Comparison of Mechanistic-Empirical Thickness Design Methods and Predicted Critical Fatigue Locations

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Abstract
With the use of mechanistic-empirical rigid pavement design methods becoming more widespread, it is important to note the differences of these methods in terms of their sensitivity to input parameters, conservativeness of the design thicknesses, and failure modes predicted. This study further demonstrated the sensitivity of input parameters such as joint spacing, shoulder type, traffic level, climatic location, and built-in curl level on the fatigue failure mechanisms predicted by several design methods. The use of widen lanes was also found to predict different fatigue failure mechanisms between design methodologies due to the assumptions of each method. An investigation into the sensitivity of the level of built-in curling showed that the thinnest design thickness does not necessarily occur with the absence of this parameter, but is minimized at a built-in curling level of approximately -6°C.

Introduction

By using the Mechanistic-Empirical Pavement Design Guide (MEPDG) version 1.0 (ARA 2007) design software in addition to another existing mechanistic-empirical design method in the state of Illinois (Zollinger and Barenberg 1989), a comparison with a mechanistic-based rigid pavement analysis software named RadiCAL (Hiller and Roesler 2005b) can be made in terms of predicted thickness design. Both the MEPDG and Illinois Department of Transportation (IDOT) methods are similar to RadiCAL in that a stress-based approach to fatigue failure is utilized and a variety of statistical distributions of input parameters are accounted for in a Miner's Hypothesis-based fatigue damage accumulation design (Miner 1945).

MEPDG JPCP Thickness Design Method

The MEPDG (ARA 2007) was developed under NCHRP 1-37A as a robust software for the design of new or rehabilitation of asphalt and concrete pavements. This program utilizes engineering mechanics to find stresses, strains, and deflections and utilizes these outputs to predict performance of the pavement over its design life. Traffic is

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characterized using a load spectra concept while accounting for steer-drive axle spacings as well as the individual axle spacing on a tandem, tridem, and quad axle. The MEPDG has the ability to predict environmental (climate) impacts on pavement response and design at virtually any location in the United States using predicted non-linear temperature profiles. One of the more unique features of the MEPDG is the ability to account for a variety of material inputs and their impact on pavement response to better capture deterioration of the pavement and improve design predictions. For JPCPs, the MEPDG utilizes a nationally-calibrated fatigue equation, as seen in the equation below, originally derived from U.S. Army Corps of Engineers airfield slab test results.

$$\mathrm{Log}(N)=2.0\left(\frac{MOR}{\sigma}\right)^{1.22} \qquad \text{(Equation 1)}$$

where:

N	=	number of repetitions until failure (50% reliability)
MOR	=	modulus of rupture of the concrete
σ	=	applied maximum stress level

The MEPDG uses a stress prediction neural network in a real-time setting in conjunction with this fatigue transfer function to predict either bottom-up or top-down transverse fatigue cracking near the mid-slab edge. The MEPDG also allows for a user-specified failure criteria in terms of both reliability and percentage of slabs cracked.

Illinois Department of Transportation JPCP Thickness Design Method

As one of the earlier mechanistic-empirical methods developed, the IDOT method for design of JPCPs employs a simplified stress-based approach that accounts for both load and temperature curling in fatigue (IDOT 2002). Stresses are determined from regression equations developed from finite element analyses using Illislab (Tabatabaie and Barenberg 1978, Ioannides 1984, Korovesis 1990, and Khazanovich 1994). Traffic is represented by an 80-kN ESAL with the lateral wheel wander of these trucks being represented by a normal distribution with a mean of 46cm from the edge and a standard deviation of 25cm. IDOT JPCP designs are designed to a reliability level of 95% and limiting the percentage of slabs cracked from bottom-up at the mid-slab edge during the design life to 20% for higher traffic volume facilities.

Temperature stresses are superimposed onto load-related stresses using an R-factor to account for the effect of slab lift-off on stress development. The IDOT method assumes three different linear temperature gradients of +0.36ºC/cm, -0.14ºC/cm, and 0ºC/cm to account for daytime, nighttime, and transition periods of the day. This method assumes that the daytime gradient condition occurs 25% of the time, the nighttime gradient condition 35% of the time, and the transition period to occur 40% of the time. For a 30.5cm JPCP slab, these gradients would represent a ΔT of 11.0ºC and -4.3ºC, which do not necessarily represent the extreme conditions that may drive fatigue damage development but instead the equivalent temperature differentials that produce the similar damage levels.

The number of repetitions until failure is determined using the Zero Maintenance (ZM) equation (Darter 1977). To develop this concrete fatigue function, Darter compiled 140 fatigue beam results from three published studies Kesler (1953), Raithby and

Galloway (1974), and Ballinger (1972) into one least square regression in the following equation:

$$\text{Log}\left(N_f\right) = 17.61 - 17.61\left(\frac{\sigma}{MOR}\right) \qquad \text{(Equation 2)}$$

Most fatigue transfer functions for concrete fatigue exhibit a semi-logarithmic relationship such as shown above. This presents a dilemma in rigid pavement analysis using a linear damage accumulation method such as Miner's Hypothesis (Miner 1945). The predicted damage accumulated using this method is primarily due to the heaviest axle loads and their associated stresses on the pavement, thereby neglecting a vast majority of loads in the damage accumulation.

Using this fatigue transfer function, one can easily assess the impact of stress differences on the number of applied loads until failure. Assuming a modulus of rupture of 4.5MPa and an applied repeated stress of 3.45MPa (stress ratio of 0.77), this transfer function would predict 11,584 repetitions to failure. A twenty percent reduction in stress to 2.76 MPa (stress ratio of 0.62) would predict almost 6,000,000 repetitions until failure. This essentially means that one repetition at 3.45MPa would equate to 3,512 repetitions at 2.76 MPa in this fatigue counting routine. Consequently, an applied stress of 2.07MPa would require over 260,000 repetitions to equal one applied stress load of 3.45MPa. Therefore, these lower applied stresses are overshadowed by a few single high stress applications and essentially do not add considerable damage under these assumptive conditions.

RadiCAL JPCP Thickness Design Method

The development of this mechanistic-based program as a fatigue damage accumulation method for multiple locations along the transverse joint and longitudinal edge can be found in Hiller and Roesler (2005a). As RadiCAL has been developed as a mechanistic tool, it does not have the direct ability to predict thickness from accumulated fatigue damage. To provide comparisons to established mechanistic-empirical design methods, the fatigue damage to cracking transfer function and reliability models from the MEDPG were utilized (ARA 2007). As both the MEPDG and RadiCAL are based on determining the number of discrete events and their associated stress levels from finite element analyses, this method was deemed most appropriate at this time.

Using the Tepfers (1979) transfer function (Equation 3) to account for stress range effects in rigid pavement analysis can help dampen the effects of the highest stresses dominating fatigue damage accumulation as the areas of the slab that undergo the highest applied stress levels also exhibit the highest curling stresses. Therefore the change in stress when the load is applied is not as great and does not dominate the damage development as much.

$$\frac{\sigma_{max}}{MOR} = 1 - \beta\left(1 - R\right)\log_{10} N \qquad \text{(Equation 3)}$$

where:

σ_{max} = maximum flexural stress applied during cyclic loading

σ_{min} = residual flexural stress in slab before load application

β	=	calibration coefficient (0.0685 for concrete by Tepfers)
R	=	$\sigma_{min} / \sigma_{max}$

RadiCAL has the ability to utilize all three of the above-mentioned fatigue transfer functions as a user input in calculating fatigue damage levels. However, to design for a given failure level in terms of slabs cracked at a specified reliability level higher than the mean, fatigue damage must be related to a field calibrated cracking model. Using reliability-based functions developed for the MEPDG (ARA 2007), these fatigue damage levels can be converted into a level of cracking to attempt to provide thickness design comparisons against existing mechanistic-empirically based procedures. While the MEPDG focuses only on locations near the mid-slab which can predict transverse cracking, RadiCAL has the ability to examine fatigue damage at every 10cm increment along the top and bottom of both the longitudinal edge and transverse joint, resulting in up to 178 potential fatigue cracking initiation points (89 on both the top and bottom of the slab).

Design Methodology Comparison

A design comparison was conducted between the MEPDG, IDOT, and RadiCAL methods for a variety of design parameters to compare predicted cracking locations and actual slab thickness values. Input parameters were modified to determine the minimum JPCP thickness (in 1.3cm increments) to achieve less than 20% of slabs cracked after 20 years of service at 95% reliability. The variables modified in this analysis are as follows:

- Joint Spacing: 3.6 and 4.6m
- Shoulder Type: AC, tied PCC, 4.3m widened slab (AC shoulder)
- Built-in Curl Level: -5.6ºC (part of the study varies from 0 to -22ºC)
- Traffic Level: 1,600 (low) and 9,575 (high) two-way AADTT corresponding to 10 and 60 million ESALs over the design life, respectively

The load spectra utilized in this study was the MEPDG default (ARA 2007). The steer-drive axle spacing distribution for this study was also kept at the MEPDG default with 33% of these spacings at 3.6m, 33% at 4.6m, and 34% at 5.5m. The vehicle class distribution was assumed to be the average of several Illinois weigh stations as presented in Hiller (2007). Other traffic characteristics kept at constant values for these analyses include the following:

- Number of lanes in design direction: 2
- Percent of trucks in design direction (%): 50
- Percent of trucks in design lane (%): 95
- Yearly Growth Factor: No Growth

For each of these design comparisons, the ZM, MEPDG, and Tepfers' stress range fatigue transfer functions can be employed in RadiCAL for both linear and non-linear temperature profiles. However, the initial thickness comparisons derived from RadiCAL are employing only the MEPDG fatigue function with non-linear temperature profiles. Later in this discussion, critical damage locations using RadiCAL are noted for all three fatigue damage functions to show how the choice of a fatigue transfer function can affect the predicted fatigue-based distress location.

Climatic Impact. The first variable this design thickness comparison focuses on is that of climate. Varying the location of the weather station used for the Enhanced Integrated Climatic Model, EICM (Larson and Dempsey 1997), in both the MEPDG and RadiCAL can modify the temperature profiles and subsequent stress states and unsupported areas of the slab due to curling and warping. A design comparison was conducted between the MEPDG, IDOT, and RadiCAL methods for the four Illinois locations seen in Figure 1 (Chicago Midway, Chicago DuPage, Peoria, and Carbondale) to represent the northern, central, and southern portions of the state.

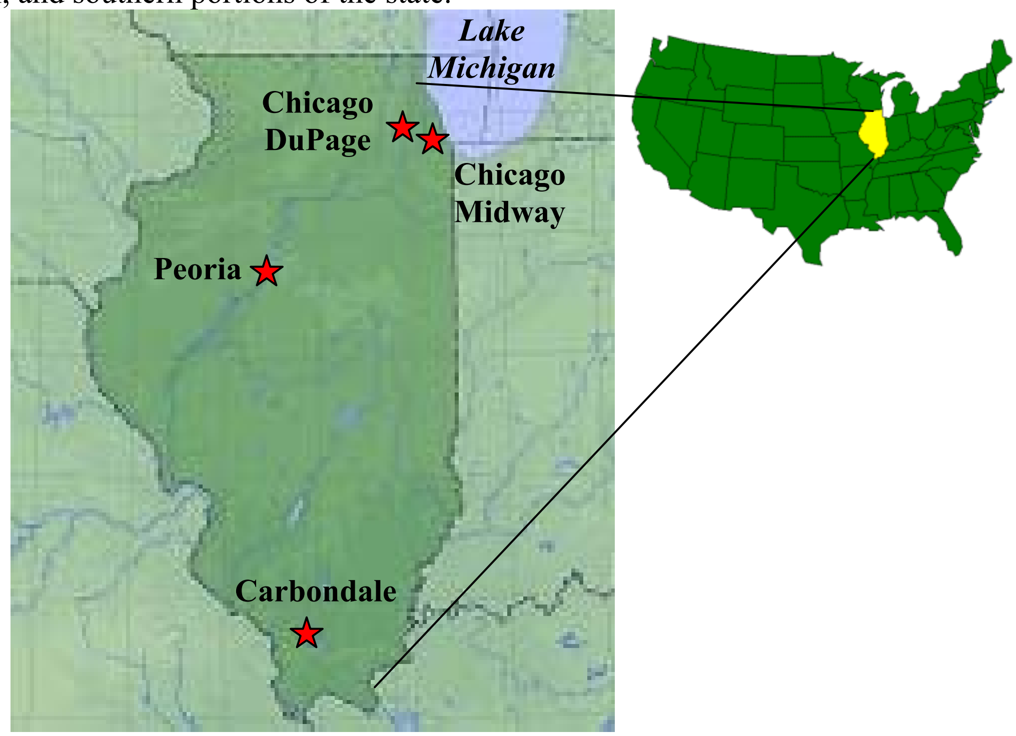

Figure 1. Climate Location of State of Illinois JPCP Design Comparisons.

Thickness Trends. Figure 2 shows the resulting design thickness for a JPCP with 4.6m joint spacing and an asphalt concrete shoulder under a relatively high level of traffic (60 million ESALs) for the four locations mentioned previously. The MEPDG method was the most sensitive to climate resulting in a 20% reduction in required thickness from Chicago Midway in comparison to Chicago DuPage and Carbondale. The IDOT method predicts a constant thickness for all locations in Illinois, as it did not include local climate conditions in the original method. The use of RadiCAL with the MEDPG fatigue transfer function predicts a 5% thinner concrete slab is needed at Chicago Midway in comparison with all other locations in the state of Illinois, which falls between the extremes of the MEPDG and IDOT thickness design trends.

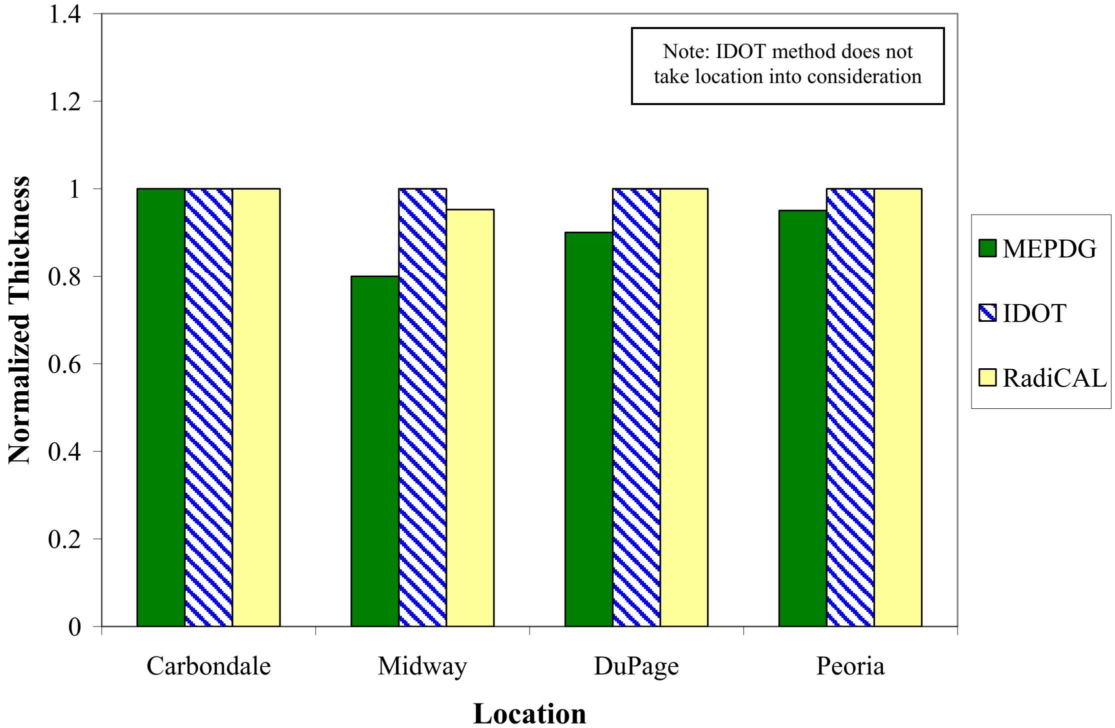

Figure 2. Impact of Climatic Location on JPCP Relative Thickness for 4.6m Joint Spacing, AC Shoulder, and 9,575 AADTT.

The straight-line distance between the Chicago Midway and Chicago DuPage weather stations is roughly 40km. This shows the tempering influence of large bodies of water on local climates in the Chicago area as Midway is only 11km from Lake Michigan, while DuPage is roughly 48km in distance from this lake. This effect can be seen by looking at the predicted frequency plot of ΔT for these four locations in Illinois (see Figure 3) using hourly output data from EICM for years 2000-2004. While DuPage, Carbondale, and Peoria show similar predicted temperature difference frequencies, Midway shows a slightly different distribution. This is most noticeable at the extreme ends of both the positive and negative ΔT where Midway is virtually absent in comparison with the other three Illinois sites. The tails of this distribution drive the highest stress levels and their subsequent damage accumulations, thereby requiring an increased thickness to compensate. With little of these extreme events comparatively, the Midway weather station would suggest that thinner slabs could be constructed in the city of Chicago with all other input parameters being equal. However, JPCP designs in a city such as Chicago would tend to require the highest level of reliability in order to reduce potential for rehabilitation and reconstruction of these sections under extremely heavy traffic levels. An increase of reliability from 95% to 99% using RadiCAL would increase the design thickness at Midway by 1.3cm in this case.

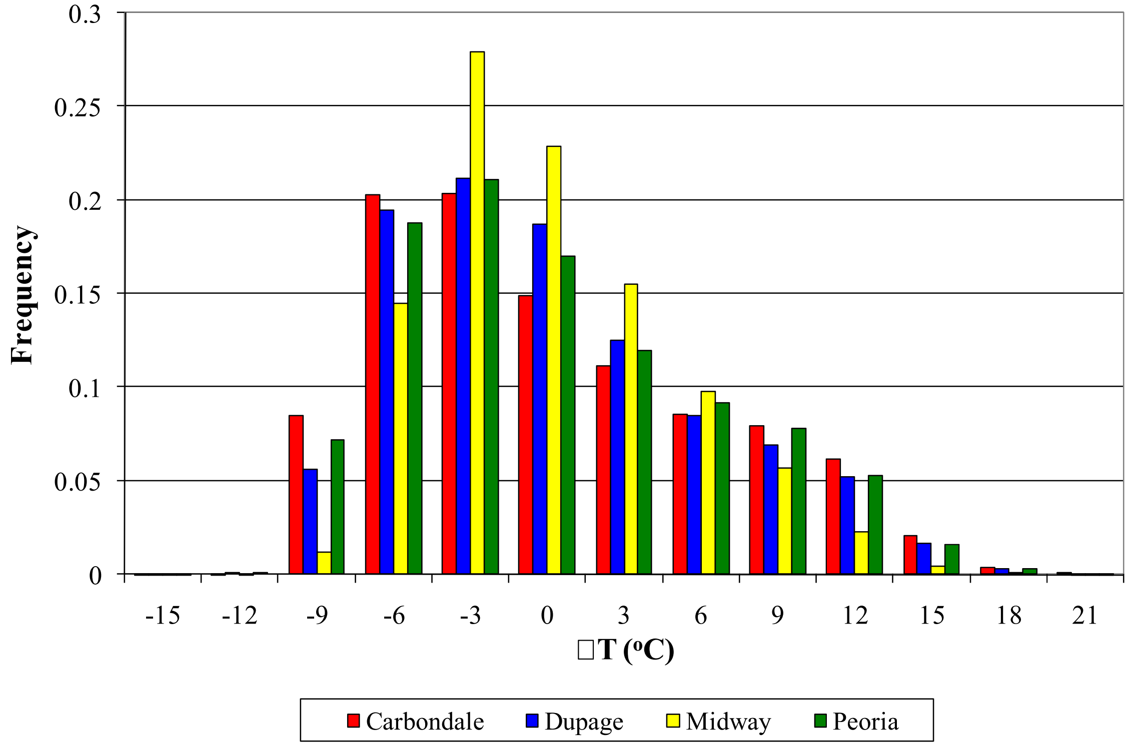

Figure 3. Frequency of Hourly Temperatu re Differences for Four Illinois Sites using EICM for Years 2000-2004.

Locations of Critical Fatigue Damage. Using linear temperature differences in RadiCAL, Table 1 shows the comparison of critical damage locations in comparison to the MEPDG and IDOT methods for three different fatigue transfer functions in terms of climatic location and traffic level. Due to its limitations, the IDOT method will predict bottom-up transverse cracking to be critical in all cases.

In most cases, the use of any fatigue function in RadiCAL predicted bottom-up cracking at mid-slab. However, the use of the stress range function found an alternative critical damage location (closer to the transverse joint along the longitudinal edge) that was not found using the other methods. The effect of greater traffic levels did not affect the critical damage location for these cases in RadiCAL despite the increase in slab thickness.

For the cases analyzed for this climatic study in Table 1 (AC shoulder, 4.6m joint spacing, A-7-6 subgrade), the MEPDG generally predicts the critical transverse cracking location to be at the bottom of the slab, with the exception of the high traffic level cases found at Carbondale. All sites except for the Chicago Midway location also showed a significant amount of relative damage (~15% of the maximum damage level) indicating top-down cracking near mid-slab, which was not predicted by RadiCAL in these cases using linear temperature differences.

For this study, the Carbondale location predicted the thickest section of any location in Illinois using the MEPDG. For cases found in this comparison, the MEPDG method will predict bottom-up transverse cracking to be critical at thicknesses less than 24cm on a A-7-6 subgrade, while thicker slabs tend to have top-down transverse cracking becoming dominant. This difference in cracking mechanism lies with the interaction between the radius of relative stiffness (ℓ) and the slab length (L). With thinner slabs, the ratio L/ℓ is higher than with thicker slabs for a fixed slab length (L). The larger this ratio becomes, the closer to an infinite slab condition exists and the tensile stresses on the top of the slab interact less near the mid-slab location when analyzing steer-drive axle load cases. This increase in stress therefore leads to higher probability of bottom-up cracking occurring in thinner JPCP sections with all other factors being equal.

Table 1. Predicted Critical Damage Locations for Four Illinois Cities using Three M-E Design Methods with Linear and Non-Linear Temperature Profiles in RadiCAL.

	MEPDG		IDOT[c]		RadiCAL				
	Transverse Cracking		Transverse Cracking		Transverse Cracking			Longitudinal	
	Bottom-up mid-slab	Top-down mid-slab	Bottom-up mid-slab	Top-down mid-slab	Bottom-up mid-slab	Top-down mid-slab	Bottom-up alternativ	Bottom-up wheelpath	Top-down between wheelpath
	ASSUMED LINEAR TEMPERATURE DIFFERENCES								
Carbondale	1600[a] high[b]	9575[a] low[b]	x		All				
DuPage	x	x[b]	x		ZM ME		SR		
Midway	x		x		ZM ME		SR		
Peoria	x	x[b]	x		ZM ME		SR		
	TRUE NON-LINEAR TEMPERATURE DIFFERENCES								
Carbondale	1600[a] high[b]	9575[a] low[b]	x		All				
DuPage	x	x[b]	x		All	ZM[b] ME[b]			
Midway	x		x		All				
Peoria	x	x[b]	x		All	ZM[b] ME[b]			

[a] Refers to the level of AADTT

[b] Refers to the significant level of relative damage (>0.15) at secondary location

[c] Due to its assumptions, IDOT method will always predict bottom-up, mid-slab transverse cracking for all locatio

SR=Tepfers stress range, ZM=Zero Maintenance, ME=MEPDG fatigue transfer function in RadiCAL

Table 1 also shows a comparison of critical damage locations except that self-equilibrating stresses from non-linear temperature profiles are accounted for in the RadiCAL cases. When doing so, the stress range fatigue function tends to predict bottom-up transverse cracking at the mid-slab location just as the ZM and MEPDG fatigue functions. This critical damage location matches both the IDOT and MEPDG and is indicated by the shaded cells of Table 1. However, both the ZM and MEPDG transfer function show a significant amount of relative damage indicating top-down transverse cracking as a possibility. As both the MEPDG and RadiCAL utilized Illislab for stress prediction algorithms and maximum stress fatigue functions in this case, there is a positive correlation that validates each method prediction of the maximum fatigue damage location.

Joint Spacing Impact. The next parameter this comparison will focus on is joint spacing. A few limitations exist between the three methods. The statewide IDOT design method does not compensate directly for thickness changes with joint spacing and instead assumes that all designs will be for a joint spacing of 4.6m. RadiCAL is limited to joint spacing of 3.6m and 4.6m as the initial development of the program was for new designs in the state of California and joint spacing is now limited considerably in that state. In contrast, the MEPDG has the ability to analyze any joint spacing ranging from 3.6 to 6.1m for JPCPs. Due to this limitation, only 3.6 and 4.6m joint spacings will be analyzed. For the joint spacing and shoulder type studies, the Carbondale climatic location was utilized.

Thickness Trends. A comparison of the impact of joint spacing on design thickness for JPCPs can be seen in Table 2 with the 3.6m joint spacing cases with an AC shoulder being the reference thickness for all three methods. For AC shoulder cases, the MEPDG method shows an increase in thickness of 42% and 18% for the low and high truck traffic values, respectively, as the joint spacing increases from 3.6 to 4.6m. Conversely, RadiCAL predicts 0 and 5% increase of required thickness for the same scenarios. The IDOT method shows the same relative thickness for 3.6m and 4.6m spacings since no guidance is given for change in thickness as joint spacing is reduced from its standard 4.6m slabs.

While required thicknesses are reduced when adding a tied PCC shoulder, RadiCAL predicts an additional reduction of required thickness up to 5% when joint spacing is reduced from 4.6 to 3.6m. The MEPDG shows a similar trend as thickness is reduced 12% for the high volume traffic and there is no reduction at the low traffic level due to the program's minimum thickness requirement of 15cm.

Using a widened slab with an asphalt shoulder, the same trends exist for the MEPDG, while RadiCAL shows no sensitivity for joint spacing in terms of minimum required thickness. It should be noted that for both the low and high traffic level scenarios, the cracking predicted does increase in RadiCAL, but not enough to affect design thickness.

Table 2. Impact of Joint Spacing on JPCP Relative Thickness for Carbondale, Illinois using Three M-E Design Methods.

AADTT 1600									
Joint Spacing (m)	AC Shoulder			Tied PCC Shoulder			Widened Slab w/ AC Shoulder		
	MEPDG	IDOT	RadiCAL	MEPDG	IDOT	RadiCAL	MEPDG	IDOT	RadiCAL
3.6	1	1	1	1	0.95	0.84	1	0.88	0.84
4.6	1.42	1	1	1	0.95	0.89	1	0.88	0.84
AADTT 9575									
Joint Spacing (m)	AC Shoulder			Tied PCC Shoulder			Widened Slab w/ AC Shoulder		
	MEPDG	IDOT	RadiCAL	MEPDG	IDOT	RadiCAL	MEPDG	IDOT	RadiCAL
3.6	1	1	1	0.82	0.98	0.95	0.82	0.90	0.95
4.6	1.18	1	1.05	0.94	0.98	0.95	0.94	0.90	0.95

Shoulder Type Impact. The next factor that impacts both thickness and critical damage location is that of the shoulder type. This analysis looks at three different types of shoulders for the three mechanistic-empirical design methods: standard slab width (3.6m) with an asphalt concrete shoulder, standard slab width with a tied PCC shoulder (LTE=50% in RadiCAL), and a widened slab (4.3m) with the lane delineation painted 0.6m from the true slab edge compared in the Carbondale climate.

Thickness Trends. For high traffic levels and a 4.6m slab length, the trend of required normalized thickness to satisfy less than 20% of slabs cracked at 95% reliability can be seen in Figure 4. RadiCAL predicts a decrease of 16% in thickness when utilizing a tied PCC shoulder or widened slab. Thickness reductions using the MEPDG are 20% for both tied shoulder and widened slab designs relative to AC shoulder designs. The IDOT method demonstrates a 2% and 12% thickness reduction when using tied shoulder and widened slabs, respectively.

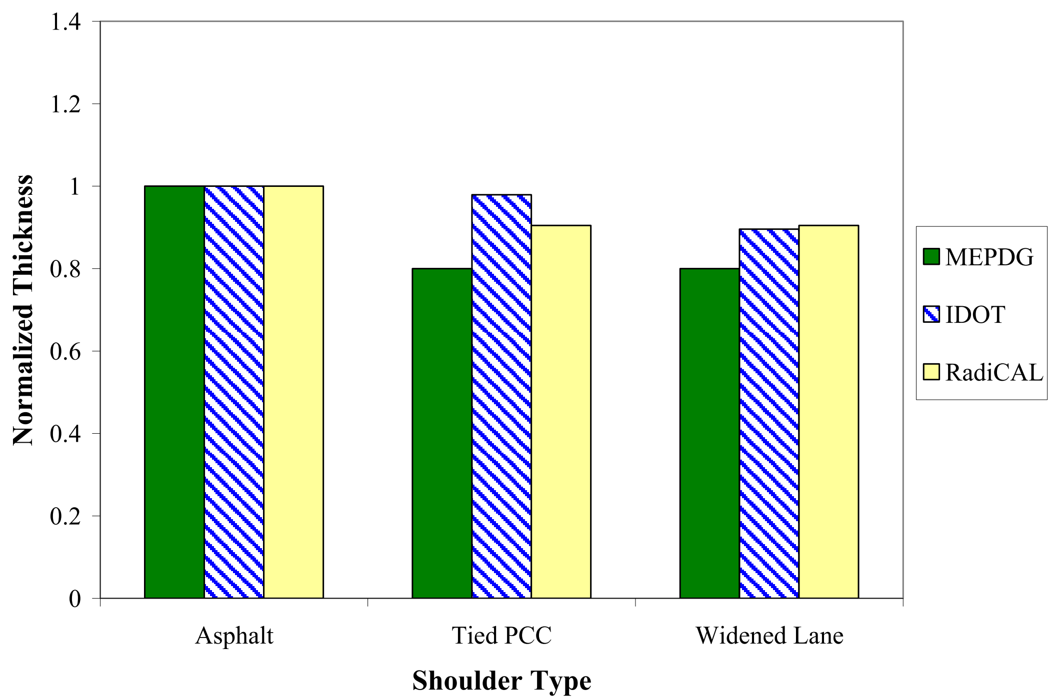

Figure 4. Impact of Shoulder Type on JPCP Relative Thickness for Carbondale, Illinois, 4.6m Joint Spacing, and 9,575 AADTT.

Locations of Critical Fatigue Damage. Table 3 compares the critical and secondary damage locations for two traffic levels (1,600 and 9,575 AADTT), two joint spacings (3.6 and 4.6m), and three shoulder types (AC shoulder, tied PCC shoulder, and widened slab with AC shoulder) using the three mechanistic-empirical design methods. Table 3 also assumes a non-linear temperature profile for the RadiCAL designs regardless of fatigue transfer function utilized.

In general, the MEPDG, IDOT, and RadiCAL methods tended to match critical fatigue damage locations at the bottom of mid-slab when using AC or tied PCC shoulders with 3.6m joint spacing, regardless of traffic level. This is noted by the shaded cells in Table 3. However, when changing the joint spacing to 4.6m, critical damage locations are not necessarily the same. In many of these cases, the Tepfers' stress range predicts an alternative bottom-up crack initiating along the longitudinal edge, but not at the mid-slab location. Instead this location is roughly halfway between the mid-slab and corner of the slab. Due to high stresses from both single and tandem axles placed at this location and the relatively low residual temperature stresses in comparison with the mid-slab edge location, the stress range approach accounts for a significant amount of fatigue damage accumulation at these locations.

Table 3. Predicted Critical Damage Level Locations by Joint Spacing, Shoulder Type, and Truck Traffic Level using Three M-E Design Methods with Non-Linear Temperature Profile in RadiCAL.

Joint Spacing (m)	MEPDG		IDOT		RadiCAL				
	Transverse Cracking		Transverse Cracking		Transverse Cracking			Longitudinal	
	Bottom-up mid-slab	Top-down mid-slab	Bottom-up mid-slab	Top-down mid-slab	Bottom-up mid-slab	Top-down mid-slab	Bottom-up alternativ	Bottom-up wheelpath	Top-down between wheelpath
AC Shoulder									
AADTT 1600									
3.6	x		x		All				
4.6	x	x[a]	x		ZM ME	ZM[a] ME[a]	SR		
AADTT 9575									
3.6	x	x[a]	x		All	ZM[a]			
4.6	x[a]	x	x		ZM ME	ZM[a] ME[a]	SR	SR[a]	
Tied PCC Shoulder									
AADTT 1600									
3.6	x		x		ZM ME		SR	ZM[a] ME[a]	
4.6	x		x		ZM ME	ZM[a]	SR	All[a]	ZM[a]
AADTT 9575									
3.6	x		x		ZM ME		SR	ME[a]	
4.6	x	x[a]	x		ZM[a] ME[a]	ZM ME	SR	SR[a]	
Widened Slab with AC Shoulder									
AADTT 1600									
3.6	x		x					All	ZM[a] ME[a]
4.6	x		x					All	ZM[a] ME[a]
AADTT 9575									
3.6	x		x					All	ZM[a] ME[a]
4.6	x	x[a]	x			ZM ME[a]		SR ME ZM[a]	ZM[a]

[a] Refers to the significant level of relative damage (>0.15) at secondary location
SR=Tepfers stress range, ZM=Zero Maintenance, ME=MEPDG fatigue transfer function in RadiCAL

For standard lane widths, the MEPDG predicts similar critical damage locations as RadiCAL when using a maximum stress fatigue approach such as the ZM or MEPDG fatigue function in the RadiCAL program. When considering widen slabs, in almost all cases RadiCAL predicts the critical damage location to be at the transverse joint under either the inner or outer wheelpath. Since the extended lane width effectively keep axle loads away from the true slab edge, the importance of loads at the transverse joint becomes imperative. In comparison, the critical location for damage accumulation in the

MEPDG for widened slabs is at the mid-slab edge, but at the adjacent lane and not the AC shoulder (ARA 2007). This difference in potential critical locations could result in different required design thicknesses.

With RadiCAL's ability to predict fatigue mechanisms at alternative locations, the program may not necessarily predict the same thickness reduction for adding either a tied PCC shoulder or extending the slab width relative to the MEPDG program. It is important to note that the fatigue damage mechanism (top-down, bottom-up, transverse, longitudinal, etc.) that is being designed against in RadiCAL may not correspond to that of either the IDOT or MEPDG design methods.

The same trend exists for tied PCC shoulder cases as the ZM and MEPDG fatigue functions in RadiCAL tend to predict the critical damage location at the bottom of the mid-slab edge at -5.6°C built-in curl. The stress range function tends to predict bottom-up transverse cracking closer to the corner of the slab in these scenarios.

A major difference between the RadiCAL method and MEPDG and IDOT methods is that a significant amount of secondary relative damage is located in several locations including the top of the longitudinal edge as well as the top or bottom of the slab at the transverse joint. These significant secondary relative damage levels could exacerbate themselves as alternative cracking mechanisms that cannot be designed against in either the MEPDG or IDOT method. With tied PCC shoulder scenarios, the stress at the bottom of the mid-slab edge is reduced in comparison with the AC shoulder scenario, while the stresses at the transverse joint are relatively similar. Even with an assumed load transfer efficiency of 70%, this reduction in bottom-up mid-slab stresses increases the importance of the consideration of longitudinal cracking potential in design of JPCPs. These secondary locations are especially important if a lower concrete strength were to be assumed at the slab surface relative to the bottom or if a higher level of built-in curling value was assumed.

It is also important to note the differences in safety and rehabilitation options between slabs containing transverse or longitudinal cracking. While transverse cracking can reduce ride quality, it is generally not considered to be a safety hazard except in the most significant cases of faulted cracks. However, longitudinal cracking is a distress that vehicles must tend with for a longer period of driving time if this continues for several slabs. Faulting along these cracks (particularly those emanating in the wheelpath) can cause severe control problems for trucks, cars, and particularly motorcycles. The rehabilitation options for these longitudinal cracks are also limited to grout insertion and stitching, which is time consuming and costly.

Analysis with RadiCAL showed that widen slab cases with AC shoulder predict longitudinal cracking emanating from the wheelpath at the transverse joint to be critical regardless of fatigue transfer function utilized. This important finding can allow for proper consideration of alternative fatigue cracking mechanisms for thickness design. It should be noted that while the critical damage location in RadiCAL is shown to be at the transverse joint for widen slab cases, there is still a reduction of thickness required in comparison with the standard lane width scenarios but not as significant as the current IDOT or MEPDG would suggest.

Built-in Curling Impact. Analyses from Hiller and Roesler (2006) demonstrate that the level of built-in curl has a dramatic effect on stress, fatigue damage level, and critical damage locations in JPCPs. This section aims to look at how the factors in turn affect the required design thickness for the MEPDG and RadiCAL. The IDOT design method does not have the ability to account for built-in curl and shows no sensitivity to this parameter.

Thickness Trends. Figure 5 shows the impact of increasing the level of built-in curl to more extreme values using non-linear temperature profiles for Carbondale. The MEPDG method predicts an increase in required thickness as the level of built-in curl becomes more negative. While RadiCAL shows a similar trend of increasing thicknesses for most of the built-in curl levels, there is one exception. At a built-in curl level of 0ºC, the required thickness according to RadiCAL is actually thicker than is required at a built-in curl level of -5.6ºC. It was found that the fatigue damage level minimized in the built-in curl range of -5ºC to -8ºC. This range is termed the "flip point" where damage changes being critical at the bottom of the slab to now being critical at the top of the slab (Hiller and Roesler 2006). This trend is also reproduced in terms of required thickness using the MEPDG fatigue and cracking models within the RadiCAL program.

At built-in curl levels more extreme than -11ºC, both the MEPDG and RadiCAL design method would tend to require thicker JPCP sections than required by the IDOT method. However, this level of built-in curl is fairly rare and would probably require a drier climate, extreme positive temperature gradient during setting, and poor curing conditions after concrete placement. The use of restraint mechanisms such as dowels and tie bars has also shown a correlation to reduced built-in curl levels (Rao 2005).

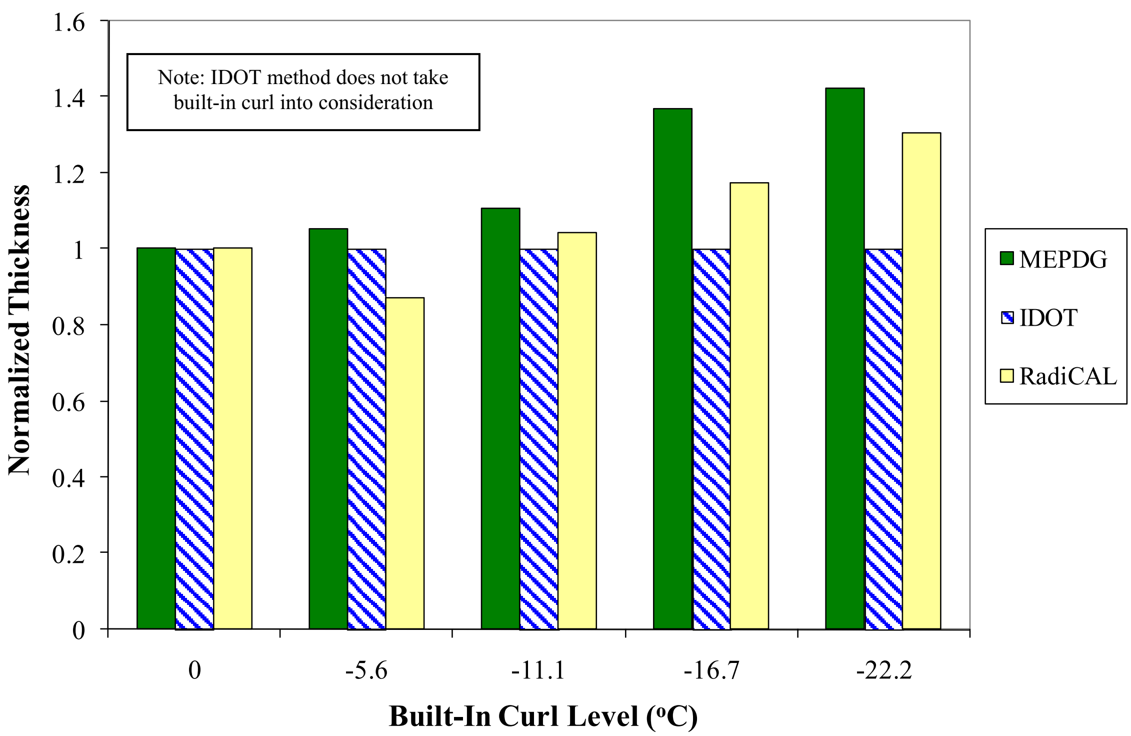

Figure 5. Impact of Built-In Curl Level on JPCP Relative Thickness for Carbondale, Illinois, AC Shoulder, 4.6m Joint Spacing, and 9,575 AADTT with Non-linear Temperature Profiles.

Locations of Critical Fatigue Damage. In both the MEPDG and RadiCAL methods (using the MEPDG fatigue and cracking functions with non-linear temperature), the "flip point" for when critical fatigue damage changed from bottom-up to top-down transverse cracking was found to be -5.6ºC with very little damage at the transverse joint.. This "flip point" occurs due to the reduction of stresses at the traditional mid-slab edge location from single axles and the increased importance of steer-drive axle spacing effects with a negative built-in curl.

For example, using the average axle load spectra found from all California WIM stations in conjunction with the probabilities of load levels and steer-drive axle spacings for a typical California rigid pavement design, the probability of stresses found from Illislab can be predicted as seen in Figure 6. This particular plot shows the probabilities of stresses at the bottom of the slab at the mid-slab edge. It can be seen that the built-in curl value greatly impacts the distribution of stresses predicted at this location that is typically assumed to be critical. Using transfer functions under a high built-in curl value, the mid-slab edge location would essentially have infinite fatigue life as the stress ratio is kept below a value of 0.50 using a flexural strength of 4.8MPa. When assuming no built-in curl value, the maximum stress at this location produces a stress ratio of 0.85 when using the same flexural strength and this would lead to a much rapid fatigue failure. Due to this reduction in stresses at the traditional bottom-up transverse cracking initiation point, stresses at other locations such as those causing top-down transverse or longitudinal cracking become more critical.

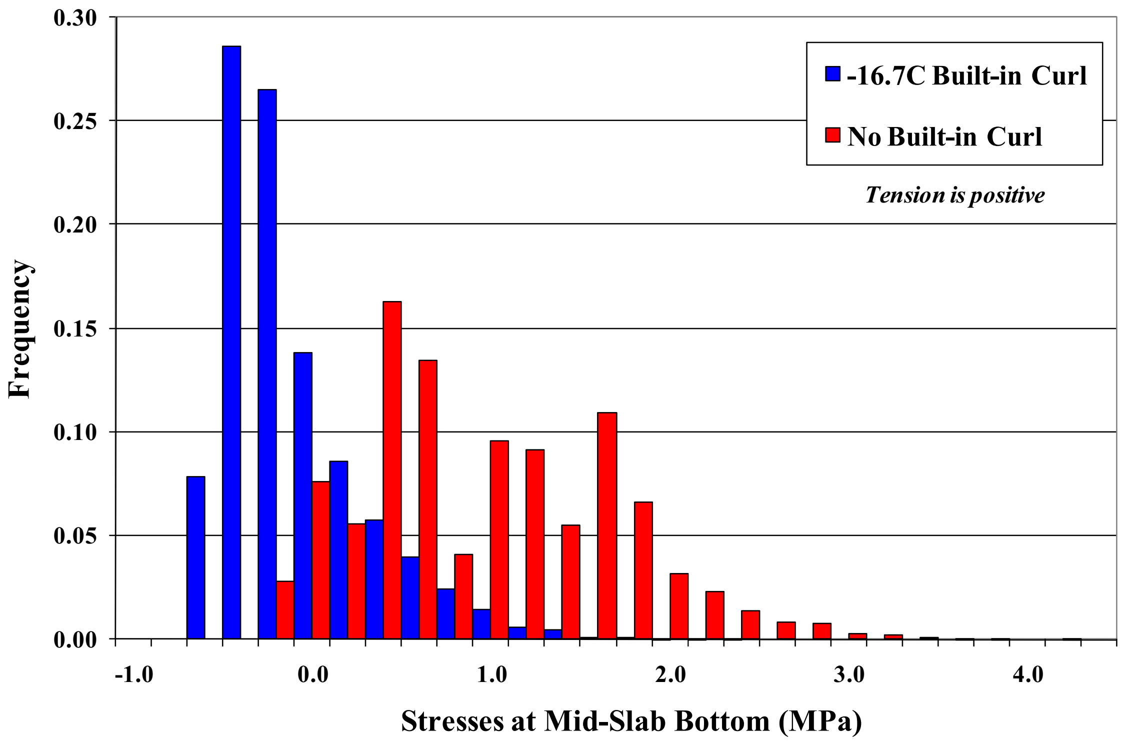

Figure 6. Probabilities of Stresses Occurring at Bottom of the Mid-Slab Edge of the Slab for 0 and -16.7C EBITD Values.

Looking at a key location at the top of the slab along the longitudinal edge (0.6m from the mid-slab location), the exact opposite trend is noted in Figure 7. At the top of the slab, the probability distribution for stresses is magnified by the inclusion of a -16.7ºC built-in curl value in this example. This inclusion of built-in curl intensifies the tensile stresses at this location significantly, thereby causing significant fatigue damage using RadiCAL or any other fatigue analysis program.

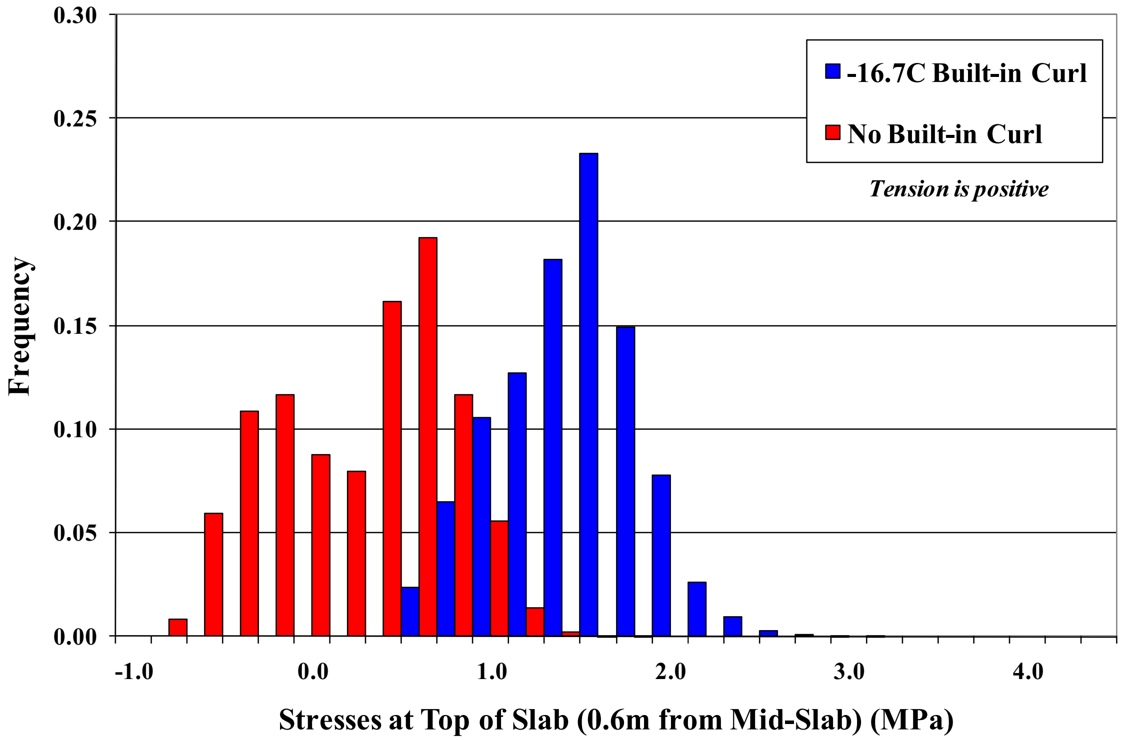

Figure 7. Probabilities of Stresses Occurring at Top of Slab (0.6m from Mid-Slab) for 0 and -16.7C EBITD Values.

It is these maximum stresses (and their associated stress ratios) that control fatigue life most directly and what largely needs to be accounted for in design since the majority of loads produce stresses in the pavement that are deemed insignificant. It is important to note that these probability distributions were created using only high load levels (>46kN for single axles, >115kN for tandem axles) and already exclude the vast majority of traffic that highway pavements would experience.

Conclusions

Several trends were noticed when comparing the MEPDG, IDOT, and RadiCAL thickness design approaches for JPCP. For Illinois sites, the Chicago Midway location was found to have a thinner required thickness using both the MEPDG and RadiCAL design methods in comparison with all other locations in Illinois, although the MEPDG appeared to be more sensitive to many input parameters. Due to the tempering effects of Lake Michigan on air temperature and subsequent temperature profiles in the pavement slabs, this effect was not noticed at the Chicago DuPage locations roughly 40km away from Chicago Midway Airport and 48km from the Lake Michigan shoreline.

The required slab thickness values were found to be very sensitive to joint spacing in the MEPDG while RadiCAL was less sensitive even with the same fatigue, cracking, and reliability functions.

Using the MEPDG for design at a built-in curl level of -5.6ºC with 4.6m joint spacing and an AC shoulder, the failure mechanism for fatigue cracking tends to change from bottom-up transverse cracking to top-down transverse cracking as thickness exceeds 24cm. This trend is not necessarily observed using RadiCAL as the failure mechanism is quite dependent on the fatigue function used and longitudinal or corner cracking can become critical. The level of built-in curl significantly affects the required thickness in the MEPDG and RadiCAL methods. While both of these methods flipped from bottom-up to top-down transverse cracking to be critical at a built-in curl level of -5.6ºC a slightly different trend of required thickness was noticed using RadiCAL. In RadiCAL cases without built-in curl, the required thickness was larger than that required at a built-in curl level of -5.6ºC. This is due to the minimization of extreme load and curling events near this level of built-in curl. When this occurs, the largest possible stresses to drive fatigue damage accumulation are avoided, thereby requiring a thinner section to resist fatigue mechanisms.

In terms of critical cracking locations, the MEPDG, IDOT, and RadiCAL methods tended to match quite well in AC shoulder cases for every fatigue transfer function ran in RadiCAL. When tied shoulders were utilized, the critical damage locations were generally similar, although RadiCAL predicts a variety of secondary fatigue cracking locations at significant damage levels producing a high potential for either bottom-up or top-down longitudinal cracking. For widen lane cases, RadiCAL generally predicted that the critical damage location remains at the transverse joint, producing longitudinal cracking emanating along the wheelpath. In comparison, both the IDOT and MEPDG predict bottom-up transverse cracking to be critical in these cases. The results from RadiCAL suggest that special attention be paid to widen slab designs using the MEPDG or IDOT methods as the critical damage location in these methods do not check for the primary cracking mechanism at the transverse joint.

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