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16. Abstract

Until recently, full-depth punchout was considered the only structural distress in continuously reinforced concrete pavement (CRCP). However, over the last few years, during punchout repair projects, it was discovered that CRCP distresses identified as full-depth punchout were actually caused by partial-depth horizontal cracking (HC) at the depth of longitudinal steel. Quite often, the bottom portion of concrete was solid, with no cracking. It appears that horizontal cracking in CRCP might have existed from the early days of CRCP usage, although not recognized until recently. Consequently, there are very few publications available on this issue. As a first report in this research project, this report summarizes the findings of three papers related to horizontal cracking. Two papers were identified that addressed HC in CRCP. Out of those two, one paper provides general discussion on HC in CRCP, without detailed analysis. The other paper investigated the effects of environmental loading, material properties, and design variables on HC in CRCP. Two-dimensional plain strain finite element modeling was used to analyze the effects of temperature variations along the slab depth, coefficient of thermal expansion (CTE) and modulus of elasticity of concrete, and number of steel layers. The findings are in agreement with what's been observed in the actual CRCP: larger temperature variations, higher values of CTE and modulus of elasticity of concrete, and one-mat steel, rather than double-mat steel, produce higher potential for HC in CRCP. One additional paper was identified that addressed HC in semiconductor application. Thermal stress as well as mechanical stress is the primary cause of the cracking. The mechanism of the horizontal crack in the electrical circuit board is very similar to that of PCC pavement.

Even though the findings in one paper show a clear relationship between design/environmental/materials variables and horizontal cracking potential, the modeling was made with simplified assumptions that are not realistic. As a result, the finite element modeling is of value as far as identifying the relationships is concerned, but not sophisticated enough to provide quantifiable relationships, which could be used to develop design standards or specifications to mitigate horizontal cracking. More realistic and sophisticated modeling using advanced theories of concrete cracking is needed, which is one of the objectives of this research project.

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Horizontal Cracking in Portland Cement Concrete Pavements: Literature Review

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Acknowledgments

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Chapter 1. Literature Review

Two papers were identified on the subject of horizontal cracking in Portland cement concrete (PCC) pavement and continuously reinforced concrete pavement (CRCP). One paper was prepared by the Virginia Department of Transportation and the other by researchers at the Center for Transportation Research (CTR) and the Texas Department of Transportation (TxDOT). In the electrical engineering area, there is a study on the horizontal cracking of commercial semiconductor.

In a paper presenting various distresses in CRCP and action plans to address those distresses, Virginia, Elfino et al. (2001) describe distresses due to horizontal cracking in CRCP. They did not specifically use the term *horizontal cracking*; rather, they depict distresses due to horizontal cracking under "Localized Areas of Broken Concrete." They did not perform any analysis or field evaluations. Instead, they described the distresses observed in the field due to horizontal cracking, and provided their explanations on the possible causes.

Figure 1.1 shows CRCP slabs in Virginia with horizontal cracking at the depth of the steel reinforcement. Horizontal cracks and what appears to be distresses caused by horizontal cracking are shown.

Figure 1.1: Horizontal Cracking in CRCP in Virginia

Elfino et al. (2001) made several statements on horizontal cracking and resulting distresses as follow:

Shear stress in slabs has a parabolic distribution, with the highest stress at mid depth, which could explain the delamination at that location.

The curling action of the concrete due to drying and temperature changes may be the most significant contributor. The dissimilarity between the reinforcing steel and the concrete in thermal and drying shrinkage may be a contributory factor in causing the delamination at the level of the steel. The selection of ingredients and their proportioning affect the shrinkage curling.

After the concrete slab has delaminated, it separates into two layers at the depth of reinforcing steel. The axle loading is carried by the upper layer, making it easy to break, particularly in the wheel path of trucks.

Kim et al. (2004), based on horizontal cracking observed in Texas, conducted theoretical analysis to estimate the effects of several design, environmental, and materials variables (number of steel layers, temperature variations, and thermal coefficient of thermal expansion and modulus of elasticity of concrete) on the potential for horizontal cracking.

For the analysis, a finite element modeling was utilized as shown in Figure 1.2.
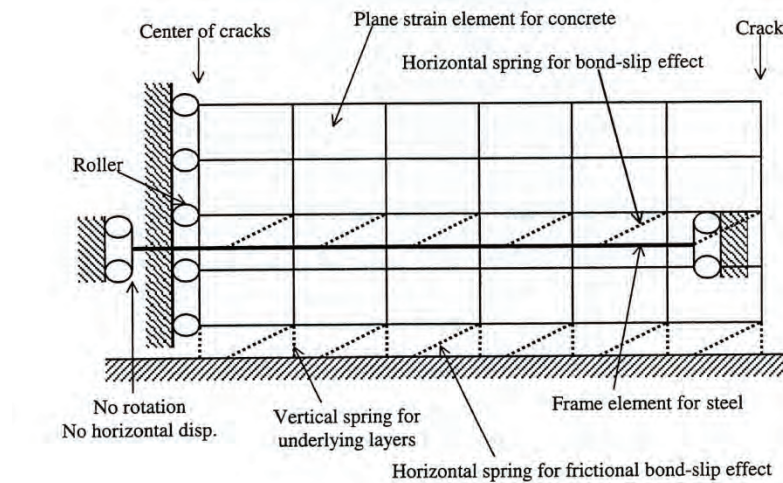
Figure 1.2: Finite element model of CRCP

Bond slip element was introduced to model the interface between concrete and longitudinal steel. Also, concrete was assumed to behave in plane strain mode.

Figure 1.3 illustrates the distributions of normal and shear stresses in concrete at the steel depth. It shows that both normal and shear stresses are maximum near the transverse crack, and almost non-existent in the other regions. This finding supports the horizontal cracking behavior observed in the field, that horizontal cracking is initiated in the transverse crack region.
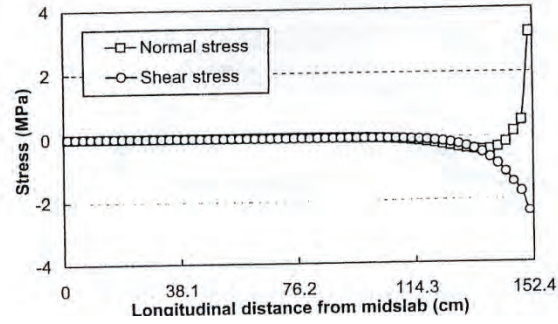
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Figure 1.3: Stress distributions of concrete along longitudinal direction at steel depth

Figure 1.4 shows normal and shear stresses in concrete along the slab depth at transverse crack for two different temperature gradients. As expected, higher temperature differentials between the top and the bottom of the slab resulted in larger concrete stresses at the depth of steel.
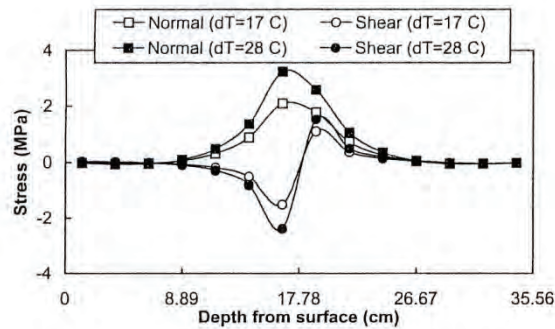

Figure 1.4: Effect of temperature variation on stress distribution along slab depth

Figure 1.5 illustrates the effects of concrete coefficient of thermal expansion (CTE) on normal and shear stresses in concrete along the slab depth. Concrete with higher CTE yields larger stresses in concrete. The results are compatible with the field observations, where concrete with high CTE—concrete containing siliceous river gravel or sandstone—is more prone to horizontal cracking than concrete with low CTE—concrete containing crushed limestone.
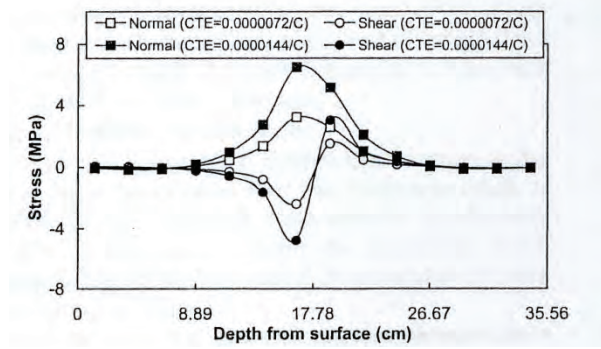
Figure 1.5: Effect of concrete coefficient of thermal expansion on concrete stress

Figure 1.6 shows the effect of concrete modulus of elasticity on the normal and shear stresses in concrete along the slab depth. It is noted that concrete with higher modulus experiences larger normal and shear stresses. This finding also corroborates the field observations, where concrete with higher modulus such as concrete containing hard siliceous river gravel has higher potential for horizontal cracking than concrete with lower modulus.
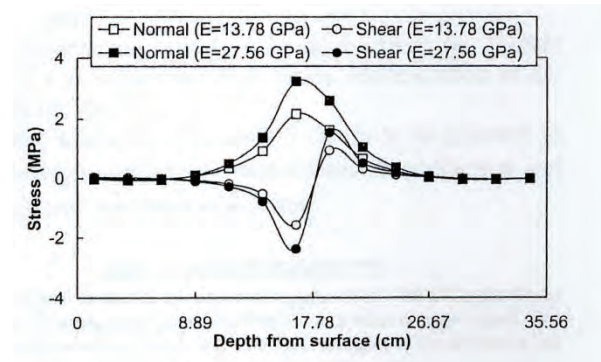
Figure 1.6: Effect of concrete modulus of elasticity on concrete

Figure 1.7 illustrates the effects of steel design on the concrete stresses along the slab depth for a 15-in. slab. It indicates higher concrete stresses with one-mat steel compared with two-mat reinforcement. The results are in agreement with field experience where a section with one-mat reinforcement resulted in horizontal cracking while very little horizontal cracking was observed in a section with double-mat reinforcement.
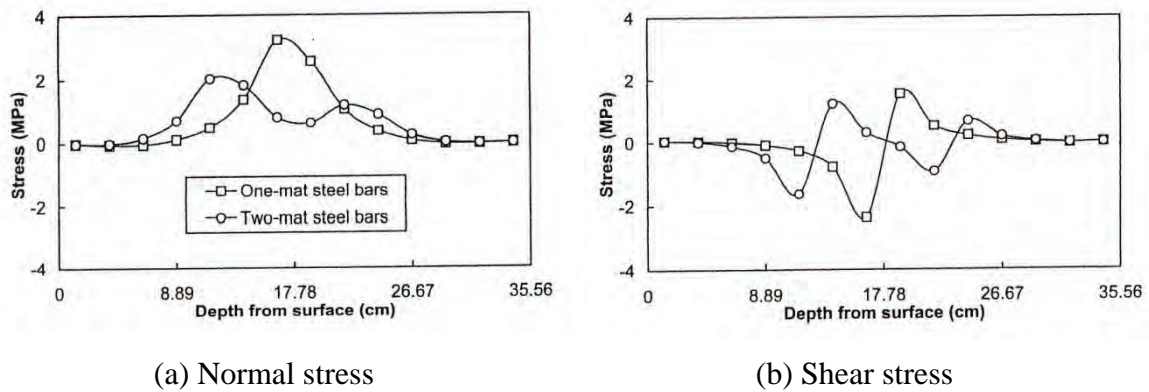
(a) Normal stress   (b) Shear stress

Figure 1.7: Comparison between one- and two-mat steel bars

Kasem et al. (1987) addressed the problem of horizontal silicon die cracking in the commercial semiconductor application. The horizontal cracking can occur in a glass-sealed ceramic dual in-line (CERDIP) package with glass as a die bonding material as shown in Figure 1.8. The fracture mode has been attributed to the combined effects of mechanical and thermal stresses. Figure 1.9 illustrates that the saw-and-break die separation method is identified as the prime source of stress raisers and die edge damage.
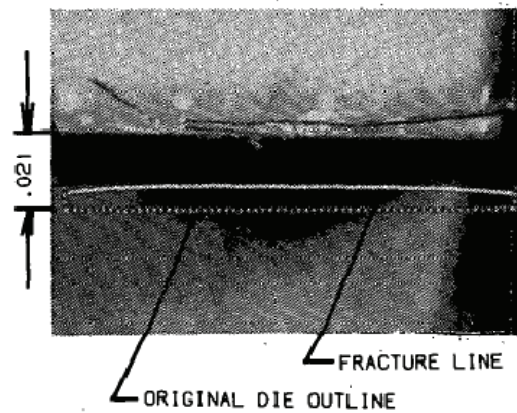

Figure 1.8: Upper portion of die split by horizontal die cracking

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(a) Edge of die separated by saw and break   (b) Failure at corner die
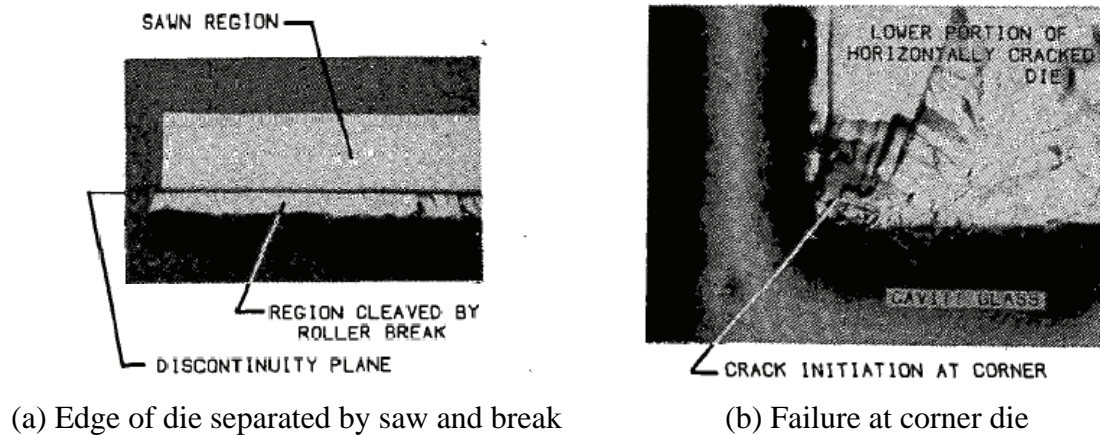
Figure 1.9: Horizontal crack at edge and corner

Sudden cooling causes internal thermal stress and mechanical loads in the assembly due to the solidification of the glass die attached medium and the mismatch of the coefficients of thermal expansion in the package components. Horizontal die fracture mechanism results from two distinct processes: crack generation and crack propagation. The first is due to extrinsic defects (surface flaws). The latter is primarily caused by the thermal loading that devices might be exposed to during die bonding, lid sealing, and temperature cycling.

Figure 1.10 illustrates a measured stress map showing all possible tensile stresses, both direct and induced. The induced stresses are based on the fact that any direct stress induces a stress of the opposite sign perpendicular to it and equal in magnitude to the direct stress multiplied by Poisson ratio. Figure 1.10 (c) shows the plane subjected to the tensile stress. This plane, due to the properties of brittle materials, is the most likely to develop a crack. In this case, the crack would be a horizontal fracture along the saw-and-break plane, which carries the highest stress fields.
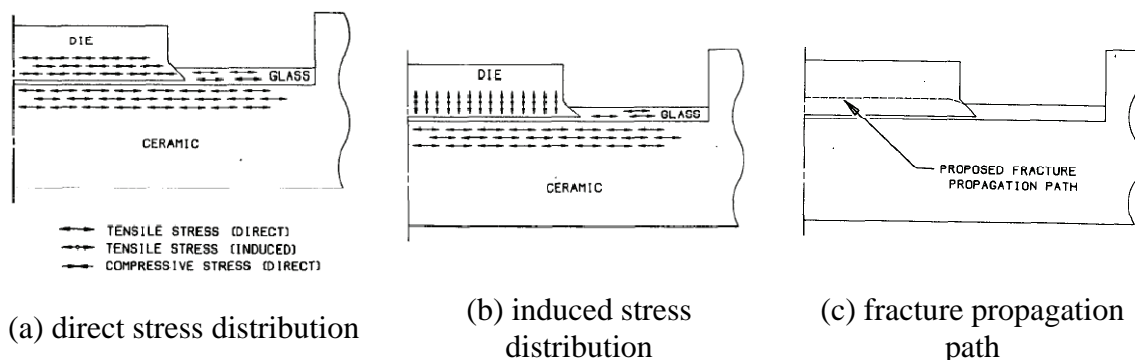

(a) direct stress distribution   (b) induced stress distribution   (c) fracture propagation path

*Figure 1.10: Stress map showing direct and induced stresses*

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A finite element analysis for the thermal stress and strain that is induced by the manual die attach process was conducted. The thermal stress contours and the package thermal distortion have been obtained for both transient and steady-state conditions for a package with a die that was 70 percent sawn through, roller broken, and manually attached. Figure 1.11 shows the right half of a CERDIP 16-lead package cross section with symmetrical boundary conditions.
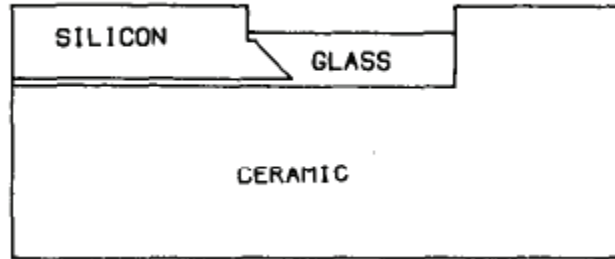

Figure 1.11: Sixteen-lead CERDIP half cross section

Figure 1.12 shows temperature distribution in CERDIP 60 seconds after removal from heater block, which is at 460°C (860°F). It indicates that 60 seconds was long enough for the glass surface to reach the glass solidification temperature of 330°C (626°F) from a die bonding. At that point in time the entire package is nearly at thermal equilibrium, with a maximum bulk temperature of 346°C (655°F). This means that the silicon is stress-free as the glass begins to solidify.

Figure 1.13 shows the steady-state tensile stress distribution inside the package at room temperature. A maximum tensile stress of 9.24×10^{-3}psi occurs inside the ceramic base. However, the highest shear stress field occurs on the die step and in the die attach layer. The direction of the principal tensile stress on the die edge is about 20° to the edge. The solution is in good agreement with the observed fracture pattern in Fig. 10(c). This confirms that a horizontal crack is very likely to propagate once the stress on the chip reached the fracture limit.
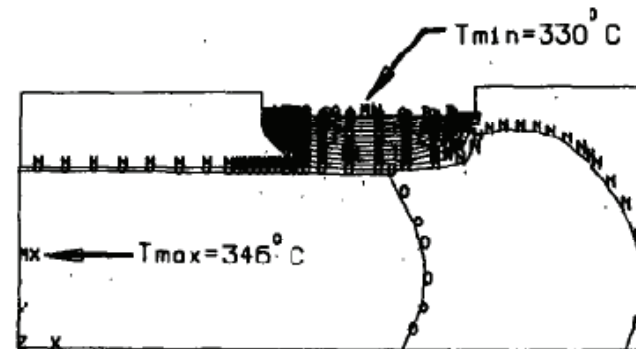
Figure 1.12: Temperature distribution 60 sec after removal from heater block
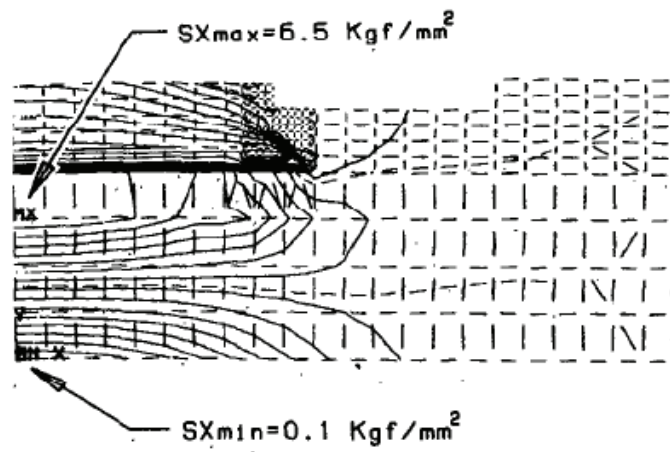
Figure 1.13: Steady-state tensile stress distribution inside package

Chapter 2. Summary

The fact that only two papers were identified that address horizontal cracking in PCC pavement indicates the unfamiliarity with this issue among researchers and practitioners. It also raises a question as to how PCC distresses due to horizontal cracking were classified in the past.

Horizontal cracking also is a common occurrence in the commercial semiconductor application. Thermal stress as well as mechanical stress is the primary cause of the cracking. The mechanism of the horizontal crack in the electrical circuit board is very similar to that of PCC pavement.

Even though the work by Kim et al. (2004) shows clear relationships between design/environmental/materials variables and horizontal cracking potential, the modeling was made with simplified assumptions that are not realistic. As a result, the finite element modeling is of value as far as identifying the relationships is concerned, but not sophisticated enough to provide quantifiable relationships, which could be used to develop design standards or specifications to mitigate horizontal cracking. More realistic and sophisticated modeling using advanced theories of concrete cracking is needed, which is one of the objectives of this research project.

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