Canadian Journal of Civil Engineering

Optimization of Parameters Affecting Horizontal Cracking in Continuously Reinforced Concrete Pavement (CRCP)

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2017-0679.R1
Manuscript Type:	Article
Date Submitted by the Author:	02-Jul-2018
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Keyword:	Horizontal cracking, CRCP, 3-D finite element analysis, Steel layout
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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**Optimization of Parameters Affecting Horizontal Cracking in Continuously Reinforced
Concrete Pavement (CRCP)**

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**SUBMITTED FOR PUBLICATION IN
CANADIAN JOURNAL OF CIVIL ENGINEERING**

ABSTRACT

Field evaluation of distresses in continuously reinforced concrete pavement (CRCP) indicated punch-out distress associated with horizontal cracking at the depth of the longitudinal steel is the most severe performance problem in CRCP. The developed 3-D model was used to perform a parametric analysis to determine the effects of critical loading location, concrete properties, and longitudinal steel design on horizontal cracking potential. The maximum vertical tensile stresses in the concrete were slightly affected by the coefficient of thermal expansion of the concrete. The critical tensile stresses in the concrete were observed to decrease as the base modulus, slab-base friction, slab thickness, and transverse crack spacing increase. The vertical tensile stresses significantly decreased when the longitudinal steel spacing decreased. The use of varying longitudinal steel spacing and reducing the depth of steel may be one of the ways to reduce the horizontal cracking potential without changing the steel ratio of the slab.

Keywords: Horizontal cracking, CRCP, 3-D finite element analysis, Steel layout

INTRODUCTION

Background

A continuously reinforced concrete pavement (CRCP) is constructed without transverse joints except with construction joints and embedded reinforcement in transverse and longitudinal directions. CRCP allows the concrete to crack as a result of drying shrinkage. The subsequent transverse cracks are held tightly together by longitudinal steel and thus provides good serviceability or ride quality. Previous research has indicated that CRCP outperforms other types of concrete pavement due to its durable nature (Smith et al. 1998). CRCP has been used primarily in urban areas where delay associated with repairs and rehabilitation causes higher user cost. Because of its durable character, the Florida Department of Transportation has movement to consider CRCP for heavy load and heavy traffic facilities (FDOT 2011).

Field evaluation of distresses indicated that punch-out distress is the most severe performance problem in CRCP (Darter et al. 1979; McCullough et al. 1980; Zollinger 1989). However, in-depth evaluations of punch-outs during their repair revealed that this type of distress was associated with horizontal cracking at the depth of the longitudinal steel. Furthermore, full-depth punch-outs are quite rare in Texas (Won 2011). The horizontal cracking has not been well recognized until recently due to the difficulty of detection before full-depth rehabilitation. The horizontal crack prevents the transverse crack propagation into the full-depth of concrete slab. These transverse and horizontal cracks may ultimately cause a half-depth punch-out (Choi et al. 2011). In addition, even though the top half of the concrete had deteriorated, the bottom of half of the concrete was still healthy (Won 2011).

Previous research has been conducted to identify the mechanism of horizontal cracking in CRCP due to environmental loading and found that the longitudinal steel plays a significant

role in the development of horizontal cracking. Significant tensile stress occurred in concrete near the longitudinal steel due to environmental load and steel restraint (Choi et al. 2011; Kim and Won 2004). In addition, horizontal cracking could be affected by concrete material properties, environmental conditions, and longitudinal steel layout (Choi et al. 2011; Won et al. 2002). However, only three research papers were identified addressing horizontal cracking and focusing on effects of environmental loading only, due to the limitation of two-dimensional (2-D) finite-element (FE) model. Even though axle loading may also affect the development of horizontal cracking of CRCP, it has not been well considered in previous studies. Therefore, the current lack of understanding of the horizontal cracking compared to other distress type under environmental and critical loading conditions is probably the greatest deficiency in the evaluation of the CRCP system. The effects of combination of environmental and wheel loading must be evaluated to prevent this type of cracking. A better understanding of the mechanism of horizontal cracking under combined action of wheel loads and environmental loads may help in the understanding of some of the existing problems and provide better guidelines for the design and construction of the CRCP system. Therefore, there is a need to develop an improved CRCP model to identify how horizontal cracking occurs.

In this study, a three-dimensional (3-D) FE model was developed for analyzing a CRCP system. The 3-D model was used to evaluate the effects of various design parameters on the vertical tensile stress in concrete near the longitudinal steel, where the horizontal cracks generally occur.

Objectives

The analysis conducted herein was focused on the evaluation of factors influencing horizontal

cracking in CRCP under combined environmental and traffic loads. The design parameters evaluated include:

- Location of combined environmental and traffic loads.
- Concrete properties (coefficient of thermal expansion, modulus of elasticity).
- Structural design parameters (base modulus, base friction coefficient, slab thickness, crack spacing).
- Steel design (longitudinal steel spacing, depth of steel layout).

Scope

In this study, a 3-D finite element model was developed for determination of vertical tensile stresses in the concrete in CRCP under critical temperature-load conditions. The developed 3-D model was used to perform a parametric analysis to determine the effects of loading location, concrete material properties, pavement design parameters, and longitudinal steel design on the vertical tensile stress near the longitudinal steel causing horizontal cracking.

MECHANISM OF HORIZONTAL CRACKING IN CRCP

The substantial change in temperature and moisture gradients can cause the pavement slabs to curl. However, this distortion can be restrained by the longitudinal steel across the transverse crack, resulting in a significant vertical tensile stress at the depth of the longitudinal steel. Because the longitudinal steel resists curling, this force is applied to the upper and lower halves of the slab. As a result, a substantial stress in the vertical direction occurs at the depth of the longitudinal steel, which may result in horizontal cracking in CRCP (Choi et al. 2011). It is expected that greater tensile stress zone would be developed under extreme temperature or

moisture condition, especially when wheel loads are applied. Figure 1 illustrates how vertical tensile stresses develop at the depth of steel when the concrete slab is subject to environmental loadings, from FE analysis results with a temperature differential of $\pm 11.1\text{ }^{\circ}\text{C}$ ($\pm 20\text{ }^{\circ}\text{F}$). When the vertical tensile stress near the steel is excessive, the concrete would crack horizontally along the plane of the slab, splitting the slab into two separate slabs of much lower thickness. The upper thin slab would easily crack under temperature and load effects. Therefore, it is important to evaluate this vertical tensile stress in order to prevent this type of cracking which will eventually lead to punch-out failure in CRCP.

FINITE ELEMENT MODEL OF CRCP

The 3-D finite element model developed in this study consists of two concrete slabs with one transverse crack supported by base and subgrade as shown Figure 2. The spacing of the transverse crack was initially assumed to be 3 m (10 ft). To eliminate the boundary condition effects, the concrete slabs were modeled at their full width and the base and subgrade layers were extended 61 cm (24 in.) on each side. The concrete slabs' contact with the base layer was maintained by applying the concrete self-weight and there was no external constraint. The concrete slab-base layer interface friction factor (μ) was assumed to be 1.5, since the AASHTO 93 Guide recommends a range of concrete-base friction of 0.9 to 2.2. The concrete slab was modeled by an assemblage of eight-node isoparametric solid brick elements and the reinforce steels were modeled as beam elements. The bond-slip between concrete and the steel bars was modeled using spring elements. Figure 3 shows the frictional bond-slip relation between concrete and steel bars which has been used by other researchers and which was used in this study (Kim et al. 1998; Kim et al. 2000). The thickness of the base layer was 15 cm (6 in.) over a 254 cm (100

in.) subgrade. It was found that increasing the thickness of the subgrade layer to more than 254 cm (100 in.) had no significant effect on the computed stresses in the concrete slabs. The base and subgrade materials were modeled as isotropic and linearly elastic, characterized by their modulus of elasticity and Poisson's ratio. The contraction and expansion of the concrete behavior due to temperature effects are also considered, and characterized by its coefficient of thermal expansion. The double symmetry of the geometry about x- and y- axes was selected in order to reduce computation time. The subgrade layer was fixed in the z-direction. The geometry and material properties used in this study were presented in Table 1.

EFFECTS OF CRITICAL LOADING CONDITION ON HORIZONTAL CRACKING

The critical loading condition had not been studied for analysis of vertical tensile stress near the longitudinal steels previously. Critical vertical stress analysis at the depth of steel was performed to determine the maximum tensile stresses in the concrete slabs if they were subject to some critical load and temperature conditions which would produce the highest thermal-load-induced stresses in the concrete. The two temperature differentials considered in the analysis were +11.1 °C (+20 °F) and -11.1 °C (-20 °F), which represent typical severe temperature differential in concrete pavement slabs in Florida. A 98 kN (22-kip) axle load, which represents the maximum legal load limit for single axle loads in Florida, was used as the applied load in the analysis. The four load positions were (1) slab corner at transverse crack, (2) slab center at transverse crack, (3) slab edge between transverse cracks, and (4) slab center between transverse cracks. Vertical tensile stresses at the depth of steel in concrete caused by the axle load for the various combination of temperature differentials and load positions were computed using the 3-D FE model developed.

Figure 4 shows the computed vertical tensile stress in concrete at the depth of steel caused by the different combinations of temperature differentials and axle load. The results of the analysis indicate that when the temperature differential in the slab is positive, the critical load position is at the slab corner. Therefore, the corner load position at transverse crack was used in the computation of the maximum thermal-load-induced vertical tensile stress for most of the cases in this study.

EFFECTS OF CONCRETE PROPERTIES

Effects of Coefficient of Thermal Expansion

The 3-D finite element model was also used to evaluate the effects of coefficient of thermal expansion (CTE) under critical loading conditions, when the load is applied to the corner of the slab as formed by the transverse cracks with a temperature differential of $+11.1\text{ }^{\circ}\text{C}$ ($+20\text{ }^{\circ}\text{F}$). The effects of the coefficient of thermal expansion of the pavement concrete ranging from 9×10^{-6} to $12.6\times 10^{-6}/^{\circ}\text{C}$ (5.0×10^{-6} to $7.0\times 10^{-6}/^{\circ}\text{F}$) on the maximum induced vertical stresses were analyzed.

For comparison purpose, the vertical tensile stresses due to environment loading only were also calculated. Using the different values of the coefficient of thermal expansion, the maximum vertical stresses at the depth of steel were calculated and presented in Figure 5. As expected, the maximum vertical tensile stresses increase as thermal coefficient of expansion increases. However, the effects of thermal expansion on the environmental tensile stress are much higher than those on the critical tensile stress, even though the magnitude of environmental stress is much lower than that of the critical tensile stress. This analysis was limited to the effects of the positive temperature differential. However, the combined effects of negative temperature differential along with drying shrinkage generally result in the cracking near the concrete

surface. Therefore, further research should consider the effects of negative temperature differential on CRCP implementation.

Effects of Concrete Modulus

The effects of elastic modulus of concrete on the maximum vertical stresses were analyzed. The maximum vertical tensile stress in the slab caused by a 98 kN (22-kip) single axle load at the edge of the transverse crack at a temperature differential of +11.1 °C (+20 °F) was computed. Figure 6 shows the maximum vertical tensile stresses as a function of elastic modulus of concrete. It can be seen that the calculated maximum stress increases by around 4.7% when the elastic modulus increased from 27.6 to 41.4 GPa (4,000 to 6,000 ksi).

However, an increase in elastic modulus of the concrete is usually accompanied by an increase in its flexural strength when the same aggregate is used. In order to evaluate the possibility for the concrete to crack at the various conditions, the maximum computed tensile stresses were divided by the flexural strength of concrete to obtain the stress-to-strength ratio. In this study, the flexural strength of the concrete was related to its elastic modulus and unit weight by the following equation for a Florida concrete made with a Florida limestone (Tia et al. 1990):

$$MR = 15.267 \times E/w^{1.5} \quad (1)$$

Where, E = elastic modulus, in kPa, MR = flexural strength, in kPa, and w = unit weight, in kg/m³.

Using this equation and a unit weight of 2,323 kg/m³ (145 pcf), the concrete flexural strengths at various values of elastic modulus were calculated, and the stress-to-strength ratios were also plotted against the concrete elastic modulus in Figure 6. It can be noted that the maximum stress-to-strength ratio decreases as the concrete modulus increases. Decrease in

stress-to-strength ratio with increase in modulus can be explained by the increase in flexural strength which can be obtained by using a lower water-cement ratio in concrete mixture. However, it must also be noted that if a different type of aggregate is used to produce a concrete of lower elastic modulus without a decrease in strength, the use of a low- modulus concrete can give a lower stress-strength ratio and a lower horizontal cracking potential.

EFFECT OF STRUCTURAL DESIGN PARAMETERS

Effects of Base Layer Modulus

The effects of base layer modulus on maximum vertical tensile stresses in CRCP were analyzed. The maximum vertical tensile stresses in the concrete slabs were computed using the same critical loading condition and environmental condition. The base modulus was varied from 0.35 GPa to 2.76 GPa (50 ksi to 400 ksi). Figure 7 shows the plots of vertical tensile stresses in concrete as a function of base modulus. It can be noted that the maximum vertical tensile stress decreases as the base modulus increases under critical loading condition. Conversely, the environmental stresses increase as the base modulus increases.

In case of the critical loading condition, the slab edge deflects down into the base layer due to traffic load and curling movement, which causes the base reaction near the transverse crack. The magnitude of base reaction at the transverse crack varies depending on the stiffness of the base layer. The higher reaction force near the transverse crack causes less bending deflection which results in less vertical tensile stresses in concrete near the longitudinal steel.

In case of the environmental loading condition, the maximum tensile stress increases as the base layer stiffness increases. Since a higher stiffness of base layer may result in smaller supporting area and higher force exerted by the weight of unsupported slab region, which causes

the higher vertical tensile stress near the steel. Thus, a softer base may offer more uniform slab support resulting in lower tensile stresses in the concrete slab due to self-weight force.

Effects of Base Friction

The frictional force between the concrete slabs and the base layer is an important factor in the early development of CRCP cracks. In the case of transverse cracks, numerous investigations have looked into the effects of slab-base friction on CRCP, but little research has been done on the effects of base friction on horizontal cracking in CRCP. In this study, the base friction coefficient was varied from 0.9 to 2.2.

Figure 8 shows the plots of maximum vertical tensile stresses in the concrete slab at the depth of steel as a function of coefficient of slab-base friction. The sensitivity study indicated that changes in base friction had very little effect on the environmental tensile stresses, while the critical tensile stresses decrease as the base friction increases. It can be explained by the fact that the frictional force increases as coefficient of base friction increases which results in decrease of slab movements near the transverse crack under critical loading condition. As a result, the vertical tensile stresses also decrease. Based on the above observation, it appears that the horizontal cracking potential decreases with increase in base friction.

Effects of Concrete Slab Thickness

The effects of slab thickness on maximum vertical stress in CRCP were analyzed and presented in Figure 9. Obviously, increasing thickness reduces the vertical tensile stress at the depth of steel. The calculated vertical tensile stresses decreased by approximately 23% when the concrete slab thickness increased from 254 mm to 330 mm (10 in. to 13 in.).

In addition to the vertical tensile stress, the principal tensile stress was also evaluated since the cracks occur in perpendicular direction to the principal stress vectors. The maximum principal stress vectors were perpendicular to the direction of longitudinal steel, which indicates that horizontal cracking was likely to occur at the half depth of slab in the longitudinal direction. As expected, the maximum principal stress also decreased as the thickness of concrete slab increased.

Effects of Transverse Cracking Spacing

As shown in the previous results, the maximum vertical stresses develop at the location of transverse cracks. The LTPP data for CRCP sections show a spectrum of transverse cracking varying from 0.08 m to 3 m (0.25 ft to 10 ft) and mean crack spacing values varying between 0.3 m and 2.3 m (1 ft and 7.5 ft) (Selezneva et al. 2003). The effects of the transverse crack spacing ranging from 0.9 m to 3 m (3 ft to 10 ft) on horizontal cracking were analyzed. Using the different values of crack spacing, the maximum vertical tensile stress and principal stress were calculated and presented in Figure 10. The critical stresses were reduced slightly when the transverse crack spacing increased. Variations in the transverse crack spacing can be noted to have a relatively minimal effect on the horizontal cracking.

EFFECT OF STEEL DESIGN PARAMETERS

Effect of Longitudinal Steel Design

The effects of longitudinal steel design on the horizontal cracking potential were analyzed. Previous study (Choi et al. 2011; Won et al. 2002) found that a two-mat steel bar has the advantages in preventing horizontal cracking. In this study, the effects of the longitudinal steel

spacing ranging from 7.62 cm to 30.48 cm (3 in. to 12 in.) on horizontal cracking potential were analyzed. Using the different longitudinal steel spacing, the maximum vertical tensile stresses were calculated and presented in Figure 11. The vertical tensile stresses were significantly reduced when the steel spacing was reduced. In addition, the analysis results indicated that the vertical tensile stress in the region far away from the tire load was little affected by longitudinal steel spacing. From this result, it can be concluded that the use of varying longitudinal steel spacing can be one of the effective ways to reduce the horizontal cracking potential. For instance, the use of narrow steel spacing under wheel path and wide steel spacing for other region could be a possible solution without changing the steel ratio of the slab. However, due to the limited study related to the longitudinal steel spacing, the validity of varying longitudinal steel needs to be further investigated and validated by field testing before being considered for implementation.

Effects of Depth of Steel Reinforcement

An early field study (Gharaibeh et al. 1999) found that the depth of steel placement in CRCP plays a significant role in the development of horizontal cracking. It was found that the closer the vertical location of the steel reinforcement is to the surface, the lower is the possibility of punch-out failure. However, keeping the reinforcement closer to the surface would increase the possibility of chloride ion penetration and reduce the consolidation of the concrete due to the lack of concrete cover for the steel. Therefore, ASSHTO (2008) recommended that the vertical position of steel reinforcement to be at a minimum depth of 7.62 cm (3.5 in.) to a maximum of one-half of the slab thickness. In this study, the effects of the depth of steel reinforcement on horizontal cracking were evaluated. Four depths, namely (1) 6.35 cm (2.5 in.), (2) 7.62 cm (3.5

in.), (3) 12.7 cm (5 in.), and (4) 19.05 cm (7.5 in.), were evaluated. Using the different vertical locations of steel layout, the maximum vertical tensile stresses were calculated and presented in Figure 12. The results indicated that the closer the steel reinforcement is to the top surface, the lower the likelihood is for horizontal cracking. The maximum vertical tensile stresses at the transverse crack were significantly reduced as the depth of the steel reinforcement decreased. However, this study on the effects of steel depth is limited to applying one fixed slab depth of 25.40 cm (10 in.) Therefore, the finding of the results would only be applicable to the specific slab depth. Accordingly, the validity of the effects of steel depth needs to be validated by field testing.

CONCLUSIONS

A 3-D finite element model was developed to study the structural response of CRCP under typical Florida conditions. The developed model was used to perform a parametric analysis to determine the effects of important pavement parameters on the maximum induced vertical tensile stresses for estimating the horizontal cracking potential. The main findings are summarized as follows:

- The results of the analysis indicate that the critical load position is at the corner of slab formed by transverse cracks when the concrete slab has a positive temperature differential.
- The maximum vertical tensile stresses under critical condition are affected little by the thermal coefficient of expansion of the concrete.
- The maximum stress-to-strength ratio decreases as the concrete's flexural strength increases.

- The maximum vertical tensile stresses decrease as the base modulus increases under critical loading condition.
- The critical tensile stresses decrease as the base friction increases under critical temperature-load condition.
- Increasing slab thickness reduces the vertical tensile stress at the depth of steel.
- The critical vertical stresses decrease slightly when the transverse crack spacing increases.
- The vertical tensile stresses are significantly reduced when the steel spacing is reduced. In addition, the vertical tensile stress in the region far away from the tire load is not affected by longitudinal steel spacing. From this result, the use of varying longitudinal steel spacing (i.e., small steel spacing under wheel path and wide steel spacing for other region) may be one of the ways to reduce the horizontal cracking potential in CRCP.
- The maximum vertical stress decreases as the depth of steel reinforcement decreases. However, the concrete cover between steel reinforcement and the top surface has to have adequate thickness for consideration of steel protection from corrosion and proper consolidation of the concrete in the CRCP.

The following procedures are recommended for analysis of CRCP to minimize horizontal cracking:

- 1) Analyze the maximum vertical tensile stress at the depth of the longitudinal steel under critical temperature-load condition.
- 2) Compare the maximum vertical tensile stress to flexural strength of the concrete used.
- 3) If the maximum tensile stress is greater than 50% of the flexural strength of the concrete, try to reduce it to 50% or less by the following options:

- (a) Reduce longitudinal steel spacing
- (b) Reduce the depth of steel reinforcement
- (c) Increase flexural strength of concrete
- (d) Increase base modulus
- (e) Increase slab thickness

ACKNOWLEDGMENTS

The Florida Department of Transportation is gratefully acknowledged for providing the financial support that made this study possible. The authors would like to acknowledge the FDOT's State Materials Office Pavement Materials Section staff for their assistance with data collection, materials testing, and technical advice.

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426 Figure 12. Effects of depth of single steel layout on maximum vertical stresses in CRCP.

427 Table 1. Geometry and material properties used in the CRCP model.

Transverse crack spacing	3 m (10 ft)
Pavement width	3.6 m (12 ft)
Pavement thickness	25.4 cm (10 in.)
Coefficient of thermal expansion (concrete)	$10.4 \times 10^{-6}/^{\circ}\text{C}$ ($5.8 \times 10^{-6}/^{\circ}\text{F}$)
Coefficient of thermal expansion (steel)	$9.0 \times 10^{-6}/^{\circ}\text{C}$ ($5.0 \times 10^{-6}/^{\circ}\text{F}$)
Elastic modulus of Concrete slab	33.1 GPa (4,800,000 psi)
Elastic modulus of steel	200 GPa (29,000,000 psi)
Depth of steel	12.7 cm (5 in.)
Diameter of longitudinal steel	19 mm (0.75 in.)
Diameter of transverse steel	16 mm (0.625 in.)
Longitudinal steel spacing	15.2 cm (6 in.)
Transverse steel spacing	45.7 cm (18 in.)

428

Draft

325x578mm (300 x 300 DPI)

455x267mm (300 x 300 DPI)

(a) Spring for bond-slip between concrete and reinforce bar

(b) Finite element model for concrete-steel interface

325x325mm (300 x 300 DPI)

(a) Slab corner loading at transverse crack

(b) Slab center loading at transverse crack

(c) Slab edge loading between transverse cracks

(d) Slab center loading between transverse cracks

155x455mm (300 x 300 DPI)

455x335mm (300 x 300 DPI)

455x335mm (300 x 300 DPI)

455x335mm (300 x 300 DPI)

455x330mm (300 x 300 DPI)

455x335mm (300 x 300 DPI)

455x335mm (300 x 300 DPI)

455x361mm (300 x 300 DPI)

455x347mm (300 x 300 DPI)