DEVELOPMENT OF NEW STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURES FOR JOINTED CONCRETE PAVEMENTS

Ying-Haur Lee[1], Shao-Tang Yen, Chao-Tsung Lee, Jean-Hwa Bair, and Ying-Ming Lee

ABSTRACT

This study focused on the development of an alternative stress estimation procedure to instantly calculate the critical stresses of jointed concrete pavements. Thus, the primary components for stress analysis including gear configurations, total wheel load, tire pressure, a widened outer lane, a tied concrete shoulder, and thermal curling due to a linear temperature differential have to be considered. The well-known ILLI-SLAB finite element program was used for the analysis. The program's applicability for stress estimation was further validated by reproducing very favorable results to the test sections of the Taiwan's second northern highway, the AASHO Road Test, and the Arlington Road Test. With the incorporation of the principles of dimensional analysis and experimental design, a series of finite element factorial runs over a wide range of pavement designs was carefully selected and conducted. Consequently, prediction equations for stress adjustments were developed using a modern regression technique (Projection Pursuit Regression). Subsequently, a simplified stress analysis procedure was proposed and implemented in a user-friendly computer program (TKUPAV) to facilitate instant stress estimations. Together with PCA's cumulative fatigue damage equation, a modified PCA stress analysis and thickness design procedure was also proposed and incorporated into the TKUPAV program. This computer program will not only instantly perform critical stress calculations, but it may also be utilized for various structural analyses and designs of jointed concrete pavements.

INTRODUCTION

Traditionally, the Westergaard's closed-form stress solutions for a single wheel load acting on the three critical loading conditions (interior, edge, and corner) were often used in various design procedures of jointed concrete pavements. However, the actual pavement conditions are often different from Westergaard's ideal assumptions of infinite or semi-infinite slab size and full contact between the slab-subgrade interface. Besides, the effects of different gear configurations, a widened outer lane, a tied concrete shoulder, a second bonded or unbonded layer may result in very different stress responses from the Westergaard's solutions. These effects may be more accurately and realistically accounted through the use of a finite element (F.E.) computer program. Nevertheless, the difficulties of the required run time, the complexity of F.E. analysis, and the possibility of obtaining incorrect results due to the improper use of the

[1] **Ying-Haur Lee, Associate Professor; Jean-Hwa Bair, Chao-Tsung Lee, Shao-Tang Yen, and Ying-Ming Lee, Graduate Research Assistants, Department of Civil Engineering, Tamkang University, E725, #151 Ying-Chuan Rd., Tamsui, Taipei, Taiwan 251, R.O.C., TEL: (886-2) 623-2408, FAX: (886-2) 620-9747, E-mail: yinghaur@tedns.te.tku.edu.tw.**

F.E. model often prevent it from being used in practical pavement design. Thus, the main objectives of this study were to develop an alternative procedure to more conveniently calculate the critical stresses of jointed concrete pavements with sufficient accuracy for design purposes [*1*].

In addition, currently most concrete pavement thickness design procedures do not consider curling stress in fatigue analysis, but many researchers indicate that it should be considered to warrant a zero-maintenance thickness design. Thus, a review of the most widely-adopted PCA design procedure was first conducted. Based on Westergaard's closed-form edge stress solution and several prediction models for stress adjustments for a variety of loading and environmental conditions, a modified PCA equivalent stress calculation and thickness design procedure was proposed and implemented in a highly user-friendly, window-based TKUPAV program for practical trial applications.

WESTERGAARD'S CLOSED-FORM SOLUTIONS

In the analysis of a slab-on-grade pavement system, Westergaard has presented closed-form solutions for three primary structural response variables, i.e., slab bending stress, slab deflection, and subgrade stress, due to a single wheel load based on medium-thick plate theory and the assumptions of an infinite or semi-infinite slab over a dense liquid (Winkler) foundation [*2*]. In addition, Westergaard has also developed equations for curling stresses caused by a linear temperature differential between the top and the bottom of the slab [*3, 4*]. Nevertheless, there exists no explicit closed-form solutions to account for the combination effect of loading plus curling on a concrete slab.

EFFECTS OF CURLING AND WARPING

Whether curling and warping stresses should be considered in concrete pavement thickness design is quite controversial. The temperature differential through the slab thickness and the self-weight of the slab induces additional thermal curling stresses. For day-time curling condition, compressive curling stresses are induced at the top of the slab whereas tensile stresses occur at the bottom; or vice versa for night-time curling condition. The moisture gradient in concrete slabs also results in additional warping stresses. Since higher moisture content is generally at the bottom of the slab, compressive and tensile stresses will occur at the bottom and at the top of the slab, respectively. A totally different situation will happen if the moisture content at the top of the slab is higher than that at the bottom right after raining.

Even though the effects of thermal curling and moisture warping have been discussed in the PCA design guide, curling stresses were not considered in the fatigue analysis due to the compensative effect of most heavy trucks driving at night and only quite limited number of day-time curling combined with load repetitions. Furthermore, since moisture gradient highly depends on a variety of factors such as the ambient relative humidity at the slab surface, free water in the slab, and the moisture content of the subbase or subgrade, which are very difficult to measure accurately, thus it was also ignored in the PCA's fatigue analysis [*5*].

On the other hand, many others have repetitively indicated that curling stress should be considered in pavement thickness design, because curling stress may be quite large and cause the slab to crack when combined with only very few number of load repetitions. Darter and Barenberg [*6*] surveyed the non-traffic loop of the AASHO Road Test and have found after 16 years most of the long slabs (40-foot) had cracks, but not in the 15-foot slabs, probably because longer slabs have much greater curling stress than shorter slabs. In consideration of zero-maintenance design, Darter and Barenberg have suggested the inclusion of curling stress for pavement thickness design. More detailed descriptions and similar suggestions to include curling stress in the fatigue analysis may also be found in the NCHRP 1-26 report [*7*].

ILLI-SLAB SOLUTIONS AND ITS APPLICABILITY

The basic tool for this analysis is the ILLI-SLAB F.E. computer program which was originally developed in 1977 and has been continuously revised and expanded at the University of Illinois over the years. The ILLI-SLAB model is based on classical medium-thick plate theory, and employs the 4-noded 12-degree-of-freedom plate bending elements. The Winkler foundation assumed by Westergaard is modeled as a uniform, distributed subgrade through an equivalent mass foundation. Curling analysis was not implemented until versions after June 15, 1987. The present version (March 15, 1989) [*8*] was successfully complied on available Unix-based workstations of the Civil Engineering Department at Tamkang University. With some modifications to the original codes, a micro-computer version of the program was also developed using Microsoft FORTRAN PowerStation [*9*].

To further investigate the applicability of the ILLI-SLAB F.E. program for stress estimation, comparisons of the resulting ILLI-SLAB stresses and the actual field measurements from some test sections of Taiwan's second northern highway, the AASHO Road Test, and the Arlington Road Test were conducted and described as follows.

Test Sections of Taiwan's Second Northern Highway

The test sections of Taiwan's second northern highway [*10, 11*] were constructed as jointed concrete pavements with an unbonded lean concrete base and the following characteristics: (Note: 1 in. = 2.54 cm, 1 psi = 0.07 kg/cm^2, 1 pci = 0.028 kg/cm^3, 1 kip = 454 kg, 1 ^{o}F = 5/9 ^{o}C)

1. finite slab size: 3-lane (one direction), L = 188 in., W = 148 in.
2. thickness of the top and the bottom layers: h_1 = 10 in., h_2 = 6 in.
3. concrete modulus of the top and the bottom layers: E_1 = 4.03E+06 psi, E_2 = 1.97E+06 psi
4. Poisson's ratio of the top and the bottom layers: $\mu_1 = \mu_2 = 0.20$
5. self-weight of the top and the bottom slabs: $\gamma_1 = \gamma_2 = 0.085$ pci
6. modulus of subgrade reaction: k = 481 pci
7. longitudinal joints: tied bars, spacing = 24 in., diameter = 5/8 in., Poisson's ratio = 0.2, elastic modulus = 2.9E+07 psi.
8. transverse joints: dowel bars, spacing = 12 in., diameter = 1.25 in., Poisson's ratio = 0.2, elastic modulus = 2.9E+07 psi, width of joint opening = 0.236 in., aggregate interlock factor (AGG) = 1000 psi, dowel concrete interaction (DCI) = 1.9E+06 lbs/in. (assumed).
9. with an AC outer shoulder.

A fully loaded truck with three different levels (60.7, 43.1, and 34.3 kips) of rear dual-tandem axle loads was placed near the slab corner. The cross section of highway pavement, gear configurations, and test layouts were shown in Figure 1 (a). Concrete temperatures were measured by embedding thermocouples into the fresh concrete. Horizontal movements of the slabs were measured using Linear Voltage Displacement Transducers (LVDT's). Strain gages were used to measure surface concrete strains. At the time of testing, a positive temperature differential ΔT = 10.8 °F was measured across the slab thickness; the slab thermal coefficient α was assumed 5.5E-06 /°F. The resulting horizontal stresses estimated by the ILLI-SLAB program were compared to the actual measured stresses and summarized as follows:

Axle load (kips)	C70		C71		C72	
	Measured (psi)	ILLI-SLAB (psi)	Measured (psi)	ILLI-SLAB (psi)	Measured (psi)	ILLI-SLAB (psi)
60.7	36.5	24.1	74.3	66.1	94.3	92.9
43.1	37.2	23.6	62.9	55.4	67.0	73.0
34.3	37.5	23.3	47.0	49.8	45.7	62.7

Note that since the strain gage locations C70 = (176.2 in., 11.8 in.), C71=(176.2 in., 74 in.), and C72=(176.2 in., 136.2 in.) was actually placed 2 in. below the slab surface, the resulting ILLI-SLAB stresses (compressive x-stress) were linearly adjusted (or reduced by 40%) while making such comparisons. As shown in Figure 1 (b), fairly good agreements were achieved.

AASHO Road Test

The following dynamic edge strain equation developed at the AASHO Road Test for single axle vehicles was used to estimate the actual edge stress measurements [*12, 13*]: (Note: 1 in. = 2.54 cm, 1 psi = 0.07 kg/cm^2, 1 pci = 0.028 kg/cm^3, 1 kip = 454 kg, 1 °F = 5/9 °C)

$$\frac{\varepsilon}{L_1} = \frac{20.54}{10^{0.0031T}\, h^{1.278}} \qquad \text{(E.1)}$$

Where:

ε = dynamic edge strain, in. (x 10^{-6});
L_1= nominal axle load of the test vehicle, kips;
h = nominal thickness of the concrete slabs, in.; and
T = the standard temperature differential as defined in the Road Test, °F.

By setting T to zero, the above equation was used to estimate the measured edge stress due to a 18-kip single axle load. The pertinent input parameters based on the Road Test condition were: E=6.25 E+06 psi, L_1=18 kips, P=9,000 lbs, μ=0.28, L=15 ft, W=12 ft, loaded area=11 x 14 in.^{2}. Six slab thickness values of 5, 6.5, 8, 9.5, 11, and 12.5 in. and three k values of 100, 150, and 200 pci were assumed. The wheel load was not directly placed on the slab edge and the offset distance between the outer face of the wheel and the slab edge was about 13 in. The resulting ILLI-SLAB loading stresses were compared to the measured ones and were shown in Figure 2 (a). Apparently, fairly good agreement was observed, especially for a k value of 150 pci, which is very close to the in-field subgrade modulus of about 130 pci under the Road Test condition.

In addition, for a 6.5-in. pavement slab under standard temperature differentials of -10, 10, 15, and 20 ^{o}F and k values of 100 and 150 pci, Lee [*13*] has also demonstrated that fairly good agreement was achieved under loading plus curling condition. The coefficient of thermal expansion was assumed to be 5.0 E-06 /^{o}F and the self weight of the slab was 0.087 pci. The results of this comparison were shown in Figure 2 (b). Also note that the resulting ILLI-SLAB edge stresses were slightly higher than the estimated actual stress measurements.

Arlington Road Test

The observed longitudinal curling stresses at the edge of the pavement slabs during the Arlington Road Test were obtained for the curling-only condition [*13, 14*]. The pertinent input parameters were: E=5.0 E+06 psi, k=200 pci, L=20 ft, W=10 ft, α=4.8 E-06 /^{o}F. The measured curling stresses and the resulting ILLI-SLAB stresses for a slab thickness of 6 in. and 9 in. were summarized as follows and were also plotted in Figure 3: (Note: 1 in. = 2.54 cm, 1 psi = 0.07 kg/cm^2, 1 pci = 0.028 kg/cm^3, 1 kip = 454 kg, 1 ^{o}F = 5/9 ^{o}C)

h = 6 in.			h = 9 in.		
ΔT (^{o}F)	Measured (psi)	ILLI-SLAB (psi)	ΔT (^{o}F)	Measured (psi)	ILLI-SLAB (psi)
18	220	238	25	191	276
14	186	186	30	298	308
21	195	276	26	306	283
18	209	238	33	302	324
20	252	263	31	329	313
20	320	263	25	213	276
19	266	250	---	---	---

Even though the results of this comparison have shown some variabilities, the curling stress estimations are generally acceptable, especially when considering the difficulties involved in measuring curling strains and the scatterness of the Road Test data obtained.

IDENTIFICATION OF MECHANISTIC VARIABLES

Westergaard's closed-form solutions were based on ideal assumptions of an infinite or semi-infinite slab size, full contact between the slab-subgrade interface, and a single loaded area. In reality, jointed concrete pavements consist of many single finite concrete slabs jointed by aggregate interlock, dowel bars, or tie bars. As shown in Figure 4, traffic loading may be in forms of dual wheel, tandem axle, or tridem axle. A widened outer lane may also shift the wheel loading away from Westergaard's critical loading locations. A tied concrete shoulder, a second bonded or unbonded layer may also result in different degrees of stress reductions. To account for these effects under loading only condition, the following relationship has been identified through many intensive F.E. studies for a constant Poisson's ratio (usually $\mu \approx 0.15$) [*1, 13*]:

$$\frac{\sigma h^2}{P}, \frac{\delta k \ell^2}{P}, \frac{q \ell^2}{P} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{s}{\ell}, \frac{t}{\ell}, \frac{D_0}{\ell}, \frac{AGG}{k\ell}, \left(\frac{h_{efft}}{h_1}\right)^2\right) \tag{E.2}$$

Where σ, q are slab bending stress and vertical subgrade stress, respectively, [FL^{-2}]; δ is the slab deflection, [L]; P = wheel load, [F]; h = thickness of the slab, [L]; a = the radius of the applied load, [L]; $\ell=(E*h^3/(12*(1-\mu^2)*K))^{0.25}$ is the radius of relative stiffness of the slab-subgrade system [L]; k = modulus of subgrade reaction, [FL^{-3}]; L, W = length and width of the finite slab, [L]; s = transverse wheel spacing, [L]; t = longitudinal axle spacing, [L]; D_0 = offset distance between the outer face of the wheel and the slab edge, [L]; AGG = aggregate interlock factor, [FL^{-2}]; $h_{efft} = (h_1^2 + h_2^2 * (E_2*h_2)/(E_1*h_1))^{0.5}$ is the effective thickness of two unbonded layers, [L]; h_1, h_2 = thickness of the top slab, and the bottom slab, [L]; and E_1, E_2 = concrete modulus of the top slab, and the bottom slab, [FL^{-2}]. Note that variables in both sides of the expression are all dimensionless and primary dimensions are represented by [F] for force and [L] for length.

Since no thermal curling effect was considered in the above relationship, the full contact assumption between the slab-subgrade interface and the principle of superposition may be applied to the analyses. Thus, the above relationship can be broken down to a series of simple analyses for each individual effect. The adjustment factors can be separately developed to account for the effect of stress reduction due to each different loading condition.

Furthermore, the following concise relationship has been identified by Lee and Darter [*15*] for the effects of loading plus thermal curling:

$$\frac{\sigma}{E}, \frac{\delta h}{\ell^2}, \frac{qh}{k\ell^2} = f\left(\frac{a}{\ell}, \alpha\Delta T, \frac{L}{\ell}, \frac{W}{\ell}, \frac{\gamma h^2}{k\ell^2}, \frac{ph}{k\ell^4}\right) \tag{E.3}$$

Where E is the slab modulus, [FL^{-2}]; α is the thermal expansion coefficient, [T^{-1}]; ΔT is the temperature differential through the slab thickness, [T]; γ is the unit weight of the concrete slab, [FL^{-3}]; $D_\gamma=\gamma*h^2/(k*\ell^2)$; and $D_p=P*h/(k*\ell^4)$. Also note that D_γ was defined as the relative deflection stiffness due to self-weight of the concrete slab and the possible loss of subgrade support, whereas D_p was the relative deflection stiffness due to the external wheel load and the loss of subgrade support. The primary dimension for temperature is represented by [T].

DEVELOPMENT OF STRESS PREDICTION MODELS

A series of F. E. factorial runs were performed based on the dominating mechanistic variables (dimensionless) identified. Several BASIC programs were written to automatically generate the F. E. input files and summarize the desired outputs. The F. E. mesh was generated according to the guidelines established in earlier studies [*16*]. As proposed by Lee and Darter [*17*], a two-step modeling approach using the projection pursuit regression (PPR) technique introduced by Friedman and Stuetzle [*18*] was utilized for the development of prediction models. Through the use of local smoothing techniques, the PPR attempts to model a multi-dimensional response surface as a sum of several nonparametric functions of projections of the explanatory variables. The projected terms are essentially two-dimensional curves which can be graphically represented, easily visualized, and properly formulated. Piece-wise linear or nonlinear regression techniques were then used to obtain the parameter estimates for the specified functional forms of the predictive models. This algorithm is available in the S-PLUS statistical package [*19*].

Proposed Edge Stress Prediction Models

To account for the effects of different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), the following equation was proposed for edge stress estimations [*1, 15, 20*]:

$$
\begin{aligned}
&\sigma_e = \sigma_{we} * R_1 * R_2 * R_3 * R_4 * R_5 + R_T * \sigma_{ce} \\
&\sigma_{we} = \frac{3(1+\mu)P}{\pi(3+\mu)h^2}\left[\ln\frac{Eh^3}{100ka^4} + 1.84 - \frac{4}{3}\mu + \frac{1-\mu}{2} + 1.18(1+2\mu)\frac{a}{\ell}\right] \\
&\sigma_{ce} = \frac{CE\alpha\Delta T}{2} = \frac{E\alpha\Delta T}{2}\left[1 - \frac{2\cos\lambda\cosh\lambda}{\sin 2\lambda + \sinh 2\lambda}\left(\tan\lambda + \tanh\lambda\right)\right]
\end{aligned}
\qquad \text{(E.4)}
$$

Where:

- σ_e = edge stress prediction, [FL^{-2}];
- σ_{we} = Westergaard's closed-form edge stress solution, [FL^{-2}];
- σ_{ce} = Westergaard/Bradbury's edge curling stress, [FL^{-2}];
- C = the curling stress coefficient ($\lambda = W/((8^{0.5})*\ell)$);
- R_1 = adjustment factor for different gear configurations including dual-wheel, tandem axle, and tridem axle;
- R_2 = adjustment factor for finite slab length and width;
- R_3 = adjustment factor for a tied concrete shoulder;
- R_4 = adjustment factor for a widened outer lane;
- R_5 = adjustment factor for a bonded/unbonded second layer; and
- R_T = adjustment factor for the combined effect of loading plus day-time curling.

The proposed prediction models for edge stress adjustments are given in Table 1. More detailed descriptions of the development process can be found in Reference [*1, 15*].

Proposed Corner Stress Prediction Models

Similar approach was adopted to develop separate prediction models for corner stress adjustments. To account for the effects of different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), the following equation was proposed for corner stress estimations [*1, 11, 21*]:

$$
\begin{aligned}
\sigma_c &= \sigma_{wc} * R_1 * R_2 * R_3 * R_4 * R_5 + R_T * \sigma_{c0} \\
\sigma_{wc} &= \frac{3P}{h^2}\left[1 - \left(\sqrt{2}\,\frac{a}{\ell}\right)^{0.6}\right] \\
\sigma_{c0} &= \frac{E\alpha\Delta T}{2(1-\nu)}
\end{aligned}
\qquad \text{(E.5)}
$$

Where:

σ_c = corner stress prediction, [FL^{-2}];
σ_{wc} = Westergaard's closed-form corner stress solution, [FL^{-2}];
σ_{c0} = Westergaard's interior curling stress for an infinite slab, [FL^{-2}];
R_1, R_3, R_4, and R_5 = same definitions as shown in equation (E.4);
R_2 = R_{2a} or R_{2b};
R_{2a} = adjustment factor for finite slab length and width for loading only condition;
R_{2b} = adjustment factor for finite slab length and width for the condition of loading plus curling but $\Delta T=0$ to allow partial contact between the slab-subgrade interface; and
R_T = adjustment factor for the combined effect of loading plus night-time curling; also note that the adjustment factors R_T and R_{2b} should be used together for higher accuracy.

The proposed prediction models for corner stress adjustments are given in Table 2. More detailed descriptions of the development process can be found in Reference [*1, 11, 21*].

Proposed Interior Stress Prediction Models

To account for the effects of different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), the following equation was proposed for interior stress estimations [*1*]:

$$
\begin{aligned}
\sigma_i &= \sigma_{wi} * R_1 * R_2 * R_3 * R_4 * R_5 + R_T * \sigma_{c0} \\
\sigma_{wi} &= \frac{3}{2\pi}(1+\nu)\frac{P}{h^2}\left[\ln\frac{2\ell}{a} - \gamma + 0.5 + \frac{\pi}{32}\left(\frac{a}{\ell}\right)^2\right] \\
\sigma_{c0} &= \frac{E\alpha\Delta T}{2(1-\nu)}
\end{aligned}
\qquad \text{(E.6)}
$$

Where:

σ_i = interior stress prediction, [FL^{-2}];
σ_{wi} = Westergaard's closed-form interior stress solution, [FL^{-2}];
γ = Euler's constant (=0.577 215 664 901 .....);
σ_{c0} = Westergaard's interior curling stress for an infinite slab, [FL^{-2}]; and
R_1, R_2 (R_{2a} or R_{2b}), R_3, R_4, R_5, and R_T = same definitions as shown in equation (E.5).

The proposed prediction models for interior stress adjustments are given in Table 3. Also Note that the effect of a tied concrete shoulder and a widened outer lane may be neglected in interior stress analysis or in other words $R_3 = R_4 = 1$. More detailed descriptions of the development process can be found in Reference [*1*].

MODIFIED PCA STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURE

The Portland Cement Association’s thickness design procedure (or PCA method) is the most well-known, widely-adopted, and mechanically-based procedure for the thickness design of jointed concrete pavements [*5*]. Based on the results of J-SLAB [*22*] finite element (F.E.) analysis, the PCA method uses design tables and charts and a PCAPAV personal computer program to determine the minimum slab thickness required to satisfy the following design factors: design period, the flexural strength of concrete (or the concrete modulus of rupture), the modulus of subbase-subgrade reaction, design traffic (including load safety factor, axle load distribution), with or without doweled joints and a tied concrete shoulder [*23*]. The PCA thickness design criteria are to limit the number of load repetitions based on both fatigue analysis and erosion analysis. Cumulative damage concept is used for the fatigue analysis to prevent the first crack initiation due to critical edge stresses, whereas the principal consideration of erosion analysis is to prevent pavement failures such as pumping, erosion of foundation, and joint faulting due to critical corner deflections during the design period. Since the main focus of this study was to develop an alternative stress analysis procedure for thickness design of concrete pavements, the erosion analysis was not within the scope of this study.

Equivalent Stress Calculations

In the PCA thickness design procedure, the determination of equivalent stress is based on the resulting maximum edge bending stress of J-SLAB F.E. analysis under a single axle (SA) load and a tandem axle (TA) load for different levels of slab thickness and modulus of subgrade reaction. The basic input parameters were assumed as: slab modulus E = 4 Mpsi, Poisson's ratio $\mu = 0.15$, finite slab length L = 180 in., finite slab width W = 144 in. A standard 18-kip single axle load (dual wheels) with each wheel load equal to 4,500 lbs, wheel contact area = 7*10 in.^{2} (or an equivalent load radius a = 4.72 in.), wheel spacing s = 12 in., axle width (distance between the center of dual wheels) D = 72 in. was used for the analysis, whereas a standard 36-kip tandem axle load (dual wheels) with axle spacing t = 50 in. and remaining gear configurations same as the standard single axle was also used. If a tied concrete shoulder (WS) was present, the aggregate interlock factor was assumed as AGG = 25000 psi. PCA also incorporated "the results of computer program MATS, developed for analysis and design of mat foundations, combined footings and slabs-on-grade" to account for the support provided by the subgrade extending beyond the slab edges for a slab with no concrete shoulder (NS). Together with several other adjustment factors, the equivalent stress was defined as follows: [*24*]

$$\pm_{eq} = \frac{6 * M_e}{h^2} * f_1 * f_2 * f_3 * f_4 \qquad \text{(E.7)}$$

$$
M_e = \begin{cases} -1600 + 2525*\log(a) + 24.42*a + 0.204*a^2 & \text{for SA/NS} \\ 3029 - 2966.8*\log(a) + 133.69*a - 0.0632*a^2 & \text{for TA/NS} \\ (-970.4 + 1202.6*\log(a) + 53.587*a) * (0.8742 + 0.01088*k^{0.447}) & \text{for SA/WS} \\ (2005.4 - 1980.9*\log(a) + 99.008*a) * (0.8742 + 0.01088*k^{0.447}) & \text{for TA/WS} \end{cases}
$$

$$
f_1 = \begin{cases} (24/SAL)^{0.06} * (SAL/18) & \text{for SA} \\ (48/TAL)^{0.06} * (TAL/36) & \text{for TA} \end{cases} \qquad f_2 = \begin{cases} 0.892 + h/85.71 - h^2/3000 & \text{for NS} \\ 1 & \text{for WS} \end{cases}
$$

$$
f_3 = 0.894 \quad \text{for 6\% truck at the slab edge}
$$

$$
f_4 = 1 / [1.235 * (1 - CV)]
$$

Where:

σ_{eq} = equivalent stress, [FL^{-2}];

f_1 = adjustment factor for the effect of axle loads and contact areas;

f_2 = adjustment factor for a slab with no concrete shoulder based on the results of MATS computer program;

f_3 = adjustment factor to account for the effect of truck placement on the edge stress (PCA recommended a 6% truck encroachment, f_3=0.894);

f_4 = adjustment factor to account for the increase in concrete strength with age after the 28*th* day, along with a reduction in concrete strength by one coefficient of variation (CV); (PCA used CV=15%, f_4=0.953); and

SAL, TAL = actual single axle or tandem axle load, kips [F].

Fatigue Analysis

PCA's fatigue analysis concept was to avoid pavement failures (or first initiation of crack) by fatigue of concrete due to critical stress repetitions. Based on Miner's cumulative fatigue damage assumption, the PCA thickness design procedure first lets the users select a trial slab thickness, calculate the ratio of equivalent stress versus concrete modulus of rupture (stress ratio, σ_{eq}/S_c) for each axle load and axle type, then determine the maximum allowable load repetitions (N_f) based on the following σ_{eq}/S_c - N_f relationship:

$$
\begin{cases} \log N_f = 11.737 - 12.077 * (\sigma_{eq}/S_c) & \text{for } \sigma_{eq}/S_c \geq 0.55 \\ N_f = \left[\dfrac{4.2577}{\sigma_{eq}/S_C - 0.4325} \right]^{3.268} & \text{for } 0.45 < \sigma_{eq}/S_c < 0.55 \\ N_f = \text{Unlimited} & \text{for } \sigma_{eq}/S_c \leq 0.45 \end{cases} \tag{E.8}
$$

The PCA thickness design procedure then uses the expected number of load repetitions dividing by N_f to calculate the percentage of fatigue damage for each axle load and axle type. The total cumulative fatigue damage has to be within the specified 100% limiting design criterion, or a different trial slab thickness has to be used and repeat previous calculations again.

Modified Equivalent Stress Calculations

PCA's equivalent stress was determined based on the assumptions of a fixed slab modulus, a fixed slab length and width, a constant contact area, wheel spacing, axle spacing, and aggregate interlock factor, which may influence the stress occurrence, in order to simplify the calculations. Thus, the required minimum slab thickness will be the same based on the PCA thickness design procedure disregard the fact that a shorter or longer joint spacing, a better or worse load transfer mechanism, different wheel spacing and axle spacing, and environmental effects are considered.

To expand the applicability of the PCA's equivalent stress for different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), the following equation was proposed [*1, 20*]:

$$\begin{aligned} \sigma_{eq} &= [\sigma_{we} * R_1 * R_2 * R_3 * R_4 * R_5 + R_T * \sigma_{ce}] * f_3 * f_4 \\ &= \sigma_e * f_3 * f_4 \end{aligned} \qquad \text{(E.9)}$$

Where:

σ_{eq} = modified equivalent stress, [FL^{-2}];

σ_{we}, σ_{ce}, σ_e, R_1, R_2, R_3, R_4, R_5, and R_T = same definitions as given in equation (E.4); and

f_3, f_4 = same definitions as given in equation (E.7).

Modified Thickness Design Procedure

A new thickness design procedure was developed based on the above "modified equivalent stresses," and the PCA's cumulative fatigue damage concept. The NCHRP 1-26 report [*7*] has suggested the inclusion of thermal curling by separating traffic repetitions into three parts: loading with no curling, loading combined with day-time curling, and loading combined with night-time curling. Nevertheless, based on practical considerations of the difficulty and variability in determining temperature differentials, a more conservative design approach was proposed by neglecting possible compensative effects due to night-time curling. Thus, only the conditions of loading with no curling, and loading combined with day-time curling were considered under this study. Separated fatigue damages are then calculated and accumulated. The 100% limiting criterion of the cumulative fatigue damage is also applied to determine the minimum required slab thickness. A brief description of the proposed thickness design procedure is as follows:

1. Data input: assume a trial slab thickness; input other pertinent design factors, material properties, load distributions, and environmental factors (i.e., temperature differentials).
2. Expected repetitions (n_i): calculate the expected repetitions for the case of loading with no curling and for the case of loading with day-time curling during the design period.
3. Modified equivalent stress (σ_{eq}): calculate the "modified equivalent stresses" using equation (E.5) for each case.
4. Stress Ratio(σ_{eq} /S_C): calculate the ratio of the modified equivalent stress versus the concrete modulus of rupture (S_C) for each case.

5. Maximum allowable load repetitions (N_i): determine the maximum allowable load repetitions for different stress ratios based on the fatigue equation (E.2).
6. Calculate the percentage of each individual fatigue damage (n_i/N_i).
7. Check if the cumulative fatigue damage Σ (n_i/N_i)<100%.
8. If not, assume a different slab thickness and repeat steps (1) - (7) again to obtain the minimum required slab thickness.

DEVELOPMENT OF THE TKUPAV PROGRAM

To facilitate practical trial applications of the proposed stress analysis and thickness design procedures, a window-based computer program (TKUPAV) was developed using the Microsoft Visual Basic software package [*25*]. The TKUPAV program was designed to be highly user-friendly and thus came with many well-organized graphical interfaces, selection menus, and command buttons for easy use. Both English version and Chinese version of the program are available. Furthermore, since all the mechanistic variables used in the proposed models are dimensionally correct, both English and metric (SI) systems can be used by the program. Several example input screens of the TKUPAV program are shown in Figure 5.

TKUPAV PROGRAM VERIFICATION

The proposed approach was further verified by comparing the results of equivalent stresses and fatigue damages using PCAPAV program, Microsoft EXCEL spreadsheets, and the window-based TKUPAV program. Suppose there exists a four-lane divided highway with the following design factors: design period = 20 years, load safety factor LSF = 1.2, modulus of subgrade reaction k = 130 pci, concrete modulus of rupture S_C = 650 psi, and coefficient of variation = 15%. The expected cumulative axle load repetitions during the analysis period are given in Table 4. A trial slab thickness h = 9.5 in. with no concrete shoulder was assumed in this case study [*1, 20, 23*]. (Note: 1 in. = 2.54 cm, 1 psi = 0.07 kg/cm^2, 1 pci = 0.028 kg/cm^3, 1 kip = 454 kg)

(1) Comparison of Equivalent Stress and Fatigue Damage Calculations (Load Only):

In this case, many important factors were implicitly specified by the PCA method: t = 50 in., s = 12 in., D = 72 in., a = 4.72 in., L = 180 in., W=144 in., AGG = 25000 psi, E = 4E+06 psi, μ = 0.15. The results of this comparison are summarized in Table 4. Note that a = 38.73 in., f_2 = 0.973, f_3 = 0.894, and f_4 = 0.953 in the PCA analysis, whereas R_1 = 0.398 for a single axle (dual-wheel) or R_1 = 0.180 for a tandem axle (dual-wheel), and R_2 = 0.992 in the proposed approach. The last column (Column (B) / Column (A)) represent the ratio of equivalent stresses determined by the proposed approach (TKUPAV) and by the PCA method. The resulting 71.4% of cumulative fatigue damage calculated by the TKUPAV program is very close to that determined by the PCAPAV program (63.4%). Apparently, very good agreement to the equivalent stress and fatigue damage calculations was obtained.

(2) TKUPAV Fatigue Analysis Example (Loading Plus Curling):

Now if we assume a very small portion (10%) of the load repetitions was affected by day-time curling, and $\Delta T = 20\ ^{o}F$, $\alpha = 5.5E\text{-}06\ /^{o}F$, $\gamma = 0.087$ pci. Thus, $\alpha\Delta T = 0.00011$, W/ª = 3.873, L/ª = 4.648, a/ª = 0.1219, DG = 4.0274, $\lambda = 1.370$, and $\sigma_c = 88.5$ psi. The results of this example are summarized in Table 5. The possible detrimental effect of loading plus day-time curling has been clearly observed by the fact that a total of 64.2% fatigue damage was caused by 90% of load repetitions, whereas a total 138.84% of fatigue damage could be induced by only 10% of loading plus curling. In this case, an additional 1/2 inch of slab thickness which may reduce the total cumulative fatigue damage from 203.0% to an acceptable level of 41.3% is required.

DISCUSSIONS

The proposed stress analysis procedures follow similar approach adopted by the NCHRP 1-26 report [7]. The ILLI-CONC program completed at the University of Illinois in 1992 can be used to calculate the slab edge stress for different axle load configurations. Nevertheless, "to estimate the combined stress due to load and temperature curling, some problems were encountered in analyzing the data using dimensional analysis" [7]. This study enhanced the approach by resolving the dimensional analysis issue as well as providing a more complete treatment of the stress analysis of three loading conditions, i.e., interior, edge, and corner. In addition, the Equivalent Single Axle Radius (ESAR) concept was replaced by stress reduction adjustment factors (R's), ranging from 0 to 1, to satisfy tentative boundary conditions in stress estimation. Since all the mechanistic variables used in the proposed models are dimensionally correct, both English and metric (SI) systems can be used by the TKUPAV program.

This study also adopted the PCA's approach to design reliability by reducing the concrete strength by a factor based on one coefficient of variation of concrete strength and by using a load safety factor. The variability of many other factors such as slab thickness, foundation support, slab modulus, etc. which may all affect fatigue analysis was not considered in either the PCA method or the proposed modification procedures. Thus, this deficiency and the associated inherent biases in determining fatigue damage should be cautioned and further investigated.

CONCLUSIONS AND RECOMMENDATIONS

An alternative procedure for the determination of the critical stresses of jointed concrete pavements was developed under this study. The effects of a finite slab size, different gear configurations, a widened outer lane, a tied concrete shoulder, a second bonded or unbonded layer, and thermal curling due to a linear temperature differential were considered. The ILLI-SLAB program's applicability for stress estimation was further validated by reproducing very favorable results to the test sections of the Taiwan's second northern highway, the AASHO Road Test, and the Arlington Road Test. Based on the dimensionless mechanistic variables identified, prediction equations for stress adjustments were developed using a modern regression technique (Projection Pursuit Regression). Subsequently, a simplified stress analysis procedure was proposed and implemented in a user-friendly computer program (TKUPAV) to facilitate instant stress estimations. Together with PCA's cumulative fatigue damage equation, a modified PCA stress analysis and thickness design procedure was also incorporated in the TKUPAV program.

This computer program will not only instantly perform critical stress calculations, but it may also be utilized for various analyses and designs of concrete pavements.

This study also enhanced the applicability of the PCA method by the fact that any different material properties, finite slab sizes, gear configurations (such as additional effects of a single axle / single wheel, and a tridem axle / dual wheels), and environmental effects (e.g., temperature differentials) could be analyzed by the proposed approach. In addition, the proposed prediction models can be utilized for both U. S. customary system or metric system since all the mechanistic variables are dimensionless. The proposed approach has been further verified by reproducing very close results to the equivalent stresses and fatigue damages using PCAPAV program, a spreadsheet program, and the window-based TKUPAV program. The possible detrimental effect of loading plus day-time curling has also been illustrated in a case study, which indicated that the effect of thermal curling should be considered.

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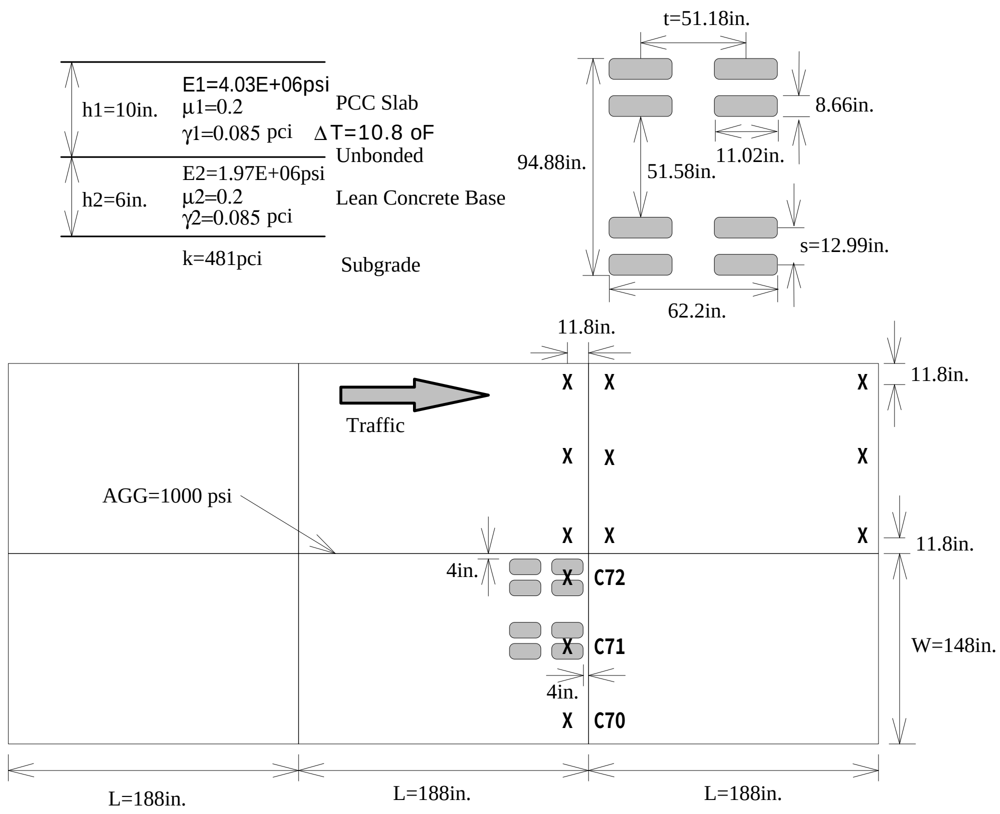
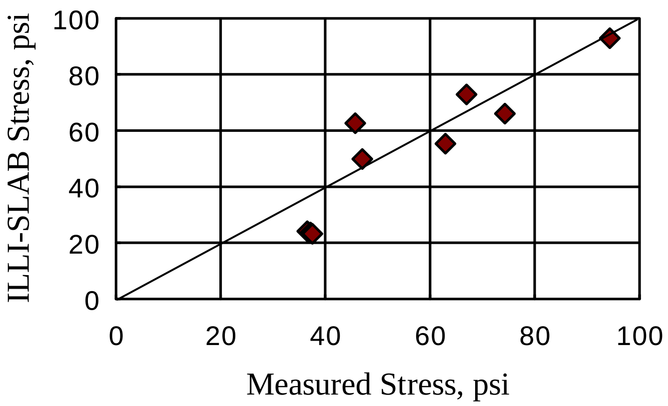
August 1995.

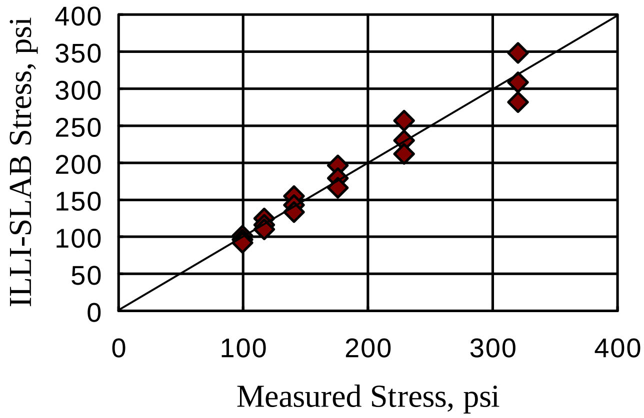


(a) Load Configurations and Test Layouts

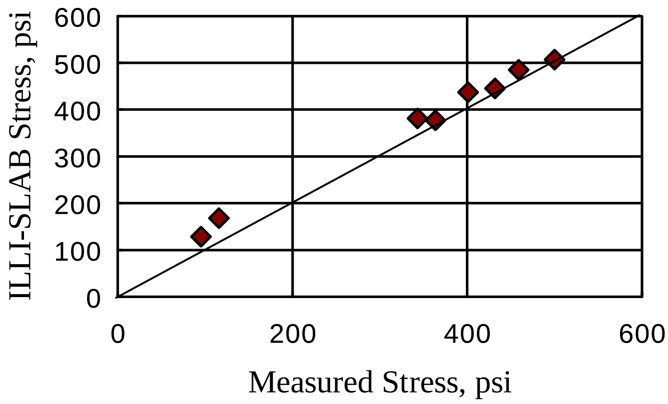


(b) Predicted versus Measured Loading Plus Curling Stresses

Figure 1 Test Sections of Taiwan's Second Northern Highway



(a) Predicted versus Measured Stresses for Loading Only



(b) Predicted versus Measured Stresses for Loading Plus Curling

Figure 2 AASHO Road Test Results

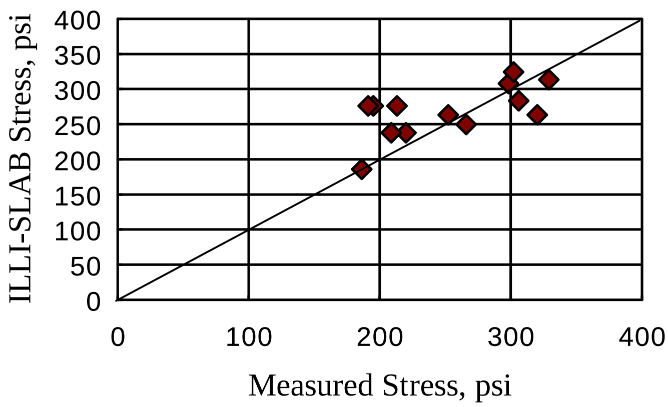


Figure 3 Arlington Road Test Results for Curling Only

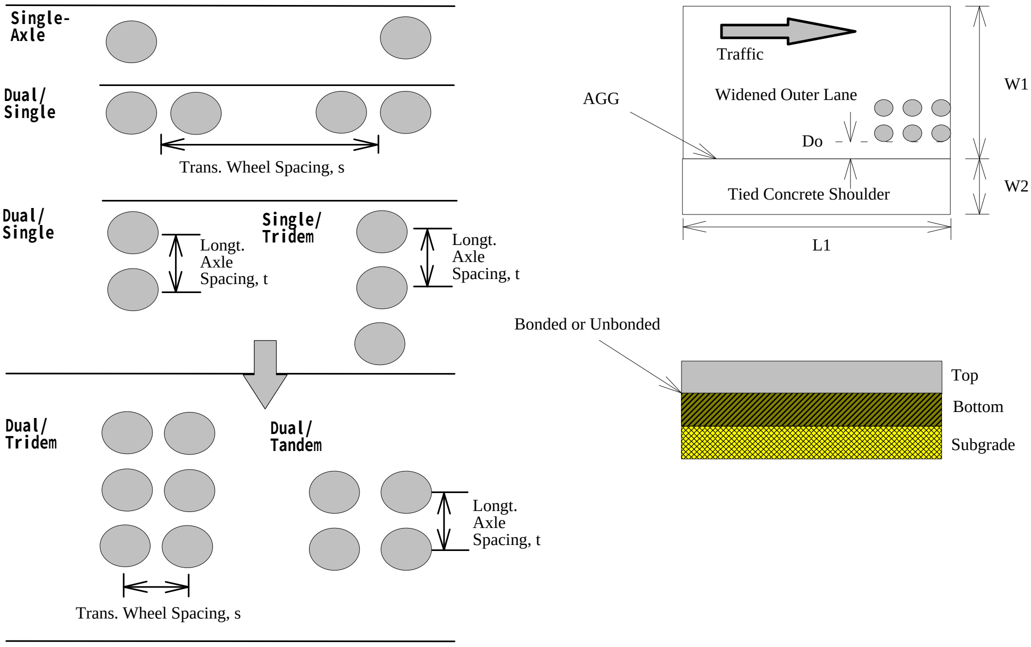


Figure 4 Various Conditions of Jointed Concrete Pavements

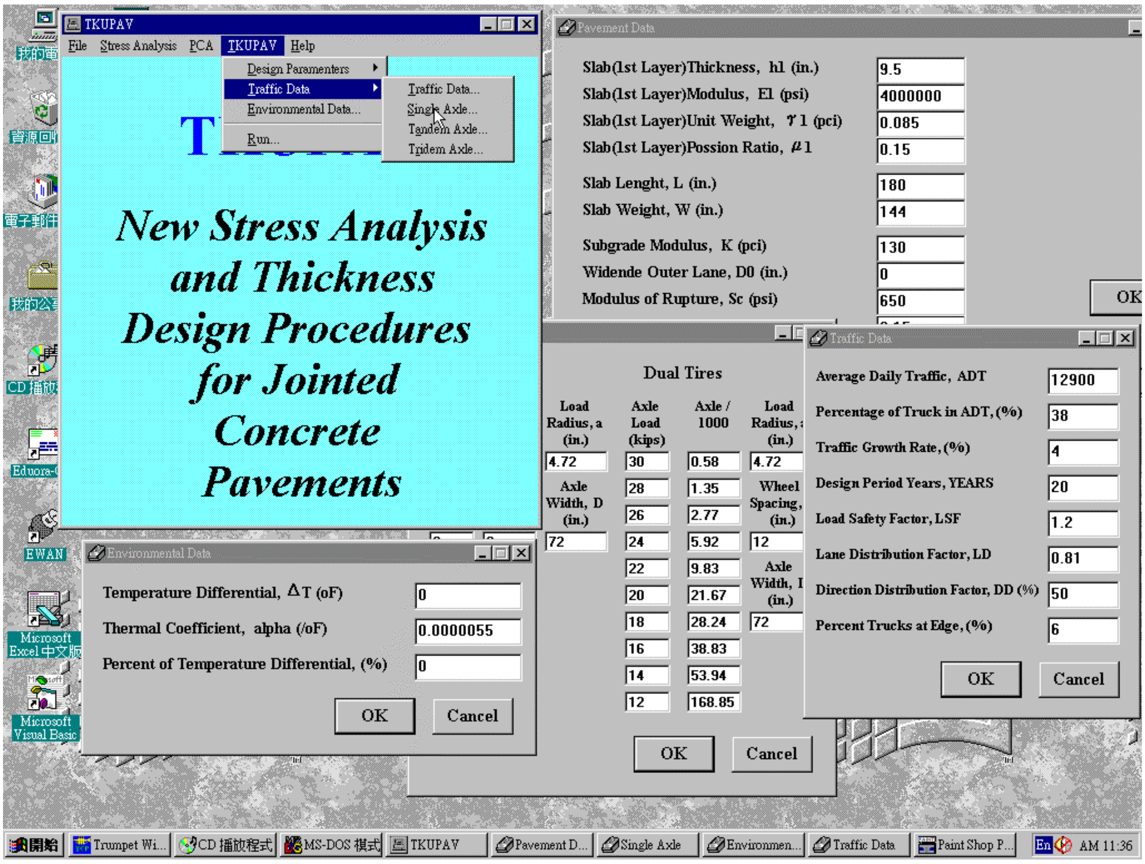


Figure 5 Sample Input Screens of the TKUPAV Program

Table 1 Proposed Prediction Models for Edge Stress Adjustments

Dual Wheel (Single Axle)	$R_1 = 0.56197 + 0.09313\Phi_1 + 0.0065\Phi_2$ $\Phi_1 = \begin{cases} -0.043 + 0.452(A1) + 0.075(A1)^2 & if\ A1 \le -2 \\ 2.997 + 6.278(A1) + 4.122(A1)^2 + 0.964(A1)^3 & if\ A1 > -2 \end{cases}$ $\Phi_2 = \begin{cases} -1.461 - 4.460(A2) + 392.524(A2)^2 + 2955.995(A2)^3 + 4914.455(A2)^4 & if\ A2 \le 0 \\ -1.425 + 45.240(A2) - 309.329(A2)^2 + 832.054(A2)^3 - 765.888(A2)^4 & if\ A2 > 0 \end{cases}$ $A1 = -0.7919x1 + 0.60762x2 + 0.06072x3$ $A2 = 0.01799x1 - 0.88168x2 + 0.4715x3$ $X = (x1, x2, x3) = \left(\frac{s}{\ell}, \frac{a}{\ell}, \frac{s \times a}{\ell^2}\right)$	$0.05 \le \frac{a}{\ell} \le 0.4$ $0 \le \frac{s}{\ell} \le 4.0$
Tandem Axle (Single Wheel)	$R_1 = 0.58306 + 0.19316\Phi_1 + 0.06236\,\Phi_2$ $\Phi_1 = \begin{cases} 0.159 + 1.604(A1) + 0.820(A1)^2 + 0.135(A1)^3 & if\ A1 \le -1 \\ 1.319 + 4.509(A1) + 1.760(A1)^2 - 0.914(A1)^3 & if\ A1 > -1 \end{cases}$ $\Phi_2 = \begin{cases} 2.151 + 11.020(A2) - 2.894(A2)^2 & if\ A2 \le -0.2 \\ 2.210 + 11.770(A2) - 16.209(A2)^2 - 70.589(A2) & if\ A2 > -0.2 \end{cases}$ $A1 = -0.51308x1 + 0.85264x2 + 0.08604x3 - 0.04849x4$ $A2 = -0.07313x1 - 0.93937x2 + 0.33502x3 + 0.00055x4$ $X = (x1, x2, x3, x4) = \left(\frac{t}{\ell}, \frac{a}{\ell}, \frac{t \times a}{\ell^2}, \frac{t}{a}\right)$	$0.1 \le \frac{a}{\ell} \le 0.4$ $0 \le \frac{t}{\ell} \le 1.6$
Tridem Axle (Single Wheel)	$R_1 = 0.44485 + 0.17726\Phi_1 + 0.02072\Phi_2$ $\Phi_1 = \begin{cases} 0.230 + 1.078(A1) + 0.177(A1)^2 & if\ A1 \le -1 \\ 2.480 + 6.329(A1) + 3.363(A1)^2 & if\ A1 > -1 \end{cases}$ $\Phi_2 = \begin{cases} -1.754 + 11.049(A2) + 8.611(A2)^2 & if\ A2 \le 0.12 \\ -2.398 + 20.152(A2) - 15.813(A2)^2 & if\ A2 > 0.12 \end{cases}$ $A1 = -0.54456x1 + 0.83346x2 - 0.09349x3 - 0.00724x4$ $A2 = 0.05007x1 + 0.87037x2 - 0.48983x3 + 0.00362x4$ $X = (x1, x2, x3, x4) = \left(\frac{t}{\ell}, \frac{a}{\ell}, \frac{t \times a}{\ell^2}, \frac{t}{a}\right)$	$0.05 \le \frac{a}{\ell} \le 0.4$ $0 \le \frac{t}{\ell} \le 3$
Finite Slab Length	$R_2 = 0.9399 + 0.07986\Phi_1$ $\Phi_1 = -4.0308 + \frac{1}{0.2029 + 0.0345(A1)^{-3.3043}}$ $A1 = -0.9436\frac{a}{\ell} + 0.3310\frac{L}{\ell}$	$2 \le \frac{L}{\ell} \le 7$ $0.05 \le \frac{a}{\ell} \le 0.3$
Finite Slab Width	$R_2 = 1.00477 + 0.01214\Phi_1$ $\Phi_1 = -0.5344 + 1.654\left[1 - A1\right]^{-10.7412}$ $A1 = 0.9951\frac{a}{\ell} - 0.09856\frac{W}{\ell}$	$2 \le \frac{W}{\ell} \le 7$ $0.05 \le \frac{a}{\ell} \le 0.3$
Tied Concrete Shoulder [24]	$R_3 = \begin{cases} 0.99864 - 0.51237(x1) - 0.0672 * \ln(x2) + 0.00315 * \ln^2(x2) \\ +0.015936(x1)^2 * \ln^2(x2) & if\ x1 \le 5 \\ 1.04284 - 0.84692(x1) - 0.0009299 * \ln(x2) + 0.06837(x1) * \ln(x2) \\ +0.63417(x1)^2 + 0.0042 * \ln^2(x2) - 0.000629(x1) * \ln(x2)^3 & if\ x1 > 5 \end{cases}$ $X = (x1, x2) = \left(\frac{a}{\ell}, \frac{AGG}{k\ell}\right)$	$0.05 \le \frac{a}{\ell} \le 0.3$ $5 \le \frac{AGG}{k\ell}$

Table 1 Proposed Prediction Models for Edge Stress Adjustments (Continue ...)

Widened Outer Lane	$R_4 = 0.61711 + 0.15373\Phi_1 + 0.02504\Phi_2$ $\Phi_1 = \begin{cases} 0.693 + 1.279(A1) + 0.369(A1)^2 + 0.037(A1)^3 & if\ A1 \le -2.5 \\ 2.839 + 8.234(A1) + 8.158(A1)^2 + 3.608(A1)^3 + 0.576(A1)^4 & if\ A1 > -2.5 \end{cases}$ $\Phi_2 = \begin{cases} -2.285 + 5.921(A2) - 6.001(A2)^2 + 7.743(A2)^3 & if\ A2 \le 0.5 \\ -3.008 + 4.693(A2) + 4.334(A2)^2 - 2.167(A2)^3 & if\ A2 > 0.5 \end{cases}$ $A1 = -0.98868x1 - 0.12214x2 - 0.08717x3$ $A2 = 0.19802x1 + 0.98019x2 + 0.00305x3$ $X = \{x1,\ x2,\ x3\} = \left\{\frac{D_0}{\ell},\ \frac{a}{\ell},\ \frac{D_0}{a}\right\}$	$0.1 \le \frac{a}{\ell} \le 0.4$ $0 \le \frac{D_0}{\ell} \le 2$
Unbonded Second Layer	$R_5 = 0.72692 + 0.14272\Phi_1 + 0.00933\Phi_2$ $\Phi_1 = \begin{cases} 3.31765 + 2.4036(A1) & if\ A1 \le -1.4 \\ 5.72684 + 4.10244(A1) & if\ A1 > -1.4 \end{cases}$ $\Phi_2 = \begin{cases} 14.535 - 20.351(A2) + 5.986(A2)^2 & if\ A2 \le 1.2 \\ 1.619 - 8.367(A2) + 4.877(A2)^2 & if\ A2 > 1.2 \end{cases}$ $A1 = 0.11914x1 - 0.99288x2$ $A2 = 0.65518x1 + 0.75547x2$ $h_{efft} = \sqrt{h_1^2 + \frac{E_2 h_2}{E_1 h_1} h_2^2}$, $X = \{x1,\ x2\} = \left\{\frac{a}{\ell},\ \left(\frac{h_{efft}}{h1}\right)^2\right\}$	$0.05 \le \frac{a}{\ell} \le 0.4$ $1 \le \left(\frac{h_{efft}}{h_1}\right)^2 \le 2$
Bonded Second Layer	$\alpha = \frac{(1/2)h_1(h_1 + h_2)}{h_1 + h_2(E_1/E_2)}$, $= (1/2)(h_1 + h_2) - \alpha$ $h_{if} = \sqrt[3]{h_1^3 + 12h_1\ ^2}$, $h_{2f} = \sqrt[3]{h_2^3 + 12h_2\ ^2}$ $h_{efft} = \sqrt{h_{1f}^2 + \left(\frac{h_{2f}}{h_{1f}}\right) h_{2f}^2}$, $X = \{x1,\ x2\} = \left\{\frac{a}{\ell},\ \left(\frac{h_{efft}}{h_{1f}}\right)^2\right\}$ Use the above unbonded prediction model to calculate R_5	(same as above)
Load plus Day-time Curling	$R_T = 0.94825 + 0.15054\Phi_1 + 0.03724\Phi_2 + 0.03395\Phi_3$ $\Phi_1 = \begin{cases} -2.5575 + 0.8003\ (A1) - 0.8003(A1)^2 & if\ A1 \le 3 \\ -2.6338 + 1.1038(A1) - 0.0914(A1)^2 & if\ 3 < A1 \le 7 \\ 0.7564 - 0.0155(A1) & if\ A1 > 7 \end{cases}$ $\Phi_2 = \begin{cases} -0.6788 + 0.0.8003(A2) - 0.8003(A2)^2 & if\ A2 \le 3 \\ 3.7674 - 2.297(A2) + 0.2963(A2)^2 & if\ 3 < A2 \le 7 \\ -7.0337 + 1.2945(A2) & if\ A2 > 7 \end{cases}$ $\Phi_3 = \begin{cases} 4.0843 + 4.8241\ (A3) & if\ A3 \le 3 \\ 0.1815 + 0.0541(A3) - 1.0899(A3)^2 & if\ -1 < A3 \le 0.5 \\ 0.0453 + 0.0383(A3) & if\ A3 > 0.5 \end{cases}$ $A1 = -0.04724X1 + 0.56954X2 - 0.08408X3 + 0.20033X4 - 0.26647X5 + 0.00375X6 + 0.73881X7 - 0.01142X8 + 0.0953X9 + 0.01121X10$ $A2 = 0.03869X1 + 0.35781X2 + 0.09078X3 - 0.04054X4 + 0.86388X5 + 0.01635X6 - 0.31246X7 + 0.00552X8 - 0.12677X9 - 0.01765X10$ $A3 = 0.58567X1 + 0.25804X2 + 0.14784X3 + 0.14984X4 + 0.12743X5 - 0.05012X6 + 0.72295X7 - 0.0131X8 - 0.01304X9 - 0.06591X10$ $X = \{x1,\ x2,\ x3,\ \ldots,\ x10\}$ $= \left\{\frac{W}{\ell},\ \frac{L}{\ell},\ AT,\ \frac{a}{\ell},\ DG,\ DP,\ \frac{L}{\ell} * \frac{a}{\ell},\ \frac{L}{\ell} * AT,\ DG * \frac{L}{\ell},\ DG * \frac{W}{\ell}\right\}$	$0.05 \le \frac{a}{\ell} \le 0.3$ $3 \le \frac{W}{\ell} \le 11$ $\frac{W}{\ell} = \frac{L}{\ell}$ $1.06 \le DG \le 9.93$ $2.61 \le DP \le 140.74$ $5.5 \le AT \le 22$ $DG = d\gamma \times 10^5$ $DP = dp \times 10^5$ $AT = \alpha \times \Delta T \times 10^5$

Table 2 Proposed Prediction Models for Corner Stress Adjustments

Dual Wheel (Single Axle)	$R_1 = 0.6028 + 0.1338\,\Phi_1 + 0.00687\Phi_2$ $\Phi_1 = \begin{cases} 0.548 + 0.861(A1) + 0.208(A1)^2 + 0.0176(A1)^3 & \text{if } A1 \le -2.0 \\ 2.963 + 4.594(A1) + 2.249(A1)^2 + 0.407(A1)^3 & \text{if } A1 > -2.0 \end{cases}$ $\Phi_2 = \begin{cases} -0.382 - 0.364(A2) & \text{if } A2 \le -0.04 \\ 1.109 + 39.675(A2) & \text{if } A2 > -0.04 \end{cases}$ $A1 = -0.986x1 + 0.00507x2 + 0.164x3 - 0.0121x4$ $A2 = -0.0412x1 - 0.918x2 + 0.393x3 + 0.00129x4$ $X = \{x1, x2, x3, x4\} = \left\{\frac{s}{\ell}, \frac{a}{\ell}, \frac{s \times a}{\ell^2}, \frac{s}{a}\right\}$	$0.05 \le (a/\ell) \le 0.4$ $0 \le (s/\ell) \le 4$
Tandem Axle (Single Wheel)	*Same as the above equations, but,* $X = \{x1, x2, x3, x4\} = \left\{\frac{t}{\ell}, \frac{a}{\ell}, \frac{t \times a}{\ell^2}, \frac{t}{a}\right\}$	$0.05 \le (a/\ell) \le 0.4$ $0 \le (t/\ell) \le 4$
Tridem Axle (Single Wheel)	$R_1 = 0.4468 + 0.1679\Phi_1$ $\Phi_1 = \begin{cases} -0.154 + 0.346(A1) + 0.0986(A1)^2 + 0.0101(A1)^3 & \text{if } A1 \le -2.5 \\ 3.169 + 5.426(A1) + 2.880(A1)^2 + 0.528(A1)^3 & \text{if } A1 > -2.5 \end{cases}$ $A1 = -0.9999x1 + 0.00576x2 - 0.0122x3$ $X = \{x1, x2, x3\} = \left\{\frac{t}{\ell}, \frac{a}{\ell}, \frac{t}{a}\right\}$	$0.05 \le (a/\ell) \le 0.4$ $0 \le (t/\ell) \le 4$
Finite Slab Size	$R_{2a} = 1.030 + 0.030\Phi_1 + 0.045\Phi_2$ $\Phi_1 = 92.145 - 149.276(A1) + 59.747(A1)^2$ $\Phi_2 = \begin{cases} -6.034 + 23.128(A2) - 22.022(A2)^2 & \text{if } A2 \le 0.6 \\ -0.117 + 0.375(A2) & \text{if } 0.6 < A2 \end{cases}$ $A1 = 0.8272x1 - 0.1219x2 + 0.0002x3 + 0.5485x4$ $A2 = -0.9034x1 + 0.2973x2 - 0.0118x3 - 0.3088x4$ $X1 = \{x1, x2, x3, x4\} = \left\{\frac{a}{\ell}, \frac{L}{\ell} + \frac{W}{\ell}, \frac{L}{\ell} \times \frac{W}{\ell}, \sqrt{\frac{L}{\ell}} + \sqrt{\frac{W}{\ell}}\right\}$	$0.05 \le a/\ell \le 0.3$ $2 \le L/\ell \le 7$ $W/\ell \le L/\ell$
Tied Concrete Shoulder	$R_3 = 0.7543 + 0.1887\Phi_1 + 0.01840\Phi_2$ $\Phi_1 = \begin{cases} 12.940 + 15.138(A1) + 5.305(A1)^2 + 0.604(A1)^3 & \text{if } A1 \le -2.55 \\ 1.321 + 0.154(A1) + 0.760(A1)^2 + 0.965(A1)^3 + 0.212(A1)^4 & \text{if } A1 > -2.55 \end{cases}$ $\Phi_2 = 0.324 + 7.064(A2) + 7.003(A2)^2$ $A1 = -0.531x1 + 0.636x2 - 0.560x3 + 0.00192x4$ $A2 = -0.176x1 - 0.682x2 + 0.710x3 + 0.00639x4$ $X = \{x1, x2, x3, x4\} = \left\{LAGG, \frac{a}{\ell}, \frac{LAGG * a}{\ell}, \frac{LAGG \times \ell}{a}\right\}$ *where,* $LAGG = \log_{10}\left(1 + \frac{AGG}{k\ell}\right)$	$0.05 \le (a/\ell) \le 0.4$ $0 \le (AGG/k\ell) \le 50000$

Table 2 Proposed Prediction Models for Corner Stress Adjustments (Continue ...)

Widened Outer Lane	$R_4 = 0.4429 + 0.1853\Phi_1 + 0.0335\Phi_2$ $\Phi_1 = \begin{cases} 0.786 + 1.434(A1) + 0.463(A1)^2 + 0.0531(A1)^3 & if \quad A1 \le -1 \\ 3.144 + 8.390(A1) + 7.674(A1)^2 + 2.667(A1)^3 & if \quad A1 > -1 \end{cases}$ $\Phi_2 = \begin{cases} -0.581 + 4.406(A2) + 16.204(A2)^2 & if \quad A2 \le 0.1 \\ -0.408 + 4.209(A2) & if \quad A2 > 0.1 \end{cases}$ $A1 = -0.780x1 - 0.0597x2 + 0.622x3 - 0.00333x4$ $A2 = 0.0524x1 - 0.781x2 + 0.622x3 - 0.00737x4$ $X = \{x1, x2, x3, x4\} = \left\{\frac{D_0}{\ell}, \frac{a}{\ell}, \frac{D_0 \times a}{\ell^2}, \frac{D_0}{a}\right\}$	$0.05 \le (a/\ell) \le 0.4$ $0 \le (D_0/\ell) \le 4$
Second Layer	Use the same bonded or unbonded equations for edge stress adjustments.	(Same as before)
Loading Plus Curling, but $\Delta T=0$	$R_{2b} = 0.9949 + 0.17037\Phi_1 + 0.03020\Phi_2$ $\Phi_1 = \begin{cases} -0.85525 + 15.53557(A1) + 1.71139(A1)^2 & if \quad (A1 \le 0.1) \\ 0.24816 + 0.28387(A1) - 0.06692(A1)^2 & if \quad (A1 > 0.1) \end{cases}$ $\Phi_2 = \begin{cases} -0.93998 + 3.72027(A2) + 11.13839(A2)^2 & if \quad (A2 \le 0.18) \\ -2.93892 + 16.93742(A2) & if \quad (A2 > 0.18) \end{cases}$ $A1 = -0.95810x1 + 0.03604x2 + 0.28368x3 - 0.00231x4 - 0.00033x5 - 0.00236x6 - 0.00144x7 + 0.01621x8$ $A2 = 0.99699x1 - 0.02358x2 + 0.05534x3 - 0.00265x4 + 0.00055x5 + 0.01611x6 - 0.00041x7 - 0.04602x8$ $X = [x1, x2, ... x8]$ $= \left\{\frac{a}{\ell}, \frac{L}{\ell}, \frac{a}{\ell} \times \frac{L}{\ell}, \frac{a}{\ell} \times DP, DP, DG, \frac{DP}{DG}, \frac{a}{\ell} \times DG\right\}$	$005 \le a/\ell \le 0.3$ $2 \le L/\ell \le 15$ $W/\ell = L/\ell$ $1 \le DG \le 10$ $2 \le DP \le 130$ $DG = D\gamma \times 10^5$ $DP = Dp \times 10^5$
Loading Plus Night-time Curling, $\Delta T<0$	$R_T = 0.2548 + 0.3076\Phi_1 + 0.1058\Phi_2 + 0.05934\Phi_3$ $\Phi_1 = \begin{cases} -0.28987 + 0.02840(A1) & if \quad A1 \le 0 \\ -0.22478 + 0.40575(A1) & if \quad A1 > 0 \end{cases}$ $\Phi_2 = \begin{cases} -1.46318 + 0.39571(A2) + 0.00231(A2)^2 - 0.00155(A2)^3 & if \quad A2 \le 15 \\ 5.06880 - 0.32371(A2) & if \quad A2 > 15 \end{cases}$ $\Phi_3 = \begin{cases} 0.73250 + 0.74738(A3) & if \quad A3 \le 0 \\ 0.68128 + 0.25940(A3) & if \quad A3 > 0 \end{cases}$ $A1 = -0.04291x1 + 0.56894x2 - 0.43915x3 + 0.05771x4 - 0.12609x5 + 0.02591x6 + 0.01885x7 - 0.15518x8 + 0.50270x9 - 0.01229x10 + 0.31315x11 - 0.00903x12 + 0.00649x13 + 0.28839x14 - 0.04413x15 + 0.03329x16 - 0.00002x17$ $A2 = -0.02058x1 + 0.83621x2 - 0.36689x3 + 0.25029x4 - 0.16713x5 + 0.04484x6 + 0.07580x7 + 0.03647x8 - 0.09497x9 + 0.00207x10 - 0.04534x11 - 0.00721x12 + 0.0007x13 + 0.23382x14 + 0.01217x15 + 0.01038x16 - 0.00016x17$ $A3 = 0.04637x1 - 0.44327x2 + 0.39157x3 + 0.47010x4 - 0.12200x5 - 0.00537x6 - 0.00851x7 - 0.01246x8 - 0.48078x9 + 0.00443x10 + 0.01520x11 + 0.00322x12 - 0.00293x13 + 0.42430x14 + 0.01628x15 - 0.01370x16 + 0.00007x17$ $X = [x1, x2, ..., X17] = \begin{bmatrix} a/\ell,\ L/\ell,\ ADT,\ (a/\ell)*(L/\ell), \\ (a/\ell)*ADT,\ (L/\ell)*ADT, \\ (a/\ell)*(L/\ell)*ADT,\ DP,\ DG, \\ DP*DG,\ DP*(a/\ell),\ DP*(L/\ell), \\ DP*ADT,\ DG*(a/\ell),\ DG*(L/\ell), \\ DG*ADT,\ ADT*(L/\ell)*(a/\ell)*DP*DG \end{bmatrix}$	$0.05 \le a/\ell \le 0.3$ $2 \le L/\ell \le 15$ $W/\ell = L/\ell$ $1 \le DG \le 10$ $2 \le DP \le 130$ $5.5 \le ADT \le 22$ $DG = D\gamma \times 10^5$ $DP = Dp \times 10^5$ $ADT = -\alpha \times \Delta T \times 10^5$

Table 3 Proposed Prediction Models for Interior Stress Adjustments

Dual Wheel (Single Axle)	$R_1 = 0.5811 \text{ H } 0.14042\Phi_1 + 0.03507\,\Phi_2$ $\Phi_1 = \begin{cases} -0.413 + 0.171(A1) + 0.029(A1)^2 + 0.003(A1)^3 & \text{if } (A1) \le -2 \\ 2.041 + 4.691(A1) + 2.971(A1)^2 + 0.657(A1)^3 & \text{if } (A1) > -2 \end{cases}$ $\Phi_2 = \begin{cases} -2.637 - 36.693(A2) - 166.057(A2)^2 - 172.818(A2)^3 & \text{if } (A2) \le -0.2 \\ 2.596 + 15.860(A2) - 34.892(A2)^2 - 179.776(A2)^3 & \text{if } (A2) > -0.2 \end{cases}$ $A1 = -0.42114x1 + 0.89947x2 + 0.10787x3 - 0.04424x4$ $A2 = -0.03365x1 - 0.97142x2 + 0.23496x3 + 0.00027x4$ $X = [x1, x2, x3, x4] = \left[\frac{s}{a}, \frac{a}{a}, \frac{s \times a}{a^2}, \frac{s}{a}\right]$	$0.05 \le \frac{a}{a} \le 0.4$ $0 \le \frac{s}{a} \le 4$
Tandem Axle (Single Wheel)	*Same as the above equations, but* $X = [x1, x2, x3, x4] = \left[\frac{t}{a}, \frac{a}{a}, \frac{t \times a}{a^2}, \frac{t}{a}\right]$	$0.05 \le \frac{a}{a} \le 0.4$ $0 \le \frac{t}{a} \le 4$
Tridem Axle (Single Wheel)	$R_1 = 0.4377 \text{ H } 0.15978\Phi_1 + 0.01638\,\Phi_2$ $\Phi_1 = \begin{cases} 1.199 + 3.182(A1) + 1.13(A1)^2 & \text{if } A1 \le -0.3 \\ 2.694 + 13.636(A1) + 21.423(A1)^2 & \text{if } A1 > -0.3 \end{cases}$ $\Phi_2 = \begin{cases} -2.336 + 6.784(A2) + 33.187(A2)^2 & \text{if } A2 \le 0.2 \\ -2.155 + 12.693(A2) - 1.494(A2)^2 & \text{if } A2 > 0.2 \end{cases}$ $A1 = -0.50223x1 + 0.862x2 - 0.06873x3$ $A2 = 0.14179x1 + 0.80027x2 - 0.58264x3$ $X = [x1, x2, x3] = \left[\frac{t}{a}, \frac{a}{a}, \frac{t \times a}{a^2}\right]$	$0.05 \le \frac{a}{a} \le 0.4$ $0 \le \frac{t}{a} \le 3$
Finite Slab Size	$R_{2a} = 1.0809 + 0.04546\Phi_1 + 0.05792\Phi_2 + 0.03742\Phi_3$ $\Phi_1 = 0.27351 + 1.28607(A1)$ $\Phi_2 = \begin{cases} 3.44232 + 1.42864(A2) & \text{if } A2 \le -1.6 \\ -15.77484 - 22.42728(A2) - 7.50782(A2)^2 & \text{if } A2 \ge -1.6 \end{cases}$ $\Phi_3 = \begin{cases} -1.85756 + 0.17921(A3) + 0.95723(A3)^2 & \text{if } A3 \le -1.0 \\ 8.62686 + 19.22734(A3) + 9.53635(A3)^2 & \text{if } A3 \ge -1.0 \end{cases}$ $A1 = -0.67019\,x1 + 0.42503\,x2 - 0.60844\,x3$ $A2 = -0.00271\,x1 - 0.42293\,x2 + 0.90616\,x3$ $A3 = -0.30625\,x1 - 0.02100\,x2 + 0.95172\,x3$ $X = [x1, x2, x3] = \left[\frac{W}{a}, \frac{L}{a}, \frac{a}{a}\right]$	$2 \le \frac{L}{a} \le 7$ $0.05 \le \frac{a}{a} \le 0.3$ $\frac{L}{a} \ge \frac{W}{a}$

Table 3 Proposed Prediction Models for Interior Stress Adjustments (Continue ...)

Second Layer	Use the same bonded or unbonded equations for edge stress adjustments.	(Same as before)
Loading Plus Curling, but ΔT=0	$R_{2b} = 1.01793 + 0.04766\Phi_1 + 0.01307\Phi_2 + 0.00926\Phi_3$ $\Phi_1 = \begin{cases} 3.29050 + 43.76038(A1) & \text{if } A1 \le -0.05 \\ 1.79888 + 19.58864(A1) + 29.42562(A1)^2 & \text{if } A1 > -0.05 \end{cases}$ $\Phi_2 = \begin{cases} 1.79888 + 19.58864(A2) + 29.42562(A2)^2 & \text{if } A2 \le -0.1 \\ 1.15306 + 7.71399(A2) - 16.29096(A2)^2 & \text{if } A2 > -0.1 \end{cases}$ $\Phi_3 = \begin{cases} -3.81059 + 48.61170(A3) - 99.25446(A3)^2 & \text{if } A3 \le 0.15 \\ -1.80221 + 2.31237(A3) + 25.17567(A3)^2 & \text{if } A3 > 0.15 \end{cases}$ $A1 = -0.20096x1 + 0.26157x2 - 0.94403x3 + 0.00008x5$ $A2 = 0.18184x1 - 0.96040x2 - 0.21105x3 + 0.00065x4 - 0.00468x5$ $A3 = 0.02777x1 + 0.99262x2 + 0.11803x3 - 0.00017x4 + 0.00200x5$ $X = \{x1, x2, x3, x4, x5\} = \left\{\frac{\ell}{W}, \frac{a}{\ell}, \frac{a}{W}, DP, DG\right\}$	$2 \le \frac{W}{\ell} \le 17$ $\frac{L}{\ell} = \frac{W}{\ell}$ $0.05 \le \frac{a}{\ell} \le 0.3$ $2 \le DP \le 130$ $1 \le DG \le 10$ $\Delta T = 0$
Load plus Day-time Curling, ΔT>0	$R_T = 0.68081 + 0.42542\Phi_1 + 0.04037\Phi_2 + 0.01861\Phi_3$ $\Phi_1 = \begin{cases} -2.480 + 0.412(A1) - 0.011(A1)^2 & \text{if } A1 \le 15 \\ -0.149 + 0.079(A1) & \text{if } A1 > 15 \end{cases}$ $\Phi_2 = \begin{cases} -0.149 + 0.079(A2) & \text{if } A2 \le -3.5 \\ 1.536 + 1.285(A2) + 0.194(A2)^2 & \text{if } A2 > -3.5 \end{cases}$ $\Phi_3 = \begin{cases} -1.164 - 0.030(A3) & \text{if } A3 \le -8 \\ 4.385 + 1.305(A3) + 0.079(A3)^2 & \text{if } A3 > -8 \end{cases}$ $A1 = 0.96370x1 - 0.02263x2 + 0.0552x3 - 0.00332x4 - 0.23136x5 + 0.03767x6 - 0.0243x7 + 0.00531x8 + 0.12549x9 - 0.00234x10$ $A2 = -0.82137x1 - 0.16949x2 - 0.0230x3 - 0.00818x4 + 0.26187x5 - 0.47149x6 + 0.0207x7 + 0.00419x8 - 0.07517x9 + 0.00137x10$ $A3 = -0.58518x1 + 0.25146x2 - 0.1576x3 - 0.04907x4 + 0.03673x5 + 0.76609x6 + 0.0013x7 + 0.00610x8 + 0.05759x9 - 0.00893x10$ $X = \{x1, x2, x3, \ldots, x10\} = \left\{\frac{W}{\ell}, \frac{a}{\ell}, ADT, DP, DG, \frac{W}{\ell} * \frac{a}{\ell}, \frac{W}{\ell} * ADT, \frac{W}{\ell} * DP, \frac{W}{\ell} * DG, DG * DP\right\}$	$0.05 \le \frac{a}{\ell} \le 0.3$ $2 \le \frac{W}{\ell} \le 15$ $\frac{W}{\ell} = \frac{L}{\ell}$ $1 \le DG \le 10$ $2 \le DP \le 130$ $5.5 \le adT \le 22$ $DG = d\gamma \times 10^5$ $DP = dp \times 10^5$ $adT = \alpha \times \Delta T \times 10^5$

Table 4 Comparison of Equivalent Stresses and Fatigue Damages (Loading Only)

(A) Single Axle (kips)			PCAPAV (f_2=0.973, f_3=0.894, f_4=0.953)						TKUPAV (R_1=0.398, R_2=0.992, f_3=0.894, f_4=0.953)					σ_{eq} Ratio
Load	Load*1.2	n_i	$6*Me/h^2$	f1	σ_{eq}, psi (A)	σ_{eq}/S_c	N_i	n_i/N_i, (%)	σ_w, psi	σ_{eq}, psi (B)	σ_{eq}/S_c	N_i	n_i/N_i, (%)	(B/A)
30	36.0	6310	243.4	1.952	393.6	0.606	26536	23.8	1186.5	398.6	0.613	21414	29.5	1.01
28	33.6	14690	243.4	1.829	368.9	0.568	76395	19.2	1107.4	372.0	0.572	66751	22.0	1.01
26	31.2	30140	243.4	1.706	344.1	0.529	234343	12.9	1028.3	345.5	0.531	218058	13.8	1.00
24	28.8	64410	243.4	1.583	319.1	0.491	1218769	5.3	949.2	318.9	0.491	1243647	5.2	1.00
22	26.4	106900	243.4	1.458	294.1	0.452	41207557	0.3	870.1	292.3	0.450	Unlimited	0.0	0.99
20	24.0	235800	243.4	1.333	268.9	0.414	Unlimited	0.0	791.0	265.7	0.409	Unlimited	0.0	0.99
18	21.6	307200	243.4	1.208	243.5	0.375	Unlimited	0.0	711.9	239.2	0.368	Unlimited	0.0	0.98
16	19.2	422500	243.4	1.081	218.0	0.335	Unlimited	0.0	632.8	212.6	0.327	Unlimited	0.0	0.98
14	16.8	586900	243.4	0.954	192.3	0.296	Unlimited	0.0	553.7	186.0	0.286	Unlimited	0.0	0.97
12	14.4	1837000	243.4	0.825	166.3	0.256	Unlimited	0.0	474.6	159.4	0.245	Unlimited	0.0	0.96
							Subtotal=	61.4%				Subtotal=	70.5%	
(B) Tandem Axle (kips)			PCAPAV (f_2=0.973, f_3=0.894, f_4=0.953)						TKUPAV (R_1=0.180, R_2=0.992, f_3=0.894, f_4=0.953)					
52	62.4	21320	226.0	1.706	319.5	0.492	1177998	0.018	2056.6	312.2	0.480	2342697	0.9	0.98
48	57.6	42870	226.0	1.583	296.4	0.456	24134471	0.002	1898.4	288.2	0.443	Unlimited	0.0	0.97
44	52.8	124900	226.0	1.458	273.1	0.42	Unlimited	0.000	1740.2	264.2	0.406	Unlimited	0.0	0.97
40	48.0	372900	226.0	1.333	249.7	0.384	Unlimited	0.000	1582.0	240.2	0.370	Unlimited	0.0	0.96
36	43.2	885800	226.0	1.208	226.1	0.348	Unlimited	0.000	1423.8	216.2	0.333	Unlimited	0.0	0.96
32	38.4	930200	226.0	1.081	202.4	0.311	Unlimited	0.000	1265.6	192.1	0.296	Unlimited	0.0	0.95
28	33.6	1656000	226.0	0.954	178.6	0.275	Unlimited	0.000	1107.4	168.1	0.259	Unlimited	0.0	0.94
24	28.8	984900	226.0	0.825	154.5	0.238	Unlimited	0.000	949.2	144.1	0.222	Unlimited	0.0	0.93
20	24.0	1227000	226.0	0.695	130.1	0.2	Unlimited	0.000	791.0	120.1	0.185	Unlimited	0.0	0.92
16	19.2	1356000	226.0	0.563	105.5	0.162	Unlimited	0.000	632.8	96.1	0.148	Unlimited	0.0	0.91
							Subtotal=	2.0%				Subtotal=	0.9%	
							$\Sigma\ n_i/N_i$ =	63.4%				$\Sigma\ n_i/N_i$ =	71.4%	

Table 5 TKUPAV Fatigue Analysis Example (Loading plus Curling)

(A) Single Axle (kips)			90% Loading Only				10% Loading plus Curling (σ_c = 88.5 psi)						Total
Load	Load*1.2	n_i	σ_{eq} , psi (A)	n_i*90%	N_i	Damage (%)	R_T	σ_{eq} , psi	σ_{eq}/S_c	n_i*10%	N_i	Damage (%)	Damage (%)
30	36.0	6310	398.6	5679	21414	26.5	0.850	462.7	0.712	631	1382	45.7	72.2
28	33.6	14690	372.0	13221	66751	19.8	0.847	435.9	0.671	1469	4345	33.8	53.6
26	31.2	30140	345.5	27126	218058	12.4	0.845	409.1	0.629	3014	13654	22.1	34.5
24	28.8	64410	318.9	57969	1243647	4.7	0.842	382.4	0.588	6441	42899	15.0	19.7
22	26.4	106900	292.3	96210	Unlimited	0.0	0.840	355.6	0.547	10690	135064	7.9	7.9
20	24.0	235800	265.7	212220	Unlimited	0.0	0.838	328.9	0.506	23580	577713	4.1	4.1
18	21.6	307200	239.2	276480	Unlimited	0.0	0.836	302.1	0.465	30720	8444924	0.4	0.4
16	19.2	422500	212.6	380250	Unlimited	0.0	0.833	275.4	0.424	42250	Unlimited	0.0	0.0
14	16.8	586900	186.0	528210	Unlimited	0.0	0.831	248.7	0.383	58690	Unlimited	0.0	0.0
12	14.4	1837000	159.4	1653300	Unlimited	0.0	0.830	222.0	0.341	183700	Unlimited	0.0	0.0
					Subtotal=	63.4%					Subtotal=	128.9%	192.3%
(B) Tandem Axle (kips)													
52	62.4	21320	312.2	19188	2342697	0.8	0.853	376.5	0.579	2132	55171	3.9	4.7
48	57.6	42870	288.2	38583	Unlimited	0.0	0.869	353.7	0.544	4287	147221	2.9	2.9
44	52.8	124900	264.2	112410	Unlimited	0.0	0.874	330.1	0.508	12490	533733	2.3	2.3
40	48.0	372900	240.2	335610	Unlimited	0.0	0.868	305.6	0.470	37290	5139145	0.7	0.7
36	43.2	885800	216.2	797220	Unlimited	0.0	0.858	280.9	0.432	88580	Unlimited	0.0	0.0
32	38.4	930200	192.1	837180	Unlimited	0.0	0.853	256.4	0.394	93020	Unlimited	0.0	0.0
28	33.6	1656000	168.1	1490400	Unlimited	0.0	0.847	232.0	0.357	165600	Unlimited	0.0	0.0
24	28.8	984900	144.1	886410	Unlimited	0.0	0.842	207.6	0.319	98490	Unlimited	0.0	0.0
20	24.0	1227000	120.1	1104300	Unlimited	0.0	0.838	183.2	0.282	122700	Unlimited	0.0	0.0
16	19.2	1356000	96.1	1220400	Unlimited	0.0	0.833	158.9	0.244	135600	Unlimited	0.0	0.0
					Subtotal=	0.8%					Subtotal=	9.8%	10.7%
					$\Sigma\ n_i/N_i$ =	64.2%					$\Sigma\ n_i/N_i$ =	138.84%	203.0%