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Ying-Haur Lee, Associate Professor
Ying-Ming Lee, Graduate Research Assistant
Shao-Tang Yen, Graduate Research Assistant
Chao-Tsung Lee, Graduate Research Assistant
Jean-Hwa Bair, Graduate Research Assistant
Department of Civil Engineering
Tamkang University, Taiwan, R.O.C.

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Ying-Haur Lee[1], Ying-Ming Lee[2], Shao-Tang Yen[2], Chao-Tsung Lee[2], and Jean-Hwa Bair[2]

ABSTRACT

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 conducted and concise modification recommendations were provided. Based on Westergaard's edge stress solution and several prediction models for stress adjustments for a variety of loading and environmental (i.e., thermal curling) conditions, a modified PCA equivalent stress analysis and thickness design procedure was proposed and implemented in a highly user-friendly, window-based TKUPAV program for practical trial applications. The proposed approach has been further verified by reproducing very close results to the equivalent stresses and fatigue damages using PCAPAV program, Microsoft EXCEL spreadsheets, and the TKUPAV program. The possible detrimental effect of loading plus day-time curling has also been illustrated in a case study, indicating that the effect of thermal curling should be considered in zero-maintenance design of concrete pavements.

PCA THICKNESS DESIGN PROCEDURE

The main objective of this study was to develop a new stress analysis and thickness design procedure for jointed concrete pavements through proposed modifications to the most widely-adopted PCA's equivalent stress calculations and fatigue analysis [*1*]. 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 [*2*]. Based on the results of J-SLAB [*3*] 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 [*4*]. 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 his study was to develop an alternative stress analysis procedure for thickness design of concrete pavements, the erosion

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[1] Associate Professor, Dept. of Civil Engr., Tamkang University, E725, #151 Ying-Chuan Rd., Tamsui, Taipei, Taiwan 251, R.O.C., TEL: (886-2) 623-2408, FAX: 620-9747, E-mail: yinghaur@tedns.te.tku.edu.tw.

[2] Graduate Research Assistant, Department of Civil Engineering., Tamkang University, Taiwan, R.O.C.

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 μ = 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: [*5*]

$$\pm_{eq} = \frac{6 * M_e}{h^2} * f_1 * f_2 * f_3 * f_4 \qquad \text{(E.1)}$$

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

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

$$f_3 = 0.894 \quad \text{for 6\% Truck at the Slab Edge}$$

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

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:

$$\begin{cases} \log N_f = 11.737 - 12.077 * (\sigma_{eq} / S_c) & \text{for } \sigma_{eq} / S_c \geq 0.55 \\ N_f = \left[\dfrac{4.2577}{\sigma_{eq} / S_C - 0.4325} \right]^{3.268} & \text{for } 0.45 < \sigma_{eq} / S_c < 0.55 \\ N_f = \text{Unlimited} & \text{for } \sigma_{eq} / S_c \leq 0.45 \end{cases} \quad \text{(E.2)}$$

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.

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 [*4*].

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*].

MODIFIED PCA STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURE

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.

Therefore, this study strives to revise PCA's equivalent stress calculation process by including the effect of thermal curling. The ILLI-SLAB [*8*] finite element program was used for the analysis. 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 fatigue analysis procedure was developed.

Development of Stress Prediction Models

To account for the effects of a finite slab, dual-wheel, tandem axle, or tridem axle, a widened outer lane, a tied concrete shoulder, a second bonded or unbonded layer 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, 9*]:

$$\frac{\sigma h^2}{P}, \frac{\delta k \ell^2}{P}, \frac{q \ell^2}{P} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{s}{\ell}, \frac{t}{\ell}, \frac{D_0}{\ell}, \frac{AGG}{k\ell}, \left(\frac{h_{efft}}{h_1}\right)^2\right) \quad \text{(E.3)}$$

Where σ, q are slab bending stress and vertical subgrade stress, respectively, [FL^{-2}]; δ is the slab deflection, [L]; P = wheel load, [F]; 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.

Furthermore, the following concise relationship has been identified by Lee and Darter [*10*] for the effects of loading plus thermal curling:

$$\frac{\pm}{E}, \frac{\text{¢}h}{a^2}, \frac{qh}{ka^2} = f\left(\frac{a}{a}, \sim\Delta T, \frac{L}{a}, \frac{W}{a}, \frac{\text{¥}h^2}{ka^2}, \frac{ph}{ka^4}\right) \qquad \text{(E.4)}$$

Where 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}]; $D_\gamma=\gamma*h^2/(k*a^2)$; and $D_P=P*h/(k*a^4)$. Also note that $D_{\text{¥}}$ 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].

A series of F. E. factorial runs were performed based on the aforementioned dominating mechanistic (dimensionless) variables 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 [*11*]. As proposed by Lee and Darter [*12*], a two-step modeling approach using the projection pursuit regression (PPR) technique was utilized for the development of prediction models. More detailed descriptions of the proposed prediction models for stress adjustments can be found in Reference [*1*].

Modified Equivalent Stress Calculations

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*]:

$$\pm_{eq} = \left(\pm_w * R_1 * R_2 * R_3 * R_4 * R_5 + R_T * \pm_c\right) * f_3 * f_4 \qquad \text{(E.5)}$$

$$\pm_w = \frac{3(1+\text{«})P}{\text{®}(3+\text{«})h^2}\left[\log_e \frac{Eh^3}{100ka^4} + 1.84 - \frac{4}{3}\text{«} + \frac{1-\text{«}}{2} + 1.18(1+2\text{«})\frac{a}{a}\right]$$

$$\pm_c = \frac{CE\sim\Delta T}{2} = \frac{E\sim\Delta T}{2}\left\{1 - \frac{2\cos a \cosh a}{\sin 2a \sinh 2a}(\tan a + \tanh a)\right\}$$

Where:

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

σ_w = Westergaard's closed-form edge stress solution, [FL^{-2}];

σ_c = Westergaard/Bradbury's curling stress, [FL^{-2}];

E = elastic modulus of the slab, [FL^{-2}];

h = slab thickness, [L];

C = the curling stress coefficient ($\lambda = W/((8^{0.5})*a)$);

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.

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 $\Sigma(n_i/N_i)<100\%$.
8. If not, assume a different slab thickness and repeat steps (1) - (7) again to obtain the minimum required slab thickness.

TKUPAV PROGRAM DEVELOPMENT

To facilitate practical trial applications of the proposed stress analysis and thickness design procedure, a window-based computer program (TKUPAV) was developed using the Microsoft Visual Basic software package [*13*]. 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 and Chinese versions of the program are available.

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 1. A trial slab thickness h = 9.5 in. with no concrete shoulder was assumed in this case study [1, 4]. (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 1. 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 ΔT= 20 ^{o}F, α = 5.5E-06 /^{o}F, γ = 0.087 pci. Thus, $\alpha\Delta T$ = 0.00011, W/ª = 3.873, L/ª = 4.648, a/ª = 0.1219, DG = 4.0274, λ = 1.370, and σ_c= 88.5 psi. The results of this example are summarized in Table 2. 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.

CONCLUSIONS AND RECOMMENDATIONS

This study focused on the development of a new stress analysis and thickness design procedure for zero-maintenance design of jointed concrete pavements through proposed modifications to the PCA's equivalent stress calculations and fatigue analysis. It 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, Microsoft EXCEL spreadsheets, 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 in zero-maintenance design of jointed concrete pavements. The possible compensative effect of night-time curling was neglected in the proposed approach, however it may be easily incorporated using an additional prediction model developed by Lee and Darter [*10*].

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Table 1 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 2 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%