

Finite-Element Analysis of Portland Cement Concrete Pavements with Cracks

JEFFERY R. ROESLER AND LEV KHAZANOVICH

It was verified that finite-element modeling could be successfully used to analyze concrete pavements with partial-depth cracks. An existing finite-element program, ILLI-SLAB, was modified (ILLI97) to allow for partial-depth crack analysis. To model a partial-depth crack, a special line spring element was added to the finite-element code. The line spring elements mimic the behavior of a crack by acting as a rotational hinge between two continuous slabs. By using available fracture mechanics techniques, a relationship was derived between the amount of moment load transfer across a crack and the crack depth. This analytical solution was then used to formulate the element stiffness matrix for the line spring element. The deflections predicted by the new finite-element program are correct, but the stresses in the vicinity of the crack tip needed to be corrected to match the stress singularity zone in front of cracks. Several example problems were used to verify the proposed finite-element model, and an example of a typical highway loading condition was analyzed.

Current mechanistic-empirical design procedures for JPCP estimate the fatigue life of uncracked pavements (1,2) as a function of maximum bending stress to the modulus of rupture of the concrete. The equations to describe the fatigue life of concrete slabs and laboratory beams are empirically derived from laboratory and field performance data and do not give insight into the mechanisms of fatigue failure. For many years engineers have tried to explain the fatigue failure of concrete through damage mechanics, probability, and most recently fracture mechanics. Experimental research has also not been able to explain why or how concrete slabs or beams fail in fatigue. However, recent experimental work at the University of Illinois indicates that stable crack propagation occurs in fully supported beams subjected to cyclic loading. Therefore, analysis of crack growth in fully supported slabs may be advantageous in solving the fatigue phenomena.

To solve the problems of a partially cracked slab, fracture mechanics must be used. Fracture mechanics allows for the determination of the stress and strain distribution in cracked structures. Fracture mechanics not only determines the stress/strain distribution at the crack tip but also allows for the determination of the zone of influence the crack has on adjacent areas in the structure.

In recent years, fracture mechanics has been used in pavement design and analysis (3–7). In 1993, Ramaswamy (8) analyzed the effect of propagation of full-depth cracks from a slab's edge to the slab's interior. He developed analytical solutions for stress distributions around the crack tip when the crack tip is located near the slab edge or is sufficiently far from it. However, Ramaswamy's solutions have significant limitations: the applied load must be placed at the crack tip, no temperature loading was considered, and the crack

must be sufficiently short or sufficiently long (i.e., no intermediate crack lengths).

In the fatigue analysis of JPCP pavements, vertical crack propagation is more critical than horizontal crack propagation. Once the crack appears at the slab's surface, it does not take many load cycles for it to propagate horizontally across the slab's surface as seen at the AASHTO Road Test (9). Therefore, analysis of partial-depth cracks is the thrust of this study.

Current finite-element programs most often used in pavement analysis, such as ILLI-SLAB, J-SLAB, KENSLAB, TEACONS, KOLA, and WESLEPID, allow for the analysis of jointed plain concrete pavements with or without dowels (10–15). Joints with aggregate interlock are considered full-depth cracks with varying degrees of shear load transfer. With the introduction of fracture mechanics to pavement design and analysis, there is a need to analyze partially cracked slabs to test and verify the behavior and sensitivity of slabs with varying degrees of vertical cracking. The finite-element method was selected as an attractive universal analytical methodology. The paper presents the incorporation of a crack model into a new finite-element code, abbreviated ILLI97, representing an extension of the finite-element program ILLI-SLAB (16) and its recent modification, ILLI.2 (16).

A distinguishing feature of the partial-depth crack is the presence of infinite stresses near the crack tip induced by virtually any applied load. This stress singularity at the crack tip complicates the finite-element formulation. The new finite-element code, ILLI97, calculates stress and displacement distributions in the cracked slab under traffic and environmental loading conditions. To improve the accuracy of the analysis, the finite-element solutions are analytically extended using fracture mechanics techniques to account for the singularity in the stress field at the crack tip.

THEORETICAL BACKGROUND

In an unrestrained, elastic, homogeneous, isotropic plate, there is no preferential direction of bending. The equations that govern the bending of the plate (M_x , M_y) are the following (17):

$$\begin{aligned}M_x &= -D \left(\frac{\partial^2 w}{\partial x^2} + \nu \frac{\partial^2 w}{\partial y^2} \right) \\M_y &= -D \left(\frac{\partial^2 w}{\partial y^2} + \nu \frac{\partial^2 w}{\partial x^2} \right)\end{aligned}\quad (1)$$

where ν is Poisson's ratio and D is the flexural rigidity of the plate defined as the following:

$$D = \frac{Eb^3}{12(1 - \nu^2)}$$

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