Center for Transportation Research
The University of Texas at Austin

Research Project Summary Report 1831-S
Project 0-1831 Improvement of Concrete Pavement Performance Model
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PROJECT SUMMARY REPORT

MECHANISTIC ANALYSIS OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

This research project was conducted to develop a realistic mechanistic model of continuously reinforced concrete pavement (CRCP) to predict early-age behavior and long-term performance of CRCP. The use of CRCP has increased over the years primarily in urban areas due to the excellent performance of CRCP, which requires little maintenance. Good performance of CRCP is ensured by tight crack widths, acceptable steel stresses, and adequate transverse crack spacings, which are determined by design, material, construction, and environmental variables.

To ensure tight crack widths and adequate crack spacings, both the effect of each variable and the interaction among these variables need to be investigated, so that optimum combinations of design, material, and construction techniques can be determined. Mechanistic modeling provides a useful tool toward this end. Since the development of the first mechanistic model, CRCP-1, under a study sponsored by the National Cooperative Highway Research Program (NCHRP) in the mid-1970s, the CRCP computer program has been modified several times to expand the ability of the mechanistic model. In 1995, all different versions of the CRCP computer programs were integrated into one computer program, CRCP-8.

Although CRCP-8 permitted pavement engineers to develop and evaluate designs of CRCP, there were limitations due to the simplified assumptions of the one-dimensional analysis. To expand the ability of the mechanistic model by incorporating the variations in temperature and moisture changes through the depth of concrete slab, a new mechanistic model, CRCP-9, was developed in this research project.

The analysis engine of this mechanistic model was developed using finite element theories, the crack spacing prediction model was developed using the Monte Carlo method, and the failure prediction model was developed using probability theories. By adding a more rigorous wheel load stress calculation procedure considering moving dynamic tandem axle loads into CRCP-9, a new version of the CRCP computer program, CRCP-10, was also developed.

What We Did...

This research project was conducted with three different phases as follows:

* Phase I: Development of two-dimensional (2-D) and three-dimensional (3-D) models of CRCP using a finite element program ABAQUS and comparison of the 2-D and 3-D analysis results.
* Phase II: Development of a finite element computer program code to use the mechanistic model using PCs and development of a new version of the CRCP computer program, CRCP-9, with a user-friendly interface for convenient use.
* Phase III: Development of formulations to calculate more realistic wheel load stresses considering moving dynamic tandem axle loads and integrating the developed formulations into the CRCP-10 computer program.

Three-Dimensional Modeling

Although the new mechanistic model was going to be developed using 2-D finite element theories to reduce the cost of computation, 3-D analyses were also performed to validate the accuracy of the 2-D model and to evaluate the significant factors to be included in the model. The results from the 3-D analysis were also helpful in achieving an improved understanding of the CRCP behavior.

For the 3-D modeling, the concrete slab was discretized using three-dimensional brick elements, the longitudinal and transverse steel bars were modeled using frame elements, the bond-slip between concrete and steel bars was modeled using horizontal 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: (1) for the bond-slip between concrete and steel bars and between concrete and base; (2) for the curling effect; and (3) for the viscoelastic material characteristics.

Two-Dimensional Modeling

A finite element computer code to calculate stresses in concrete and steel bars was developed using a 2-D model of CRCP. Because the CRCP behavior can be assumed to be symmetric with respect to the midslab for the environmental loads, half of CRCP between two adjacent transverse cracks was modeled.

Concrete and longitudinal steel bars were discretized using plane elements and frame elements, respectively. Various bond stress and slip models between concrete and longitudinal steel bars were developed using spring elements. The boundary conditions of the finite element model should be correctly defined to obtain viable results.

At cracks, there are no restraints for concrete and no longitudinal and rotational displacements for longitudinal steel bars. At the midslab, vertical degrees of freedom exist, and the longitudinal and rotational displacements are restrained. Figure 1 shows the finite element model developed in this research. The creep effect was also included using the effective modulus method.

Crack Spacing Prediction

The crack will occur when and where the concrete stress exceeds the tensile strength of concrete. If the concrete slab is assumed to be homogeneous, the new crack will occur at the center of the two previously formed transverse cracks because the maximum concrete stress occurs at the center. However, since the tensile strength of concrete is governed by the weakest element in it, there exists variation in concrete tensile strength from location to location.

To include the effect of the variation of the tensile strength along the pavement length in the model, the concrete tensile strength at each finite element is selected randomly using a normal distribution because the concrete tensile strength distribution along the pavement length is reported to be sufficiently close to the normal distribution.

Once the tensile strength at each finite element is determined and the stresses are calculated from the model, the difference between the tensile strength and the concrete stress is obtained at each finite element. Where the concrete stress exceeds the tensile strength and the difference between them is the largest, the new crack will occur. This methodology is known as the Monte Carlo method.

Punchout Protection

There are structural failures and functional failures in the pavement systems. The structural failures lead to functional failures in CRCP, and the major failure manifestation is the punchout. The punchout is a structural failure in which a small segment of pavement is loosened from the main body and displaced downward under traffic.

The punchout usually is bounded by two closely spaced transverse cracks, a longitudinal crack, and the pavement edge. Even though the punchout development mechanism is complicated, it is assumed that the longitudinal crack is the most significant contributing factor in the punchout development. Therefore, it is assumed that longitudinal cracks result in punchouts.

Once the crack spacings along the pavement length are obtained from the analysis, the transverse stresses are calculated for each crack spacing and the number of load applications corresponding to various probabilities of the punchout is calculated.

After the relationship between the punchout and load applications has been obtained for each crack spacing, the final punchout versus load application curve can be obtained by adding each curve from each crack spacing.

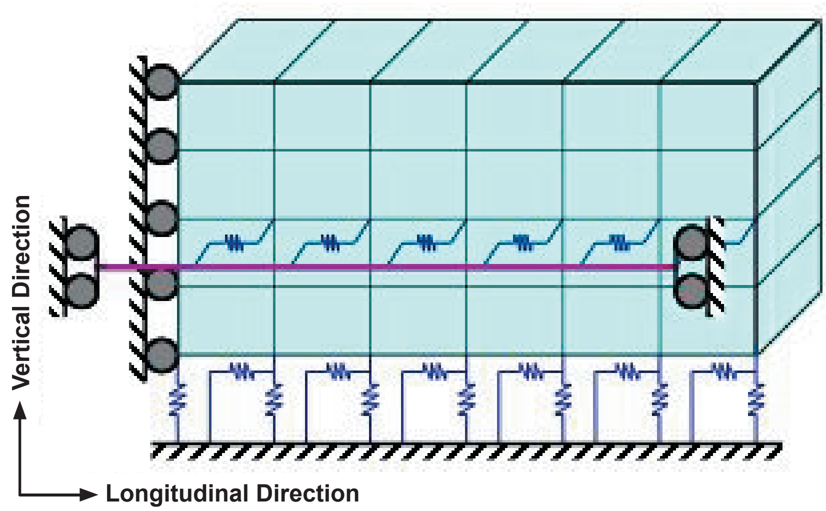

Figure 1: Finite element model of CRCP

CRCP-9 Development

The computer codes to predict concrete and steel stresses, crack spacing distributions, and punchouts were developed and all these codes were integrated to develop a final CRCP-9 source code. To provide a convenient use of CRCP-9, a Windows-based user-friendly interface was developed and linked with the source code.

The major characteristics of CRCP-9 that differ from those of CRCP-8 include consideration of nonlinear variations in temperature and drying shrinkage through the depth of the concrete slab, nonlinear bond-slip relationship between concrete and steel bars, viscoelastic effect of concrete, curling and warping effects, and the ability to investigate the effect of placing the longitudinal steel bars at different depths.

CRCP-10 Development

CRCP-9 and previous versions of the CRCP computer programs such as CRCP-8 consider the wheel load effects by calculating wheel load stresses using the Westergaard equations, which means that they consider only the static single wheel load. Moving trucks, however, generate moving dynamic loads, and the pavement stresses will be affected by the dynamic loads and geometry of tandem axles.

To improve the wheel load stress calculation, formulations were developed in the transformed field domain using: (1) a double Fourier transform in space and moving space for moving loads of constant amplitude; (2) a triple Fourier transform in time, space, and moving space for moving loads of arbitrary variation; and (3) a double Fourier transform in space and moving space for the steady-state response to moving harmonic loads.

From the developed formulations, the effects of vehicle speed, multiple wheel loads, variation of the load, and viscoelasticity of underlying layers can be evaluated. The updated CRCP computer program, CRCP-10, was developed by adding these formulations into CRCP-9 to predict the more realistic wheel load stresses due to the moving dynamic tandem axle loads.

What We Found...

The analysis engines of the CRCP-9 and -10 computer programs were developed using 2-D finite element theories to calculate stresses in concrete and steel bars due to environmental loads such as changes in temperature and drying shrinkage through the depth of the concrete slab. From the comparison with 3-D models, it was found that predicted stresses from the 2-D models were very close to those from the 3-D models except in the regions within about 10 in. from the edge. The 2-D models with plane strain elements slightly overestimated 3-D analysis results, and those with plane stress elements slightly underestimated 3-D results but were much closer than with plane strain elements.

The CRCP-9 and -10 programs also predict crack spacing distributions and punchout failures, and the Monte Carlo method and probability theories were used for these purposes. For the wheel load stress calculation, CRCP-9 considers a static single wheel load using the Westergaard equations, and CRCP-10 considers moving dynamic tandem axle loads using the transformed field domain analysis in time, space, and moving space.

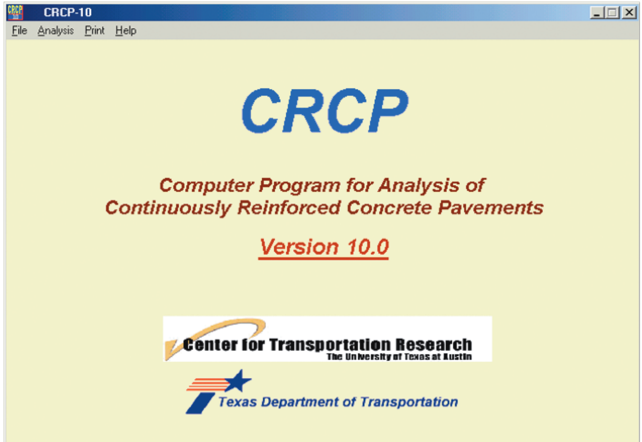

Figure 2: Introductory screen of CRCP-10

CRCP-9 and CRCP-10

The introductory screen of CRCP-10 is shown in Figure 2. The input variables in CRCP-9 and -10 include pavement geometry, concrete and steel material properties, bond-slip relationships between concrete and steel bars and concrete and base layers, environmental and external wheel loads, finite element types, and creep parameters.

When defining concrete material properties, users can select one of eight different coarse aggregate types; then the program automatically generates concrete material properties with the selected coarse aggregates, including thermal coefficient, elastic modulus, tensile strength, and drying shrinkage, from the curing curves developed with the experiments. The bond-slip relationship between concrete and steel bars can be defined as several different approaches, including linear, linear with an ultimate slip, bilinear, and bilinear with an ultimate slip relationships. The analysis results are very sensitive to the bond-slip relationship.

The environmental loads (temperature and drying shrinkage) can be defined as one of the three cases-uniform, linear, and nonlinear - through the depth of the concrete slab. The wheel load stress is calculated considering a static single wheel load using the Westergaard equations in CRCP-9. The more realistic wheel load stress calculation procedure has been integrated into CRCP-10 incorporating tandem axles, dynamic load variation, and moving loads. Figure 3 shows the input screen to define variables needed to calculate wheel load stresses.

The outputs of CRCP-9 and -10 include time histories of mean crack spacing, of mean crack width, and of mean steel stress, crack spacing distribution, and punchout failures according to the wheel load applications. The output screen for the time history of mean crack spacing is shown in Figure 4. As shown in the figure, the screens of crack spacing, crack width, and steel stress time histories list a mean value of analysis results each day until 28 days after the placement of concrete and on the last day of the analysis, and these mean values are plotted. The inputs and outputs of the analysis can be reviewed on a separate screen, and those can be saved for a later use. The analysis summary and the input and output screens can also be printed.

The Researchers Recommend...

Efforts have been made to develop a more realistic mechanistic model that predicts behavior and performance of CRCP. In order to improve the accuracy of the CRCP-10 computer program, the researchers recommend that further calibration of the program with field data be performed to obtain more reasonable ranges of input values and analysis results.

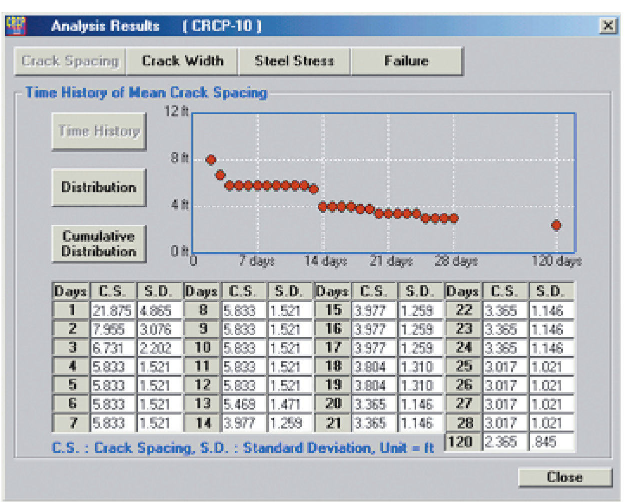

Figure 3: Sample input screen of CRCP-10

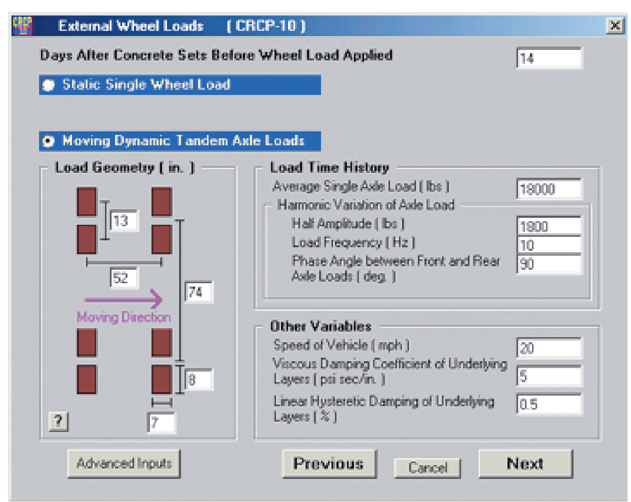

Figure 4: Sample output screen of CRCP-10

For More Details...

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The research is documented in the following reports:

1831-1 *Three-Dimensional Nonlinear Finite Element Analysis of Continuously Reinforced Concrete Pavements,* February 2000
1831-2 *CRCP-9: Improved Computer Program for Mechanistic Analysis of Continuously Reinforced Concrete Pavements*, February 2001
1831-3 *CRCP-9 Computer Program User's Guide*, February 2001
1831-4 *CRCP-10 Computer Program User's Guide*, August 2001
1831-5 *Transformed Field Domain Analysis of Pavements Subjected to Moving Dynamic Tandem Axle Loads and Integrating Their Effects into CRCP-10 Program*, August 2001

To obtain copies of a report: CTR Library, Center for Transportation Research,
(512) 232-3138, email: ctrlib@uts.cc.utexas.edu

TxDOT Implementation Status
May 2003

The CRCP 9 and 10 programs developed by this project will be implemented in further designs of CRC pavements in TxDOT. Training in the use of these programs will be included in a web-based system developed under IPR 5-1869. TxDOT employees will have access to this training through a link in the Intranet that will also allow the downloading of the programs.

For more information, contact: Dr. German Claros, P.E., Research and Technology Implementation Office, (512) 467-3881, gclaros@dot.state.tx.us.

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