

# Modeling of Interaction Between Steel and Concrete in Continuously Reinforced Concrete Pavements

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16. Abstract Continuously reinforced concrete pavement (CRCP) contains continuous longitudinal reinforcement with no transverse expansion within the early life of the pavement and can continue to develop cracks in the long-term. The accurate modeling of CRCPs main features is of primary importance in a mechanistic-empirical pavement design procedure. Design tool such as CRCP-9 and CRCP-10 have the capability to analyze continuous pavements under traffic, environmental, and thermal loads and has the capability to predict crack spacing. CRCP-9 and 10 were developed using 2-D and 3-D finite element theory to calculate stresses in concrete and steel bars due to environmental loads. In order to develop a reliable model that better represents the behavior of CRCP, a clear understanding of the interaction between the concrete and steel is essential. Therefore, a parametric analysis was developed, using the 3-D finite element model of the CRCP computer programs in ABAQUS, to investigate the concrete stress distribution while varying the slab thickness.			
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## **Chapter 1 – Introduction**

Early concrete pavements were poured without joints and were not reinforced. Due to traffic loading, formation level, and environmental effects, these pavements began to develop random cracks and eventually caused pavement distresses and failures. In an effort to control the development of cracks, joints were added to the pavements and were placed either to guarantee no cracks or to ensure cracks only at controlled areas (Won et al. 1991). Jointed concrete pavements (JCP) are now the most commonly used type of rigid pavements. However, major pavement distresses due to traffic and environmental loads, e.g., faulting, are observed on JCPs (McCullough and Office 1994). To avoid transverse joints, continuously-reinforced concrete pavement (CRCP) was developed by the U.S. Bureau of Public Roads (Pasko 1998). The primary advantages of the use of CRCPs include the improvement of ride quality, safety, long life, and limited need for maintenance (Won et al. 1991). The increased usage of CRCPs has resulted in continuous investigation and in the development of many design models. Although there are many benefits that can be attributed to CRCPs, it is important to investigate the relationship between the common types of distresses found in this type of pavements.

### **Problem Statement**

Continuously-reinforced concrete pavement is a portland cement concrete (PCC) pavement type containing continuous longitudinal reinforcement with no transverse expansion or contraction joints except at bridges or pavement ends (Plei and Tayabji 2012). The accurate modeling of CRCPs main response features is of primary importance in a mechanistic-empirical pavement design procedure. CRCPs develop a distinct pattern of transverse cracking within the early life of the pavement. Many factors affect cracking pattern, including environmental conditions at the time of construction, the thickness of concrete slab, the amount of depth of steel reinforcement, friction between the slab and the subbase, and concrete strength (Zollinger et al. 1999a). The purpose of steel reinforcement in CRCP is to ensure that the transverse cracks are tightly held together and, as a result, provide high load transfer over the life of the pavement. The major structural distress of CRCP is punchout, caused by either steel corrosion, inadequate amount of steel, excessively wide shrinkage cracks or excessively close shrinkage cracks (Utah Department of Transportation 2009). For years the primary focus of CRCP design has been on the percent of reinforcement steel and on the temperature changes the pavement is subjected to during the course of a year (Huang 2003). A complex method, such as FEM, is required to determine the complex interaction of reinforcement steel and concrete as well as slab-foundation interaction due to friction and temperature changes.

Significant amount of research has been conducted to improve the design of continuously-reinforced concrete pavements. Design tools such as CRCP-9 and CRCP-10 and the new mechanistic-empirical pavement design procedure have the capability to analyze continuous pavements under traffic, environmental, and thermal loads. CRCP-9 and 10 were developed using 2-D and 3-D finite element theory to calculate stresses in concrete and steel bars due to environmental loads (Won and McCullough 2001). A fundamental limitation of this approach is that it only considers a section of the pavement in the analysis of wheel load stresses and dynamic tandem axle loads. The use of FE in CRCP-9 and 10 also limits the analysis to simple pavement structure instead of multiple pavement layers. Identifying and understanding the potentials, limitations and applicability of current analysis tools is essential for the development of a new

analysis tool that significantly enhances the efficiency and capabilities of FE-based continuous concrete pavement models.

## **Objective**

The performance of rigid pavements depends on the stresses and deflections imposed by repeated traffic and environmental loads. During the initial stages, cracks within CRCP develop due to temperature and moisture variations. After the pavement is subjected to traffic, cracks develop due to wheel loads. Crack spacing together with poor support conditions have shown a strong correlation with a high frequency of punchout distress (Zollinger et al. 1999a). A reliable prediction of pavement responses is essential in a mechanistic-empirical design procedure to evaluate the effect of environmental and traffic loads and to estimate the frequency of distresses. The structural model used for those predictions should (1) adequately describe the pavement structure; (2) account for discontinuities in the pavement structures (cracks and joints); (3) analyze multi-wheel loading with non-uniform tire print distribution; and (4) analyze environmental loading (such as temperature curling and moisture warping).

In order to develop a reliable model that represents the behavior of this type of pavement, a clear understanding of the interaction between concrete and steel is essential. Therefore, a parametric analysis was carried out using the 3-D finite element model of the CRCP-9 computer program, to investigate the concrete stress distribution along the longitudinal direction while varying the concrete slab thickness.

## Chapter 2 – Mechanistic Model of CRCP

The first mechanistic model of continuously-reinforced concrete pavements was developed in the mid 1970's under a study sponsored by the National Cooperative Highway Research Program (NCHRP, Kim et al. 2001b). CRCP-1 was the first computer program with the capability to evaluate the effects of continuous pavement design variables under traffic and environmental loads. In 1996, after continuous development, The Texas Department of Transportation (TxDOT) Project 0-1758 developed a two-dimensional FEM by incorporating the variations in temperature and moisture changes occurring through the depth of the concrete slab. In 1998, TxDOT funded the development of a new mechanistic model for CRCP systems (CRCP-9), using two and three-dimensional FE models. The crack spacing prediction model in CRCP-9 was developed using the Monte Carlo simulation method and the failure prediction model was developed using probability theories (Won and McCullough 2001b). CRCP-9 analyzes the stresses due to curling and warping of the concrete slab by considering the variations of temperature and drying shrinkage through the depth of the concrete slab. CRCP-9 has the capability to predict crack spacing and estimate the number of punchouts per mile (Kim et al. 2001b). One limitations of CRCP-9 include the calculation of wheel load stresses by using the Westergaard equations and not the FE method. To obtain more realistic wheel load stresses, CRCP-10 was developed to include the effect of the moving dynamic tandem axle loads. This improvement was done by developing a double Fourier transform in space and moving space for moving loads of constant amplitude and for the steady state response to moving harmonic loads and a triple Fourier transformation in time, space and moving space for moving loads of arbitrary variation (Won and McCullough 2001a). Within the computer program, dynamic tandem axle loads are calculated by defining related variables, such as the load geometry and load time history, and by assuming that the loads are moving, each loaded area is rectangular, and the critical stress is induced by multiple wheels in a tandem axle and by their dynamic variations (Kim et al. 2001a).

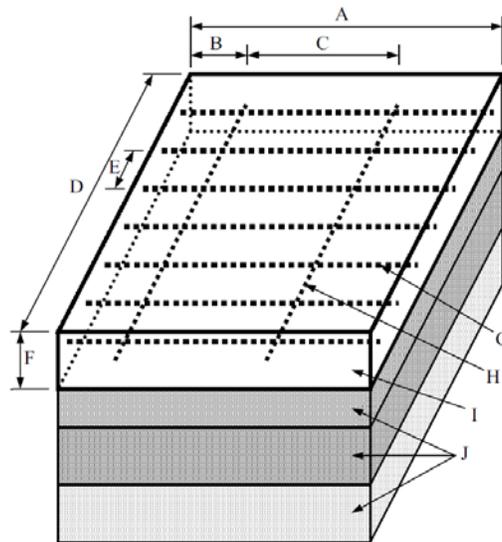
The 2-D and 3-D models used in the CRCP programs were developed using a finite element program, ABAQUS. To determine the most reliable model, a comparison between the two models was performed. Modeling in the transverse direction cannot be considered in 2-D models and consequently the transverse steel bars and the bond slip between the bars and concrete in the transverse direction cannot be modeled (Kim et al. 2000). Therefore, the 3-D analysis was performed to validate the accuracy of the 2-D model and to include the modeling of transverse bars in CRCP. The analysis on crack width distribution between the two models determined that the 2-D analysis with the plane stress element underestimates the crack width from the 3-D analysis. It was also determined that the 2-D analysis with the plane strain element overestimates the crack width from the 3-D analysis. In addition, the 2-D model cannot predict the variation of the crack width in the transverse direction (Kim et al. 2000).

## Chapter 3 – Finite Element Modeling of CRCP

Using the 3-D model from the CRCP computer programs, an analysis was performed to determine the interaction between concrete and steel in CRCP using ABAQUS, a finite element analysis computer program.

### Three-Dimensional Model

The structure of CRCP is shown in Figure 3.1, and the material properties of the CRCP model are provided in Table 3.1.



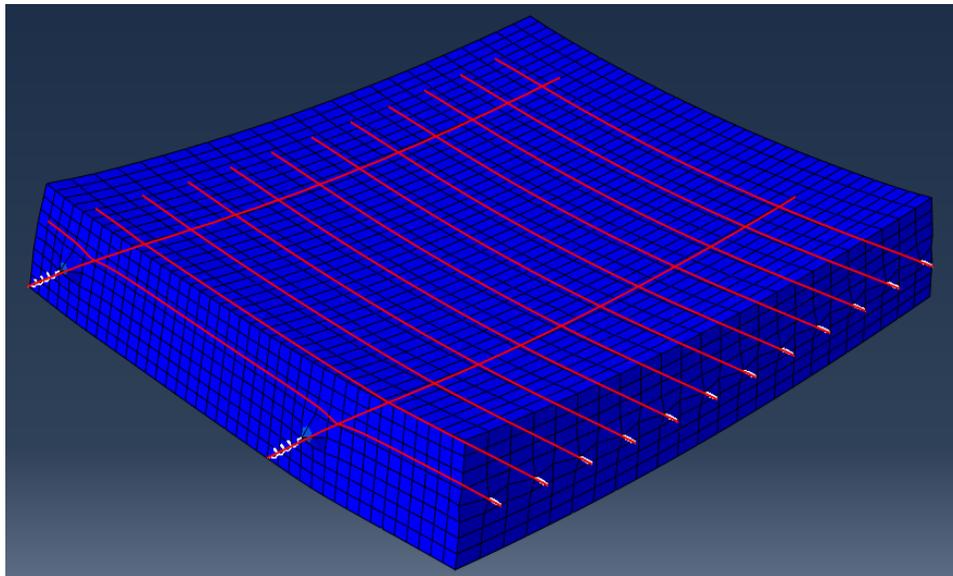
- A: Crack spacing
- B: Distance to transverse steel
- C: Transverse steel spacing
- D: Slab width
- E: Longitudinal steel spacing
- F: Slab thickness
- G: Longitudinal steel
- H: Transverse steel
- I: Concrete slab
- J: Underlying layers

**Figure 3.1 – Continuously Reinforced Concrete Pavement Structure (Kim et al. 2000)**

**Table 3.1 – Material Properties of CRCP Model**

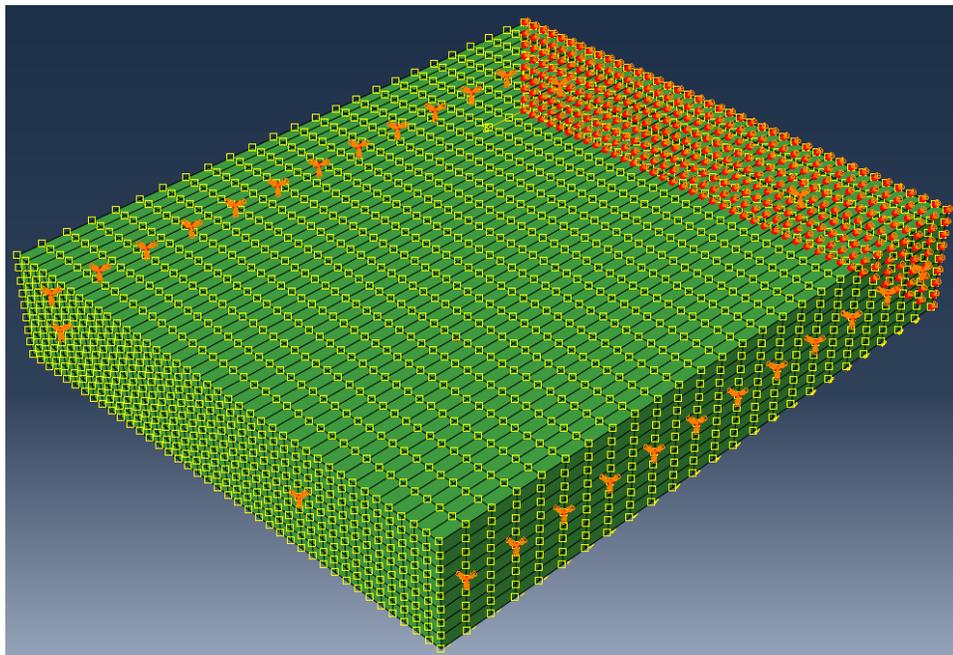
Crack spacing	5 ft.	Expansion coefficient of concrete	0.000006/°F
Longitudinal steel spacing	6 in.	Expansion coefficient of steel	0.000005/°F
Transverse steel spacing	4 ft.	Surface temperature	85°F
Steel location from surface	6 in.	Bottom temperature	100°F
Concrete modulus of elasticity	4,000,000 psi	Reference Temperature	120°F
Poisson's ratio	0.15	Vertical stiffness of underlying layers	400 psi/in.
Diameter of longitudinal steel	0.75	Bond slip stiffness between concrete and steel	700,000 psi/in.
Diameter of transverse steel	0.625	Bond slip stiffness between concrete and base	150 psi/in.

The CRCP model created in ABAQUS is shown in Figure 3.2. The concrete slab was discretized by using three-dimensional brick elements; reinforcing steel was modeled using beam elements; and the bond slip between concrete and steel, in both longitudinal and transverse direction, were modeled using horizontal springs. For this study, bond slip between concrete and steel was assumed linear. The underlying layers and the frictional resistance between concrete and the base were modeled using vertical and horizontal springs, respectively. The size of each element were selected to be 1.5 in. in the longitudinal and vertical directions and 3 in. in the transverse direction.



**Figure 3.2 – Three-Dimensional CRCP Model in ABAQUS**

Boundary conditions of the finite element model consist of the proper representation for the pavement section. Figure 3.3 shows the boundary conditions applied to the CRCP model in ABAQUS. For this study, a 12-ft-long slab was modeled with cracks 5 ft apart. At cracks, there are no restraints for concrete and no longitudinal and rotational displacements at the longitudinal steel bars. At longitudinal joints, there are no restraints for concrete and no transverse and rotational displacements for the transverse steel. The stress-producing mechanism was a linear temperature variation throughout the depth of the concrete slab. When CRCP is subjected to environmental loading, the response of the pavement system is symmetric with respect to the centerline along the longitudinal direction, therefore, half of the slab (6 ft) was 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.



**Figure 3.3 – Boundary Conditions of the CRCP Model in ABAQUS**

## Chapter 4 – Parametric Study

The primary factor affecting transverse crack development is the resistance to the change of length of the concrete slab (Zollinger et al. 1999b). This change of length occurs due to temperature change in the concrete material and to shrinkage due to the loss of moisture during the hardening and maturing stages of concrete (Zollinger et al. 1999b). Other factors affecting crack development include (1) the amount of reinforcing steel; (2) concrete properties; (3) bond characteristics between concrete and steel; (4) bonding or friction between the slab and subbase; (5) mechanical tie to adjacent lanes; and (5) construction factors such as time of placement and temperature at time of placement.

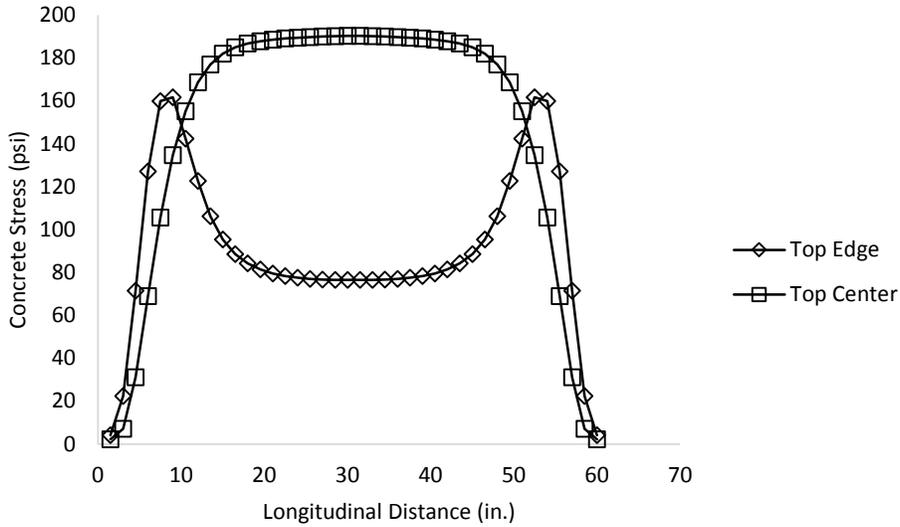
In CRCP, cracking occurs where the concrete stress exceeds the tensile strength of concrete. While there are many important factors in the development of cracks, this study's focus was on the effects of slab thickness in crack development by analyzing the concrete stress distribution in the longitudinal direction. Table 4.1 provides the parameters perturbed for this study. Six cases, including the case-control (P3-C), were analyzed.

**Table 4.1 – Pavement Case Parameters**

Pavement case	Slab thickness (F)	Steel location from surface
P1	10 in.	5 in.
P2	11 in.	5.5 in.
P3-C	12 in.	6 in.
P4	13 in.	6.5 in.
P5	14 in.	7 in.
P6	15 in.	7.5 in.

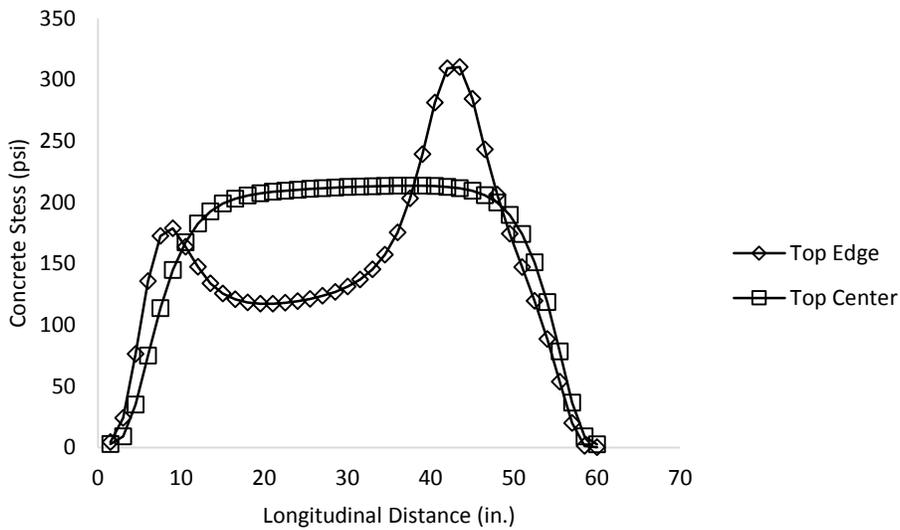
### Concrete Stress Distribution

The concrete stress distribution at the top of the slab along the longitudinal direction was investigated. Stresses at the top edge of the slab are higher at transverse steel location, whereas at the top center of the slab, stresses are higher along the center of the crack width. For the case-control P3-C, when the transverse steel spacing is at 4 ft starting 3 in. from the left crack (C=4 ft and B=3 in. from Figure 3.1), the maximum stress occurs at the top center of the slab, as demonstrated by the graph in Figure 4.1.



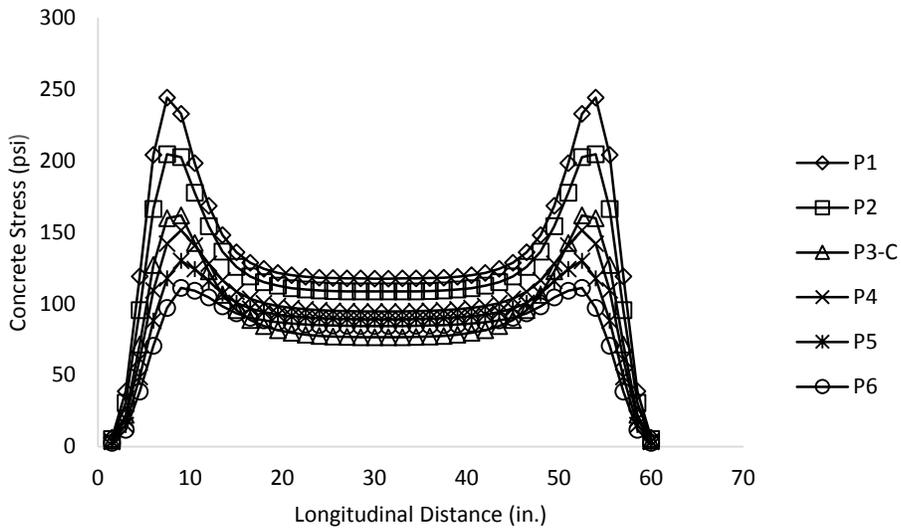
**Figure 4.1 – Stress Distribution for Case-Control**

The relationship above also determine the stress distribution in all other pavement cases. However, when C is reduced to 3 ft and B=3 in., the maximum stress occurs at the edge of the slab, as shown in Figure 4.2. This behavior can imply a possible crack formation propagating from the edge at the transverse steel location.

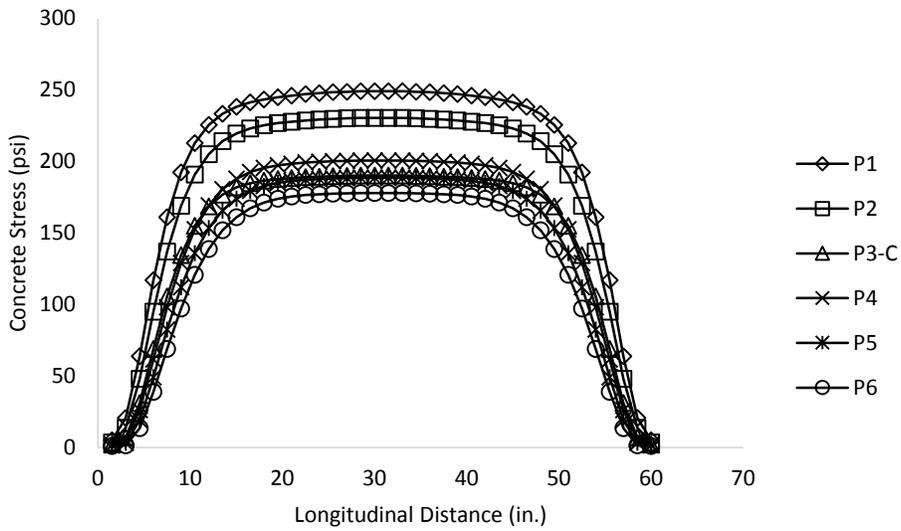


**Figure 4.2 – Concrete Stress Distribution for Case-Control when C=3 ft and B=3 in.**

The concrete stress distributions at the top edge and top center along the longitudinal direction for all pavement cases are shown in Figure 4.3. There is a decrease in the concrete stress as the thickness of the slab increases.



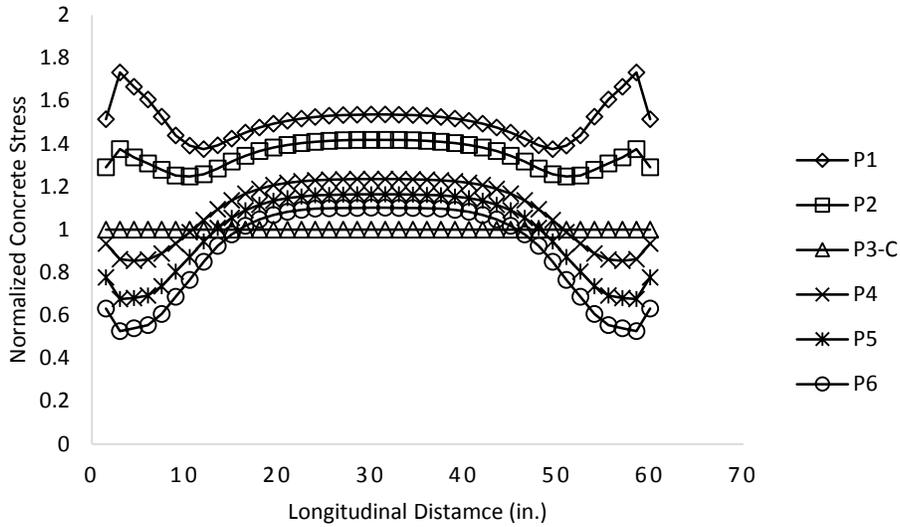
**(a) Top Edge**



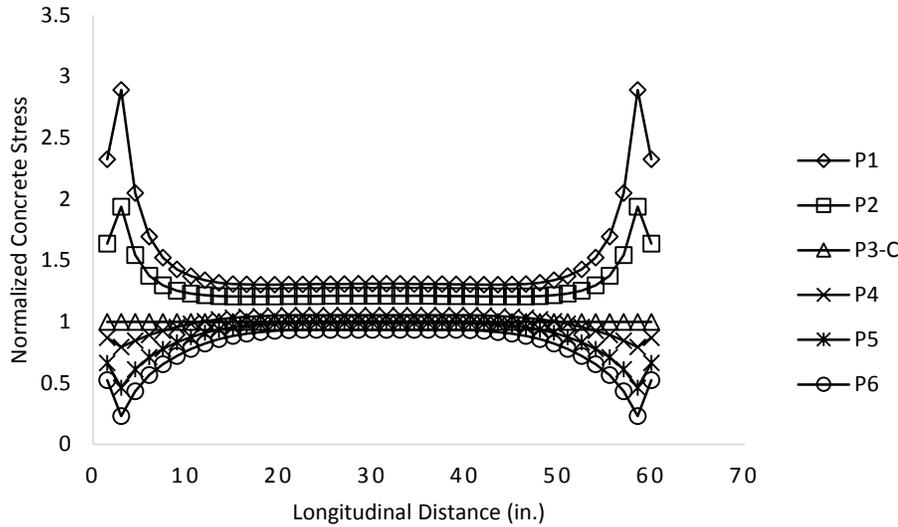
**(b) Top Center**

**Figure 4.3 – Concrete Stress Distribution**

To obtain a better representation of the stress distribution in comparison to the case-control, the data were normalized. Figure 4.4 shows the normalized concrete stress distribution at (a) top edge and (b) top center of the slab.



(a) Top Edge



(b) Top Center

**Figure 4.4 – Normalized Concrete Stress Distribution**

An interesting observation can be made from the normalized concrete stress distribution at the top edge of the slab, Figure 4.4a. As the concrete thickness increases, the stress decreases. However, there is an inconsistency between the concrete stress distribution for pavement case P2 and case-control P3-C. The stresses of P2 are much higher than the stresses of P3-C. The concrete stress distributions for pavement case P4, P5, and P6 are situated in between the difference of P2 and P3-C. This observation suggests that there might be a greater decrease in the stresses of case-control P3-C due to the arrangement of steel within the slab. In the case of the stress distribution at the top center of the slab, all pavement cases decrease according to change in slab thickness.

## **Chapter 5 – Summary and Conclusions**

The accurate modeling of CRCPs main features is of primary importance in a mechanistic-empirical pavement design procedure. CRCPs develop a distinct pattern of transverse cracking within the early life of the pavement. Crack spacing together with poor support conditions have shown a strong correlation with a high frequency of punchout distress, the major structural distress type of CRCP. In order to develop a reliable model that represents the behavior of this type of pavement, a clear understanding of the relationship between concrete and steel is essential. Therefore, a parametric analysis was performed using the 3-D finite element model of the CRCP-9 computer program.

The concrete stress distribution along the longitudinal direction was investigated by varying the concrete slab thickness in 1 in. intervals (ranging from 10 in. to 15 in). Six pavement cases were analyzed. It was observed that small increases in slab thickness can decrease the concrete stress at the top edge and center of the slab. This can imply a decrease in the formation of new cracks and with it a reduction in the number of punchouts. At the top edge of the slab, a large difference between the stress distribution of a pavement with thickness of 11 in. and case-control pavement with a thickness of 12 in was observed. This can imply that stresses, at the top edge, are smaller in the case-control due to steel bar spacing in either the transverse or longitudinal direction. It was also observed that reducing the spacing of transverse steel between the two cracks produces a maximum stress at the edge of the slab located at the transverse steel bar furthest from the crack. This observation can imply that there is a high risk of crack formation at the edge of the slab when the transverse bar is located at a significant distance from the crack. Further investigation will be conducted to understand the relationship between the transverse steel spacing, longitudinal steel spacing, and the thickness of the concrete and their effects on crack development.

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