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The Effect of Bridge Deck Design Methodology on Crack Control

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16. Abstract

At present, the Idaho Transportation Department (ITD) Bridge Design Manual allows engineers to use the AASHTO empirical method to design concrete bridge decks. However, the ITD Bridge Section would like to compare their design practices to those employed by other state DOTs. The Bridge Section is also interested in the ability of the empirical deck design method to control deck cracking.
AASHTO's empirical deck design method and traditional design method are summarized. We reviewed the literature regarding the effect of bridge deck design methodology on deck cracking. Many researchers agree that the empirical bridge deck design method needs to be modified to limit cracking. For example, Frosch and Radabaugh believe that the empirical method does not require a large enough reinforcement ratio to adequately control cracking. Others such as Krauss believe that the deck-to-girder stiffness has a greater effect on deck cracking and should be increased in the empirical method.

We also surveyed bridge deck design methods and typical deck designs for all of the states in the U.S. Bridge deck properties such as deck thickness, rebar size and rebar spacing from other states were compared to those specified by ITD. Most states and Canada use a significantly smaller spacing and larger reinforcement bar size. We believe that reducing the spacing and increasing the size of rebar would mitigate ITD's deck cracking problem, although the degree to which deck crack spacing and width would be mitigated would require further research.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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ABSTRACT

At present, the Idaho Transportation Department (ITD) Bridge Design Manual allows engineers to use the AASHTO empirical method to design concrete bridge decks. However, the ITD Bridge Section would like to compare their design practices to those employed by other state DOTs to ensure that consistent and best practices are employed. The Bridge Section is also interested in the ability of the empirical deck design method to control deck cracking.

AASHTO's empirical deck design method and traditional design method are summarized. We reviewed the literature regarding the effect of bridge deck design methodology on deck cracking. Many researchers agree that the empirical bridge deck design method needs to be modified to limit cracking. For example, Frosch and Radabaugh believe that the empirical method does not require a large enough reinforcement ratio to adequately control cracking. Others, such as Krauss, believe that the deck-to-girder stiffness has a greater effect on deck cracking and should be increased in the empirical method.

We also surveyed bridge deck design methods and typical deck designs for all of the states in the U.S. Bridge deck properties such as deck thickness, rebar size and rebar spacing from other states were compared to those specified by ITD. Most states and Canada use a significantly smaller spacing and larger reinforcement bar size. We believe that reducing the spacing and increasing the size of rebar would mitigate ITD's deck cracking problem, although the degree to which deck crack spacing and width would be mitigated would require further research.

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INTRODUCTION

At present, the Idaho Transportation Department (ITD) Bridge Design Manual allows engineers to use the American Association of State Highway and Transportation Officials (AASHTO) empirical method to design concrete bridge decks. However, ITD is concerned that this design method has not been widely adopted by state transportation departments. An obstacle to its adoption is the questioned ability of the empirical deck design methods to control bridge deck cracking.

The key objectives for this project are as follows:

- Determine if the AASHTO Load and Resistance Factor Design (LRFD) empirical deck design method adequately controls cracks.
- Review current research and summarize any proposed steel reinforcement requirements to address crack control.
- Determine which deck design methods are used in other states, including specifically steel reinforcement requirements for crack control.
- Recommend specifications for crack control using the empirical deck design method.

We first examined why bridge decks experience cracking, the different types of cracking, and some methods of bridge deck crack control. We then examined the two primary bridge deck design methods: AASHTO's empirical method and the traditional method. A literature review revealed numerous changes and recommendations from researchers to control cracking in bridge decks. A state by state comparison of bridge deck design methods noted certain design methods individual states use to help control cracking in bridge decks. From the literature review and the survey of state deck design methodologies, we were able to make recommendations that should reduce bridge deck cracking, ultimately reducing bridge deck maintenance and increasing the life of the structure.

Background

Engineers have been trying to reduce the cracking in concrete bridge decks for years. Numerous methods have been attempted – adding more steel, designing thicker decks, decreasing girder spacing – but cracks continue to plague the bridge decks of many transportation agencies. Our research began by examining crack control in general and then focusing on AASHTO's empirical design of bridge decks.[(1)]

Causes of Deck Cracking

There are many different types of concrete bridge deck cracking and numerous causes of cracking. Transverse cracks run perpendicular to the girders in the bridge. Longitudinal cracks move along the girder lines. Map cracks move in apparently random directions, resembling at times a spider web pattern.

There are three primary reasons for the appearance of cracks in concrete bridge decks.[(2)]

1) Shrinkage: The reduction in volume of concrete during the hydration phase though evaporation and thermal expansion.

2) Sloughing: The loss of volume through water loss and consolidation of constituent parts of concrete. Reinforcement restrains consolidation and shrinkage, which results in the formation of cracks.

3) Load Induced Cracking: Load induced stresses in the concrete that exceed the tensile capacity of the concrete. These stresses may be caused by vehicle loads or vibrations.

The New York State Department of Transportation (NYDOT) found that cracking of the bridge deck was related to the vibration of the bridge superstructure during the passage of live loads. [(3)] Glynn indicated that, "In time, such a phenomenon can cause cracking or make existing cracks, especially any transverse cracks, deeper and wider" [(3)] and concluded that:

1) Vibration severity is the most significant parameter influencing bridge deck cracking. Higher severity results in higher deck cracking.

2) Longer spans exhibit more cracking than shorter spans.

3) Long spans and severe vibrations result in the most significant cracking.

Transverse cracks are the most common type of cracking, and are the result of both evaporation- and thermal-shrinkage. [4] Transverse cracking is frequently seen in older bridges near piers between shorter end spans continuous with longer center spans. These cracks can be caused by permit loads or overloads which cause stresses that exceed the combined slab compression caused by the dead loads and the tensile strength of the slab. [5] This report focuses on the control of transverse cracking running perpendicular to the girders of the bridge, which is the objective of the AASHTO Empirical Deck Design method.[1]

Methods of Bridge Deck Crack Control

Many states and agencies agree that cracking of concrete decks cannot be completely eliminated; however, the size and frequency of cracks can be reduced. Changes in material properties and physical design changes can limit cracking and crack width. The material properties include changes of the grade of steel or strength of concrete, and also the type and mix proportions of the concrete. The design properties include rebar size, spacing, and orientation as well as deck placing sequence, deck thickness, and girder spacing. This research considers only the physical design properties affecting bridge deck cracking. It summarizes recommendations from various state bridge agencies and researchers. If there are contrasting ideas, all are presented along with a suggested resolution.

Bridge Deck Design Methods

The AASHTO LRFD Bridge Design Specifications provide two primary methods for designing concrete bridge decks: the Traditional Method and the Empirical Method. The following section describes each of the two design methods. Each method specifies slab thickness, reinforcing bar sizes and spacing in both the longitudinal and transverse directions. The AASHTO LRFD Empirical Method requires no design effort, whereas the Traditional Method requires design effort and is conservative.

AASHTO LRFD Empirical Method

The AASHTO LRFD Empirical Method, also called the Ontario Method due to its origins, is based upon fairly recent research which showed that the primary structural action by which slabs resist live loads is not flexure, as was previously believed. Instead, a complex internal membrane stress state, referred to as internal arching, distributes the live loads from the deck to the supporting girders. [6] This internal arching arises when the concrete cracks in the positive moment region which results in an upward shift of the neutral axis in that portion of the slab. [6] As a result, in-plane or membrane compressive stresses are developed which transmit the vertical live load from the deck to the girders, relying on the lateral confinement at the girder that occurs with the use of a composite design. AASHTO compares this arching action to a compressive dome. In the case of the deck slab, failure usually only occurs when there is overstraining around the perimeter of the wheel footprint. This failure comes in the form of punching shear and not flexure as assumed in the Traditional Method. There is, however, a small flexural component, which the minimum amount of isotropic reinforcement should be able to withstand. [6] The isotropic reinforcement also creates a global confinement, which is required to produce the arching effects. [6]

Tests have been conducted to compare the factors of safety for the Traditional and Empirical Methods. AASHTO has found that the working stress design (Traditional Method) has a factor of safety of at least 10.0, while the Empirical Method has a comparable factor of safety
around 8.0. Thus the Empirical Method – although not as conservative a design as the Traditional Method – still has an enormous amount of reserve strength. [6]

AASHTO specifies a number of design conditions in order to use the Empirical Method: [6]

1) Cross-frames or diaphragms must be used throughout the cross-section at lines of support.
2) For cross-sections involving torsionally stiff units, such as individual separated box beams, either intermediate diaphragms between the boxes shall be provided at a spacing not to exceed 25.0 ft., or the need for supplemental reinforcement over the webs to accommodate transverse bending between the box units must be investigated and reinforcement is provided, if necessary.
3) The supporting components must be made of steel and/or concrete.
4) The deck must be fully cast-in-place and water cured.
5) The deck shall be of uniform depth, except for haunches at girder flanges and other local thickening.
6) The ratio of effective length to design depth must not exceed 18.0 and must not be less than 6.0.
7) Core depth of the slab must not be less than 4.0 in.

8) The effective length shall not exceed 13.5 ft.
9) The minimum depth of the slab shall not be less than 7.0 in., excluding a sacrificial wearing surface where applicable.
10) There must be an overhang beyond the centerline of the outside girder of at least 5.0 times the depth of the slab; this condition is satisfied if the overhang is at least 3.0 times the depth of the slab and a structurally continuous concrete barrier is made composite with the overhang.
11) The specified 28-day strength of the deck concrete shall not be less than 4.0 ksi.
12) The deck must be made composite with the supporting structural components.

The commentary to the AASHTO LRFD specification indicates that item six in this list is the most important parameter concerning the resistance of concrete slabs to wheel loads. Exceeding this limit would make the deck more susceptible to cracking due to live loads.

The reinforcement requirements specified by the Empirical Method assume a deck thickness of 7.5 in. The minimum reinforcement requirements for the bottom layer are 0.27 in^2 of reinforcement per foot of slab width (in^2/ft) and 0.18 in^2/ft for the top layer. However, when a slab thickness other than 7.5 in. is used, these values appear to need to be adjusted. [6]

AASHTO Traditional Method

The traditional method is the more complex of the two design methods and leads to a more conservative design. It assumes the live load force effects are transmitted to the supporting girders by slab flexure. The resultant forces and stresses due to flexure are determined using the methods outlined in Article 4.6.2.1. [6] Many of the states using this method have developed design tables that place more reinforcement in the center of the bridge cross-section between the girders. The reinforcement in the secondary direction in the bottom of slabs is specified as a percentage of the positive moment reinforcement. [6]

Review of Literature

The TRIS and Compendex indexes provided papers, journal articles, and magazine articles which described new and more efficient design methods to control cracks in bridge decks. The suggestions for crack control were not always unanimous; some directly contradicted each other. Below is a summary of the pertinent sources and the ideas they presented.

Empirical Design Method

Csagoly and Lybas examined the main load-carrying mechanism in concrete bridge decks and confirmed that internal arching, not elastic plate bending, is responsible for the bulk of a bridge deck's load-carrying capacity once cracking occurs. (7) These findings verify ideas presented by the Canadian Highway Bridge Design Code in 1979, as well as the empirical design method offered in the AASHTO Code in 1992. (1, 3)

In a separate paper, Csagoly examined the amount of reinforcement needed to adequately control cracks in a prototype model of a thin concrete bridge deck. He found that if the bridge deck meets certain geometrical and structural criteria set forth in the Ontario Highway Bridge Design Code, then an isotropic reinforcement ratio of 0.3 percent satisfies both serviceability (as pertaining to crack control) and ultimate limit states requirements of the Ontario Bridge Code. (8) More specifically Csagoly examined both punching shear and overall vehicle weight effects for the ultimate limit state and found only hairline cracks for service live loads. Since these cracks did not open up during his testing, the reinforcement ratio of 0.3 percent was accepted. The current ACI temperature and shrinkage reinforcement requirements require a 0.3 percent reinforcement ratio when the length between movement joints is 30 ft. or less. Fang's finite element models agree that using an isotropic reinforcement ratio of 0.3 percent is adequate for crack control in bridge decks and he recommends not completing any additional checks pertaining to crack control as long as the following AASHTO empirical method criteria are satisfied: girder spacing less than 12.1 ft, span length-to-thickness ratio less than 15, deck thickness of at least 9.0 in., maximum bar spacing of 12 in., and maximum diaphragm spacing of 26 feet. (9)

Sabnis found the empirical method to be more resistant to cracking than the traditional AASHTO method. (10) Researchers from the Michigan and New York transportation departments have investigated the adequacy of the empirical method and have recommended using it in all situations where the deck falls within AASHTO's empirical bridge deck guidelines.(7, 8, 9) Others such as Barth, Blackman, Frosch, and Radabaugh disagree, saying that a reinforcement ratio of 0.6 percent is necessary for adequate crack control based upon full-scale tests and a review of previously constructed bridge decks which utilized AASHTO's empirical bridge deck design method. (10, 11) Based on their full-scale tests these researchers found that decks with a 0.6 percent reinforcement ratio most consistently resisted significant cracking. Our survey of state deck design requirements indicates that most states – even those using AASHTO's empirical method – provide a deck reinforcement ratio of approximately 0.6 percent.

Transverse Cracking

We next looked at factors that affect transverse cracking and remedies to control cracking. Saadeghvaziri and Hadidi developed finite element models that indicated that the ratio of girder to deck stiffness is the most important factor for controlling deck cracking. (11) They would minimize this ratio by increasing the deck thickness, decreasing girder spacing, and reducing the girder moment of inertia.(12, 13) Many others also agreed that increasing the deck thickness reduces transverse cracking and increases strength. (12) Krauss suggests that bridge decks be no less than 8.0 in. thick.(13) Barker, Krauss, McDonald and Rogalla conducted laboratory and field tests showing that increasing the deck stiffness significantly decreases the amount of transverse cracks in bridge decks. (15, 16)

Reinforcement cover is another factor affecting the probability of transverse cracks. Babaei and Fouladgar suggest using a minimum of 2.0 in. cover to reduce the deck's tendency to crack. (14) Other researchers examined how reinforcement bar size and spacing affect transverse deck cracks. Many investigators agree that using larger than No. 5 bars for reinforcement is not advisable since larger bars are usually spaced farther apart which results in larger transverse cracks. (18, 19, 20, 21, 22, 23) Krauss, Rogalla, Frosch and Blackman agree, saying that using more bars of smaller diameter will reduce crack width and crack frequency. (15, 4) They also point out that the alignment of bars must also be considered. Krauss and Rogalla state that when the top and bottom transverse bars align vertically, they form a weakened section within the concrete that is more susceptible to cracking. (15) Others have also suggested that altering the standard bar alignment by placing the top longitudinal bars above the top transverse bars could mitigate transverse deck cracking. [16]

Summary of Current Research

The research agrees that the best way to control transverse cracking is to increase the deck stiffness in relation to the girder stiffness. There is also a consensus that deck reinforcing bars should be No. 5 or smaller. However, there is some disagreement as to how much steel is required in bridge decks to control cracking. Some say a longitudinal and transverse reinforcement ratio of 0.3 percent is sufficient, while others suggest a minimum reinforcement ratio of 0.6 percent. Most states currently utilize a reinforcement ratio closer to 0.6 percent. Later in the report, Idaho's reinforcement ratio will be compared to other states' requirements.

Survey of State Bridge Deck Design Methods

Next, we investigated the methods each state department of transportation has used to design bridge decks and their design requirements. We began by searching through each state's bridge design manual for bridge deck design information. After examining the bridge deck design manuals, we contacted engineers from each transportation department's bridge design section to verify that we had recorded the appropriate bridge deck design method for that state. The results from our initial survey are shown below in Figure 1 and Table 1, which indicate that currently only 17 out of the 50 state DOT's, including Idaho, are using or occasionally using the AASHTO LRFD Empirical Method in their bridge deck designs.

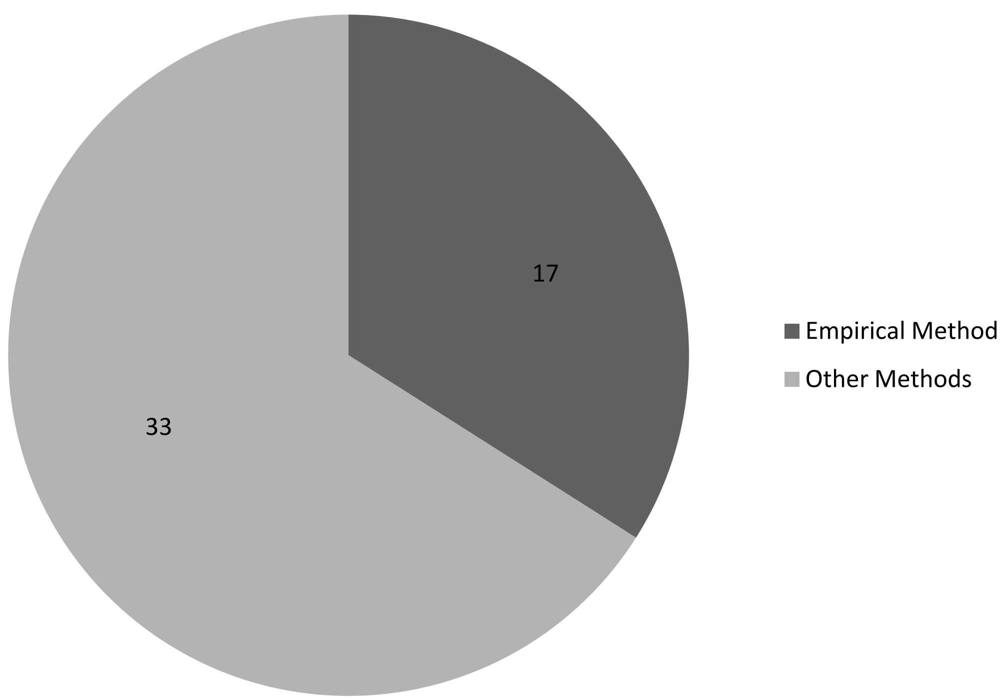

Figure 1. Survey Results - DOTs' Preferred Bridge Deck Design Methodology

Table 1. Bridge Deck Design Method Survey Results

State	Uses LRFD Empirical Method	Method
Alabama	No	Custom Design Tables
Alaska	No	Equivalent Strip Method
Arizona	No	Elastic Method (4.6.2.1)
Arkansas	No	Traditional Method (9.7.3)
California	No	Traditional Method (9.7.3)
Colorado	No	Design Charts
Connecticut	Yes	Empirical Method (9.7.2)
Delaware	No	Elastic Method (4.6.2.1)
Florida	Yes	Empirical Method & Traditional Method
Georgia	No	Service Load Design
Hawaii	No	Traditional Method (9.7.3)
Idaho	Yes	Empirical Method (9.7.2)
Illinois	No	Traditional Method (9.7.3)
Indiana	Yes	Empirical Method (9.7.2)
Iowa	Yes	Empirical Method & Traditional Method
Kansas	No	Traditional Method (9.7.3)
Kentucky	No	Traditional Method (9.7.3)
Louisiana	Yes-Rarely	Empirical Method & Traditional Method
Maine	No	Precast Panels
Maryland	No	Traditional Method (9.7.3)
Massachusetts	No	Traditional Method (9.7.3)
Michigan	Yes-Rarely	Empirical Method (9.7.3)
Minnesota	No	Traditional Method (9.7.3)
Mississippi	No	LRFD Strip Method
Missouri	No	Traditional Method (9.7.3)
Montana	Yes-Rarely	Traditional Method (9.7.3)
Nebraska	Yes	Empirical Method (9.7.2)
Nevada	No	Updating Methods Now
New Hampshire	No	LRFD Non-Empirical
New Jersey	Yes-Rarely	Traditional Method (9.7.3)
New Mexico	No	Custom Design Tables
New York	Yes-Rarely	Empirical Under Certain Conditions
North Carolina	No	Traditional Method (9.7.3)
North Dakota	No	Traditional Method (9.7.3)
Ohio	No	Traditional Method (9.7.3)
Oklahoma	Yes-Rarely	Traditional Method (9.7.3)
Oregon	No	Traditional Method (9.7.3)
Pennsylvania	No	Traditional Method (9.7.3) Primarily
Rhode Island	No	Elastic Method (4.6.2.1)
South Carolina	No	Traditional Method (9.7.3)
South Dakota	No	Traditional Method (9.7.3)
Tennessee	No	Elastic Method (4.6.2.1)
Texas	Yes-Rarely	Traditional Method (9.7.3)
Utah	Yes	Empirical Method & Traditional Method
Vermont	Yes-Rarely	Traditional Method (9.7.3)
Virginia	No	Traditional Method (9.7.3)
Washington	No	Traditional Method (9.7.3)
West Virginia	Yes	Empirical Method & Traditional Method
Wisconsin	Yes-Rarely	Empirical Method & Traditional Method
Wyoming	No	Traditional Method (9.7.3)

*The numbers in the preferred method column refer to the section of the AASHTO LRFD code describing that method.

Typical Bridge Deck Designs

We designed a standardized bridge deck using the procedures specified by each state to illustrate the differences between the various specifications. Selections from those designs are presented below. The standardized prototype bridge used for these comparisons was a 65 ft long, simply supported bridge with 11.5 ft girder spacing. A transverse section through the bridge is shown in Figure 2 with the bridge deck design based upon ITD's bridge design manual. The girder length and spacing are the same on all of the drawings represented in this report.

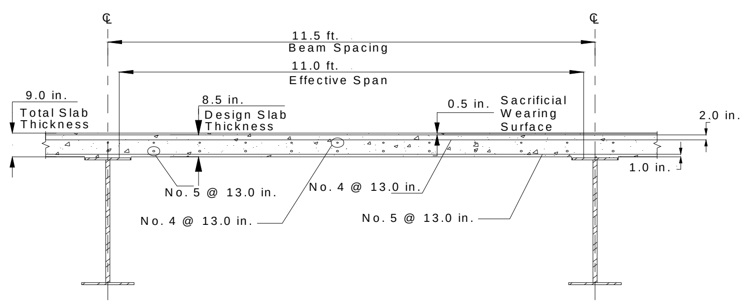

Figure 2. Typical Bridge Section

An enlarged detail of this section is shown in Figure 3. This design used No. 4 top bars at 13 in. spacing and No. 5 bottom bars at 13 in. spacing.

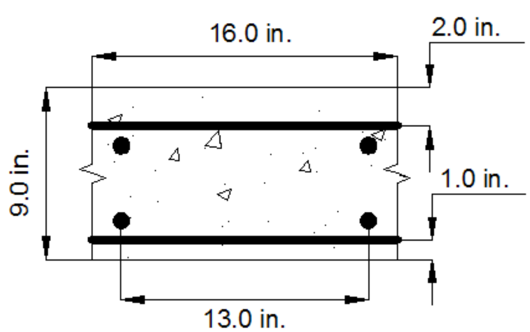

Figure 3. Idaho Bridge Deck Design – Transverse Section

The bridge deck designs for other DOTs are shown in Table 2, which is grouped by DOTs using the empirical method followed by those that do not use the empirical method. Not all states' information was available because we had difficulties contacting the designers or they failed to reply. Table 2 includes designs from ITD, 31 other states, and Canada that we were able to verify.

Table 2. Bridge Deck Designs for Standard Prototype Bridge*

DOT	Uses LRFD Empirical Method	Girder Spacing (ft)	Total Deck Thick (in.)	Offsets Top and Bottom Bars	Upper Bars Trans. size@spacing	Upper Bars Long. size@spacing	Lower Bars Trans. size@spacing	Lower Bars Long. size@spacing
Canada	Yes	11.5	8.0	Yes	No. 5@11.8	No. 5@11.8	No. 5@11.8	No. 5@11.8
Connecticut	Yes	11.5	8.5	Yes	No. 4@12	No. 4@12	No. 5@12	No. 5@12
Florida	Yes	11.5	8.0	Yes	No. 5@12	No. 5@12	No. 5@12	No. 5@12
Idaho	Yes	11.5	9.0	No	No. 4@13	No. 4@13	No. 5@13	No. 5@13
Indiana	Yes	11.5	8.0	No	No. 4@12	No. 4@12	No. 5@12	No. 5@12
Michigan	Yes	11.5	9.0	No	No. 4@13	No. 4@13	No. 5@13	No. 5@13
Nebraska	Yes	11.5	8.5	Yes	No. 4@12	No. 4@12	No. 5@12	No. 5@12
New Jersey	Yes	11.5	10.0	Yes	No. 6@9	No. 5@10	No. 6@9	No. 5@10
New York	Yes	11.0	9.5	Yes	No. 4@8	No. 4@8	No. 4@8	No. 4@8
Oklahoma	Yes	11.5	8.0	Yes	No. 4@12	No. 4@12	No. 5@12	No. 5@12
Texas	Yes	11.5	8.5	No	No. 4@13	No. 4@13	No. 5@13	No. 5@13
Utah	Yes	11.5	8.0	Yes	No. 4@12	No. 4@12	No. 5@12	No. 5@12
Vermont	Yes	11.5	8.5	No	No. 5@12	No. 5@12	No. 5@12	No. 5@12
West Virginia	Yes	11.5	8.0	Yes	No. 5@6	No. 5@6	No. 5@6	No. 5@6
Arizona	No	11.5	9.5	Yes	No. 5@5	No. 5@9	No. 5@6.5	No. 5@9
Colorado	No	11.5	8.75	Yes	No. 5@5	No. 5@5	No. 5@5	No. 5@6.5
Georgia	No	11.5	8.5	No	No. 5@5	No. 4@ 8.5 & 5	No. 5@5	No. 4@ 8.5 & 5
Kansas	No	11.5	8.5	Yes	No. 5@5	No. 5@5	No. 5@5	No. 5@5
Louisiana	No	11.5	8.0	Yes	No. 6@5.5	No. 4@6.5	No. 6@5.5	No. 4@ 4 & 6.5
Maine	No	11.5	10.5	Yes	No. 5@6	No. 5@15	No. 5@6	No. 5@8
Maryland	No	11.5	10.0	Yes	No. 5@5	No. 5@17.25	No. 5@5	No. 5@ 11.5 & 10
Massachusetts	No	11.5	9.5	No	No. 5@5	No. 4@ 8&4.5	No. 5@5	No. 4@ 8 & 4.5
Minnesota	No	11.5	9.5	Yes	No. 5@5	No. 4@18	No. 5@7	No. 4@6
Montana	No	11.5	8.5	Yes	No. 6@7	No. 4@17.5	No. 6@7	No. 4@ 5 & 7.5
Nevada	No	11.5	8.5	Yes	No. 6@6	No. 6@6	No. 5@6	No. 5@7
New Mexico	No	11.5	10.0	Yes	No. 5@6	No. 4@6	No. 5@6	No. 4@ 12 & 6
Ohio	No	11.5	9.5	No	No. 5@5	No. 4@9.5	No. 5@5	No. 5@10
Oregon	No	11.5	9.25	No	No. 5@5	No. 5@7	No. 5@5	No. 5@7
South Carolina	No	11.5	8.5	Yes	No. 5@5	No. 5@9	No. 5@6.5	No. 5@9
Washington	No	11.5	8.0	Yes	No. 5@6	No. 5@6	No. 5@6	No. 5@6
Wisconsin	No	11.5	9.5	Yes	No. 5@6.5	No. 4@7	No. 5@6.5	No. 4@7
Wyoming	No	11.5	8.5	Yes	No. 6@12	No. 6@7	No. 5@12	No. 5@7

*We did not receive complete responses from all states. The states included in this table are those that provided enough information to complete a deck design based on their standards.

The results of this design study indicate that very few bridge deck designs were identical to Idaho's design. Of the seventeen states that use the Empirical Method, only Connecticut, Indiana, Michigan, Nebraska, Oklahoma, Texas, and Utah's designs were similar to Idaho's design. The designs from Michigan, Texas, and Idaho used identical amounts of reinforcement. The designs from Connecticut, Indiana, Nebraska, Oklahoma, and Utah used the same sizes of reinforcement as Michigan, Texas, and Idaho, but with slightly smaller bar spacing, e.g. 12-inch bar spacing rather than 13-inch bar spacing. Comparing Idaho's design to the designs from states that did not use the empirical method shows even greater variations with some states requiring three or even four times as much steel for the same deck area.

Example deck designs from two states adjacent to Idaho – Washington and Oregon – are shown in Figure 4. Neither of these two states uses the empirical deck design method. Note that both designs utilize much smaller bar spacing than the Idaho design, the top and bottom bars in the Washington design are offset, and the top longitudinal bars in the Oregon design are above the top transverse bars.

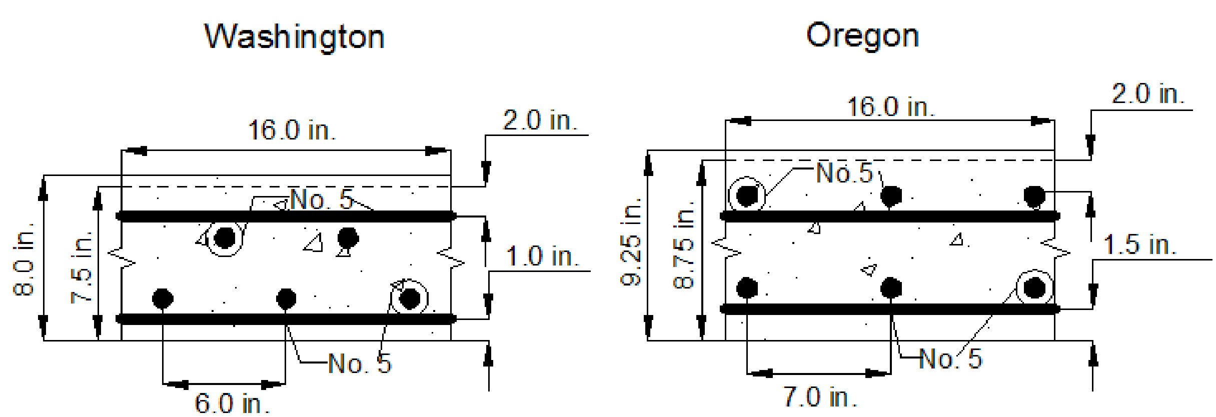

Figure 4. Neighboring States Bridge Deck Design - Transverse Sections

Offsetting the top bars from the bottom bars reduces the tendency for cracks to occur during the consolidation of the concrete. Oregon DOT and New York DOT do not offset the top bars from the bottom bars, but they do specify that the longitudinal bars be placed above the transverse bars in both the top and bottoms layers in an attempt to minimize longitudinal shrinkage cracks.

The Canadian Highway Bridge Design Code (CHBDC), the successor to the Ontario Bridge Code and the basis for the AASHTO LRFD Empirical Bridge Deck Design Method¸ is used throughout Canada. The bridge deck design using the CHBDC is shown in Figure 5. Note that this design uses the same bars sizes and spacing for both the top and bottom layers of reinforcement. Also, this design offsets the top and bottom layers of reinforcement which is similar to most other states. Of the states which use the AASHTO Empirical Bridge Deck Design Method, Florida and Vermont use designs which are very similar to the CHBDC design. In order to more easily provide adequate interior cover between the top longitudinal reinforcement and the bottom longitudinal reinforcement, some of the departments of transportation that use the empirical design method have chosen to use thicker slabs than the CHBDC design. New Jersey and British Columbia both utilize a minimum deck thickness of 10 in. which is 2 in. thicker than the standard CHBDC deck design, and have increased the amount of reinforcement to maintain a reinforcement ratio of 0.60 percent.

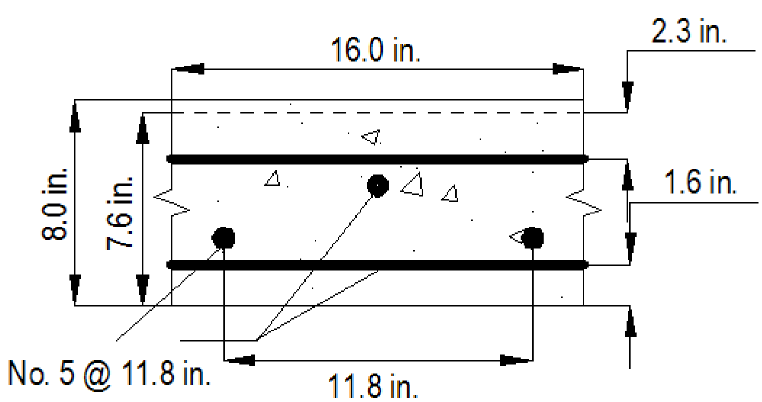

Figure 5. CHBDC Bridge Deck Design - Transverse Section

The Florida and the New Jersey deck designs are shown in Figure 6. Both of these designs require that the top layers of reinforcement be offset from the bottom layers.

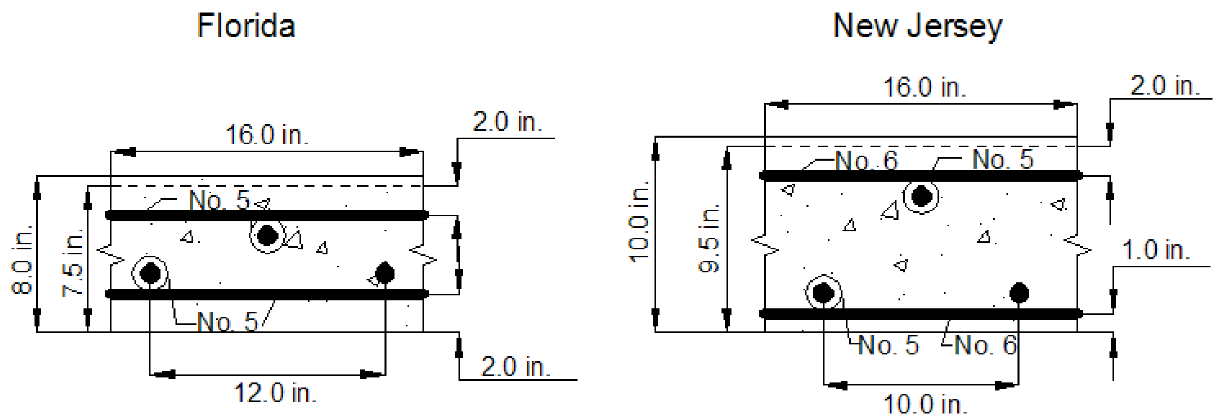

Figure 6. Bridge Decks Designed Using LRFD Empirical Method - Transverse Sections

Two bridge deck designs from states that do not use the empirical method are shown in Figure 7. Both of these designs use considerably more steel for a given deck area than the Idaho design. In addition, these designs also require that the top layers of reinforcement be offset from the bottom layers.

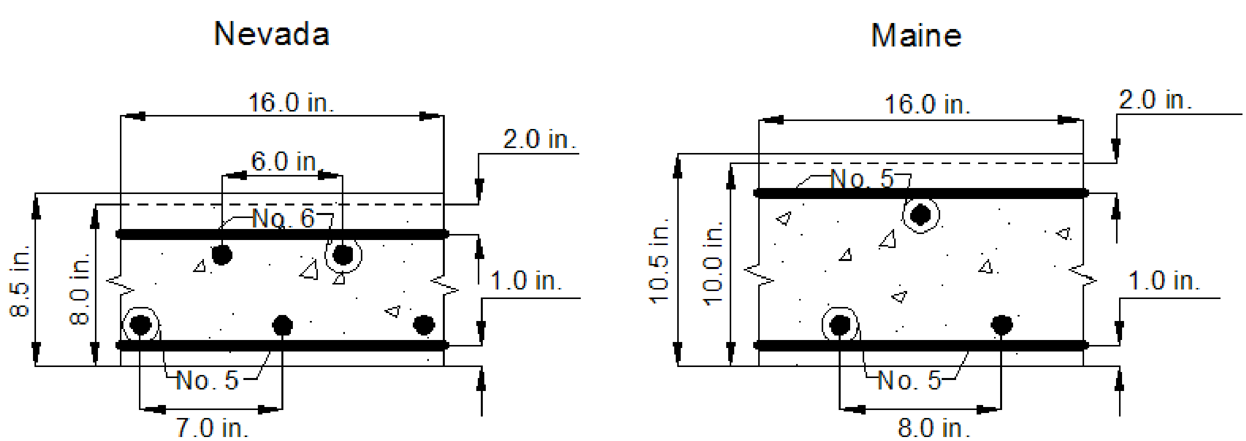

Figure 7. Bridge Deck Designs Using Traditional Methods – Transverse Sections

Crack Control Methods Survey Results From States that Responded

Some states that responded to our email survey provided additional information that is relevant to this report. Those additional comments are as follows:

New Mexico:

- To reduce the severity of shrinkage cracking in the deck slabs of continuous beam bridges, they place deck slabs sequentially. The sequence specified in the plans requires that positive moment areas be placed first and that negative moment areas be placed last. NMDOT has used thinner decks in a few instances over the years.
- They have found that thinner decks do not have the long-term durability of the standard deck slab details.
- To reduce transverse cracking in newly constructed bridge decks, they offset the transverse bars in the top and bottom mats of deck slab reinforcement by ½ of the bar spacing.

Washington State:

- The minimum slab thickness is established in order to ensure that overloads on the bridge will not result in premature slab cracking. Their minimum deck thickness is 7.5 in. [17]

Montana:

- They suggest that transverse post tensioning minimizes cracking.
- They use smaller diameter bars for the same steel cross sectional area to provide better crack-size control. [18]

Oregon:

- ODOT does not use the empirical design method for deck reinforcing steel. They specify that excessive deck cracking, apparently due to under reinforcement, precludes the use of this method until further notice.
- The preferred orientation of the top mat of deck steel has the longitudinal bars on top. This orientation places the longitudinal bars closer to the surface thereby reducing the size of deck shrinkage cracks. [19]

Nevada:

- The top and bottom transverse reinforcing steel is offset, preferable at half the spacing, so that the top mat is not placed directly above the bottom mat. This requirement is intended to reduce the potential for transverse deck cracking due to concrete consolidation. [20]

Nebraska:

- They have not seen any increased cracking in their bridge decks with the use of the empirical method. They still do see some cracking, but believe it is due to other factors (composite design, pouring sequence, type of cement, curing, temperature at the time of pour etc.) rather than the method of design. [21]

New York:

- Since they started using isotropic deck reinforcement they did not notice an increase or decrease in transverse cracking. Since transverse deck cracking is a nationwide problem, they attribute that to many other causes beside the design method used. [3]

Florida:

- To minimize shrinkage and deflection cracking in cast-in-place decks, they designate a deck casting sequence for continuous flat slab and beam/girder superstructures and simple span beam/girder superstructures with continuous decks. The direction of each deck pour is specified to minimize cracking in the freshly poured concrete and previously cast sections of deck. The sequence should result in construction joints spaced at locations of the points of contra-flexure, unless limited by the size of the pour. [22]

Recommendations: Deck Reinforcing

Our research determined that there is a wide variation in the methods that states currently use to design their bridge decks. Our literature search and surveys revealed that 17 states make some use of the AASHTO LRFD empirical deck design method, while 33 states continue to rely on some form of AASHTO LRFD traditional deck design.

For those states using traditional methods, a key issue appears to be the application of provisions of AASHTO LRFD Article 5.7.3.4 Control of Cracking by Distribution of Reinforcement for the traditional design method. While some states appear to closely follow the crack control provisions in Article 5.7.3.4, other states rely on standardized historical amounts and spacing of steel reinforcement. In addition, the provisions of this Article and the amount and spacing of reinforcement require a larger reinforcement ratio and closer bar spacing than the empirical deck design method. Trial designs included in this research also confirm this inconsistency, which can be seen when comparing designs from Florida and Nevada, noting the large discrepancies in their reinforcement ratios.

Research by Csagoly and others considered crack control under service live loads for empirical deck design. [(7, 8)] Reportedly some states feel the amounts of steel provided by the empirical method are insufficient to control this type of cracking. On the other hand, some states feel the provisions of Article 5.7.3.4 are excessive.

Research by Frosh indicates that for empirical design a closer spacing and minimum bar size is necessary to control cracking due to shrinkage and drying. [(4, 29)]

Based on our literature review and survey, Idaho may want to consider altering its bridge deck design requirements to minimize cracking associated with deck design, thereby increasing the cost-effectiveness and durability of its bridge deck designs.

It appears the 0.3 percent reinforcement ratio prescribed by the AASHTO empirical deck design procedure is adequate for strength requirements; however it is smaller than the 0.6 percent reinforcement ratio recommended by other researchers to control cracking. [4, 23)] The AASHTO empirical deck design method specifies a minimum deck thickness of 7.0 in. and a minimum deck thickness-to-span ratio of 1:20. These requirements affect the deck-to-girder stiffness ratio. Many researchers agree that increasing this ratio is the primary method to control cracking.[(11)]

We believe the following recommendations will help the Idaho Transportation Department control concrete bridge deck cracking more effectively.

- Researchers and an analysis of states current practices agree that the reinforcement ratios for the deck should be increased by limiting the top and bottom, longitudinal and transverse bar spacing to a maximum of 6 in. using No. 4 bars. ITD currently utilizes a 13-in. bar spacing in all directions with No. 4 bars. For an 8 in. thick deck, this amounts to an approximate reinforcement ratio of 0.18 percent in each direction. Although this provides sufficient strength in accordance with the empirical design method, many researchers agree that a low reinforcement ratio, such as Idaho's, will result in shrinkage and drying cracks.(23, 4) Reducing the spacing to six inches will reduce shrinkage and drying cracks, while putting the reinforcement ratio on par with most of the states that we surveyed which specify a minimum reinforcement ratio around 0.6 percent. The Indiana Department of Transportation conducted full scale tests and found that a 6 in. bar spacing will increase the frequency of the cracks but greatly decrease the cracks' width to approximately 16 mils.(13, 4) Most states' bar spacing requirements conform to these recommendations; however our survey did not investigate the reasons for their spacing requirements.

- ITD currently utilizes an 8 in. minimum bridge deck thickness.[1] Increasing the minimum deck thickness to 8.5 in. would put Idaho on par with the average deck thickness used by the majority of other states as well as slightly increase their deck stiffness. AASHTO currently requires a minimum deck thickness of 7 in. However many researchers agree that this will provide insufficient deck stiffness for crack control. (12) Our review of literature indicates that reducing the girder-to-deck stiffness ratio by increasing the deck stiffness is the most effective method to limit deck cracking.(11)

- The top and bottom bars should not be placed in a vertical plane that may encourage cracking. Rather, bars should be offset to enhance concrete consolidation.(15, 16) This is practiced by many state agencies; currently 33 of the 47 responding states offset their top and bottom bars.

Adopting these recommendations would allow ITD to use AASHTO's empirical deck design method with the same bar sizes and spacing in the top and bottom layers while providing greater crack control. These recommended changes would align ITD's design practice with the majority of other states' practices.

[1] Idaho's deck design for the standard prototype bridge in Table 2 is 8.5 in. thick to satisfy deck-to-girder stiffness ratio requirements.

Summary and Conclusions

The goal of this report was to address ITD's inquiries regarding the effectiveness of the AASHTO empirical method of bridge deck design with regards to crack control. We examined the causes and types of bridge deck cracking which enabled us to narrow our research towards transverse cracking, which is the most common type of cracking in bridge decks.
We reviewed the two current methods of bridge deck design: the empirical method and traditional method. The traditional method is the more conservative of the two. Although the empirical method has many requirements for use, many researchers agreed that the empirical method is not sufficient for crack control. In addition to the rebar spacing and size addressed in the empirical and traditional methods, most researchers agree that the ratio of deck to girder stiffness significantly affects deck cracking.

We also conducted a survey to determine the bridge deck design methods used by other states. Most states use a larger rebar size at a smaller spacing than is required by ITD. These findings led us to recommend increasing the bar size and decreasing the bar spacing as well as using a thicker deck and staggering the bars.

Increasing the amount and size of reinforcement for a given bridge should decrease bridge deck cracking, which will ultimately reduce bridge maintenance costs and extend bridge life. It will also reduce the severity of cracking, resulting in a finer mesh of cracks which are closer together and much smaller in width.

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APPENDIX – Bridge Deck Designs

Idaho Transportation Department

Florida Department of Transportation

Maine Department of Transportation

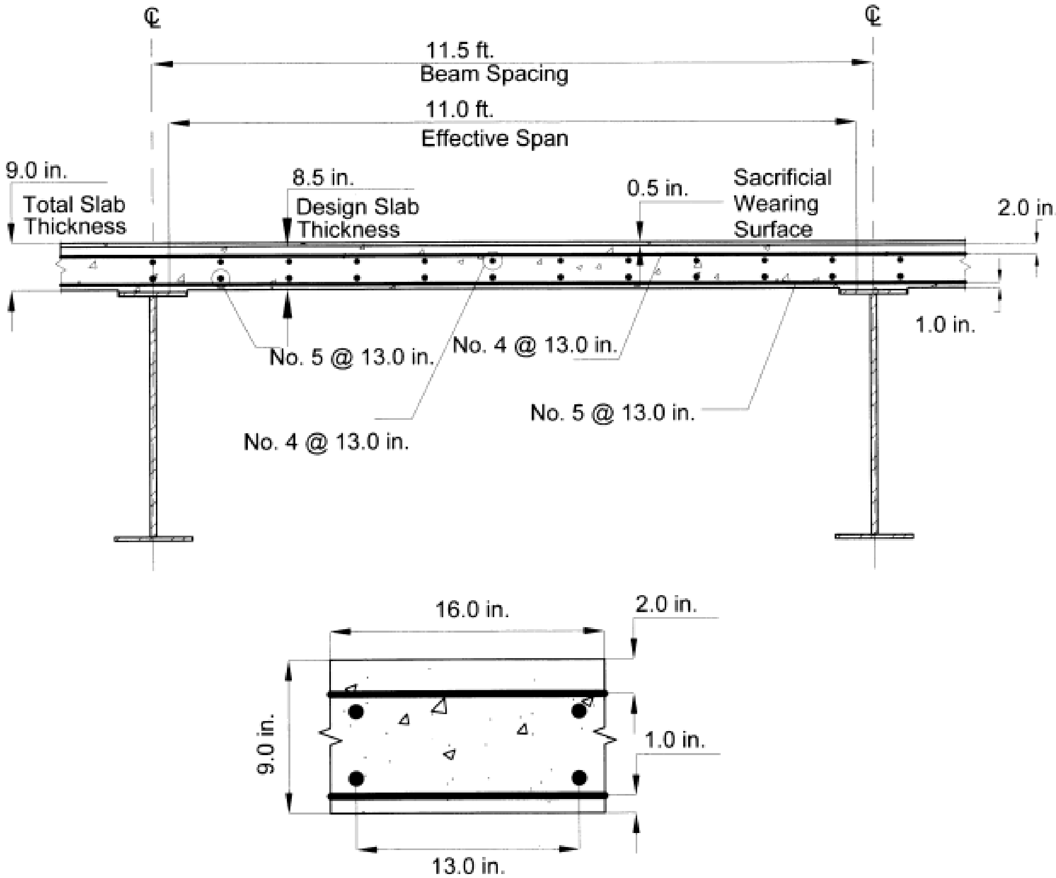
New Jersey Department of Transportation

Nevada Department of Transportation

Oregon Department of Transportation

Washington Department of Transportation

Canadian Highway Bridge Design Code



Deck Properties

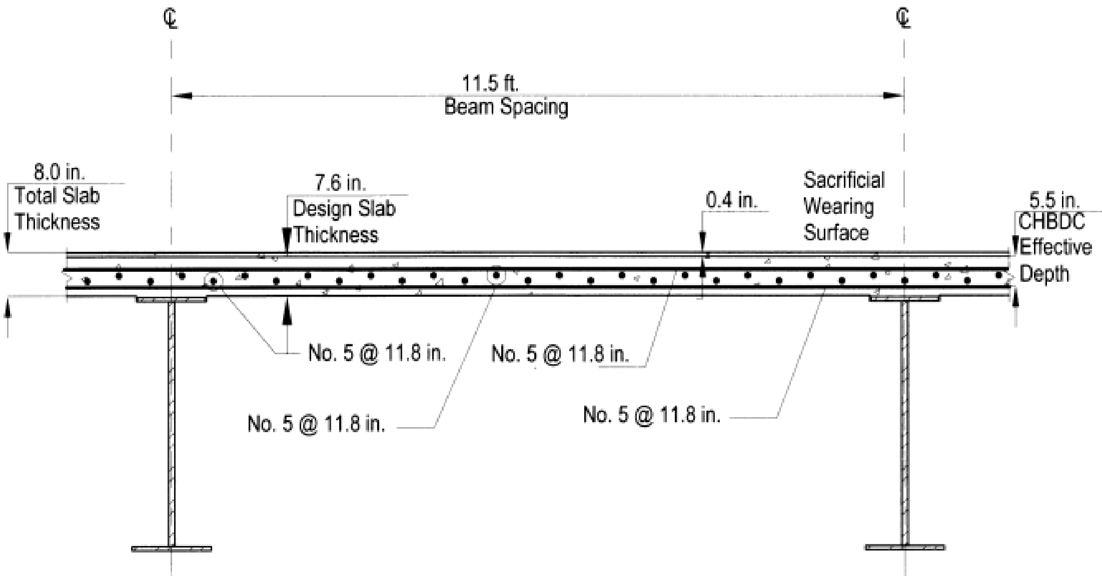
1.) Beam Spacing = 11.5 ft., Effective Span = 11.0 ft., Top Flange Width = 12.8 in.

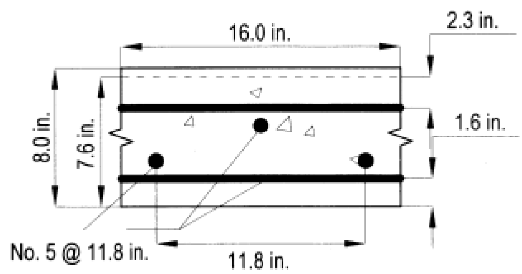
2.) Reinforcing Bars (Area/Unit Width)
Top Longitudinal Reinforcement = .185 in²/ft, Bottom Longitudinal Reinforcement = .287 in²/ft,
Top Transverse Reinforcement = .185 in²/ft, Bottom Transverse Reinforcement = .287 in²/ft
Meeting all ITD's Empirical Deck Design Method Reinforcement Requirements.

3.) Top Mat Cover (Excluding Sacrificial Wearing Surface) = 2.0 in., Bottom Mat Cover = 1.0 in., Exterior Cover = 2.0 in.

4.) ITD Empirical Methodology for a 65 ft. Long Bridge, with Steel Girders Spaced at 11.5 ft.

Idaho Transportation Department	ITD EMPIRICAL DECK DESIGN 65 ft. LONG BRIDGE, NO SKEW STEEL BEAMS, 11.5 ft. BEAM SPAC.	DATE OF ISSUE 6-18-08 DRAWN BY CRAIG SHINER DRAWING NUMBER 1.2





Deck Properties

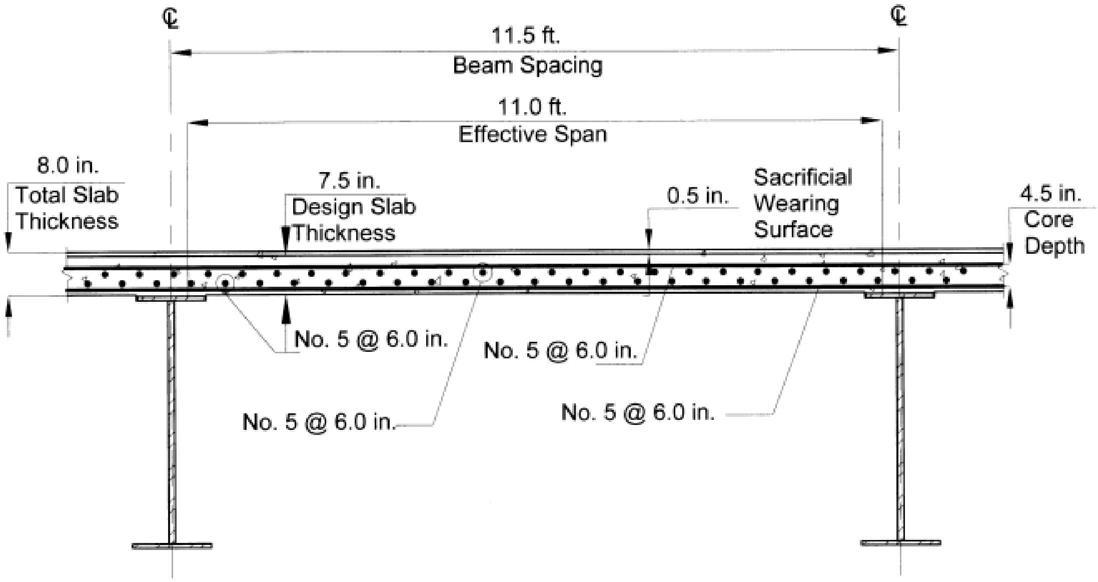
1.) Beam Spacing = 11.5 ft., Effective Depth = 5.5 in., Top Flange Width = 12.8 in.

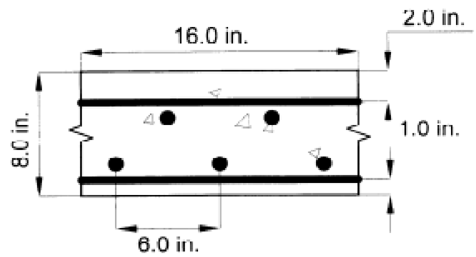
2.) Reinforcing Bars (Area/Unit Width)
Top Longitudinal Reinforcement = 0.315 in²/ft, Bottom Longitudinal Reinforcement = 0.315 in²/ft,
Top Transverse Reinforcement = 0.315 in²/ft, Bottom Transverse Reinforcement = 0.315 in²/ft
Meeting all CHBDC's Empirical Deck Design Method Reinforcement Requirements.

3.) Top Mat Cover (Excluding Sacrificial Wearing Surface) = 2.3 in., Bottom Mat Cover = 1.6 in., Core Depth = 2.2 in.

4.) Empirical Methodology for a 65 ft. long Bridge, with Steel Girders Spaced at 11.5 ft.

Canadian Highway Bridge Design Code	CHBDC EMPIRICAL DECK DESIGN 65 ft. LONG BRIDGE, NO SKEW STEEL, 11.5 ft. BEAM SPACING	DATE OF ISSUE 7-1-08 DRAWN BY CRAIG SHINER DRAWING NUMBER 2.2





Deck Properties

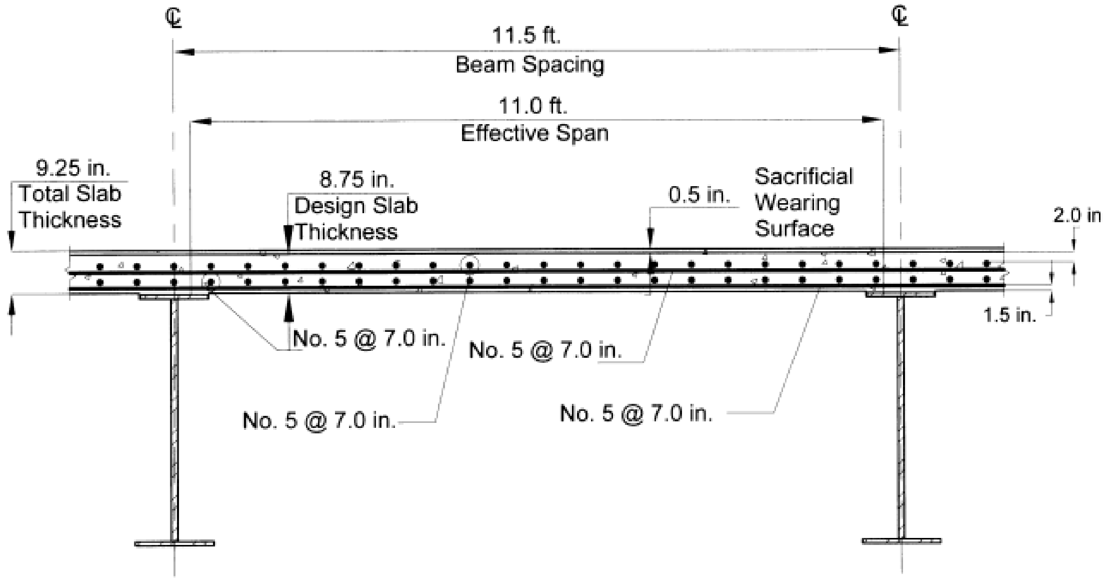
1.) Beam Spacing = 11.5 ft., Effective Span= 11.0 ft., Top Flange Width = 12.8 in.

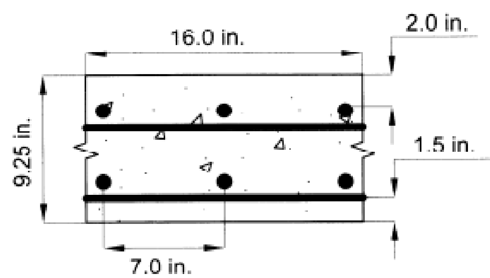
2.) Reinforcing Bars (Area/Unit Width)
Top Longitudinal Reinforcement = 0.573 in^2/ft, Bottom Longitudinal Reinforcement = 0.573 in^2/ft,
Top Transverse Reinforcement = 0.573 in^2/ft, Bottom Transverse Reinforcement = 0.573 in^2/ft
Meeting all WSDOT's Traditional Deck Design Method Reinforcement Requirements.

3.) Top Mat Cover (Excluding Sacrificial Wearing Surface) = 2.0 in., Bottom Mat Cover = 1.0 in., Core Depth =4.5 in.

4.) Traditional Methodology for a 65 ft. long Bridge, with Steel Girders Spaced at 11.5 ft.

Washington State Department of Transportation	WSDOT TRADITIONAL DECK DESIGN 65 ft. LONG BRIDGE, NO SKEW STEEL, 11.5 ft. BEAM SPACING	DATE OF ISSUE 7-7-08 DRAWN BY CRAIG SHINER DRAWING NUMBER 3.2





Deck Properties

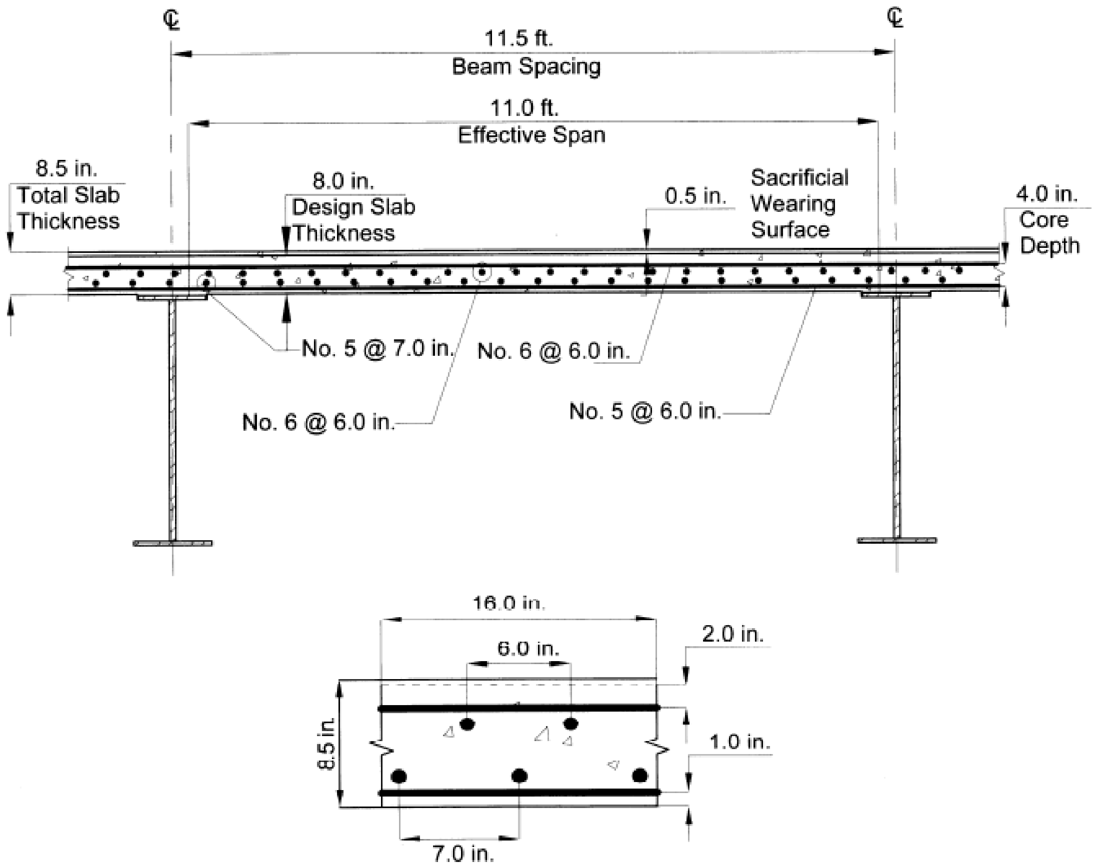
1.) Beam Spacing = 11.5 ft., Effective Span= 11.0 ft., Top Flange Width = 12.8 in.

2.) Reinforcing Bars (Area/Unit Width)
Top Longitudinal Reinforcement = 0.532 in²/ft, Bottom Longitudinal Reinforcement = 0.532 in²/ft,
Top Transverse Reinforcement = 0.743 in²/ft, Bottom Transverse Reinforcement = 0.743 in²/ft
Meeting all ODOT's Traditional Deck Design Method Reinforcement Requirements.

3.) Top Mat Cover (Excluding Sacrificial Wearing Surface) = 2.0 in., Bottom Mat Cover = 1.5 in.

4.) Traditional Methodology for a 65 ft. long Bridge, with Steel Girders Spaced at 11.5 ft.

Oregon Department of Transportation	ODOT TRADITIONAL DECK DESIGN 65 ft. LONG BRIDGE, NO SKEW STEEL, 11.5 ft. BEAM SPACING	DATE OF ISSUE 7-8-08 DRAWN BY CRAIG SHINER DRAWING NUMBER 4.2



Deck Properties

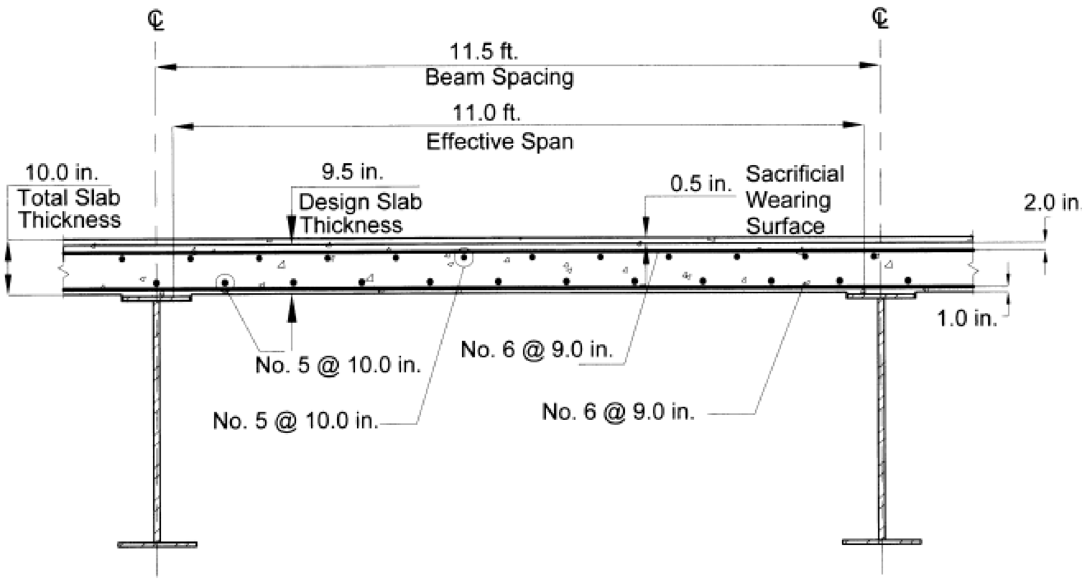
1.) Beam Spacing = 11.5 ft., Effective Span= 11.0 ft., Top Flange Width = 12.8 in.

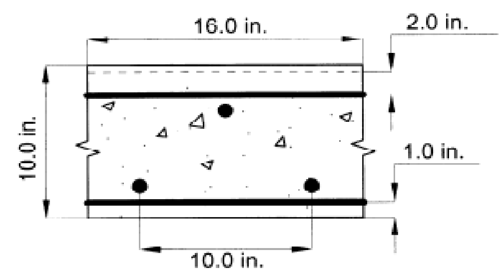
2.) Reinforcing Bars (Area/Unit Width)
Top Longitudinal Reinforcement = 0.88 in²/ft, Bottom Longitudinal Reinforcement = 0.530 in²/ft,
Top Transverse Reinforcement = 0.88 in²/ft, Bottom Transverse Reinforcement =0.62 in²/ft
Meeting all NDOT's Traditional Deck Design Method Reinforcement Requirements.

3.) Top Mat Cover (Excluding Sacrificial Wearing Surface) = 2.0 in., Bottom Mat Cover = 1.5 in., Core Depth = 4 in.

4.) Strip Method for a 65 ft. long Bridge, with Steel Girders Spaced at 11.5 ft.

Nevada Department of Transportation	NDOT STRIP METHOD DECK DESIGN 65 ft. LONG BRIDGE, NO SKEW STEEL, 11.5 ft. BEAM SPACING	DATE OF ISSUE 7.16.08 DRAWN BY CRAIG SHINER DRAWING NUMBER 6.2





Deck Properties

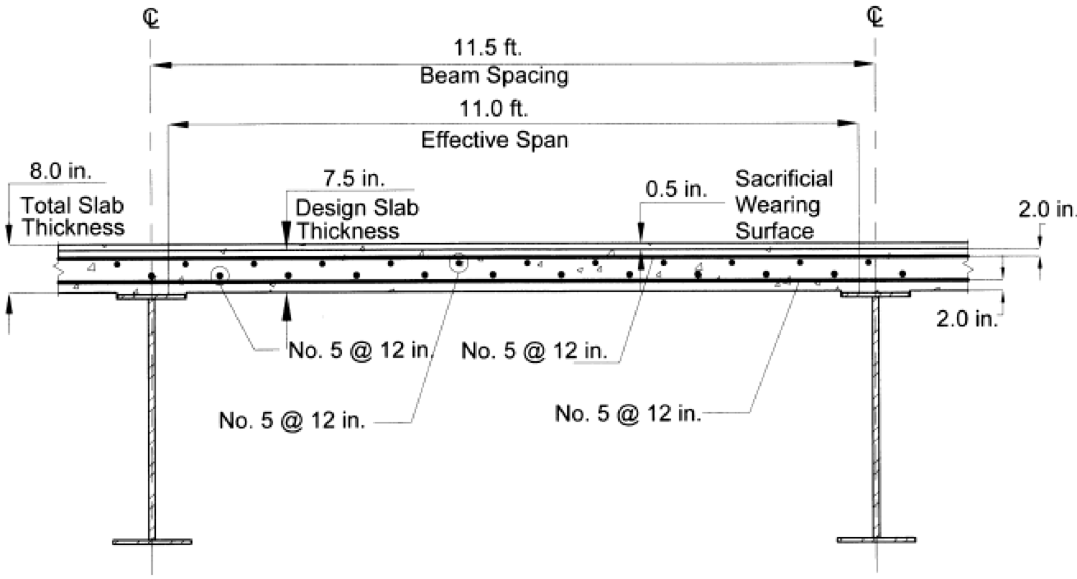
1.) Beam Spacing = 11.5 ft., Effective Span = 11.0 ft., Top Flange Width = 12.8 in.

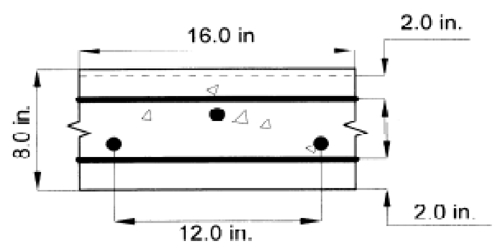
2.) Reinforcing Bars (Area/Unit Width)
Top Longitudinal Reinforcement = .372 in²/ft, Bottom Longitudinal Reinforcement = .372 in²/ft,
Top Transverse Reinforcement = .587 in²/ft, Bottom Transverse Reinforcement = .587 in²/ft
Meeting all New Jersey's Empirical Deck Design Method Reinforcement Requirements.

3.) Top Mat Cover (Excluding Sacrificial Wearing Surface) = 2.0 in., Bottom Mat Cover = 1.0 in., Exterior Cover = 2.0 in.

4.) New Jersey Empirical Methodology for a65 ft. Long Bridge, with Steel Girders Spaced at11.5 ft.

New Jersey Department of Transportation	NJDOT EMPIRICAL DECK DESIGN 65 ft. LONG BRIDGE, NO SKEW STEEL BEAMS, 11.5 ft. BEAM SPAC.	DATE OF ISSUE 8-13-08 DRAWN BY CRAIG SHINER DRAWING NUMBER 13.2





Deck Properties

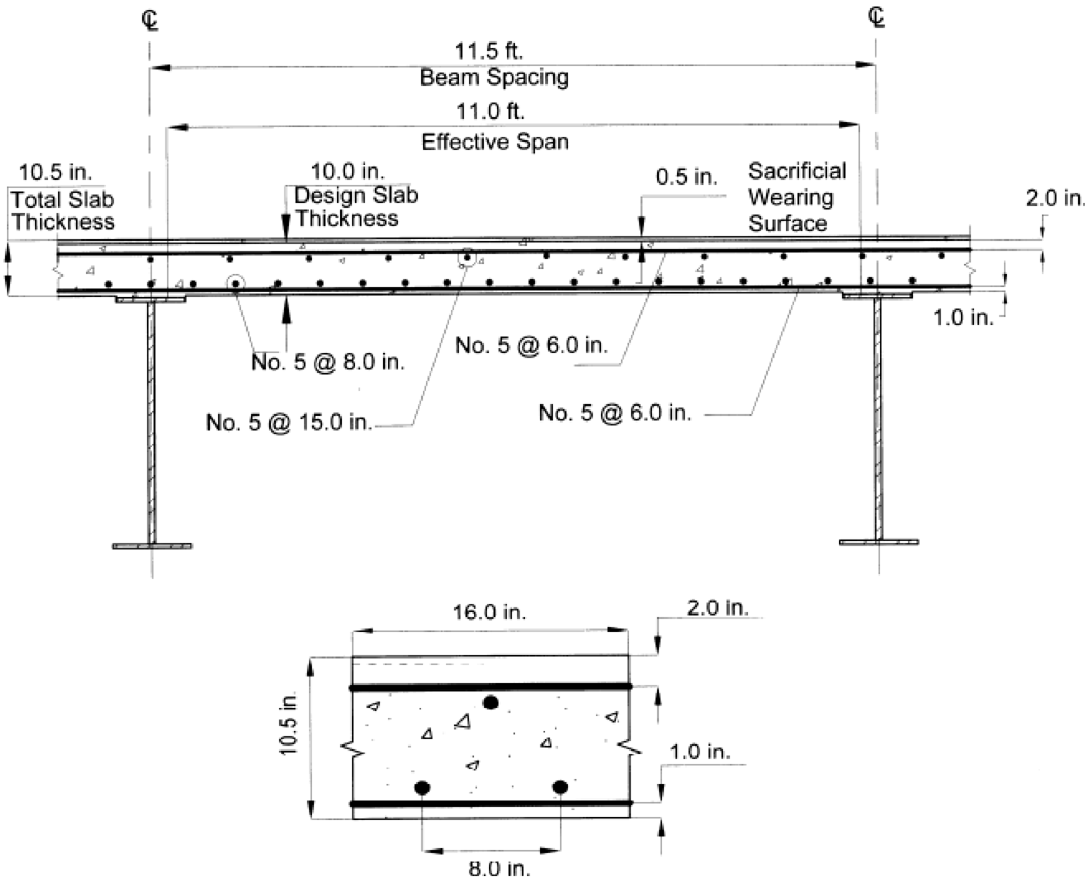
1.) Beam Spacing = 11.5 ft., Effective Span = 11.0 ft., Top Flange Width = 12.8 in.

2.) Reinforcing Bars (Area/Unit Width)
Top Longitudinal Reinforcement = .31 in²/ft, Bottom Longitudinal Reinforcement = .31 in²/ft,
Top Transverse Reinforcement = .31 in²/ft, Bottom Transverse Reinforcement = .31 in²/ft
Meeting all Florida's Empirical Deck Design Method Reinforcement Requirements.

3.) Top Mat Cover (Excluding Sacrificial Wearing Surface) = 2.0 in., Bottom Mat Cover = 2.0 in., Exterior Cover = 50 mm 2.0 in.

4.) Florida Empirical Methodology for a 65 ft. Long Bridge, with Steel Girders Spaced at 11.5 ft.

Florida Department of Transportation	FDOT EMPIRICAL DECK DESIGN 65 ft. LONG BRIDGE, NO SKEW STEEL BEAMS, 11.5 ft. BEAM SPAC.	DATE OF ISSUE 8-15-08 DRAWN BY CRAIG SHINER DRAWING NUMBER 14.2



Deck Properties

1.) Beam Spacing = 11.5 ft., Effective Span = 11.0 ft., Top Flange Width = 12.8 in.

2.) Reinforcing Bars (Area/Unit Width)
Top Longitudinal Reinforcement = .248 in²/ft, Bottom Longitudinal Reinforcement = .465 in²/ft,
Top Transverse Reinforcement = .620 in²/ft, Bottom Transverse Reinforcement = .620 in²/ft
Meeting all MDOT's Traditional Deck Design Method Reinforcement Requirements.

3.) Top Mat Cover (Excluding Sacrificial Wearing Surface) = 2.0 in., Bottom Mat Cover = 1.0 in., Exterior Cover = 2.0 in.

4.) MDOT Traditional Methodology for a 65 ft. Long Bridge, with Steel Girders Spaced at 11.5 ft.

Maine Department of Transportation	MAINE TRADITIONAL DECK DESIGN 65 ft. LONG BRIDGE, NO SKEW STEEL BEAMS, 11.5 ft BEAM SPAC.	DATE OF ISSUE 8-26-08 DRAWN BY CRAIG SHINER DRAWING NUMBER 19.2