Influence Function Approach to Analysis of Jointed Portland Cement Concrete Pavement

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A technique for analyzing the interactions between typical highway loads and jointed rigid pavements by using influence functions is presented. Influence functions are generated by using a modified version of the ILLI-SLAB finite-element model. These influence functions can be used to estimate the minimum and maximum responses caused by moving wheel loads for any point of interest on the slab. A parametric study of the model is presented showing the effects of various key input parameters on the influence functions and stress distributions in the slab. A field model validation case study is presented for M-14, a 229-mm pavement built in Michigan in 1965. Traffic distributions were broken down into equivalent single axle loads per hour. Temperature and moisture gradient effects were estimated for a typical day. These factors were then reduced to obtain the daily fatigue loss. The results of the study indicate that the upward curled or nighttime temperature condition is prevalent and most severe. This results in the peak tensile stresses being located in the top of the slab. Results from the study compare well with field distress surveys for the test pavement.

Recently there has been a large push to develop more mechanistic approaches for pavement analysis and design that are based primarily on sound engineering principles. Most design methods in use are largely empirical and are often based on small data bases. Many question their accuracies and validities. An accurate mechanistic determination of the stresses and strains in a pavement caused by moving vehicle loads is complicated. The problem falls into the broad study of soil-structure interaction problems.

The problem begins immediately after the slab is placed. This is typically done with slip-form paving machines, which require the use of concrete that is fairly workable and has resulting high levels of shrinkage. The concrete begins to undergo drying shrinkage during curing. It does not shrink uniformly, however. The top of the slab, which is exposed to air, typically shrinks more and faster than the bottom. This results in a curled or warped upward condition (Figure 1). The top of the slab will be in tension because of the self-weight of the lifted corners. The pavement will immediately begin to go through daily and annual cycles of moisture and temperature gradients and subgrade strength fluctuations. As the top surface of the slab expands or contracts relative to the bottom, curling results. Friction forces develop along the bottom of the slab because of foundation restraint as the slab undergoes changes in length because of temperature fluctuation. When the slab contracts, tensile stress develops because of the friction. When it expands compression results. Contraction joints are used to minimize the stresses resulting from these phenomena and to control cracking. The contraction joints are typically saw cut to one-third of the pavement thickness as soon as possible after the slab is placed. A joint sealant is then used to prevent water from infiltrating the cracks. The joints are typically doweled by using 25.4- to 38.1-mm steel dowel bars. Coatings are used on the dowels to prevent corrosion and to debond them from the concrete such that expansion and contraction is allowed to occur while wheel loads are transferred from slab to slab. In dry, nonfreezing environments, joints without dowels are often used. They rely on aggregate interlock for load transfer. Cracks that form between planned joints also use this mechanism. These discontinuities cause the stresses in the slab to increase near the joint because of the larger deflections and curvatures in the slab when the load is on or near the joint. The consequences of curling and warping are residual stresses present in the pavement before loading. It can be shown that these stresses are significant and that they must be included in any rationally based mechanistic design procedure. Current empirically based methods typically ignore these aspects.

Traffic is the next part of the problem. The only vehicles of concern are the large trucks because of their large axle loads. Although passenger cars make up most of the traffic volume, they induce very little stress in the pavement. Another concern is the time of day that the trucks are traveling. This is a highly variable site-specific parameter.

Axle spacing, allowable static wheel loads, and tire configurations vary from vehicle to vehicle and also geographically. As the pavement ages and becomes more rough the static axle loads get magnified to a greater extent as the vehicle travels over the surface irregularities, inducing higher stresses. They are velocity, suspension, tire, and road profile dependent.

When all of the coupled effects previously mentioned are reviewed and the variables counted, it is easy to understand the complexity of the problem of estimating the state of stress for different points on the pavement. Presented in this paper is a method for estimating the stress distributions in jointed rigid pavements. This is accomplished by generating influence functions (Figure 2) by using a modified version of the ILLI-SLAB finite-element computer model. Because an influence function represents a continuous response of any point of interest versus load position, it is a powerful tool for determining the location of the load relative to the point of interest that causes the maximum response, even in the presence of residual stresses.

MODIFIED ILLI-SLAB

One of the most promising mechanistic tools currently being developed is the finite-element method (FEM). The computer pro-

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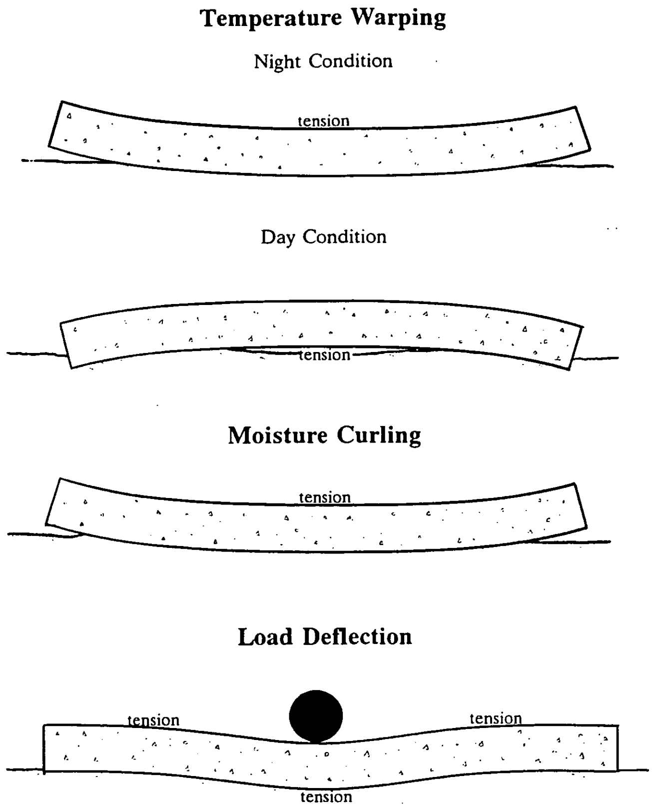

FIGURE 1 Temperature-, moisture-, and load-related curvatures.

gram ILLI-SLAB is an FEM model based on linear elasticity. It was developed at the University of Illinois for analyzing load transfer systems for jointed rigid pavements (*1*). FEM attempts to model the nonlinear response by dividing the problem into small interconnected elements that respond linearly. It uses what is referred to as plate elements to model the concrete slabs in bending. The slabs are connected by beam elements that transmit shear and moment for the doweled joints or spring elements that transmit shear only for the aggregate interlock joints. It can estimate the bending stresses caused by loads in the vertical direction and temperature gradients. A number of subgrade models are available.

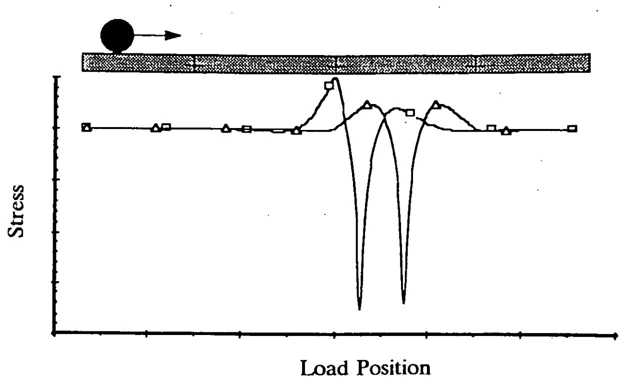

FIGURE 2 Typical shapes for pavement influence functions.

This study focuses on the region from the central joint to the center of a slab along the wheelpath.

In a previous study on the effects of heavy vehicle characteristics on pavement response and performance (*2*) the ILLI-SLAB program was modified to generate influence functions. Influence functions are a way of showing the response (stress, strain, or deflection) at a point of interest versus load position as the load approaches and passes over the point. Shown in Figure 2 are influence functions for stress at the bottom of the slab along the wheelpath caused by a 40-kN wheel load passing over points in the center and near a joint of a 7.62-m-long by 3.65-m-wide, doweled, 229-mm-thick slab with no temperature gradient. In this study only the stress along the wheelpath is examined. The wheelpath is defined as 838 mm from the edge of the pavement for a 3.65-m lane. As the tire approaches the point of interest there is a point at which the deflection basin (Figure 1) caused by the load begins to influence the stresses. Initially the bottom of the slab goes into compression and the top goes into tension. This corresponds to the initial curved downward portion of the deflection basin. The point of maximum compressive stress shown in Figure 2 would correspond to the point of maximum downward curvature in the deflection basin shown in Figure 1. Then as the tire moves on top of the point of interest the slab is curved upward and the bottom of the slab is in tension. As the tire moves away from the point of interest the bottom of the slab once again undergoes compression and then goes back to zero stress as shown or to its residual stress level if temperature or moisture gradients exist. There are two compression peaks and one tension peak at the bottom of the slab per passing wheel. The stress condition at the top of the slab is always assumed to be of equal magnitude but opposite sign compared with that at the bottom of the slab.

In a previous study by Nasim et al. (*3*) instrumented slabs were used to compare strain histories predicted by the modified ILLI-SLAB with strain gauge response. The curved upward response, or tension on the bottom of the slab, showed a very good correlation. For the curved downward response, or tension on the top of the slab, the correlation was adequate but not as good. This may be because of hairline cracks from shrinkage that appear on the top of the slab (*4*) affecting the bending response. When the slab goes into downward curvature (tension on top) these cracks would open up, affecting the neutral axis in bending. The cracks would close during curved upward bending and the slab would behave more as it is modeled, with the neutral axis at midslab.

In a modified ILLI-SLAB run the wheel load is moved across the pavement model at 76.2-mm intervals so that its center rests on a nodal point of the mesh. The response for each node along the wheelpath is recorded for each load position. The result is that influence functions can be generated for points at intervals of every 76.2 mm along the pavement by plotting load position versus response at a given node. Notice that in Figure 2 the maximum tensile and compressive stresses are shown to be higher for a point near the transverse joint. This is because of the higher curvature and deflections caused by the load in the presence of the discontinuity or joint.

When the minimum and maximum stresses from each influence function are plotted versus distance from the transverse joint, it is observed that at some distance away from the joint the stresses reach a maximum. The stresses drop to a stable value as the load moves away from the joint and toward the middle of the slab, where the stresses are no longer affected by the discontinuity (Figure 3).

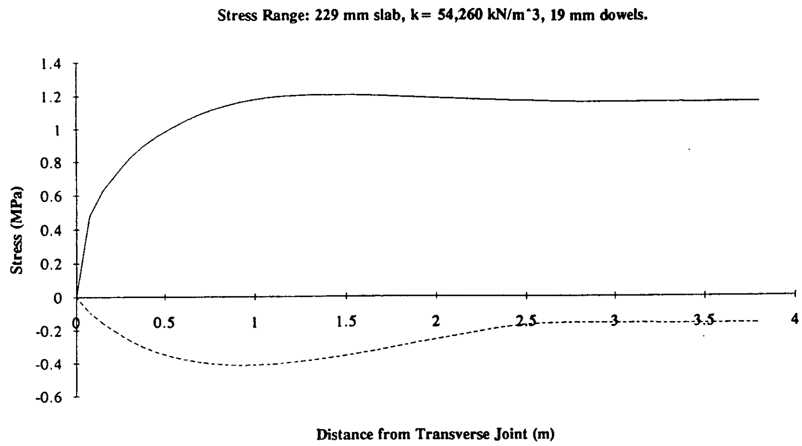

FIGURE 3 Resulting stress range for points along wheelpath as tension on top of slab/compression on bottom of slab.

PARAMETRIC STUDY OF MODIFIED ILLI-SLAB

A parametric study of the modified ILLI-SLAB model was performed to show how the input parameters affect the shapes of the influence functions and the resulting stress ranges in the slab. Some of the variables studied and their relative effects are described below.

Temperature Gradients

By far the most interesting and severe effects observed in the study were those caused by curling and warping. Shown in Figure 4 is the effect of slab length on residual stresses along the wheelpath caused by nighttime temperature gradients. In this situation the top of the slab is in tension and the bottom is in compression. It shows the concept of critical slab length (*5*). For this pavement-subgrade combination the critical slab length is between 7.62 and 9.14 m. It can be seen that as the slab length is increased beyond 9.14 m the tensile stresses caused by the slab's self-weight in response to thermal warping do not increase in the interior of the slab.

How varying the temperature gradients in a 279-mm slab of 6.1 m in length affects the stress range along the bottom of the slab caused by a passing 40-kN wheel load is shown in Figure 5. Remember that on the basis of this model a compressive stress on the bottom of the slab is accompanied by a tensile stress of equal magnitude at the top of the slab. The residual stress caused by the temperature gradient is not shown in Figure 5, but the coupled response of a temperature gradient and a 40-kN wheel load is shown. During the nighttime gradient condition for portions toward center slab, the bottom of the 279-mm slab will never experience tension as the 40-kN load passes. For these portions the top of the slab is in a constant state of tension. As the load approaches a point of interest the tension at the top of the slab increases as the curved down portion of the deflection basin passes over the point. Then the stress goes almost to zero as the load is directly above the point of interest. The tensile stress at the bottom of the slab caused by the wheel is not as large as the residual compressive stress caused by the temperature gradient. The stress then increases above the residual stress level as the trailing curved downward portion of the deflection basin passes over the point of interest and eventually returns to its residual stress level. In a 178-mm slab the deflections and curvature caused by the load are great enough to cause the top of the slab to go from residual tension to compression and then back to tension.

Moisture and shrinkage gradients that behave similarly to nighttime temperature gradients can completely cancel the effect of the daytime temperature gradients. The result is that the slabs are predominantly in a curled upward condition or nighttime gradient condition. This results in the critical tensile stresses being located on the top of the slab when the curved down portion of the deflection basin passes over the point of maximum residual stress, and there are two of these tensile peaks for each pass of a wheel load.

It must be pointed out that during periods of high afternoon temperature gradients the slab is expanding and foundation restraint friction forces are inducing compressive stresses, reducing the effect. During the night, however, the slab is contracting and the foundation restraint is inducing tensile stresses, increasing the effect. Also, the location of the maximum residual stress is not on the wheelpath. However, the stress range is at a maximum along the wheelpath. Thus it is here that the loading is most cyclic in nature and load repetitions become a more important consideration.

Temperature gradients typically vary from 0.087 to 0.109°C/mm in the daytime to 0.044 to 0.065°C/mm in the nighttime (*6,7*).

Moisture and Shrinkage Gradients

Work by Tremper and Spellman (*8*) has shown that upward curvature is the predominant condition for highway pavement slabs

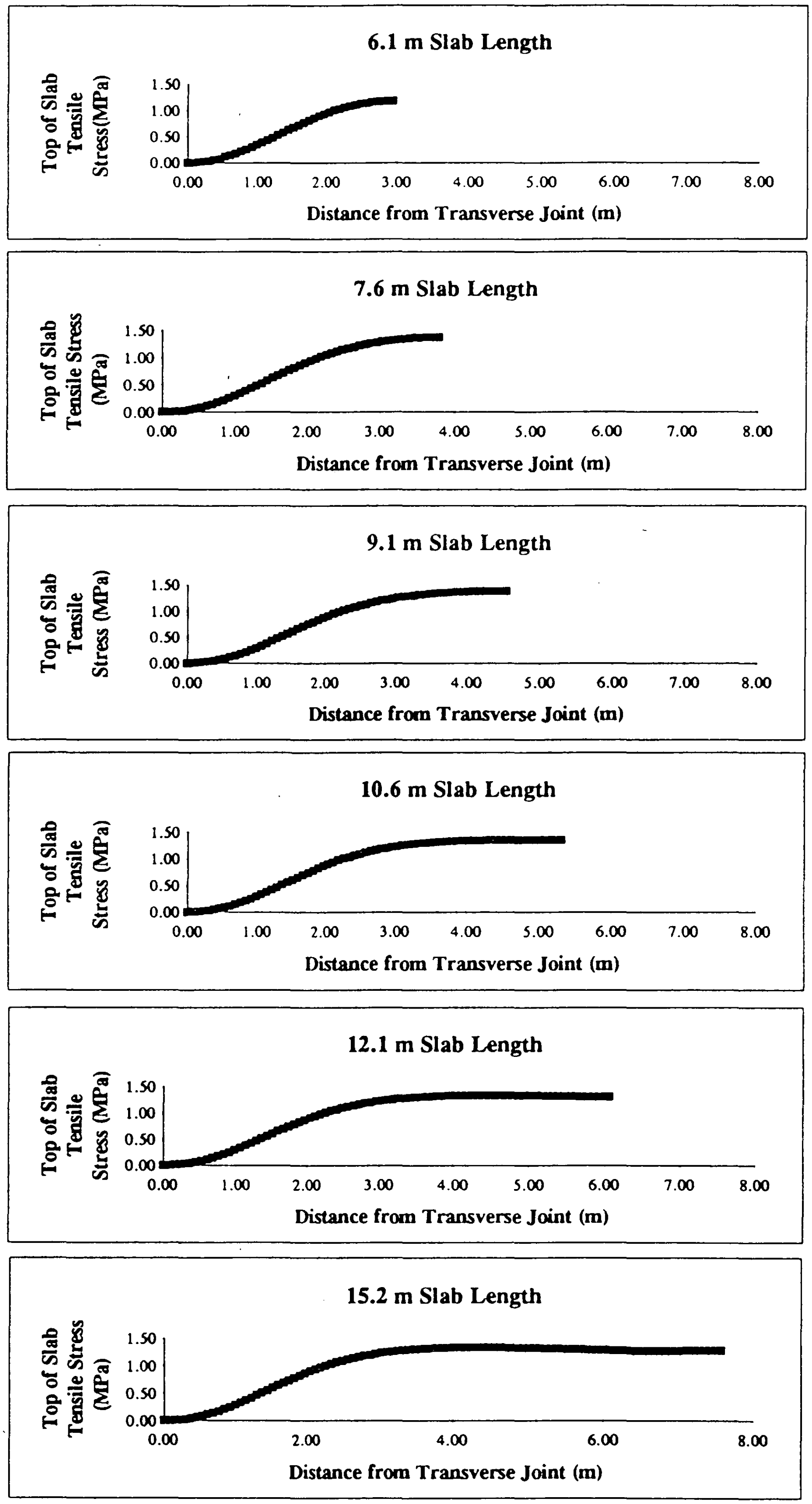

FIGURE 4 Residual stresses caused by nighttime temperature differential (tension on top of slab) along wheelpath for various slab lengths from joint to center of slab.

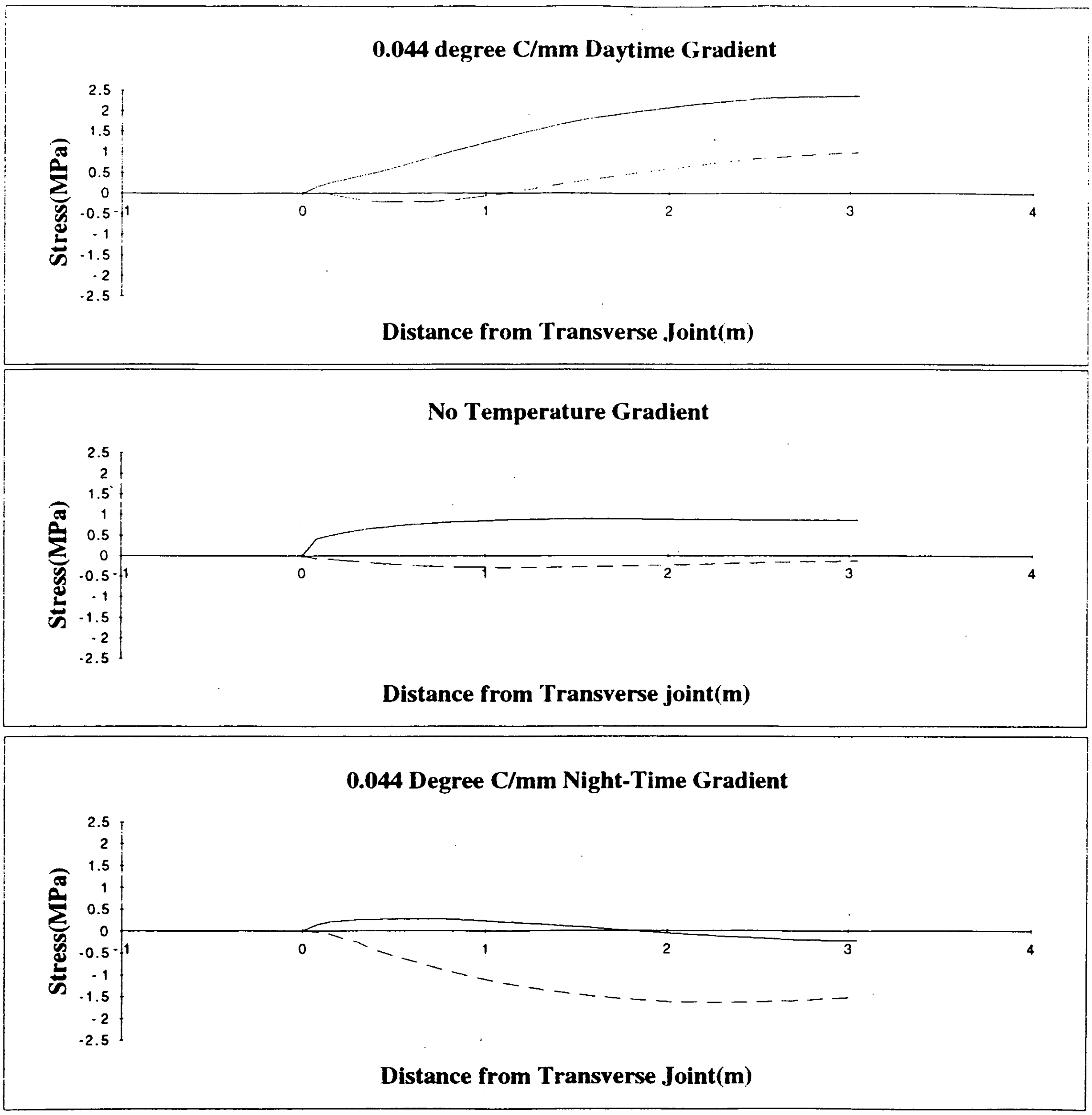

FIGURE 5 Stress variations for different temperature gradients for a 40-kN single tire as tension on bottom of slab (279-mm slab, 6.1-m slab length, 25.4-mm dowels at 305 mm; k = 54, 260 kN/m^3).

and that highway slabs are typically drier on the top than the bottom. They showed that the afternoon gradients were seldom great enough to cause the slab to go into downward curvature. They also point out that the state of California has shown that slabs constructed with concrete that exhibits higher levels of shrinkage have greater curling.

Janssen (*4*) has studied moisture profiles in highway pavements and has shown that the moisture gradient is nonlinear over the depth of the pavement. He estimates that the resulting movement owing to typical moisture gradients is not enough to fail the slab in bending but is enough to cause cracking in the top 19 mm of the slab because of the locally high level of shrinkage that causes high tensile stresses.

All of the factors described previously are typically modeled as equivalent nighttime temperature gradients (i.e., curved upward). Reddy et al. (*9*) have estimated that the moisture gradients encountered have equivalent nighttime temperature gradients of 0.065 to 0.13°C/mm of slab thickness. This combined with the average range of temperature gradients indicates that the slab will be curled upward, with effective temperature gradients varying between 0.022°C/mm in the daytime to 0.13°C/mm in the nighttime.

Results from a study of pavements in Chile (*10*) show that the curved upward condition dominates. During periods with high levels of rainfall the upward curvature is reduced, and in dry periods it is most extreme.

Load Magnitude

The stress variation in the pavement is nonlinear with respect to load magnitude. This is because for small loads the pavement slab, which is much stiffer than the Winkler subgrade, carries most of the load. As the load magnitude is increased and deflections increase, a larger and larger fraction of the load is carried by the subgrade. The increase in stress in the pavement slab for each load increase is reduced accordingly.

The shape of the deflection basin, that is, the locations of points of maximum curvature and stress, does not change much as the load magnitude is increased. This results in changes in the influence functions and stress range functions essentially only in magnitude but not in shape.

Joint Opening

Stress distributions are largely affected by the size of the joint opening. The effects of various joint openings on the range of stresses in the slab are shown in Figure 6. When the joint opening is very small the stress is distributed uniformly in the slab. As the joint opening increases larger deflections occur, resulting in the distribution of the load over a greater area. This results in higher curvatures and bending stresses in the slab that move farther away from the joint as the joint opening increases.

Joint opening is affected by slab length, the coefficient of thermal expansion, and the foundation restraint.

Dowel Size

Dowel size has an interesting effect. The results for dowels of various diameters are shown in Figure 7. When 19.1-mm dowels were analyzed the maximum stress in the slab was predicted to be far from the joint. In this case the joint is relatively flexible and the ends of the slabs at the joint are more free to deflect. This pushes the points of maximum curvature away from the joint.

When 38.1-mm-diameter dowels were analyzed an interesting phenomenon became apparent. The stresses were concentrated near the joint and the magnitude of the stresses increased sharply. These results indicate that there is an optimum dowel size for a given slab thickness. In this case it is the 31.75-mm bars.

Other Input Variables

All of the other input parameters studied had very little effect on the resulting magnitude of the estimated stresses and little effect on the locations of the resulting stresses.

MODEL VALIDATION CASE STUDY

Analysis of M-14 Ann Arbor, Mich.

M-14 is a 229-mm portland cement concrete pavement constructed in 1965. It has two 3.66-m lanes with 30.5-m joint spacing and 31.75-mm dowel bars spaced at 3.66 m. The slab rests on 102 mm of select gravelly sand compacted in place and underlain by 76.2 mm of compacted sand subbase. The local geology can be classified as glacial end moraine. The modulus of subgrade reaction for this section was estimated to be 67 825 kN/m^3, but in this environment support would be expected to be quite variable.

Shown in Figure 8 is the distribution of what will be referred to as medium and heavy trucks and the resulting equivalent single axle loads (ESALs) per hour. The data are based on a 1992 weigh-in-motion (WIM) survey of the design lane. The ESALs per hour were estimated by using a truck factor of 1.39 for heavy trucks and 0.41 for medium trucks (G. Siwek, Method of Calculating 18-kip Axle Equivalencies, unpublished position paper). It is interesting to note that most of the ESALs occur when the worst possible nighttime gradient conditions exist.

Crack surveys have been performed at 5-year intervals since the time of construction. Shown in Figure 9 is the distribution of cracks at 5 and 15 years after construction. Shown in the plot at 5 years is the number of cracks as a function of distance from the transverse joint. In the plot for 15 years is shown the number of cracks as a function of distance from cracks that existed at 5 and 10 years. Once a crack forms in one of the 30.5-m slabs it behaves as two slabs of shorter lengths connected by an aggregate interlock joint. At 5 years the greatest numbers of cracks occur at 4.6 to 4.9 m, 10.1 to 10.4 m, and 14.6 to 15.2 m from the transverse joint. The majority of the cracks that appeared in the 15-year survey were 4.6 to 4.9 m from previous cracks.

Analysis Method

An ILLI-SLAB model of the pavement was established. Influence functions were obtained for 40-kN loads passing over the slabs with temperature gradients of −0.044°C/mm for daytime conditions and 0, 0.044, 0.087, and 0.131°C/mm for nighttime conditions. The daily traffic was divided up into three ranges representing daytime (10 a.m. to 6 p.m.), average (6 a.m. to 10 a.m. and 6 p.m. to 10 p.m.), and nighttime (10 p.m. to 6 a.m.) conditions. It was assumed that the combined moisture and temperature effects resulted in effective temperature gradients of 0°C/mm for the daytime condition, 0.044°C/mm for the average condition, and 0.087°C/mm for the nighttime condition. The stress and ESAL distributions for each condition were analyzed with available fatigue models to roughly estimate the damage versus distance from the transverse joint that would occur for each condition. The results for the three conditions were added together to yield damage per day.

M-14 Analysis Results

Shown in Figure 10 is the response of a 15.2-m slab model of M-14 to a 40-kN load for various temperature gradients. Since the critical slab length for this pavement model is about 9.1 m the model response for a 15.2- or a 30.5-m slab will be the same beyond about 4.6 m from the joint. When the slab is curled upward the location of maximum stress varies only slightly for the different temperature gradients and occurs at 4.6 to 5.1 m from the joint. The maximum stress occurs during the nighttime condition, on the top of the slab, after the tire has gone by the point of interest and the trailing curved downward portion of the deflection basin is passing through the point. Each point of the re-

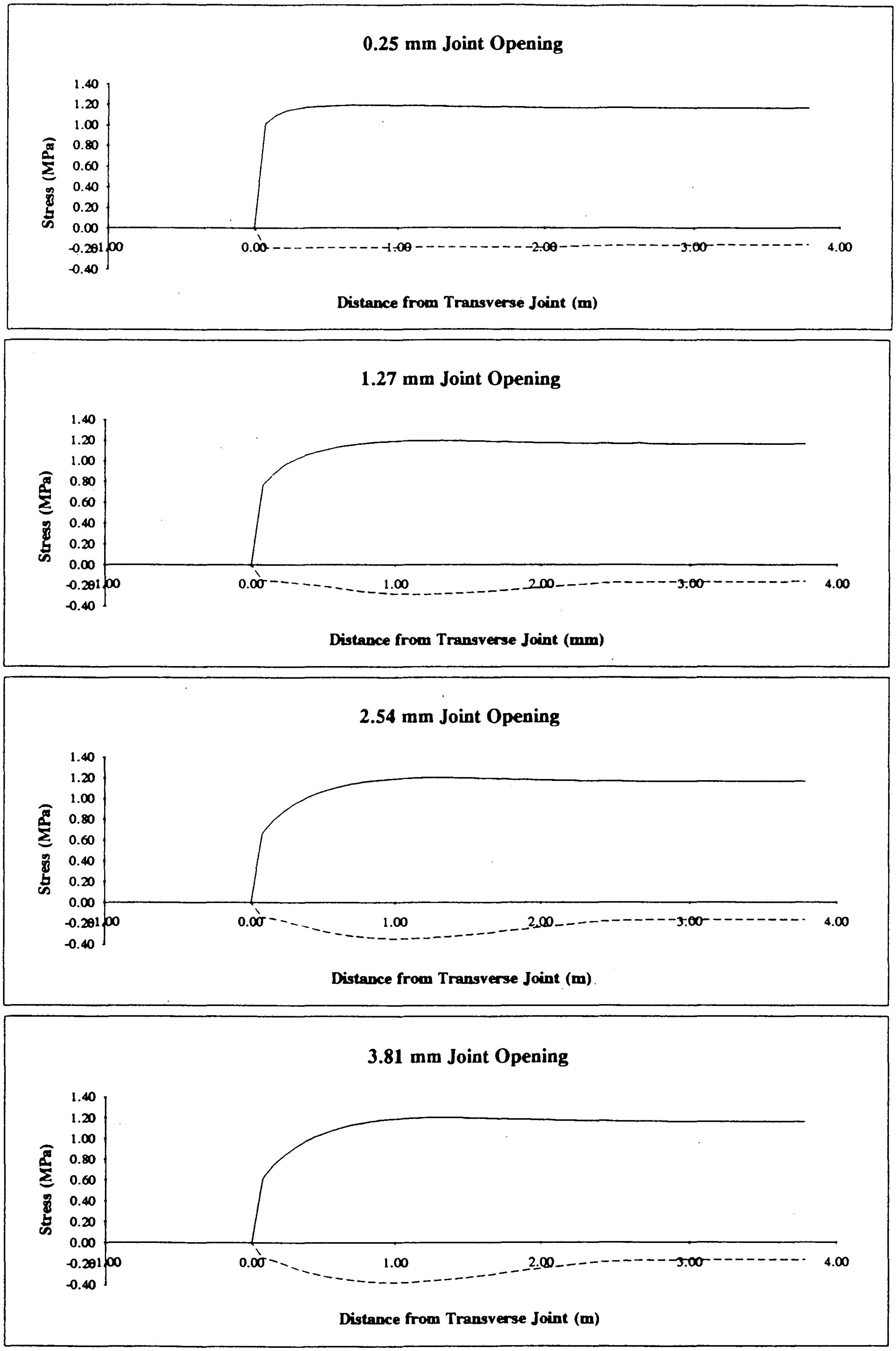

FIGURE 6 Relationship between joint opening and longitudinal stress.

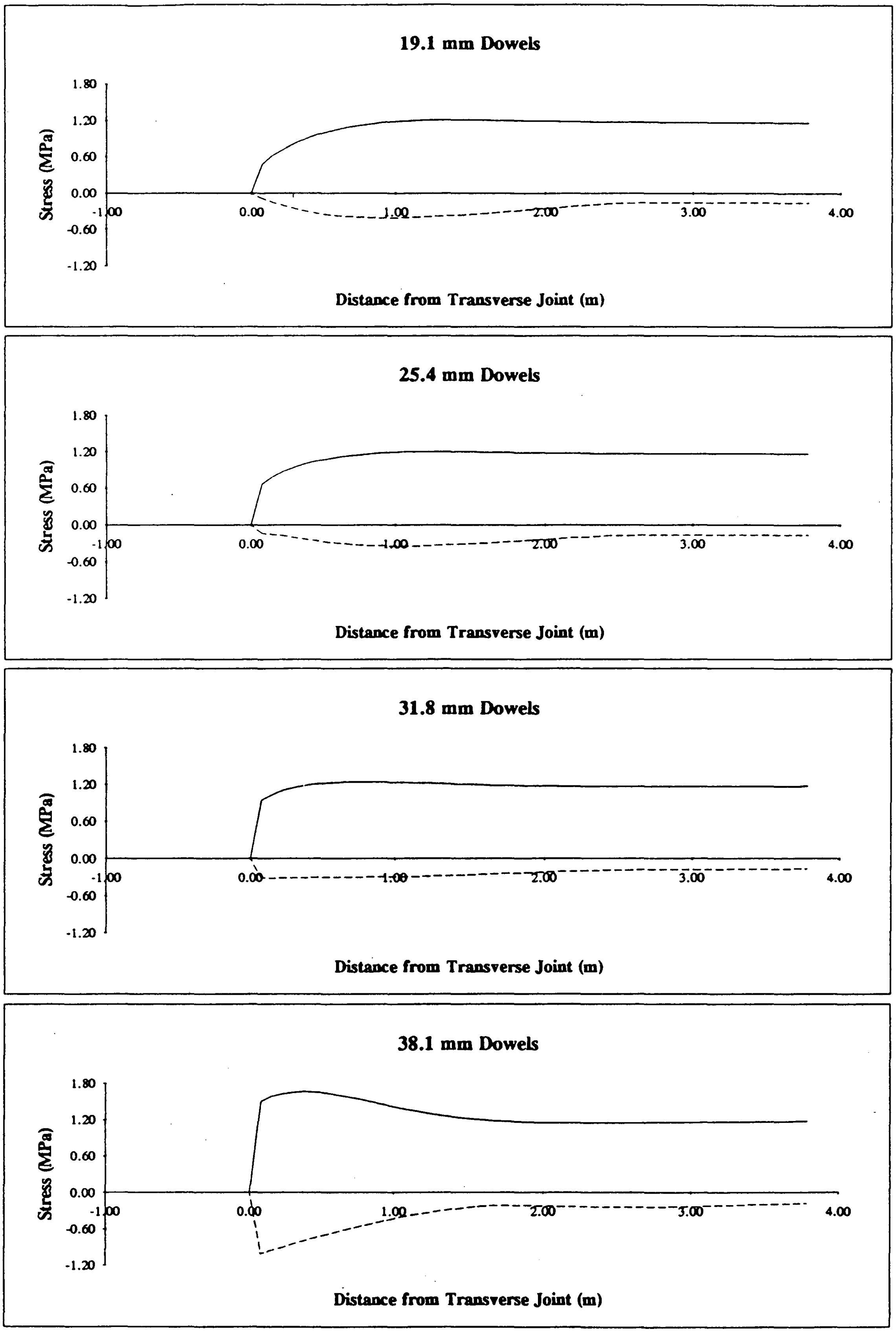

FIGURE 7 Relationship between dowel size and longitudinal stress.

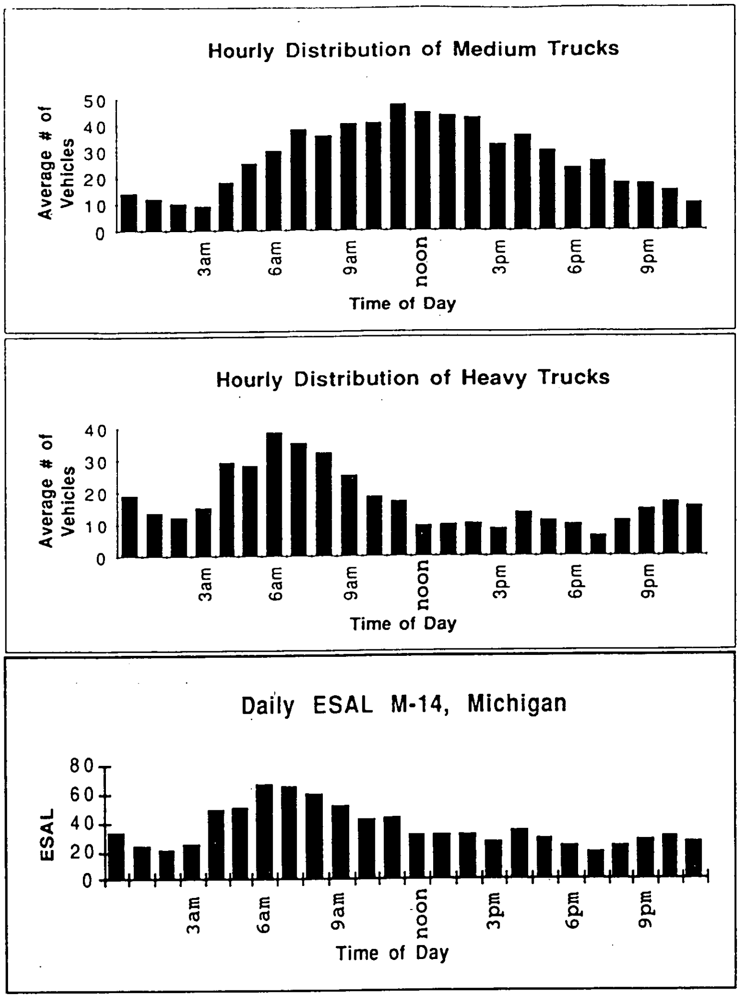

FIGURE 8 Average hourly truck distribution for M-14 in Ann Arbor, Mich., on the basis of a 1993 WIM study.

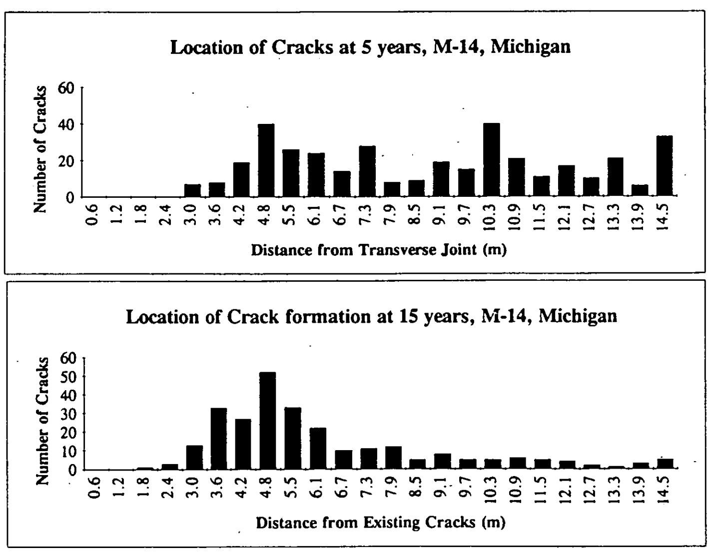

FIGURE 9 Crack distribution from M-14 distress surveys.

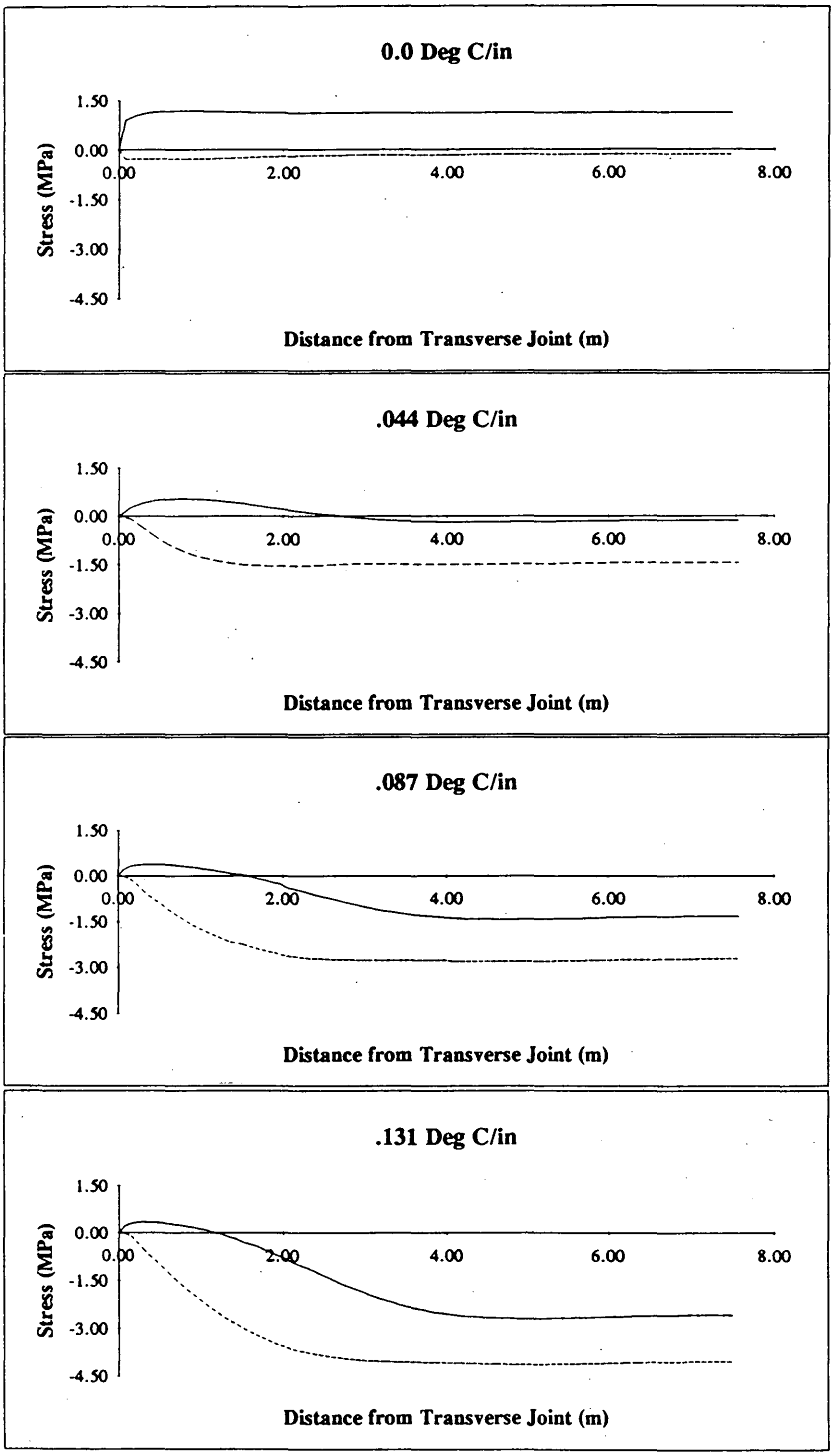

FIGURE 10 Response of M-14 model to nighttime gradients.

sulting stress distributions was analyzed with the PCA, Vesic, and Darter fatigue models (*2*) to estimate its daily fatigue loss. Shown in Figure 11 are the results based on a 4.48-MPa modulus of rupture. None of the models was developed on the basis of load patterns similar to those shown in an influence function. Hence they are not considered to be accurate. Qualitatively, however, they all predict that the maximum distress will occur at about 4.6 m from the joint. When this is compared with the crack locations from the distress surveys the match is very good.

CONCLUSIONS

Described in this paper has been an influence function approach to rigid pavement analysis. The influence function approach, de-

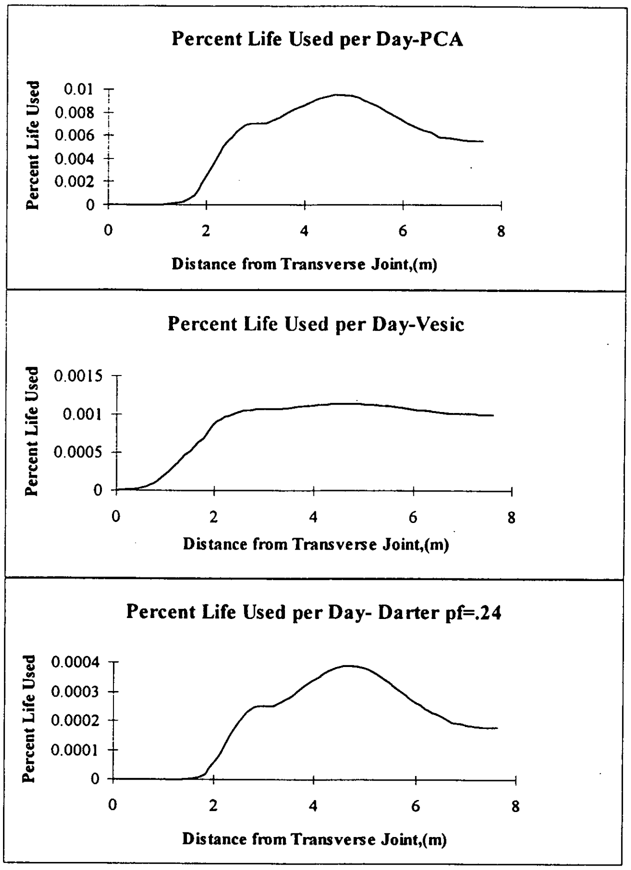

FIGURE 11 Estimated damage from various fatigue models for described method.

veloped at the University of Michigan Transportation Research Institute (*2*), is demonstrated to be a very powerful tool for pavement analysis. The recent studies cited on thermal, moisture, and shrinkage gradients have all shown that they have a significant effect on the residual stresses and that the highway slabs are predominantly in the upward curled condition, placing the top of the slab in tension. When this condition exists the peak tensile stresses are on the top of the slab when the curved downward portions of the deflection basin pass over the point of interest. There are two of these peaks for each pass of a tire. It is the combined residual stresses caused by the curling, warping, and load that have the most significant effects. When all of these factors are modeled with the modified ILLI-SLAB and the resulting stresses are analyzed with existing fatigue models, the estimated location of the maximum damage per day matches well with the observed crack locations from M-14.

The influence functions can also be used to compare different joint properties. It was demonstrated that there was an optimum dowel size and that the stress distribution around the joint is sensitive to joint opening.

This influence function approach can help in the development of greater understanding of the problem of vehicle-pavement interaction and shows good potential as a mechanistic-empirical design approach. Before this, work must be done in the areas of fatigue models based on the type of stress histories described here, determination of regional moisture and temperature conditions, specific mix design factors and their impacts in the context of this model, and determination of how to handle the load magnitude distribution (i.e., ESAL concept). This will allow engineers to more effectively design pavements and for the more effective regulation of the trucking industry.

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