=bsp9,element shift=20000,shift nodes=20000
*elcopy,old set=bsp9,new set=bsp10,element shift=20000,shift nodes=20000
*elcopy,old set=bsp10,new set=bsp11,element shift=20000,shift nodes=20000
*elcopy,old set=bsp11,new set=bsp12,element shift=20000,shift nodes=20000
*elset, elset=bondsp
bsp1,bsp2,bsp3,bsp4,bsp5,bsp6,bsp7,bsp8,bsp9,bsp10,bsp11,bsp12
*spring, elset=bondsp
1,1
2474000.
*element, type=spring2, elset=bsc1
12041,10441,11041
*elcopy,old set=bsc1,new set=bsc2,element shift=20000,shift nodes=20000
*elcopy,old set=bsc2,new set=bsc3,element shift=20000,shift nodes=20000
*elcopy,old set=bsc3,new set=bsc4,element shift=20000,shift nodes=20000
*elcopy,old set=bsc4,new set=bsc5,element shift=20000,shift nodes=20000
*elcopy,old set=bsc5,new set=bsc6,element shift=20000,shift nodes=20000
*elcopy,old set=bsc6,new set=bsc7,element shift=20000,shift nodes=20000
*elcopy,old set=bsc7,new set=bsc8,element shift=20000,shift nodes=20000
*elcopy,old set=bsc8,new set=bsc9,element shift=20000,shift nodes=20000
*elcopy,old set=bsc9,new set=bsc10,element shift=20000,shift nodes=20000
*elcopy,old set=bsc10,new set=bsc11,element shift=20000,shift nodes=20000
*elcopy,old set=bsc11,new set=bsc12,element shift=20000,shift nodes=20000
*elset, elset=bondsp1
bsc1,bsc2,bsc3,bsc4,bsc5,bsc6,bsc7,bsc8,bsc9,bsc10,bsc11,bsc12
*spring, elset=bondsp1
1,1
1237000.
*element, type=spring2, elset=bsl1
12001,10401,11001
*elcopy,old set=bsl1,new set=bsl2,element shift=20000,shift nodes=20000
*elcopy,old set=bsl2,new set=bsl3,element shift=20000,shift nodes=20000
*elcopy,old set=bsl3,new set=bsl4,element shift=20000,shift nodes=20000
*elcopy,old set=bsl4,new set=bsl5,element shift=20000,shift nodes=20000
*elcopy,old set=bsl5,new set=bsl6,element shift=20000,shift nodes=20000
*elcopy,old set=bsl6,new set=bsl7,element shift=20000,shift nodes=20000
*elcopy,old set=bsl7,new set=bsl8,element shift=20000,shift nodes=20000
*elcopy,old set=bsl8,new set=bsl9,element shift=20000,shift nodes=20000
*elcopy,old set=bsl9,new set=bsl10,element shift=20000,shift nodes=20000
*elcopy,old set=bsl10,new set=bsl11,element shift=20000,shift nodes=20000
*elcopy,old set=bsl11,new set=bsl12,element shift=20000,shift nodes=20000
*elset, elset=bondsp2
bsl1,bsl2,bsl3,bsl4,bsl5,bsl6,bsl7,bsl8,bsl9,bsl10,bsl11,bsl12
*spring, elset=bondsp2
1,1
1237000.
*************************************************
**Modeling of underlying layers using springs
*************************************************
*element, type=spring1, elset=vertsp
13002,10002
23002,20002
33002,30002
43002,40002
53002,50002
63002,60002
73002,70002
83002,80002
93002,90002
103002,100002
113002,110002
123002,120002
133002,130002
143002,140002
153002,150002
163002,160002
173002,170002
183002,180002
193002,190002
203002,200002
213002,210002
223002,220002
233002,230002
*elgen, elset=vertsp
13002,39,1,1
23002,39,1,1
33002,39,1,1
43002,39,1,1
53002,39,1,1
63002,39,1,1
73002,39,1,1
83002,39,1,1
93002,39,1,1
103002,39,1,1
```

```
113002,39,1,1
123002,39,1,1
133002,39,1,1
143002,39,1,1
153002,39,1,1
163002,39,1,1
173002,39,1,1
183002,39,1,1
193002,39,1,1
203002,39,1,1
213002,39,1,1
223002,39,1,1
233002,39,1,1
*spring, elset=vertsp
2
1800.
*element, type=spring1, elset=vertsp1
3002,2
*elgen, elset=vertsp1
3002,39,1,1
*spring, elset=vertsp1
2
900.
*element, type=spring1, elset=vertsp2
243002,240002
*elgen, elset=vertsp2
243002,39,1,1
*spring, elset=vertsp2
2
900.
*element, type=spring1, elset=vertsp3
13001,10001
*elgen, elset=vertsp3
13001,23,10000,10000
*spring, elset=vertsp3
2
900.
*element, type=spring1, elset=vertsp4
13041,10041
*elgen, elset=vertsp4
13041,23,10000,10000
*spring, elset=vertsp4
2
900.
*element, type=spring1, elset=vertsp5
3001,1
*spring, elset=vertsp5
2
450.
*element, type=spring1, elset=vertsp6
3041,41
*spring, elset=vertsp6
2
450.
*element, type=spring1, elset=vertsp7
243001,240001
*spring, elset=vertsp7
2
450.
*element, type=spring1, elset=vertsp8
243041,240041
*spring, elset=vertsp8
2
450.
*elset, elset=vertspa
vertsp,vertsp1,vertsp2,vertsp3,vertsp4,vertsp5,vertsp6,ve
rtsp7,vertsp8
************************************************
**Modeling of frictional bond in longitudinal direction
**between conc and base using springs
************************************************
*element, type=spring1, elset=horspx
14002,10002
24002,20002
34002,30002
44002,40002
54002,50002
64002,60002
74002,70002
84002,80002
94002,90002
104002,100002
114002,110002
124002,120002
134002,130002
144002,140002
154002,150002
164002,160002
174002,170002
184002,180002
194002,190002
204002,200002
214002,210002
224002,220002
234002,230002
*elgen, elset=horspx
14002,39,1,1
24002,39,1,1
34002,39,1,1
44002,39,1,1
54002,39,1,1
64002,39,1,1
74002,39,1,1
84002,39,1,1
94002,39,1,1
104002,39,1,1
114002,39,1,1
124002,39,1,1
134002,39,1,1
144002,39,1,1
154002,39,1,1
164002,39,1,1
174002,39,1,1
184002,39,1,1
194002,39,1,1
204002,39,1,1
214002,39,1,1
224002,39,1,1
234002,39,1,1
*spring, elset=horspx
```

```
1
675.
*element, type=spring1, elset=horspx1
4002,2
*elgen, elset=horspx1
4002,39,1,1
*spring, elset=horspx1
1
337.5
*element, type=spring1, elset=horspx2
244002,240002
*elgen, elset=horspx2
244002,39,1,1
*spring, elset=horspx2
1
337.5
*element, type=spring1, elset=horspx3
14001,10001
*elgen, elset=horspx3
14001,23,10000,10000
*spring, elset=horspx3
1
337.5
*element, type=spring1, elset=horspx4
14041,10041
*elgen, elset=horspx4
14041,23,10000,10000
*spring, elset=horspx4
1
337.5
*element, type=spring1, elset=horspx5
4001,1
*spring, elset=horspx5
1
168.75
*element, type=spring1, elset=horspx6
4041,41
*spring, elset=horspx6
1
168.75
*element, type=spring1, elset=horspx7
244001,240001
*spring, elset=horspx7
1
168.75
*element, type=spring1, elset=horspx8
244041,240041
*spring, elset=horspx8
1
168.75
************************************************
**Modeling of frictional bond in transverse direction
**between conc and base using springs
************************************************
*element, type=spring1, elset=horspz
17002,10002
27002,20002
37002,30002
47002,40002
57002,50002
67002,60002
77002,70002
87002,80002
97002,90002
107002,100002
117002,110002
127002,120002
137002,130002
147002,140002
157002,150002
167002,160002
177002,170002
187002,180002
197002,190002
207002,200002
217002,210002
227002,220002
237002,230002
*elgen, elset=horspz
17002,39,1,1
27002,39,1,1
37002,39,1,1
47002,39,1,1
57002,39,1,1
67002,39,1,1
77002,39,1,1
87002,39,1,1
97002,39,1,1
107002,39,1,1
117002,39,1,1
127002,39,1,1
137002,39,1,1
147002,39,1,1
157002,39,1,1
167002,39,1,1
177002,39,1,1
187002,39,1,1
197002,39,1,1
207002,39,1,1
217002,39,1,1
227002,39,1,1
237002,39,1,1
*spring, elset=horspz
3
675.
*element, type=spring1, elset=horspz1
7002,2
*elgen, elset=horspz1
7002,39,1,1
*spring, elset=horspz1
3
337.5
*element, type=spring1, elset=horspz2
247002,240002
*elgen, elset=horspz2
247002,39,1,1
*spring, elset=horspz2
3
337.5
*element, type=spring1, elset=horspz3
```

```
17001,10001
*elgen, elset=horspz3
17001,23,10000,10000
*spring, elset=horspz3
3
337.5
*element, type=spring1, elset=horspz4
17041,10041
*elgen, elset=horspz4
17041,23,10000,10000
*spring, elset=horspz4
3
337.5
*element, type=spring1, elset=horspz5
7001,1
*spring, elset=horspz5
3
168.75
*element, type=spring1, elset=horspz6
7041,41
*spring, elset=horspz6
3
168.75
*element, type=spring1, elset=horspz7
247001,240001
*spring, elset=horspz7
3
168.75
*element, type=spring1, elset=horspz8
247041,240041
*spring, elset=horspz8
3
168.75
**********************************************
**Modeling of y and z compatibility bet. steel and conc.
**********************************************
*element, type=spring2, elset=yrigid
15001,10401,11001
*elgen, elset=yrigid
15001,41,1,1,12,20000,20000
*spring, elset=yrigid
2,2
10000000000.
*element, type=spring2, elset=zrigid
16001,10401,11001
*elgen, elset=zrigid
16001,41,1,1,12,20000,20000
*spring, elset=zrigid
3,3
10000000000.
**********************************************
**Modeling of transverse reinforcement
**********************************************
*node
500005,6.,6.,0.
740005,6.,6.,72.
500029,42.,6.,0.
740029,42.,6.,72
*ngen, nset=nsttr1
500005,740005,10000
*ngen, nset=nsttr2
500029,740029,10000
*nset, nset=allsttr
nsttr1,nsttr2
*element, type=b31, elset=sttr1
500005,500005,510005
*elgen, elset=sttr1
500005,24,10000,10000
*elcopy, old set=sttr1,new set=sttr2,element
shift=24,shift nodes=24
*elset, elset=sttr
sttr1,sttr2
*beam section, elset=sttr, material=trsteel, section=circ
0.3125
-1.,0.,0.
*material, name=trsteel
*elastic
2.9e7
*expansion
0.000005
**********************************************
**Modeling of bond-slip between transv. steel and conc.
**********************************************
*element, type=spring2, elset=bsptr1
511005,10405,510005
*elgen, elset=bsptr1
511005,23,10000,10000
*elcopy,old set=bsptr1,new set=bsptr2,element
shift=24,shift nodes=24
*elset, elset=bondsptr
bsptr1,bsptr2
*spring, elset=bondsptr
3,3
4123339.5
*element, type=spring2, elset=bsbtr1
741005,240405,740005
*elcopy,old set=bsbtr1,new set=bsbtr2,element
shift=24,shift nodes=24
*elset, elset=bondspt1
bsbtr1,bsbtr2
*spring, elset=bondspt1
3,3
2061669.75
*element, type=spring2, elset=bsftr1
501005,405,500005
*elcopy,old set=bsftr1,new set=bsftr2,element
shift=24,shift nodes=24
*elset, elset=bondspt2
bsftr1,bsftr2
*spring, elset=bondspt2
3,3
2061669.75
**********************************************
**Modeling of compatibility for transv. reinforcement
**********************************************
*element, type=spring2, elset=xrigidtr
502005,405,500005
*elgen, elset=xrigidtr
502005,2,24,24,25,10000,10000
*spring, elset=xrigidtr
```

```
1,1
10000000000.
*element, type=spring2, elset=yrigidtr
503005,405,500005
*elgen, elset=yrigidtr
503005,2,24,24,25,10000,10000
*spring, elset=yrigidtr
2,2
10000000000.
******************************************
*nset, nset=bottom, gen
1,41
10001,10041
20001,20041
30001,30041
40001,40041
50001,50041
60001,60041
70001,70041
80001,80041
90001,90041
100001,100041
110001,110041
120001,120041
130001,130041
140001,140041
150001,150041
160001,160041
170001,170041
180001,180041
190001,190041
200001,200041
210001,210041
220001,220041
230001,230041
240001,240041
*nset, nset=botmid1, gen
101,141
10101,10141
20101,20141
30101,30141
40101,40141
50101,50141
60101,60141
70101,70141
80101,80141
90101,90141
100101,100141
110101,110141
120101,120141
130101,130141
140101,140141
150101,150141
160101,160141
170101,170141
180101,180141
190101,190141
200101,200141
210101,210141
220101,220141
230101,230141
240101,240141
*nset, nset=botmid2, gen
201,241
10201,10241
20201,20241
30201,30241
40201,40241
50201,50241
60201,60241
70201,70241
80201,80241
90201,90241
100201,100241
110201,110241
120201,120241
130201,130241
140201,140241
150201,150241
160201,160241
170201,170241
180201,180241
190201,190241
200201,200241
210201,210241
220201,220241
230201,230241
240201,240241
*nset, nset=botmid3, gen
301,341
10301,10341
20301,20341
30301,30341
40301,40341
50301,50341
60301,60341
70301,70341
80301,80341
90301,90341
100301,100341
110301,110341
120301,120341
130301,130341
140301,140341
150301,150341
160301,160341
170301,170341
180301,180341
190301,190341
200301,200341
210301,210341
220301,220341
230301,230341
240301,240341
*nset, nset=middle, gen
401,441
10401,10441
20401,20441
30401,30441
40401,40441
```

```
50401,50441
60401,60441
70401,70441
80401,80441
90401,90441
100401,100441
110401,110441
120401,120441
130401,130441
140401,140441
150401,150441
160401,160441
170401,170441
180401,180441
190401,190441
200401,200441
210401,210441
220401,220441
230401,230441
240401,240441
*nset, nset=midtop1, gen
501,541
10501,10541
20501,20541
30501,30541
40501,40541
50501,50541
60501,60541
70501,70541
80501,80541
90501,90541
100501,100541
110501,110541
120501,120541
130501,130541
140501,140541
150501,150541
160501,160541
170501,170541
180501,180541
190501,190541
200501,200541
210501,210541
220501,220541
230501,230541
240501,240541
*nset, nset=midtop2, gen
601,641
10601,10641
20601,20641
30601,30641
40601,40641
50601,50641
60601,60641
70601,70641
80601,80641
90601,90641
100601,100641
110601,110641
120601,120641
130601,130641
140601,140641
150601,150641
160601,160641
170601,170641
180601,180641
190601,190641
200601,200641
210601,210641
220601,220641
230601,230641
240601,240641
*nset, nset=midtop3, gen
701,741
10701,10741
20701,20741
30701,30741
40701,40741
50701,50741
60701,60741
70701,70741
80701,80741
90701,90741
100701,100741
110701,110741
120701,120741
130701,130741
140701,140741
150701,150741
160701,160741
170701,170741
180701,180741
190701,190741
200701,200741
210701,210741
220701,220741
230701,230741
240701,240741
*nset, nset=top, gen
801,841
10801,10841
20801,20841
30801,30841
40801,40841
50801,50841
60801,60841
70801,70841
80801,80841
90801,90841
100801,100841
110801,110841
120801,120841
130801,130841
140801,140841
150801,150841
160801,160841
170801,170841
180801,180841
190801,190841
200801,200841
```

```
210801,210841
220801,220841
230801,230841
240801,240841
***nset, nset=left, gen
**1,240001,10000
**101,240101,10000
**201,240201,10000
**301,240301,10000
**401,240401,10000
**501,240501,10000
**601,240601,10000
**701,240701,10000
**801,240801,10000
*nset, nset=stleft, gen
11001,231001,20000
*nset, nset=stright, gen
11041,231041,20000
*nset, nset=trstfron
500005,500029
*nset, nset=trstback
740005,740029
*nset, nset=rigtopcr, gen
841,240841,10000
*nset, nset=leftopcr, gen
801,240801,10000
*elset, elset=topedge, gen
230701,230740,1
*elset, elset=topcent, gen
701,740,1
*boundary
front,3
stleft,1
stleft,4,6
stright,1
stright,4,6
trstfron,3
trstfron,4,6
trstback,3
trstback,4,6
*initial conditions, type=temperature
allnodes,120.
allsteel,120.
allsttr,120.
*******************
*step
*static
*temperature
top,85.
midtop3,86.875
midtop2,88.75
midtop1,90.625
middle,92.5
botmid3,94.375
botmid2,96.25
botmid1,98.125
bottom,100.
allsteel,92.5
allsttr,92.5
*dload
conc,by,-0.084
stbar,py,-0.125275
sttr,py,-0.086997
*el print, elset=topcent
S11
*el print, elset=topedge
S11
***el print, elset=vertspa
**E11
*node print, nset=leftopcr
u1
*node print, nset=rigtopcr
u1
*end step
```

APPENDIX D:

SAMPLE INPUT FOR 3-D NONLINEAR CRCP MODEL

```
*heading
CRCP3DNON
************************************************
**Slab length=5ft
**Base friction in both. direc. considered (Nonlinear)
**Dead load of concrete and steel considered
**Spring elements for underlying layers (Tensionless)
**Springs are defined line by line for easy modifying
**Transverse reinforcement is considered (spacing=3ft)
**Two transverse steel bars (B=6 in.)
**Nonlinear system
************************************************
*preprint, echo=no
**restart,write
************************************************
**Discretize concrete slab using 3D brick elements
************************************************
*node
1,0.,0.,0.
41,60.,0.,0.
801,0.,12.,0.
841,60.,12.,0.
240001,0.,0.,72.
240041,60.,0.,72.
240801,0.,12.,72.
240841,60.,12.,72.
*ngen,nset=bottom1
1,41
*ngen,nset=bottom2
240001,240041
*ngen,nset=top1
801,841
*ngen,nset=top2
240801,240841
*nfill,nset=front
bottom1,top1,8,100
*nfill,nset=back
bottom2,top2,8,100
*nfill,nset=allnodes
front,back,24,10000
*element,type=c3d8,elset=conc
1,1,2,102,101,10001,10002,10102,10101
*elgen,elset=conc
1,40,1,1,8,100,100,24,10000,10000
*solid section,elset=conc,material=concrete
*material,name=concrete
*elastic
2.e6,0.15
*expansion
0.000006
*viscoelastic, time=prony
0.45,0.45,48.
************************************************
** Discretize longitudinal steel bar using beam elements
************************************************
*node
11001,0.,6.,3.
11041,60.,6.,3.
231001,0.,6.,69.
231041,60.,6.,69.
*ngen, nset=nsteel1
11001,11041
*ngen, nset=nsteel12
231001,231041
*nfill, nset=allsteel
nsteel1,nsteel12,11,20000
*element, type=b31, elset=stb1
11001,11001,11002
*elgen, elset=stb1
11001,40,1,1
*elcopy,old set=stb1,new set=stb2,element
shift=20000,shift nodes=20000
*elcopy,old set=stb2,new set=stb3,element
shift=20000,shift nodes=20000
*elcopy,old set=stb3,new set=stb4,element
shift=20000,shift nodes=20000
*elcopy,old set=stb4,new set=stb5,element
shift=20000,shift nodes=20000
*elcopy,old set=stb5,new set=stb6,element
shift=20000,shift nodes=20000
*elcopy,old set=stb6,new set=stb7,element
shift=20000,shift nodes=20000
*elcopy,old set=stb7,new set=stb8,element
shift=20000,shift nodes=20000
*elcopy,old set=stb8,new set=stb9,element
shift=20000,shift nodes=20000
*elcopy,old set=stb9,new set=stb10,element
shift=20000,shift nodes=20000
*elcopy,old set=stb10,new set=stb11,element
shift=20000,shift nodes=20000
*elcopy,old set=stb11,new set=stb12,element
shift=20000,shift nodes=20000
*elset, elset=stbar
stb1,stb2,stb3,stb4,stb5,stb6,stb7,stb8,stb9,stb10,stb11,st
b12
*beam section, elset=stbar, material=steel, section=circ
0.375
*material, name=steel
*elastic
2.9e7
*expansion
0.000005
**When stresses in steel are not wanted to plot, use the
below lines
***beam general section, elset=stbar, section=circ
**0.375
**
**2.9e7,,0.000005
********************************************
**Connect longitudinal steel and concrete by springs
********************************************
*element, type=spring2, elset=bsp1
12002,10402,11002
*elgen, elset=bsp1
12002,39,1,1
*elcopy,old set=bsp1,new set=bsp2,element
shift=20000,shift nodes=20000
```

```
*elcopy,old set=bsp2,new set=bsp3,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp3,new set=bsp4,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp4,new set=bsp5,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp5,new set=bsp6,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp6,new set=bsp7,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp7,new set=bsp8,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp8,new set=bsp9,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp9,new set=bsp10,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp10,new set=bsp11,element
shift=20000,shift nodes=20000
*elcopy,old set=bsp11,new set=bsp12,element
shift=20000,shift nodes=20000
*elset, elset=bondsp
bsp1,bsp2,bsp3,bsp4,bsp5,bsp6,bsp7,bsp8,bsp9,bsp10,bs
p11,bsp12
*spring, elset=bondsp, nonlinear
***spring, elset=bondsp
1,1
**2474000.
0.,-0.008
-954.3,-0.004
-2721.4,-0.002
-2474.,-0.001
0.,0.
2474.,0.001
2721.4,0.002
954.3,0.004
0.,0.008
*element, type=spring2, elset=bsc1
12041,10441,11041
*elcopy,old set=bsc1,new set=bsc2,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc2,new set=bsc3,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc3,new set=bsc4,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc4,new set=bsc5,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc5,new set=bsc6,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc6,new set=bsc7,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc7,new set=bsc8,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc8,new set=bsc9,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc9,new set=bsc10,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc10,new set=bsc11,element
shift=20000,shift nodes=20000
*elcopy,old set=bsc11,new set=bsc12,element
shift=20000,shift nodes=20000
```

```
*elset, elset=bondsp1
bsc1,bsc2,bsc3,bsc4,bsc5,bsc6,bsc7,bsc8,bsc9,bsc10,bsc
11,bsc12
*spring, elset=bondsp1, nonlinear
***spring, elset=bondsp1
1,1
**1237000.
0.,-0.008
-477.15,-0.004
-1360.7,-0.002
-1237.,-0.001
0.,0.
1237.,0.001
1360.7,0.002
477.15,0.004
0.,0.008
*element, type=spring2, elset=bsl1
12001,10401,11001
*elcopy,old set=bsl1,new set=bsl2,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl2,new set=bsl3,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl3,new set=bsl4,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl4,new set=bsl5,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl5,new set=bsl6,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl6,new set=bsl7,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl7,new set=bsl8,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl8,new set=bsl9,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl9,new set=bsl10,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl10,new set=bsl11,element
shift=20000,shift nodes=20000
*elcopy,old set=bsl11,new set=bsl12,element
shift=20000,shift nodes=20000
*elset, elset=bondsp2
bsl1,bsl2,bsl3,bsl4,bsl5,bsl6,bsl7,bsl8,bsl9,bsl10,bsl11,b
sl12
*spring, elset=bondsp2, nonlinear
***spring, elset=bondsp2
1,1
**1237000.
0.,-0.008
-477.15,-0.004
-1360.7,-0.002
-1237.,-0.001
0.,0.
1237.,0.001
1360.7,0.002
477.15,0.004
0.,0.008
************************************************
**Modeling of underlying layers using spr. (Tensionless)
************************************************
*element, type=spring1, elset=vertsp
```

```
13002,10002
23002,20002
33002,30002
43002,40002
53002,50002
63002,60002
73002,70002
83002,80002
93002,90002
103002,100002
113002,110002
123002,120002
133002,130002
143002,140002
153002,150002
163002,160002
173002,170002
183002,180002
193002,190002
203002,200002
213002,210002
223002,220002
233002,230002
*elgen, elset=vertsp
13002,39,1,1
23002,39,1,1
33002,39,1,1
43002,39,1,1
53002,39,1,1
63002,39,1,1
73002,39,1,1
83002,39,1,1
93002,39,1,1
103002,39,1,1
113002,39,1,1
123002,39,1,1
133002,39,1,1
143002,39,1,1
153002,39,1,1
163002,39,1,1
173002,39,1,1
183002,39,1,1
193002,39,1,1
203002,39,1,1
213002,39,1,1
223002,39,1,1
233002,39,1,1
***spring, elset=vertsp
*spring, elset=vertsp, nonlinear
2
**1800.
-3600.,-2.
0.,0.
*element, type=spring1, elset=vertsp1
3002,2
*elgen, elset=vertsp1
3002,39,1,1
***spring, elset=vertsp1
*spring, elset=vertsp1, nonlinear
2
**900.
-1800.,-2.
0.,0.
*element, type=spring1, elset=vertsp2
243002,240002
*elgen, elset=vertsp2
243002,39,1,1
***spring, elset=vertsp2
*spring, elset=vertsp2, nonlinear
2
**900.
-1800.,-2.
0.,0.
*element, type=spring1, elset=vertsp3
13001,10001
*elgen, elset=vertsp3
13001,23,10000,10000
***spring, elset=vertsp3
*spring, elset=vertsp3, nonlinear
2
**900.
-1800.,-2.
0.,0.
*element, type=spring1, elset=vertsp4
13041,10041
*elgen, elset=vertsp4
13041,23,10000,10000
***spring, elset=vertsp4
*spring, elset=vertsp4, nonlinear
2
**900.
-1800.,-2.
0.,0.
*element, type=spring1, elset=vertsp5
3001,1
***spring, elset=vertsp5
*spring, elset=vertsp5, nonlinear
2
**450.
-900.,-2.
0.,0.
*element, type=spring1, elset=vertsp6
3041,41
***spring, elset=vertsp6
*spring, elset=vertsp6, nonlinear
2
**450.
-900.,-2.
0.,0.
*element, type=spring1, elset=vertsp7
243001,240001
***spring, elset=vertsp7
*spring, elset=vertsp7, nonlinear
2
**450.
-900.,-2.
0.,0.
*element, type=spring1, elset=vertsp8
243041,240041
***spring, elset=vertsp8
```

```
*spring, elset=vertsp8, nonlinear
2
**450.
-900.,-2.
0.,0.
***elset, elset=vertspa
**vertsp,vertsp1,vertsp2,vertsp3,vertsp4,vertsp5,vertsp6,
vertsp7,vertsp8
************************************************
**Modeling of frictional bond in longitudinal direction
**between conc and base using springs
************************************************
*element, type=spring1, elset=horspx
14002,10002
24002,20002
34002,30002
44002,40002
54002,50002
64002,60002
74002,70002
84002,80002
94002,90002
104002,100002
114002,110002
124002,120002
134002,130002
144002,140002
154002,150002
164002,160002
174002,170002
184002,180002
194002,190002
204002,200002
214002,210002
224002,220002
234002,230002
*elgen, elset=horspx
14002,39,1,1
24002,39,1,1
34002,39,1,1
44002,39,1,1
54002,39,1,1
64002,39,1,1
74002,39,1,1
84002,39,1,1
94002,39,1,1
104002,39,1,1
114002,39,1,1
124002,39,1,1
134002,39,1,1
144002,39,1,1
154002,39,1,1
164002,39,1,1
174002,39,1,1
184002,39,1,1
194002,39,1,1
204002,39,1,1
214002,39,1,1
224002,39,1,1
234002,39,1,1
*spring, elset=horspx
1
675.
*element, type=spring1, elset=horspx1
4002,2
*elgen, elset=horspx1
4002,39,1,1
*spring, elset=horspx1
1
337.5
*element, type=spring1, elset=horspx2
244002,240002
*elgen, elset=horspx2
244002,39,1,1
*spring, elset=horspx2
1
337.5
*element, type=spring1, elset=horspx3
14001,10001
*elgen, elset=horspx3
14001,23,10000,10000
*spring, elset=horspx3
1
337.5
*element, type=spring1, elset=horspx4
14041,10041
*elgen, elset=horspx4
14041,23,10000,10000
*spring, elset=horspx4
1
337.5
*element, type=spring1, elset=horspx5
4001,1
*spring, elset=horspx5
1
168.75
*element, type=spring1, elset=horspx6
4041,41
*spring, elset=horspx6
1
168.75
*element, type=spring1, elset=horspx7
244001,240001
*spring, elset=horspx7
1
168.75
*element, type=spring1, elset=horspx8
244041,240041
*spring, elset=horspx8
1
168.75
************************************************
**Modeling of frictional bond in transverse direction
**between conc and base using springs
************************************************
*element, type=spring1, elset=horspz
17002,10002
27002,20002
37002,30002
47002,40002
```

```
57002,50002
67002,60002
77002,70002
87002,80002
97002,90002
107002,100002
117002,110002
127002,120002
137002,130002
147002,140002
157002,150002
167002,160002
177002,170002
187002,180002
197002,190002
207002,200002
217002,210002
227002,220002
237002,230002
*elgen, elset=horspz
17002,39,1,1
27002,39,1,1
37002,39,1,1
47002,39,1,1
57002,39,1,1
67002,39,1,1
77002,39,1,1
87002,39,1,1
97002,39,1,1
107002,39,1,1
117002,39,1,1
127002,39,1,1
137002,39,1,1
147002,39,1,1
157002,39,1,1
167002,39,1,1
177002,39,1,1
187002,39,1,1
197002,39,1,1
207002,39,1,1
217002,39,1,1
227002,39,1,1
237002,39,1,1
*spring, elset=horspz
3
675.
*element, type=spring1, elset=horspz1
7002,2
*elgen, elset=horspz1
7002,39,1,1
*spring, elset=horspz1
3
337.5
*element, type=spring1, elset=horspz2
247002,240002
*elgen, elset=horspz2
247002,39,1,1
*spring, elset=horspz2
3
337.5
*element, type=spring1, elset=horspz3
17001,10001
*elgen, elset=horspz3
17001,23,10000,10000
*spring, elset=horspz3
3
337.5
*element, type=spring1, elset=horspz4
17041,10041
*elgen, elset=horspz4
17041,23,10000,10000
*spring, elset=horspz4
3
337.5
*element, type=spring1, elset=horspz5
7001,1
*spring, elset=horspz5
3
168.75
*element, type=spring1, elset=horspz6
7041,41
*spring, elset=horspz6
3
168.75
*element, type=spring1, elset=horspz7
247001,240001
*spring, elset=horspz7
3
168.75
*element, type=spring1, elset=horspz8
247041,240041
*spring, elset=horspz8
3
168.75
************************************************
**Modeling of y and z compatibility bet. steel and conc.
************************************************
*element, type=spring2, elset=yrigid
15001,10401,11001
*elgen, elset=yrigid
15001,41,1,1,12,20000,20000
*spring, elset=yrigid
2,2
10000000000.
*element, type=spring2, elset=zrigid
16001,10401,11001
*elgen, elset=zrigid
16001,41,1,1,12,20000,20000
*spring, elset=zrigid
3,3
10000000000.
************************************************
**Modeling of transverse reinforcement
************************************************
*node
500005,6.,6.,0.
740005,6.,6.,72.
500029,42.,6.,0.
740029,42.,6.,72
*ngen, nset=nsttr1
```

```
500005,740005,10000
*ngen, nset=nsttr2
500029,740029,10000
*nset, nset=allsttr
nsttr1,nsttr2
*element, type=b31, elset=sttr1
500005,500005,510005
*elgen, elset=sttr1
500005,24,10000,10000
*elcopy, old set=sttr1,new set=sttr2,element
shift=24,shift nodes=24
*elset, elset=sttr
sttr1,sttr2
*beam section, elset=sttr, material=trsteel, section=circ
0.3125
-1.,0.,0.
*material, name=trsteel
*elastic
2.9e7
*expansion
0.000005
**************************************************
**Modeling of bond-slip between transv. steel and conc.
**************************************************
*element, type=spring2, elset=bsptr1
511005,10405,510005
*elgen, elset=bsptr1
511005,23,10000,10000
*elcopy,old set=bsptr1,new set=bsptr2,element
shift=24,shift nodes=24
*elset, elset=bondsptr
bsptr1,bsptr2
*spring, elset=bondsptr, nonlinear
***spring, elset=bondsptr
3,3
**4123339.5
0.,-0.008
-1590.43,-0.004
-4535.674,-0.002
-4123.34,-0.001
0.,0.
4123.34,0.001
4535.674,0.002
1590.43,0.004
0.,0.008
*element, type=spring2, elset=bsbtr1
741005,240405,740005
*elcopy,old set=bsbtr1,new set=bsbtr2,element
shift=24,shift nodes=24
*elset, elset=bondspt1
bsbtr1,bsbtr2
*spring, elset=bondspt1, nonlinear
***spring, elset=bondspt1
3,3
**2061669.75
0.,-0.008
-795.215,-0.004
-2267.837,-0.002
-2061.67,-0.001
0.,0.
2061.67,0.001
2267.837,0.002
795.215,0.004
0.,0.008
*element, type=spring2, elset=bsftr1
501005,405,500005
*elcopy,old set=bsftr1,new set=bsftr2,element
shift=24,shift nodes=24
*elset, elset=bondspt2
bsftr1,bsftr2
*spring, elset=bondspt2, nonlinear
***spring, elset=bondspt2
3,3
**2061669.75
0.,-0.008
-795.215,-0.004
-2267.837,-0.002
-2061.67,-0.001
0.,0.
2061.67,0.001
2267.837,0.002
795.215,0.004
0.,0.008
**************************************************
**Modeling of compatibility for transv. reinforcement
**************************************************
*element, type=spring2, elset=xrigidtr
502005,405,500005
*elgen, elset=xrigidtr
502005,2,24,24,25,10000,10000
*spring, elset=xrigidtr
1,1
10000000000.
*element, type=spring2, elset=yrigidtr
503005,405,500005
*elgen, elset=yrigidtr
503005,2,24,24,25,10000,10000
*spring, elset=yrigidtr
2,2
10000000000.
********************************************
*nset, nset=bottom, gen
1,41
10001,10041
20001,20041
30001,30041
40001,40041
50001,50041
60001,60041
70001,70041
80001,80041
90001,90041
100001,100041
110001,110041
120001,120041
130001,130041
140001,140041
150001,150041
160001,160041
170001,170041
```

```
180001,180041
190001,190041
200001,200041
210001,210041
220001,220041
230001,230041
240001,240041
*nset, nset=botmid1, gen
101,141
10101,10141
20101,20141
30101,30141
40101,40141
50101,50141
60101,60141
70101,70141
80101,80141
90101,90141
100101,100141
110101,110141
120101,120141
130101,130141
140101,140141
150101,150141
160101,160141
170101,170141
180101,180141
190101,190141
200101,200141
210101,210141
220101,220141
230101,230141
240101,240141
*nset, nset=botmid2, gen
201,241
10201,10241
20201,20241
30201,30241
40201,40241
50201,50241
60201,60241
70201,70241
80201,80241
90201,90241
100201,100241
110201,110241
120201,120241
130201,130241
140201,140241
150201,150241
160201,160241
170201,170241
180201,180241
190201,190241
200201,200241
210201,210241
220201,220241
230201,230241
240201,240241
*nset, nset=botmid3, gen
301,341
10301,10341
20301,20341
30301,30341
40301,40341
50301,50341
60301,60341
70301,70341
80301,80341
90301,90341
100301,100341
110301,110341
120301,120341
130301,130341
140301,140341
150301,150341
160301,160341
170301,170341
180301,180341
190301,190341
200301,200341
210301,210341
220301,220341
230301,230341
240301,240341
*nset, nset=middle, gen
401,441
10401,10441
20401,20441
30401,30441
40401,40441
50401,50441
60401,60441
70401,70441
80401,80441
90401,90441
100401,100441
110401,110441
120401,120441
130401,130441
140401,140441
150401,150441
160401,160441
170401,170441
180401,180441
190401,190441
200401,200441
210401,210441
220401,220441
230401,230441
240401,240441
*nset, nset=midtop1, gen
501,541
10501,10541
20501,20541
30501,30541
40501,40541
50501,50541
60501,60541
70501,70541
```

```
80501,80541
90501,90541
100501,100541
110501,110541
120501,120541
130501,130541
140501,140541
150501,150541
160501,160541
170501,170541
180501,180541
190501,190541
200501,200541
210501,210541
220501,220541
230501,230541
240501,240541
*nset, nset=midtop2, gen
601,641
10601,10641
20601,20641
30601,30641
40601,40641
50601,50641
60601,60641
70601,70641
80601,80641
90601,90641
100601,100641
110601,110641
120601,120641
130601,130641
140601,140641
150601,150641
160601,160641
170601,170641
180601,180641
190601,190641
200601,200641
210601,210641
220601,220641
230601,230641
240601,240641
*nset, nset=midtop3, gen
701,741
10701,10741
20701,20741
30701,30741
40701,40741
50701,50741
60701,60741
70701,70741
80701,80741
90701,90741
100701,100741
110701,110741
120701,120741
130701,130741
140701,140741
150701,150741
160701,160741
170701,170741
180701,180741
190701,190741
200701,200741
210701,210741
220701,220741
230701,230741
240701,240741
*nset, nset=top, gen
801,841
10801,10841
20801,20841
30801,30841
40801,40841
50801,50841
60801,60841
70801,70841
80801,80841
90801,90841
100801,100841
110801,110841
120801,120841
130801,130841
140801,140841
150801,150841
160801,160841
170801,170841
180801,180841
190801,190841
200801,200841
210801,210841
220801,220841
230801,230841
240801,240841
***nset, nset=left, gen
**1,240001,10000
**101,240101,10000
**201,240201,10000
**301,240301,10000
**401,240401,10000
**501,240501,10000
**601,240601,10000
**701,240701,10000
**801,240801,10000
*nset, nset=stleft, gen
11001,231001,20000
*nset, nset=stright, gen
11041,231041,20000
*nset, nset=trstfron
500005,500029
*nset, nset=trstback
740005,740029
*nset, nset=rigtopcr, gen
841,240841,10000
*nset, nset=leftopcr, gen
801,240801,10000
*elset, elset=topedge, gen
230701,230740,1
*elset, elset=topcent, gen
```

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701,740,1
*elset, elset=left0, gen
701,230701,10000
*elset, elset=left15, gen
710,230710,10000
*elset, elset=left30, gen
720,230720,10000
*boundary
front,3
stleft,1
stleft,4,6
stright,1
stright,4,6
trstfron,3
trstfron,4,6
trstback,3
trstback,4,6
*initial conditions, type=temperature
allnodes,0.
allsteel,0.
allsttr,0.
*amplitude, name=tem
0.,0.,12.,1.
********************
*step
***static
*visco
4.,12.,0.5
*temperature, amplitude=tem
top,-35.
midtop3,-33.125
midtop2,-31.25
midtop1,-29.375
middle,-27.5
botmid3,-25.625
botmid2,-23.75
botmid1,-21.875
bottom,-20.
allsteel,-27.5
allsttr,-27.5
*dload
conc,by,-0.084
stbar,py,-0.125275
sttr,py,-0.086997
*el print, elset=left0
S11
S33
*el print, elset=left15
S11
S33
*el print, elset=left30
S11
S33
*el print, elset=topcent
S11
S33
*el print, elset=topedge
S11
S33
*node print, nset=leftopcr
u1
*node print, nset=rigtopcr
u1
*end step
```