EVALUATION OF CRACKING PERFORMANCE OF BRIDGE DECKS INCORPORATING NONMETALLIC FIBERS

By
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A Report on Research Sponsored by

CONSTRUCTION OF LOW-CRACKING HIGH-PERFORMANCE BRIDGE DECKS INCORPORATING NEW TECHNOLOGY TRANSPORTATION POOLED-FUND PROGRAM PROJECT NO. TPF-5(392)

Structural Engineering and Engineering Materials
SL Report 22-1
July 2022

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

The Minnesota Department of Transportation (MnDOT) identified 20 monolithic (one-course) bridge decks, constructed between 2015 and 2018, for cracking surveys to investigate the effectiveness of nonmetallic fibers in reducing bridge deck cracking. Of the 20 monolithic decks, 13 were constructed with concrete mixtures containing nonmetallic fibers and seven without fibers. Of the bridge decks constructed with nonmetallic fibers, nine are supported by precast-prestressed concrete girders and four are supported by steel girders. Of the decks constructed without fibers, six are supported by precast-prestressed concrete girders and one is supported by steel girders.

The first portion of the report (Chapters 1 through 4) presents a description of the crack survey procedures, followed by information about the decks. A comparison of the decks is then made by converting the survey results to equivalent crack densities at 36 months of age. The second portion of the report (Chapters 5 and 6) investigates the effects of paste content, fibers, and construction procedures on the cracking performance of the 20 bridge decks surveyed in this study using comparisons with the results of crack surveys of 74 other bridge deck placements, conducted in Kansas, Virginia, and Indiana.

Results show that for the decks surveyed in this study, the majority of cracks that contributed to crack density had lengths greater than 1 ft and there is no apparent correlation between the use of fibers and crack width. Low-cracking bridge decks require the use of concrete with a low paste content (27.1% or less), and when the paste content is 27.1% or less, there is no significant difference in the average 36-month crack densities between bridge decks with and without fibers. More generally, good construction practices are needed for low-cracking decks, and with poor construction practices, even decks with low paste content, with or without fibers, can exhibit high cracking.

Key words: bridge decks, construction procedures, cracking, crack density, fiber-reinforced concrete, nonmetallic fibers, paste content

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CHAPTER 1: INTRODUCTION

1.1 GENERAL

Bridges are essential components of the U.S. infrastructure. Of the 617,000 bridges in the United States, 42% were constructed over 50 years ago and are the most likely to need rehabilitation or replacement. In 2021, the American Society of Civil Engineers (ASCE) reported that 7.5% of the U.S. bridges were categorized as structurally deficient (ASCE 2021). Furthermore, travel demands and the costs associated with bridge rehabilitation and replacement continue to increase while funding is limited (Koch et al. 2002). As a result, the federal government estimates the backlog of bridge rehabilitation and replacement costs to be $125 billion (ASCE 2021).

Over the past sixty years, transportation agencies and researchers have attempted to minimize cracking in concrete bridge decks by employing crack-reducing technologies. Fiber-reinforced concrete (FRC) is often considered as a method to reduce cracking in bridge decks (Feng and Darwin 2020). In this study, the effectiveness of nonmetallic fibers to reduce cracking is evaluated based on crack surveys of 20 monolithic bridge decks constructed between 2015 and 2018. The crack survey method used is presented first, followed by information on the decks in this study. The survey results, presented in Chapter 3, are converted to equivalent crack densities at 36 months of age to allow a fair comparison between decks. A discussion on the results and comparisons with prior crack surveys are provided in Section 6.1. The summary and conclusions are presented in Section 7.1.

1.2 CRACK SURVEY METHOD

The crack surveys were performed using a standardized procedure that enables survey crews to provide consistent results (Lindquist et al. 2005, 2008, Pendergrass and Darwin 2014). The crack survey procedure is summarized next. The full bridge deck survey specifications are provided in Appendix A.

1.2.1 CRACK SURVEY PROCEDURE

Crack surveys are conducted on a day with a minimum air temperature of 60 °F (16 °C), with weather that is mostly sunny. Crack surveys are only conducted when the bridge deck surface is completely dry. No surveys are permitted on a wet surface. Crack survey results obtained under conditions that don't meet these requirements are invalid.

A plan view of the deck for drawing the crack map, with a scale of 1 in. = 10 ft (25.4 mm = 3.1 m) and a 10 × 10 ft (3.1 × 3.1 m) grid, is prepared before conducting the cracking survey. To establish the scaled length and location of the cracks, a 5 ft × 5 ft (1.5 m × 1.5 m) grid with a scale of 1 in. = 10 ft (25.4 mm = 3.1 m) is printed separately and is placed underneath the crack map. The grid should be aligned so that the grid points spaced at 5 ft × 5 ft (1.5 m × 1.5 m) match the grid lines on the crack map. The crack map also indicates the north compass direction to further assist the crack survey crews.

State department of transportation (DOT) crews provide traffic control by closing at least one lane to the traffic. The surveyors start marking the grids on the deck at 40-ft (12.1-m) increments in the longitudinal and 5-ft (1.5 m) increments in the transverse directions using sidewalk chalk corresponding with the scaled crack map. The surveyors then only mark cracks with sidewalk chalk that are visible when bending at the waist to waist height as they walk over the deck. Once a crack is observed, surveyors are allowed to bend closer to the deck to complete marking the crack. Once a crack is marked, surveyors must resume the identification of cracks that are only visible from waist height. Each portion of the deck is surveyed by at least two surveyors. The cracks marked on the bridge deck are transferred to the crack map, using the 5 ft × 5 ft (1.5 m × 1.5 m) grid map. The hand-drawn map is used to calculate the crack density of the bridge deck.

To calculate crack density, the hand-drawn map is scanned and converted into an AutoCAD file, and the crack lengths are measured using the built-in AutoCAD command, Data Extraction. The output is an Excel file in a CAD output folder showing the measured crack lengths of the individual cracks (in AutoCAD units). The summation of these measurements is the total crack length in AutoCAD units. Two scaling factors are defined to convert the AutoCAD unit measurements. One scaling factor is defined as the ratio between the actual bridge length and the length of the bridge drawn in AutoCAD (measured after scanning the hand-drawn crack map into AutoCAD). Similarly, the second scaling factor is defined as the ratio between the actual bridge width and the width of the bridge in AutoCAD. The average of these two scaling factors is used for the calculations. The actual crack lengths are obtained by multiplying the crack lengths in AutoCAD units by the average scaling factor. The crack density is calculated by dividing the crack length by the deck area and reported in m/m^2.

1.2.2 CRACK WIDTH

A number of randomly selected cracks from the bridge deck are measured for crack width. Cracks are selected so as to be representative based on length (short or long), orientation (transverse, parallel, or diagonal to traffic), and shape (straight or nonlinear). The width of cracks generally increases along with crack density. The widest point of the crack is measured as the crack width. A bank card-sized crack width comparator, with an accuracy of 0.001 in. (0.025 mm), is used for the measurements.

1.2.3 STUDENT'S T-TEST

Student's t-test is used to determine if the difference between the means of two small data sets, X_1 and X_2, drawn from two normally distributed populations, with unknown means and standard deviations, is due to random variation or represents an actual difference in the populations. The means of two samples are often compared on the basis of the p-value, which indicates the probability that the difference between two means is due to chance at a preselected significance level (α) when, in fact, they are the same. Thus, the smaller the value of p, the lower the probability that the observed difference is due to chance. A p-value greater than the significance level, in this case 0.05, would indicate that the difference between two means is likely to have been due to chance. Values of $p \leq 0.05$ are usually taken as indicating that the difference between two means is statistically significant.

CHAPTER 2: MINNESOTA BRIDGE DECKS

This section provides the information regarding bridge decks surveyed in this study, including location, type, mixture proportions, and concrete properties**.**

2.1 BRIDGE DECK INFORMATION

The Minnesota Department of Transportation (MnDOT) identified 20 monolithic (one-course) bridge decks, constructed between 2015 and 2018, for cracking surveys to investigate the effectiveness of nonmetallic fibers in reducing bridge deck cracking. Of the 20 monolithic decks, thirteen were constructed with concrete mixtures containing nonmetallic fibers and seven had no fibers. Of the bridge decks constructed with nonmetallic fibers, nine are supported by prestressed concrete girders and four are supported by steel girders. Of the decks constructed with no fibers, six are supported by prestressed concrete girders and one is supported by steel girders. Table 2.1 summarizes the information on bridge decks included in this study. In the cases where the bridge decks were constructed in multiple placements, the placement number (p#) is added after the bridge name. Because records were not available on the location of the individual placements on the decks, crack densities are only reported based on the entire deck.

Table 2.2 summarizes the bridge deck geometry. The number of spans ranges from one to seven. The lengths of the bridges range from 89.7 to 1175 ft (27.3 to 358.1 m), and the roadway widths range from 30 to 67 ft (9.1 to 20.4 m).

Table 2.1: Bridge deck information

Bridge Number	Location	County/Township/City	Girder Typed	Deck Type	Date of Construction
27W06	Franklin Ave. over I-35 W and T.H. 65	Minneapolis	Prestressed	Monolithic[a]	4/30/2018
07051	T.H.22 over Big Cobb river	Beauford Township	Prestressed	Monolithic	8/24/2017
9691	I-94 WB over C.S.A.H.88	Fergus Falls	Steel	Monolithic	8/11/2016
21802	I-94 EB over T.H.79	Evansville Township	Prestressed	Monolithic	9/19/2017
21803	I-94 WB over T.H.114	La Grand Township	Prestressed	Monolithic	-[b]
21804	I-94 EB over T.H.114	La Grand Township	Prestressed	Monolithic	9/5/2017
55009	T.H.52 WB over T.H.63	Rochester Township	Steel	Monolithic	8/31/2016
58821	I-35 SB over St. Corix Valley Railroad	Pine County	Prestressed	Monolithic	10/6/2016
58824	I-35 NB over Snake River	Pine City	Prestressed	Monolithic	6/27/2018
62729-p1	I-35E SB over Goose Lake Rd.	City of Vadnais Height	Prestressed	Monolithic	8/16/2016
62729-p2					10/4/2016
62731	T.h.36 WB over Lexington Ave.	City of Roseville	Prestressed	Monolithic	8/8/2016
62831	I-94 EB over I-94 WB	City of St. Paul	Steel	Monolithic	10/2/2015
62873	I-35 W under County Rd.	Arden Hills City	Prestressed	Monolithic	7/16/2016
62890	C.S.A.H.12 over I-35W	Arden Hills City	Prestressed	Monolithic	10/13/2015
69137	T.H.37 over T.H.53	Fayal Township	Prestressed	Monolithic	8/29/2018
69839	Michigan St. over T.H.194 SB	City of Duluth	Steel	Monolithic	9/19/2018
71004-p1	T.H.24 over Mississippi River	Clearwater	Prestressed	Monolithic	4/21/2017
71004-p2					5/4/2017
71004-p3					6/1/2017
71004-p4					6/6/2017
73047	T.H.4 over Sauk River	Melrose Township	Prestressed	Monolithic	7/31/2015
74805	C.S.A.H.31 over I-35	Owatonna	Prestressed	Monolithic	10/4/2017
85849-p1	T.H.90 WB over T.H.61 NB	Dresbach Township	Steel	Monolithic	8/14/2015
85849-p2					8/18/2015
85849-p3					8/24/2015
85849-p4					8/27/2015

[a] Monolithic = one-course bridge decks
[b] Data is not available from MnDOT

Table 2.2: Bridge deck geometry

Bridge Number	Spans	Skew	Length		Roadway Width	
			ft	m	ft	m
27W06	4	-0^{o} 40'15"	262.6	80.0	67.0	20.4
07051	3	45^{o} 0'0"	275.6	83.9	40.0	12.2
9691	3	-39^{o} 57'0"	150.7	45.9	39.4	12.0
21802	3	-33^{o} 39'0"	146.9	44.7	39.2	11.9
21803	3	37^{o} 2'30"	156.1	47.5	38.0	11.6
21804	3	37^{o} 2'30"	156.1	47.5	38.0	11.6
55009	4	13^{o} 48'0"	varied [a]			
58821	3	-49^{o} 29'30"	220.0	67.1	42.0	12.8
58824	3	0^{o} 0'0"	283.5	86.4	40.0	12.2
62729	2	49^{o} 57'36"	219.4	66.9	54.6	16.6
62731	1	0^{o} 0'0"	89.7	27.3	42.0	12.8
62831	2	varied[b]	219.4	66.9	32.0	9.8
62873	2	-7^{o} 41'49"	227.2	69.2	43.0	13.1
62890	2	-8^{o} 30'57"	280.9	85.6	33.0	10.1
69137	2	10^{o} 37'1"	233.8	71.2	40.0	12.2
69839	3	varied[c]	312.0	95.0	30.2	9.2
71004	7	0^{o} 0'0"	1175.0	358.1	44.0	13.4
73047	2	0^{o} 0'0"	144.6	44.0	36.0	10.9
74805	4	0^{o} 0'0"	206.8	63.0	30.0	9.1
85849	5	varied[d]	1157.8	352.9	42.0	12.8

[a] Bridge Length: 299.7 ft (91.4 m) to 301.2 ft (91.8 m); Bridge Width: 50.2 ft (15.3 m) to 56.2 ft (17.1 m)
[b] Skew: -33^{o}54'33" to -43^{o}34'3"; [c] Skew: -35^{o} 35'30" to 35^{o} 35'30"; [d] Skew: -0^{o} 39'21" to 0^{o} 39'21"

2.2 CONCRETE MIXTURE PROPORTIONS

Concrete mixture proportions based on oven-dry (OD basis) aggregates (MnDOT standard) are presented in Tables 2.3 and 2.4. The total weight of cementitious material ranged from 570 to 672 lb/yd^3 (338.2 to 398.7 kg/m^3) for the bridge decks containing fibers and from 535 to 595 lb/yd^3 (317.4 to 353.0 kg/m^3) for the bridge decks with no fibers. The water-to-cementitious material (*w/cm*) ratios ranged from 0.40 to 0.44 for the decks. The paste content (volume fraction of cementitious materials and mixing water) ranged from 23.9 to 29.6% for the bridge decks containing fibers and 24.0 to 26.8% for the bridge decks with no fibers.

The details of the cementitious material percentages and aggregate proportions are shown in Table 4. Three bridge decks (9691, 21802, and 21804) contained portland cement as the only cementitious material; 11 (27W06, 07051, 58821, 58824, 62731, 62831, 69137, 69839, 73047, 74805, and 85849) used binary mixtures with cement and fly ash; two (55009 and 71004) used ternary mixtures with cement, fly ash, and silica fume; and three (62729, 62873, and 62890) used ternary mixtures with cement, slag cement, and fly ash as the cementitious materials. The mixture proportions of bridge 21803 could not be provided by MnDOT.

Table 2.3: Cementitious material content, water content, *w/cm* ratio of bridge decks

Bridge Number	Cementitious Material Content (lb/yd^3)	Water Content (lb/yd^3)	*w/cm* Ratio	Paste Content (%)
27W06	600	252	0.42	27.1
07051	600	240	0.40	26.6
9691	535	233	0.44	23.9
21802	535	235	0.44	24.0
21803	-[a]	-[a]	-[a]	-[a]
21804	535	235	0.44	24.0
55009	570	240	0.42	25.8
58821	595	250	0.42	26.8
58824	595	250	0.42	26.8
62729	581	250	0.43	26.4
62731	595	250	0.42	26.8
62831	573	241	0.42	25.9
62873	580	232	0.40	25.3
62890	581	250	0.43	26.4
69137	579	248	0.43	26.5
69839	579	248	0.43	26.5
71004	672	269	0.40	29.6
73047	600	245	0.41	26.2
74805	595	250	0.42	26.9
85849	570	240	0.42	25.8

[a] Data is not available from MnDOT
Note: 1 lb/yd^3 = 0.593 kg/m^3

Table 2.4: Cementitious material percentages and aggregate proportions (OD basis)

Bridge Number	Cementitious Material Percentage[a]	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)
27W06	70% C 30% FA-F	1731	1249
07051	70% C 30% FA-F	1643	1324
9691	100% C	1429/456[c]	1151
21802	100% C	1308/491[c]	1270
21803	-[b]	-[b]	-[b]
21804	100% C	1308/491[c]	1270
55009	68%C 28% FA-C 4% SF	1769	1280
58821	75% C 25% FA-F	1712	1311
58824	75% C 25% FA-F	1712	1311
62729	70% C 15% S 15 FA-C/F	1726	1302
62731	75% C 25% FA-F	1712	1311
62831	71% C 29% FA-C	1687	521/859[c]
62873	65% C 20% S 15% FA-F	1784	1292
62890	70% C 15% S 15 FA-C/F	1726	1302
69137	70% C 30% FA-F	1429/309[c]	1301
69839	70% C 30% FA-F	1429/309[c]	1301
71004	66% C 29% FA-C 5% SF	1611	1270
73047	79% C 21% FA-C	1735	1257
74805	80% C 20% FA-F	1647	1367
85849	70% C 30% FA-F	1237/485[c]	1280

[a] Percentages by total weight of cementitious material; C = portland cement; S = Grade 100 slag cement; F-FA = Class F fly ash; C-FA = Class C fly ash; SF = Silica Fume
[b] Data is not available
[c] Two types of aggregates
Note: 1 lb/yd^3 = 0.593 kg/m^3

Table 2.5 lists the type of fibers used in some of the bridge decks in this study. Five decks (27W06, 5509, 58824, 69137, and 69839) used a macrofiber; seven decks (07051, 9691, 62729, 62731, 71004, 73047, and 74805) used a blend of microfiber and macrofiber. The length of macrofiber ranged from 1.25 to 2.1 in. (31.8 to 53.3 mm). The length of microfiber was either 0.375 or 0.5 in. (9.5 or 12.7 mm). The specific gravities of fibers ranged from 0.91 to 1.3. The equivalent diameter was not provided for the macrofiber used in decks 27W06 and 58824. The fiber properties of deck 21803 were not provided.

Table 2.5: Properties of fiber reinforcement

Bridge Number	Dosage (lb/yd^3)	Type	Length (in.)	Equivalent Diameter (in.)	Specific Gravity	Material
27W06	5	Monofilament/Macro	1.5	-[b]	0.91	Polypropylene
07051	4	Monofilament/Macro	2.1	0.03	0.91	Polypropylene
	0.5	Monofilament/Macro	2.1	0.03	0.91	
9691	5	Monofilament Micro	0.5	0.012	0.91	polyolefin
		Monofilament Macro	1.85	0.03	0.91	
55009	5	Monofilament/Macro	1.5	0.025	0.91	Polyolefin
58824	5	Monofilament/Macro	1.5	-[b]	0.91	Polypropylene
62729	4	Monofilament/Macro	2.1	0.03	0.91	Polypropylene
	0.5	Monofilament/Micro	0.5	0.0005	0.91	
62731	4	Monofilament/Macro	2.1	0.03	0.91	Polypropylene
	0.5	Monofilament/Micro	0.5	0.0005	0.91	
62831	-[a]	-[a]	-[a]	-[a]	-[a]	-[a]
69137	4	Monofilament/Macro	2.0	0.027	0.92	polypropylene/ polyethylene
69839	4	Monofilament/Macro	2.0	0.027	0.92	polypropylene/ polyethylene
71004	1.5	Monofilament/Micro	0.375	0.0017	1.3	Polyvinyl
	3.5	Monofilament/Macro	1.25	0.026	1.3	
73047	1.5	Monofilament/Micro	0.375	0.0017	1.3	Polyvinyl
	3.5	Monofilament/Macro	1.25	0.026	1.3	
74805	4	Monofilament/Macro	2.1	0.03	0.91	Polypropylene
	0.5	Monofilament/Micro	0.5	0.0005	0.91	

[a] Data is not available from MnDOT
[b] Data is not available from the manufacturer
Note: 1 in. = 25.4 mm.

2.3 CONCRETE PROPERTIES

The average concrete properties of each deck placement are shown in Table 2.6. Deck 62729 was constructed in two placements and decks 71004 and 85849 were constructed in four placements on different days. The other decks were constructed in a single placement. The average air contents for the deck placements ranged from 5.7 to 7.9%, the average slumps ranged from 2½ to 6 in. (65 to 150 mm), the average concrete temperature ranged from 63 to 78 °F (17.2 to 25.5 °C), and the 28-day compressive strength ranged from 4410 to 7310 psi (30.4 to 50.4 MPa). No concrete test results are available for decks 21803, 62831, and 62890. The 28-day strength results are not available for Placements 3 and Placement 4 of deck 85849.

Table 2.6: Average concrete properties in each bridge deck

Bridge Number	Air Content (%)	Slump (in.)	Concrete Temperature °F	Concrete Temperature °C	28-day Strength (psi)
27W06	7.9	5	63	17.2	5110
07051	7.4	4½	76	24.4	5070
9691	7.8	2½	73	22.7	4410
21802	7.5	3	68	20.0	5570
21803	-[a]	-[a]	-[a]	-[a]	-[a]
21804	7.2	2¼	67	19.4	6360
55009	7.3	4	79	26.1	5220
58821	7.7	3½	67	19.4	6150
58824	5.6	4½	72	22.2	6970
62729-p1	6.0	4	78	25.5	6710
62729-p2	6.7	4	64	17.7	4560
62731	6.3	4¼	72	22.2	5230
62831	-[a]	-[a]	-[a]	-[a]	-[a]
62873	7.2	3½	71	21.6	5470
62890	-[a]	-[a]	-[a]	-[a]	-[a]
69137	5.7	4½	66	18.8	5000
69839	6.5	4	71	21.6	6510
71004-p1	7.7	3¾	70	21.1	7310
71004-p2	7.3	5¾	67	19.4	6700
71004-p3	7.8	5¼	64	17.7	5700
71004-p4	7.3	6	69	20.5	6690
73047	6.9	3	76	24.4	5820
74805	6.7	3¾	73	22.7	5820
85849-p1	6.1	5	76	24.4	4900
85849-p2	6.4	4	74	23.3	4850
85849-p3	6.2	4½	65	18.3	-[a]
85849-p4	6.9	4½	70	21.1	-[a]

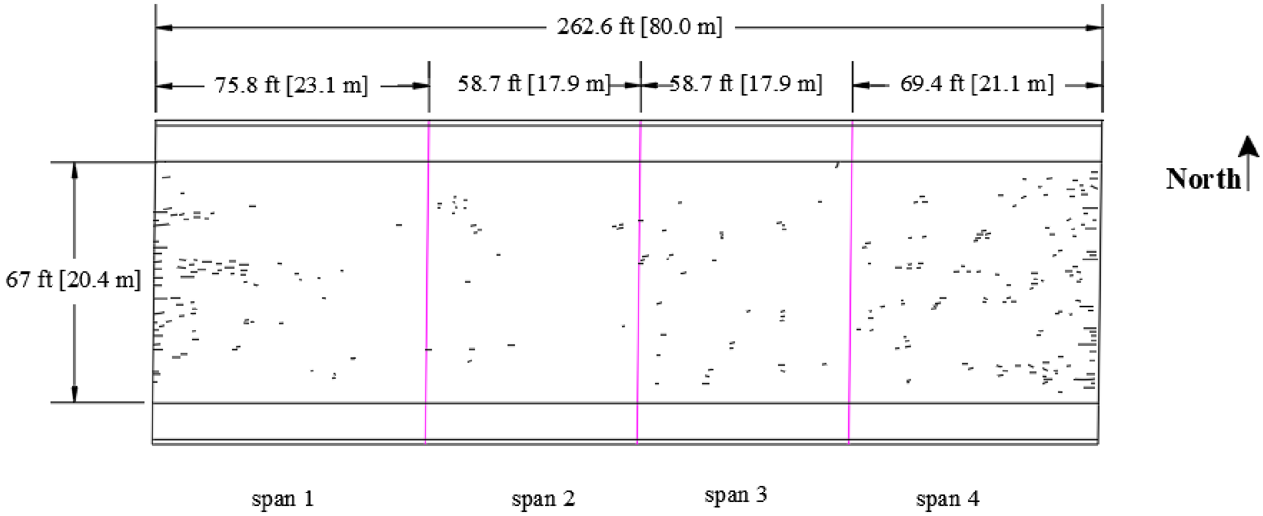
[a] Data is not available
Note: 1 in. = 25.4 mm; 1 psi = 6.89×10^{-3} MPa

CHAPTER 3: CRACK SURVEY RESULTS

The cracking performance of the 20 bridge decks surveyed in this study is described in this chapter.

3.1 BRIDGE 27W06 (WITH FIBERS)

Bridge 27W06 was constructed in one placement on April 30, 2018. The bridge carries two-way traffic on Franklin Ave. over I-35 W and T.H. 65 in Minneapolis, Minnesota. The concrete supplier and the contractor were Aggregate Industries and Lunda Construction, respectively. The bridge has four spans with lengths of 75 ft-9 ¾ in. (23.1 m), 58 ft-9 in. (17.9 m), 58 ft-9 in. (17.9 m), and 68 ft-3 in. (21.1 m), with a total length of 262 ft-6 ¾ in. (80.0 m). The deck has a 67 ft (20.4 m) wide roadway, a 1 ft-5 in. (430 mm) wide barrier and a 10 ft (3.0 m) sidewalk on each side, for a total deck width of 89 ft-10 in. (27.3 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of -0º 40’15”. The crack survey was performed at a deck age of 26.7 months, and the deck had a crack density of 0.066 m/m^2. The crack map is shown in Figure 3.1.



Bridge Number: 27W06
Bridge Location: Franklin Ave. over I-35W and T.H.65, Minneapolis, MN
Construction Date: 4/30/2018
Crack Survey Date: 7/21/2020

Bridge Length: 262.6 ft (80.0 m)
Bridge Width: 67.0 ft (20.4 m)
Skew: -0°40'14.6"
Number of Spans: 4
- **Span 1:** 75.8 ft (23.1 m)
- **Span 2:** 58.7 ft (17.9 m)
- **Span 3:** 58.7 ft (17.9 m)
- **Span 4:** 69.4 ft (21.1 m)

Number of Placements: 1

Bridge Age: 26.7 months
Crack Density: 0.066 m/m^2
- **Span 1:** 0.081 m/m^2
- **Span 2:** 0.017 m/m^2
- **Span 3:** 0.032 m/m^2
- **Span 4:** 0.120 m/m^2

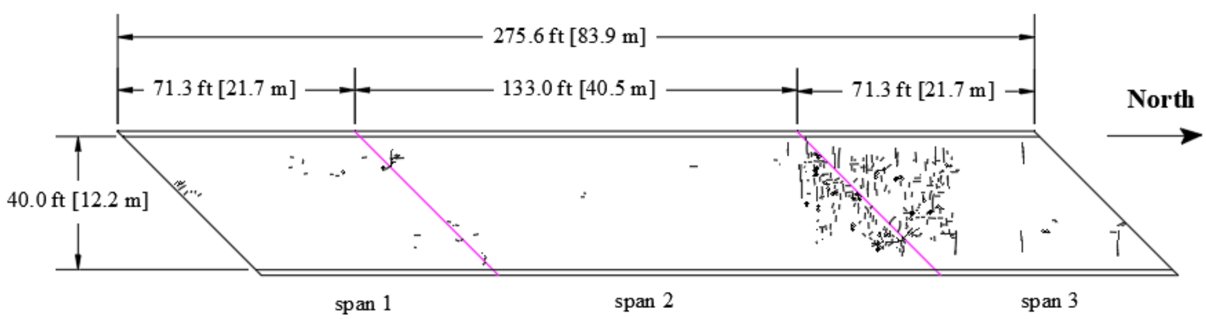
Figure 3.1: Crack survey of bridge 27W06

Figure 3.2: Scaling damage of bridge 27W06

The 67-ft (20.4 m) roadway of the bridge deck, but not the shoulders, was surveyed. The majority (67%) of the cracks were longitudinal with lengths greater than or equal to 1 ft (305 mm). The cracks were mainly concentrated near the east and west abutments, possibly due to restraint from the abutments in the transverse direction (Schmitt and Darwin 1995, Miller and Darwin 2000). Surface scaling, shown in Figure 3.2, was observed, mainly in the two middle spans. Crack widths ranged from 0.002 in. (0.051 mm) to 0.005 in. (0.127 mm), with an average of 0.003 in. (0.076 mm).

3.2 BRIDGE 07051 (WITH FIBERS)

Bridge 07051 was constructed in one placement on August 24, 2017. The two-lane bridge carries traffic on T.H. 22 over Big Cobb River in Beauford Township, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and Minnowa Construction Inc, respectively. The bridge has three spans with lengths of 71 ft-4 in. (21.7 m), 133 ft (40.5 m), and 71 ft-4 in. (21.7 m), with a total length of 275 ft-8 in. (83.9 m). The deck has a 40 ft (12.1 m) wide roadway and a 1 ft-8 in. (490 mm) wide barrier on each side, for a total deck width of 43 ft-4 in. (13.1 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of 45°. The crack survey was performed at a deck age of 35.3 months, and the deck had a crack density of 0.139 m/m^2. The crack map is shown in Figure 3.3.



Bridge Number: 07051
Bridge Location: T.H.22 over Big Cobb river, Beauford Township, MN
Construction Date: 8/24/2017
Crack Survey Date: 8/3/2020

Bridge Length: 275.6 ft (83.9 m)
Bridge Width: 40.0 ft (12.2 m)
Skew: 45°
Number of Spans: 3
Span 1: 71.3 ft (21.7 m)
Span 2: 133 ft (40.5 m)
Span 3: 71.3 ft (21.7 m)
Number of Placements: 1

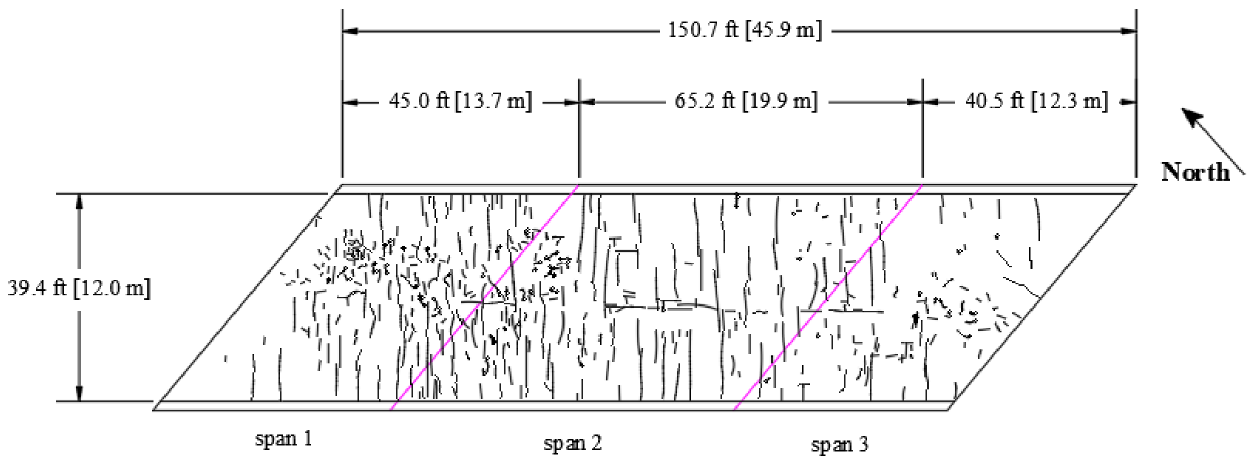
Bridge Age: 35.3 months
Crack Density: 0.139 m/m^2
Span 1: 0.032 m/m^2
Span 2: 0.120 m/m^2
Span 3: 0.282 m/m^2

Figure 3.3: Crack survey of bridge 07051

The highest concentration of cracking was observed near the north end of the deck around the pier. The concrete at this location was ground heavily compared to concrete elsewhere on the deck. The MnDOT personnel mentioned that the concrete had been placed in the transverse direction rather than the skew direction of the bridge and that they had some issues with the concrete levelness in this area. Seventy percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Some cracks were observed perpendicular to the skew of the deck at both ends and piers. Crack widths ranged from 0.003 in. (0.076 mm) to 0.013 in. (0.330 mm), with an average of 0.008 in. (0.203 mm).

3.3 BRIDGE 9691 (WITH FIBERS)

Bridge 9691 was constructed in one placement on August 11, 2016. The bridge carries westbound traffic on I-94 WB over C.S.A.H. 88. in Fergus Falls, Minnesota. The concrete supplier and the contractor were Aggregate Industries and PCI Roads LLC, respectively. The bridge has three spans with lengths of 45 ft (13.7 m), 65 ft-2 ⅝ in. (19.9 m), and 40 ft-6 in. (12.3 m), with a total length of 150 ft-8 ⅝ in. (45.9 m). The deck has a 39 ft-5 in. (12.0 m) wide roadway and a 1 ft-8 in. (490 mm) wide barrier on each side, for a total deck width of 42 ft-9 in. (13.0 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by steel girders with a skew of -39º 57'. The crack survey was performed at a deck age of 46.8 months, and the deck had a crack density of 0.779 m/m^2. The crack map is shown in Figure 3.4.



Bridge Number: 9691
Bridge Location: I-94 WB over CSAH 88, Fergus Falls, MN
Construction Date: 8/11/2016
Crack Survey Date: 7/6/2020

Bridge Length: 150.7 ft (45.9 m)
Bridge Width: 39.4 ft (12.0 m)
Skew: -39°57'
Number of Spans: 3
Span 1: 45.0 ft (13.7 m)
Span 2: 65.2 ft (19.9 m)
Span 3: 40.5 ft (12.3 m)
Number of Placements: 1

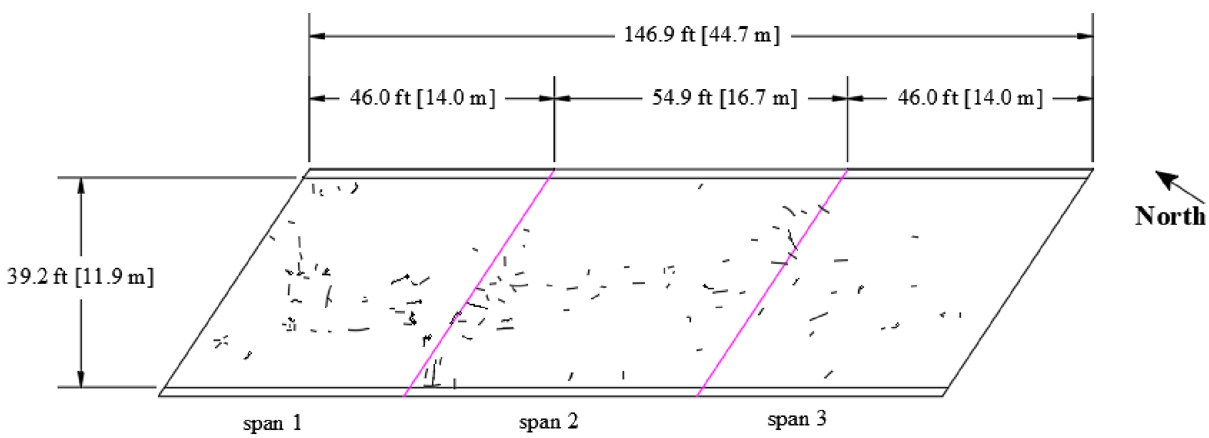
Bridge Age: 46.8 months
Crack Density: 0.779 m/m^2
Span 1: 0.803 m/m^2
Span 2: 0.869 m/m^2
Span 3: 0.609 m/m^2

Figure 3.4: Crack survey of bridge 9691

This bridge is one of the top three most cracked bridge decks surveyed in this study. The majority of the cracks were oriented in the transverse direction parallel to the top deck reinforcement, not parallel to the skew of the bridge. These cracks were observed throughout the deck. A number of longitudinal cracks were found mainly in the middle span and over the piers. Some cracks were observed perpendicular to the skew of the deck at both ends and piers. A few diagonal cracks had propagated from the south abutment. Eighty-seven percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Crack widths ranged from 0.004 in. (0.102 mm) to 0.030 in. (0.762 mm), with an average of 0.012 in. (0.305 mm).

3.4 BRIDGE 21802 (WITHOUT FIBERS)

Bridge 21802 was constructed in one placement on September 19, 2017. The bridge carries eastbound traffic on I-94 EB over T.H. 79 in Evansville Township, Minnesota. The concrete supplier and the contractor were Alexandria Concrete and Lunda Construction Company, respectively. The bridge has three spans with lengths of 45 ft-11 ⅝ in. (14.0 m), 54 ft-11 in. (16.8 m), and 45 ft-11 ⅝ in. (14.0 m), with a total length of 146 ft-10 ¼ in. (44.7 m). The deck has a 39 ft-2 in. (11.9 m) wide roadway and a 1 ft-8 in. (490 mm) wide barrier on each side, for a total deck width of 42 ft-6 in. (12.9 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of -33° 39'. The crack survey was performed at a deck age of 33.6 months, and the deck had a crack density of 0.103 m/m^2. The crack map is shown in Figure 3.5.



Bridge Number: 21802
Bridge Location: I-94 EB over T.H.79, Evansville Township, MN
Construction Date: 9/19/2017
Crack Survey Date: 7/6/2020

Bridge Length: 146.9 ft (44.7 m)
Bridge Width: 39.2 ft (11.9 m)
Skew: -33°39'
Number of Spans: 3
Span 1: 46.0 ft (14.0 m)
Span 2: 54.9 ft (16.8 m)
Span 3: 46.0 ft (14.0 m)
Number of Placements: 1

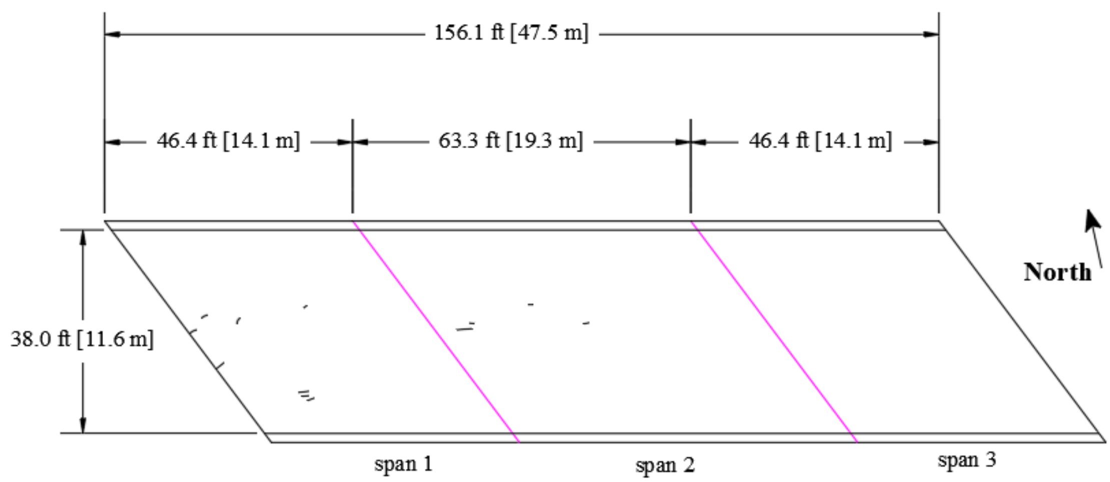
Bridge Age: 33.6 months
Crack Density: 0.103 m/m^2
Span 1: 0.125 m/m^2
Span 2: 0.135 m/m^2
Span 3: 0.042 m/m^2

Figure 3.5: Crack survey of bridge 21802

The majority of cracks were randomly positioned, mainly distributed over spans 1 and 2 of the bridge (Figure 3.5). A few transverse cracks were located near the shoulders. Crack widths ranged from 0.004 in. (0.102 mm) to 0.009 in. (0.229 mm), with an average of 0.005 in. (0.127 mm).

3.5 BRIDGE 21803 (WITHOUT FIBERS)

Bridge 21803 was constructed in one placement. The date of construction is not available. The bridge carries westbound traffic on I-94 WB over T.H. 114 in La Grand Township, Minnesota. Information on the concrete supplier and the contractor is not available. The bridge has three spans with lengths of 46 ft-5 ⅛ in. (14.1 m), 63 ft-3 ⅛ in. (19.3 m), and 46 ft-5 ⅛ in. (14.1 m), with a total length of 156 ft-1 ⅜ in. (47.5 m). The deck has a 38 ft (11.6 m) wide roadway and a 1 ft-8 in. (490 mm) wide barrier on each side, for a total deck width of 41 ft-4 in. (12.5 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of 37º 2'30". The crack density was 0.009 m/m^2. The age of the deck at the time of the survey is not known. The crack map is shown in Figure 3.6.



Bridge Number: 21803
Bridge Location: I-94 WB over T.H.114, La Grand Township, MN
Construction Date: / /2017
Crack Survey Date: 7/7/2020

Bridge Length: 156.1 ft (47.5 m)
Bridge Width: 38.0 ft (11.6 m)
Skew: 37°2'30"
Number of Spans: 3
Span 1: 46.4 ft (14.1 m)
Span 2: 63.3 ft (19.3 m)
Span 3: 46.4 ft (14.1 m)
Number of Placements: 1

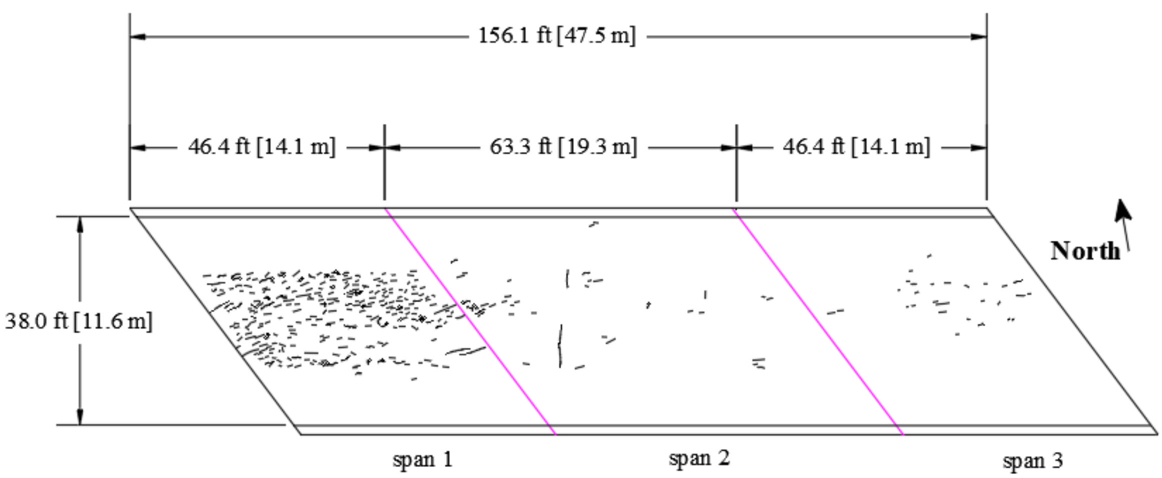
Bridge Age: months
Crack Density: 0.009 m/m^2
Span 1: 0.021 m/m^2
Span 2: 0.008 m/m^2
Span 3: 0.000 m/m^2

Figure 3.6: Crack survey of bridge 21803

The majority of cracks were randomly positioned and distributed over spans 1 and 2 of the bridge deck. A few longitudinal cracks were located near the west abutment. No cracking was observed in span 3. Crack widths had an average of 0.004 in. (0.102 mm).

3.6 BRIDGE 21804 (WITHOUT FIBERS)

Bridge 21804 was constructed in one placement on September 5, 2017. The bridge carries eastbound traffic on I-94 EB over T.H. 114 in La Grand Township, Minnesota. The concrete supplier and the contractor were Alexandria Concrete and Lunda Construction Company, respectively. The bridge has three spans with lengths of 46 ft-5 ⅛ in. (14.1 m), 63 ft-3 ⅛ in. (19.3 m), and 46 ft-5 ⅛ in. (14.1 m), with a total length of 156 ft-1 ⅜ in. (47.5 m). The deck has a 38 ft (11.6 m) wide roadway and a 1 ft-8 in. (490 mm) wide barrier on each side, for a total deck width of 41 ft-4 in. (12.5 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of 37º 2’30”. The crack survey was performed at a deck age of 34.1 months, and the deck had a crack density of 0.206 m/m^2. The crack map is shown in Figure 3.7.



Bridge Number: 21804
Bridge Location: I-94 EB over T.H.114, La Grand Township, MN
Construction Date: 9/5/2017
Crack Survey Date: 7/7/2020

Bridge Length: 156.1 ft (47.5 m)
Bridge Width: 38.0 ft (11.6 m)
Skew: 37°2'30"
Number of Spans: 3
Span 1: 46.4 ft (14.1 m)
Span 2: 63.3 ft (19.3 m)
Span 3: 46.4 ft (14.1 m)
Number of Placements: 1

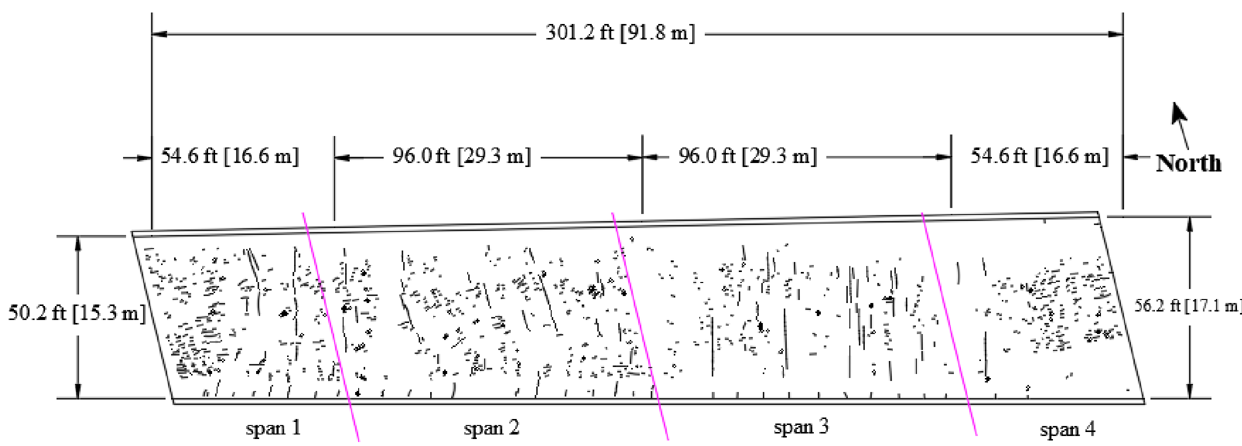
Bridge Age: 34.1 months
Crack Density: 0.206 m/m^2
Span 1: 0.549 m/m^2
Span 2: 0.071 m/m^2
Span 3: 0.047 m/m^2

Figure 3.7: Crack survey of bridge 21804

The highest concentration of cracks was observed in span 1, near the centerline of the bridge deck. The majority of cracks are oriented in the longitudinal direction. Some longitudinal cracks were found along the east end of the deck. Two longer transverse cracks, approximately 5 and 8 ft (1.5 and 2.4 m) in length, had developed approximately 70 ft (21.3 m) from the west abutment. Some cracks were observed perpendicular to the skew of the deck at the west end and the pier in span 1. Crack widths ranged from 0.004 in. (0.102 mm) to 0.012 in. (0.305 mm), with an average of 0.006 in. (0.152 mm).

3.7 BRIDGE 55009 (WITH FIBERS)

Bridge 55009 was constructed in one placement on August 31, 2016. The bridge carries westbound traffic on T.H.52 WB over T.H.63 in Rochester, Minnesota. The concrete supplier and the contractor were Ready Mix Concrete Company and Icon Construction LLC, respectively. The bridge has four spans with a polygonal surface in plan view. The nominal lengths of the spans are 54 ft-7 ⅛ in. (16.6 m), 96 ft (29.3 m), 96 ft (29.3 m), and 54 ft-7 ⅛ in. (16.6 m), with a total length of 301 ft-2 ¼ in. (91.8 m). The deck has a nominal 50 ft-2 ⅝ in. (15.3 m) to 56 ft-1 ⅞ in. (17.1 m) wide roadway and a 1 ft-8 in. (490 mm) wide barrier on each side. The nominal deck thickness is 8 in. (205 mm). The bridge deck is supported by steel girders with a skew of 13º 48’0”. The crack survey was performed at a deck age of 47.1 months, and the deck had a crack density of 0.293 m/m^2. The crack map is shown in Figure 3.8.



Bridge Number: 55009
Bridge Location: T.H.52WB over T.H.63, Rochester Township, MN
Construction Date: 8/31/2016
Crack Survey Date: 8/4/2020

Bridge Length: 301.2 ft (91.8 m)
Bridge Width: 50.2 ft (15.3 m)-56.2 ft (17.1 m)
Skew: 13°48'
Number of Spans: 4
Span 1: 54.6 ft (16.6 m)
Span 2: 96.0 ft (29.3 m)
Span 3: 96.0 ft (29.3 m)
Span 4: 54.6 ft (16.6 m)
Number of Placements: 1

Bridge Age: 47.1 months
Crack Density: 0.293 m/m^2
Span 1: 0.460 m/m^2
Span 2: 0.316 m/m^2
Span 3: 0.214 m/m^2
Span 4: 0.238 m/m^2

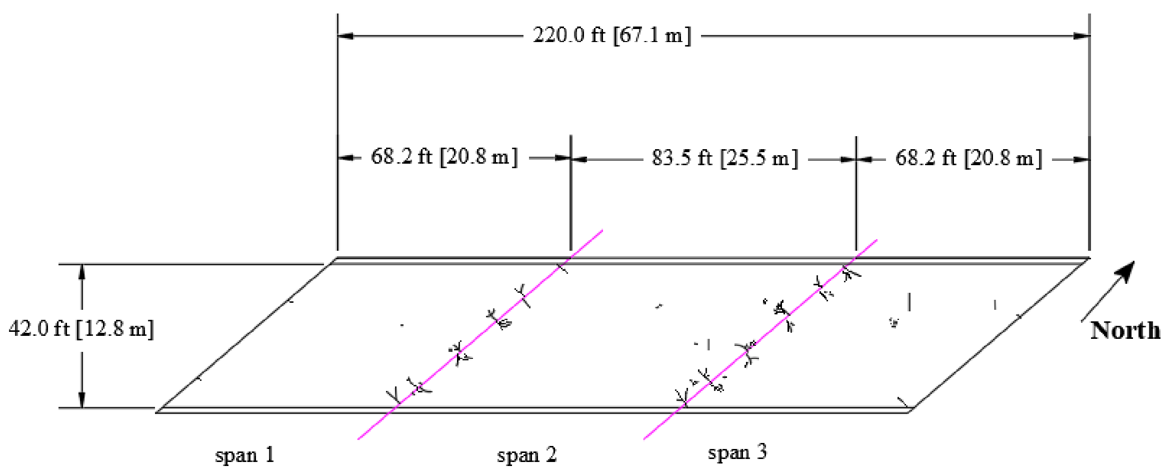
Figure 3.8: Crack survey of bridge 55009

Significant short (crack lengths smaller than 1 ft [305 mm]) and longitudinal-oriented cracks were found throughout the deck, possibly caused by plastic shrinkage. A number of transverse cracks were observed in each span of the deck, with approximately 5 to 20 ft (1.5 to 6 m) in length. A number of cracks were found in the shoulder area on the south side of the deck. Forty percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Some cracks were observed perpendicular to the skew of the deck at both ends and piers. Crack widths ranged from 0.003 in. (0.076 mm) to 0.013 in. (0.330 mm), with an average of 0.008 in. (0.203 mm).

3.8 BRIDGE 58821 (WITHOUT FIBERS)

Bridge 58821 was constructed in one placement on October 6, 2016. The bridge carries southbound traffic on I-35 SB over St. Corix Valley Railroad in Pine City, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and Redstone Construction Company, respectively. The bridge has three spans with lengths of 68 ft-3 in. (20.8 m), 83 ft-6 in. (25.5 m), and 68 ft-3 in. (20.8 m), with a total length of 220 ft (67.1 m). The deck has a 42 ft (12.8 m) wide roadway and a 1 ft-8 in. (490 mm) wide barrier on each side, for a total deck width of 45 ft-4 in. (13.8 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of -49º 29’30”. The crack survey was performed at a deck age of 46.1 months, and the deck had a crack density of 0.071 m/m^2. The crack map is shown in Figure 3.9.

Figure shows the crack map of bridge 21803.



Bridge Number: 58821
Bridge Location: I-35 SB over St. Croix Valley Railroad, Pine county, MN
Construction Date: 10/6/2016
Crack Survey Date: 8/10/2020

Bridge Length: 220.0 ft (67.1 m)
Bridge Width: 42.0 ft (12.8 m)
Skew: -49°29'30"
Number of Spans: 3
Span 1: 68.2 ft (20.8 m)
Span 2: 83.5 ft (25.5 m)
Span 3: 68.2 ft (20.8 m)
Number of Placements: 1

Bridge Age: 46.1 months
Crack Density: 0.071 m/m^2
Span 1: 0.048 m/m^2
Span 2: 0.090 m/m^2
Span 3: 0.069 m/m^2

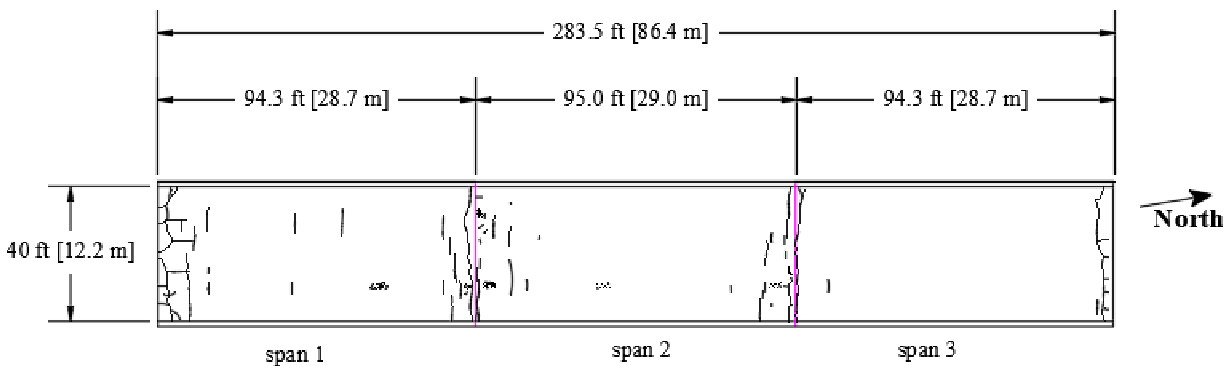
Figure 3.9: Crack survey of bridge 58821

The majority of cracks were located on either side of the piers, normal to the skew orientation. Some randomly oriented cracks were found at all spans. A few cracks were observed perpendicular to the skew of the deck at both abutments. Crack widths ranged from 0.009 in. (0.229 mm) to 0.020 in. (0.508 mm), with an average of 0.015 in. (0.381 mm).

3.9 BRIDGE 58824 (WITH FIBERS)

Bridge 58824 was constructed in one placement on June 27, 2018. The bridge carries southbound traffic on I-35 SB over St. Croix Valley Railroad in Pine City, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and Ames Construction, respectively. The bridge has three spans with lengths of 94 ft-3 in. (28.7 m), 95 ft (29.0 m), and 94 ft-3 in. (28.7 m), with a total length of 283 ft-6 in. (86.4 m). The deck has a 40 ft (12.2 m) wide roadway and a 1 ft-6 in. (460 mm) wide barrier on each side, for a total deck width of 43 ft (13.1 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of 0º. The crack survey was performed at a deck age of 25.5 months, and the deck had a crack density of 0.141 m/m^2. The crack map is shown in Figure 3.10.

Figure shows the crack map of bridge 21803.



Bridge Number: 58824
Bridge Location: I-35 NB over Snake River, Pine City, MN
Construction Date: 6/27/2018
Crack Survey Date: 8/10/2020

Bridge Length: 283.5 ft (86.4 m)
Bridge Width: 40 ft (12.2 m)
Skew: 0°
Number of Spans: 3
Span 1: 94.3 ft (28.7 m)
Span 2: 95.0 ft (29.0 m)
Span 3: 94.3 ft (28.7 m)
Number of Placements: 1

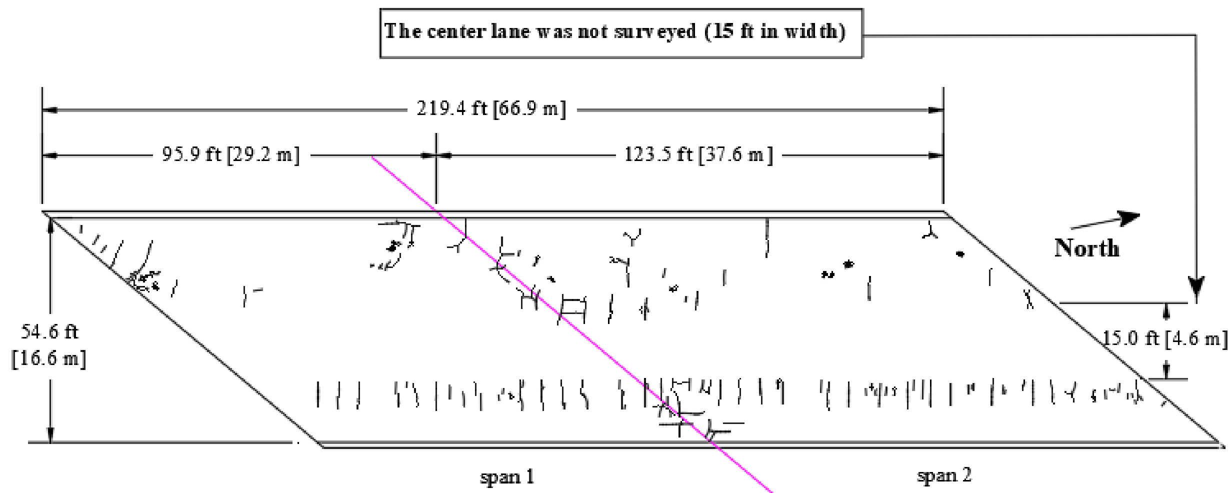
Bridge Age: 25.5 months
Crack Density: 0.141 m/m^2
Span 1: 0.211 m/m^2
Span 2: 0.122 m/m^2
Span 3: 0.091 m/m^2

Figure 3.10: Crack survey of bridge 58824

The majority of the cracks are transverse cracks located near the abutments and piers of the bridge deck. These cracks occasionally extended across the entire deck width. A number of crazing cracks were found near the east shoulder. Some longitudinal cracks extend from each abutment. Forty-eight percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Some cracks were observed perpendicular to the skew of the deck at both ends and piers. Crack widths ranged from 0.006 in. (0.152 mm) to 0.020 in. (0.508 mm), with an average of 0.016 in. (0.406 mm).

3.10 BRIDGE 62729 (WITH FIBERS)

Bridge 62729 was constructed in two placements. Placement 1 was constructed on August 16, 2016, and Placement 2 was constructed on October 4, 2016. The bridge carries southbound traffic on I-35 SB over Goose Lake Rd. in Vadnais Height, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and Ames Construction, respectively. The bridge has two spans with lengths of 95 ft-11 ¾ in. (29.2 m) and 123 ft-5 ¾ in. (37.6 m), with a total length of 219 ft-5 ½ in. (69.3 m). The deck has a 54 ft-7 ½ in. (16.6 m) wide roadway, a 1 ft-8 in. (490 m) wide barrier on the west side, and a 1 ft-4 in. (390 mm) wide barrier on the east side, for a total deck width of 57 ft-7 ½ in. (17.6 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of 49º 57'36". The crack survey was performed at a deck age of 47.1 months for Placement 1 and 45.5 months for Placement 2. The concrete placement locations are not available. The crack density of 0.238 m/m^2 was calculated for the entire deck. The crack map is shown in Figure 3.11.



Bridge Number: 62729
Bridge Location: I-35E SB over Goose Lake Rd and BNSF Railroad, City of Vadnais Height, MN
Construction Date:
Placement 1: 8/16/2016
Placement 2: 10/4/2016
Crack Survey Date: 7/20/2020

Bridge Length: 219.4 ft (66.9 m)
Bridge Width: 54.6 ft (16.6 m)
Skew: 49°57'36"
Number of Spans: 2
Span 1: 95.9 ft (29.2 m)
Span 2: 123.5 ft (37.6 m)
Number of Placements: 2

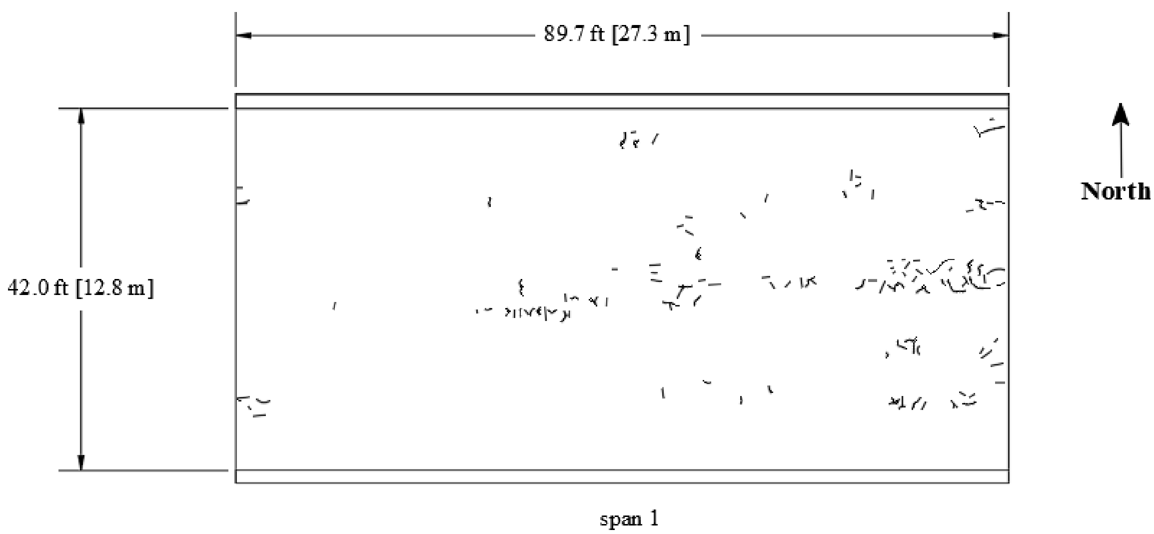
Bridge Age: months
Placement 1: 47.1 months
Placement 2: 45.5 months
Crack Density: 0.238 m/m^2
Span 1: 0.235 m/m^2
Span 2: 0.240 m/m^2

Figure 3.11: Crack survey of bridge 62729

A 15 ft (4.6 m) section in the center of the roadway was not surveyed due to traffic lane closure limitations. The cracking performance of the deck can be described based on cracking on the west side of the deck (the top section as shown in Figure 3.11) and cracking on the east side of the deck (bottom section in Figure 3.11). The majority of the cracks on the west side were randomly oriented or transverse, with some cracks extending from the south end of the deck or normal to the skew orientation. The majority of cracks on the east side were transverse, 5 to 10 ft (1.5 to 3.1 m) apart along the bridge length. Eighty-five percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Crack widths ranged from 0.005 in. (0.127 mm) to 0.016 in. (0.406 mm), with an average of 0.010 in. (0.254 mm).

3.11 BRIDGE 62731 (WITH FIBERS)

Bridge 62731 was constructed in one placement on August 8, 2016. The bridge carries westbound traffic on T.H. 36 over Lexington Ave. in Roseville, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and Ames Construction, respectively. The bridge has one span with a total length of 89 ft-8 in. (27.3 m). The deck has a 42 ft (12.8 m) wide roadway, a 1 ft-8 in. (490 mm) wide barrier on the north side, and a 1 ft-6 in. (460 mm) wide barrier on the south side, for a total deck width of 45 ft-2 in. (13.8 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with no skew. The crack survey was performed at a deck age of 47.4 months, and the deck had a crack density of 0.120 m/m^2. The crack map is shown in Figure 3.12.



Bridge Number: 62731
Bridge Location: T.H.36 WB over Lexington Ave., City of Roseville, MN
Construction Date: 8/8/2016
Crack Survey Date: 7/21/2020

Bridge Length: 89.7 ft (27.3 m)
Bridge Width: 42.0 ft (12.8 m)
Skew: 0°
Number of Spans: 1
Span 1: 89.7 ft (27.3 m)
Number of Placements: 1

Bridge Age: 47.4 months
Crack Density: 0.120 m/m^2
Span 1: 0.120 m/m^2

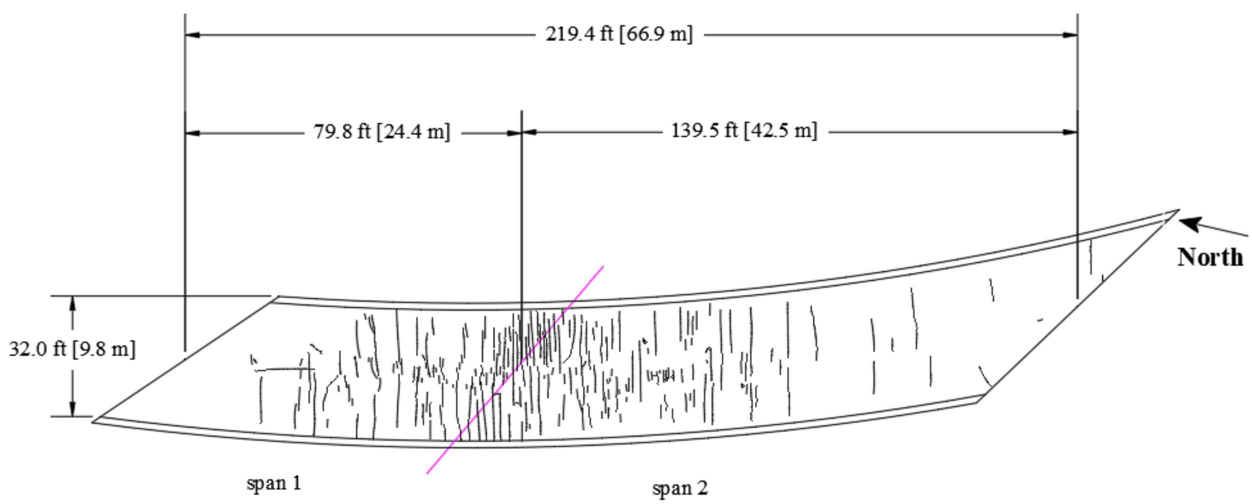
Figure 3.12: Crack survey of bridge 62731

Figure 3.13: Fiber ball pop-out in 62731

The majority of the cracks were short (with crack lengths below 1 ft [305 mm]) and randomly positioned over the bridge deck. Most of the cracks were observed near the east abutment. Some longitudinal cracks extend from each abutment. A single fiber ball pop-out was found approximately 5 ft (1.5 m) from the west abutment, as shown in Figure 3.13. Forty-seven percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Some cracks were observed perpendicular to both end abutments. Crack widths ranged from 0.004 in. (0.102 mm) to 0.010 in. (0.254 mm), with an average of 0.006 in. (0.152 mm).

3.12 BRIDGE 62831 (WITH FIBERS)

Bridge 62831 was constructed in one placement on October 2, 2015. The bridge carries eastbound traffic on I-94 EB over I-94 WB in St. Paul, Minnesota. The concrete supplier and the contractor were Aggregate Industries and Lunda Construction Company, respectively. The curved bridge has two spans. The lengths of the spans as shown on the plans are 79 ft-10⅛ in. (24.4 m) and 139 ft-6¼ in. (42.5 m), with a total length of 219 ft-4⅜ in. (69.9 m). The deck has a 32 ft (9.8 m) wide roadway and a 1 ft-8 in. (490 mm) wide barrier on each side. The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by steel girders with a skew ranging from -33º 54'33" to -43º 34'3". The crack survey was performed at a deck age of 57.6 months, and the deck had a crack density of 0.567 m/m^2. The crack map is shown in Figure 3.14.



Bridge Number: 62831
Bridge Location: I-94EB (on ramp) over I-94WB , City of St. Paul, MN
Construction Date: 10/2/2015
Crack Survey Date: 7/20/2020

Bridge Length: 219.4 ft (66.9 m)
Bridge Width: 32.0 ft (9.8 m)
Skew: -33°54'33" to -43°34'03"
Number of Spans: 2
Span 1: 79.8 ft (24.4 m)
Span 2: 139.5 ft (42.5 m)
Number of Placements: 1

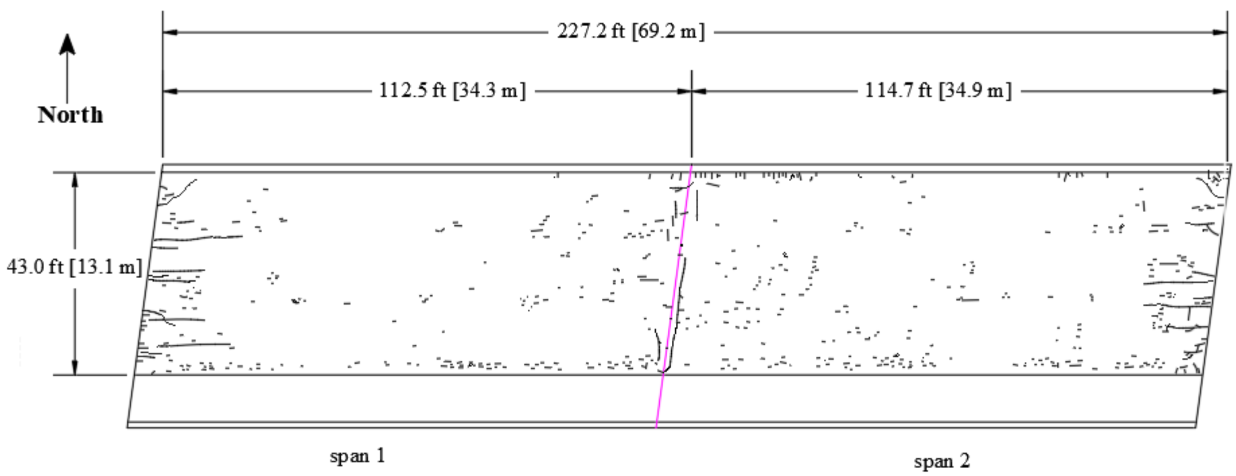
Bridge Age: 57.6 months
Crack Density: 0.567 m/m^2
Span 1: 0.504 m/m^2
Span 2: 0.597 m/m^2

Figure 3.14: Crack survey of bridge 62831

The majority of the cracking is in the transverse direction. These cracks were observed throughout the deck and formed parallel to the top deck reinforcement, not parallel to the skew of the bridge. The concentration of the cracks was mainly around the pier located 80 ft (24.4 m) from the north abutment. A single, longitudinal crack, extending approximately 15 ft (4.6 m), has formed along the centerline in the north span 1. In addition, a single diagonal crack propagated from the south end abutment. Ninety-one percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Crack widths ranged from 0.009 in. (0.229 mm) to 0.025 in. (0.635 mm), with an average of 0.019 in. (0.483 mm).

3.13 BRIDGE 62873 (WITHOUT FIBERS)

Bridge 62873 was constructed in one placement on July 13, 2016. The bridge carries eastbound traffic on I-35 W under County Rd. in Arden Hills, Minnesota. The concrete supplier and the contractor were AVR Inc. and Ames Construction, respectively. The bridge has two spans with lengths of 112 ft-5 ½ in. (34.3 m) and 114 ft-8 ½ in. (34.9 m), with a total length of 227 ft-2 in. (69.2 m). The deck has a 43 ft (13.1 m) wide roadway with a 10 ft (3.1 m) sidewalk on the south side, a 1 ft-8 in. (490 mm) wide barrier on the north side, and a 1 ft-3 in. (380 mm) wide barrier on the south side, for a total deck width of 55 ft-11 in. (17.0 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of -7º 41’49”. The crack survey was performed at a deck age of 48.3 months, and the deck had a crack density of 0.207 m/m^2. The crack map is shown in Figure 3.15.



Bridge Number: 62873
Bridge Location: I-35 W Under County Rd, Arden Hills City, MN
Construction Date: 7/13/2016
Crack Survey Date: 7/22/2020

Bridge Length: 227.2 ft (69.2 m)
Bridge Width: 43.0 ft (13.1 m)
Skew: -7°41'49"
Number of Spans: 2
Span 1: 112.5 ft (34.3 m)
Span 2: 114.7 ft (34.9 m)
Number of Placements: 1

Bridge Age: 48.3 months
Crack Density: 0.207 m/m^2
Span 1: 0.195 m/m^2
Span 2: 0.219 m/m^2

Figure 3.15: Crack survey of bridge 62873

Only the 43-ft (13.1 m) roadway was surveyed. While the majority of cracks (75%) observed on the deck were short longitudinal cracks (crack lengths below 1 ft [305 mm]) distributed over the entire deck area, several larger longitudinal cracks were found near the abutments, possibly due to restraint from the abutments in the transverse direction (Schmitt and Darwin 1995, Miller and Darwin 2000). Transverse cracks also formed near the center pier, with cracks ranging in length from 7 to 25 ft (2.1 to 7.6 m). Crack widths ranged from 0.003 in. (0.076 mm) to 0.020 in. (0.508 mm), with an average of 0.010 in. (0.254 mm).

3.14 BRIDGE 62890 (WITHOUT FIBERS)

Bridge 26890 was constructed in one placement on October 13, 2015. The bridge carries traffic on C.S.A.H.12 over I-35W in Arden Hills, Minnesota. The concrete supplier and the contractor were Cemstone and Ames Construction, respectively. The bridge has two equal span lengths of 140 ft-5 ½ in. (42.8 m), for a total length of 280 ft-11 in. (86.7 m). The deck has a 33 ft (10.1 m) wide roadway with a 10 ft (3.0 m) sidewalk on the south side, a 1 ft-8 in. (490 mm) wide barrier on the north side, and a 1 ft-3 in. (380 mm) wide barrier on the south side, for a total deck width of 45 ft-11 in. (13.9 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of -8º 30'57". The crack survey was performed at a deck age of 57.3 months, and the deck had a crack density of 0.060 m/m^2. The crack map is shown in Figure 3.16.

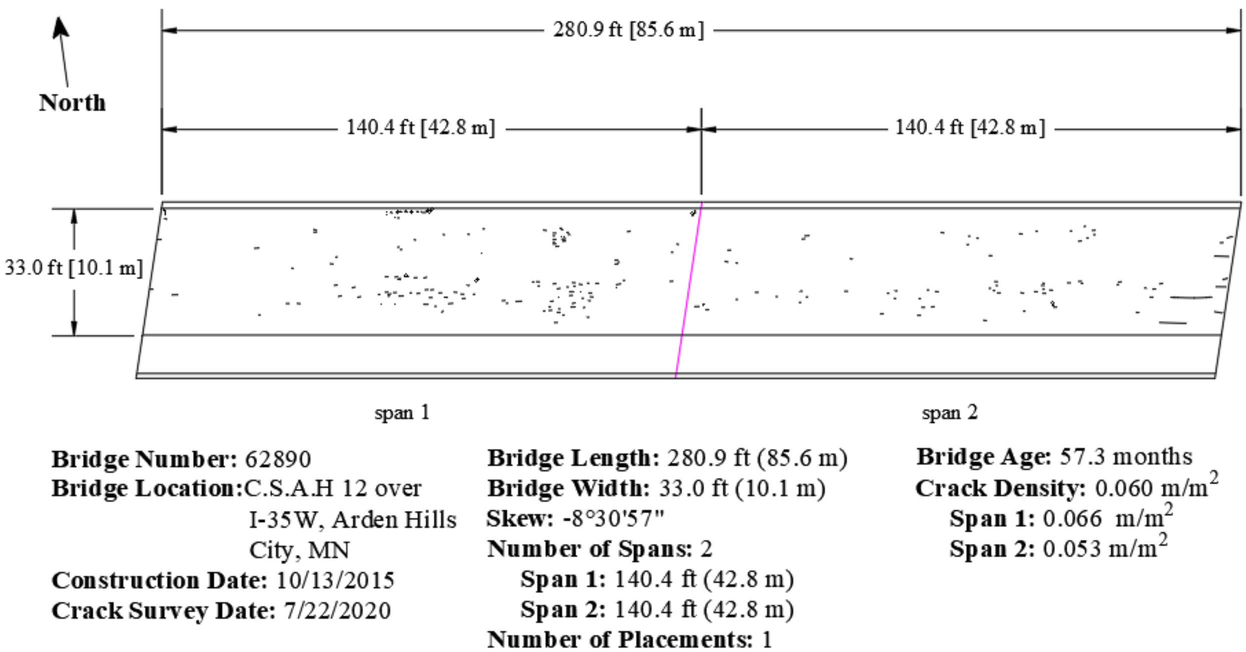
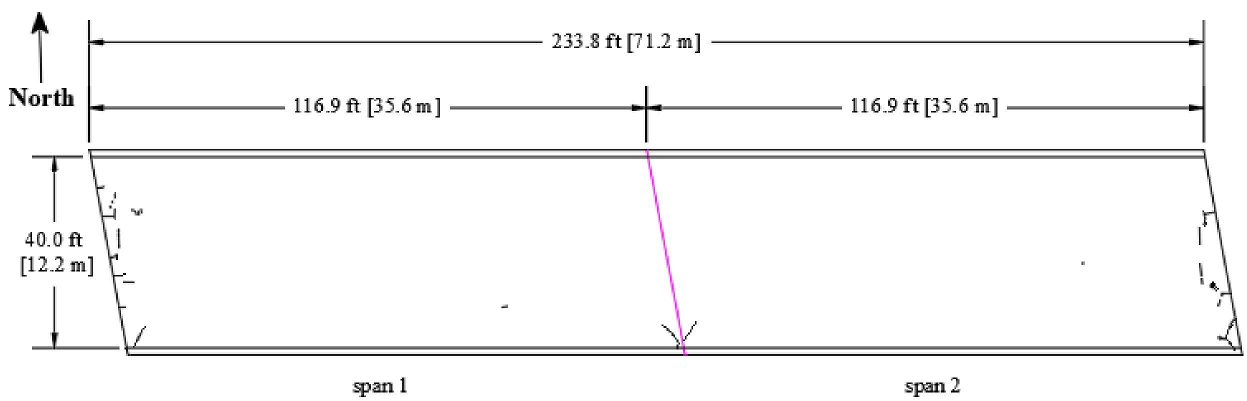


Figure 3.16: Crack survey of bridge 62890

Only the 33-ft (10.1 m) roadway of the bridge deck was surveyed. The majority of cracks (87%) were short longitudinal cracks (crack lengths below 1 [305 mm]) distributed over the entire deck area. Some longitudinal cracks extended from the east abutment. Crack widths ranged from 0.002 in. (0.051 mm) to 0.010 in. (0.254 mm), with an average of 0.004 in. (0.102 mm).

3.15 BRIDGE 69137 (WITH FIBERS)

Bridge 69137 was constructed in one placement on August 29, 2018. The bridge carries traffic on T.H. 37 over T.H. 53 W in Fayal Township, Minnesota. The concrete supplier and the contractor were Duluth Ready Mix and Redstone Construction, respectively. The bridge has two equal span lengths of 116 ft-10 ½ in. (35.6 m), for a total length of 233 ft-9 in. (71.2 m). The deck has a 40 ft (12.2 m) wide roadway, with a 1 ft-6 in. (460 m) wide barrier on each side, for a total deck width of 43 ft (13.1 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with a skew of 10º 37’1”. The crack survey was performed at a deck age of 23.5 months, and the deck had a crack density of 0.026 m/m^2. The crack map is shown in Figure 3.17.



Bridge Number: 69137
Bridge Location: T.H.37 over T.H.53, Fayal TWP, MN
Construction Date: 8/29/2018
Crack Survey Date: 8/12/2020

Bridge Length: 233.8 ft (71.2 m)
Bridge Width: 40.0 ft (12.2 m)
Skew: 10°37'4.1"
Number of Spans: 2
Span 1: 116.9 ft (35.6 m)
Span 2: 116.9 ft (35.6 m)
Number of Placements: 1

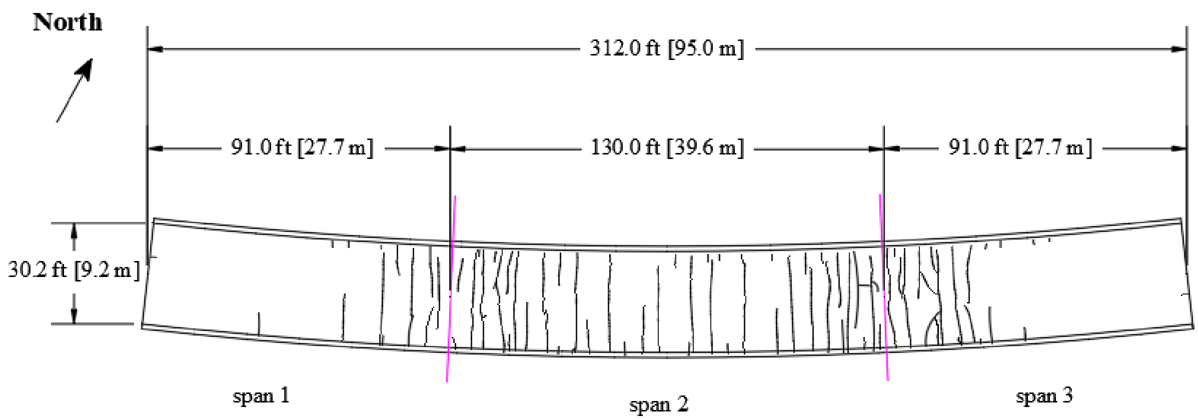
Bridge Age: 23.5 months
Crack Density: 0.026 m/m^2
Span 1: 0.026 m/m^2
Span 2: 0.025 m/m^2

Figure 3.17: Crack survey of bridge 69137

The majority of the cracks were longitudinal and transverse cracks extended from and near east and west abutments. Two diagonal cracks were observed on either side of the central pier, with approximately 5 ft (1.5 m) in length. Seventy percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Crack widths ranged from 0.007 in. (0.178 mm) to 0.009 in. (0.229 mm), with an average of 0.008 in. (0.203 mm).

3.16 BRIDGE 69839 (WITH FIBERS)

Bridge 69839 was constructed in one placement on September 9, 2018. The bridge carries traffic on Michigan St. over T.H. 194 SB in Duluth, Minnesota. The concrete supplier and the contractor were Duluth Ready Mix and PCI Roads, respectively. The curved bridge has three spans. The nominal lengths of the spans are 91 ft (27.7 m), 130 ft (39.6 m), and 91 ft (27.7 m), with a total length of 312 ft (95.0 m). The deck has a 30 ft-4 in. (9.2 m) wide roadway and a 1 ft-6 in. (460 m) wide barrier on each side, for a total deck width of 33 ft-4 in. (10.2 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by steel girders with a skew ranging from -35º 35’30” to 35º 35’30”. The crack survey was performed at a deck age of 22.8 months, and the deck had a crack density of 0.374 m/m^2. The crack map is shown in Figure 3.18.



Bridge Number: 69839
Bridge Location: Michigan St. over T.H. 194 SB, City of Duluth, MN
Construction Date: 9/19/2018
Crack Survey Date: 8/11/2020

Bridge Length: 260.0 ft (79.2 m)
Bridge Width: 30.2 ft (9.2 m)
Radius: 1432.395 ft
Number of Spans: 3
Span 1: 91.0 ft (27.7 m)
Span 2: 130.0 ft (39.6 m)
Span 3: 91.0 ft (27.7 m)
Number of Placements: 1

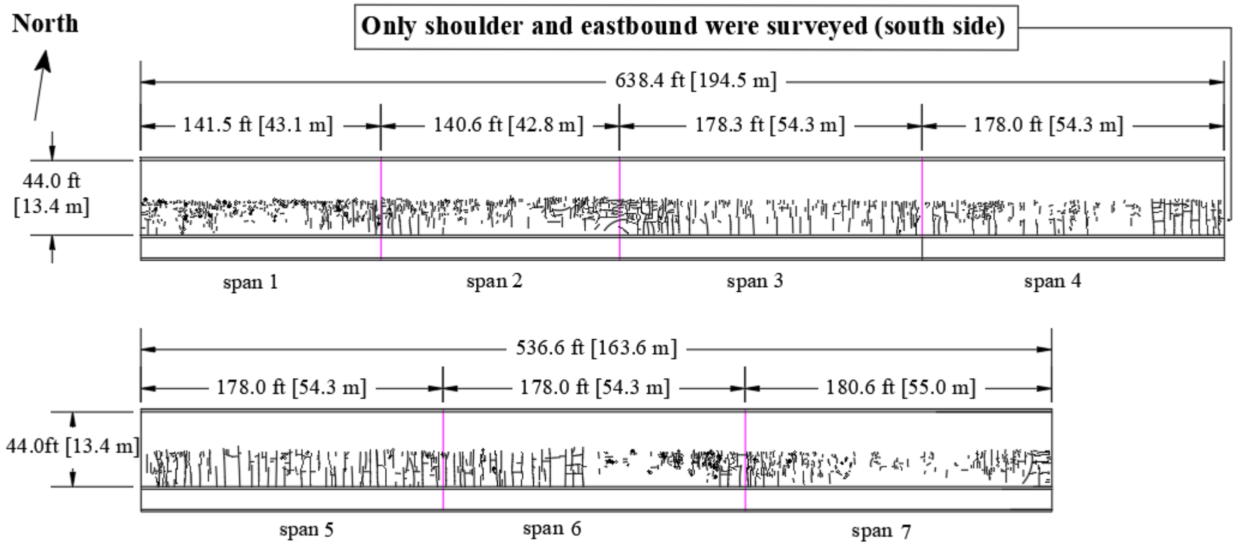
Bridge Age: 22.8 months
Crack Density: 0.374 m/m^2
Span 1: 0.182 m/m^2
Span 2: 0.566 m/m^2
Span 3: 0.292 m/m^2

Figure 3.18: Crack survey of bridge 69839

The majority of cracks propagated in the transverse direction, occasionally extending across the entire deck width. Transverse cracks were observed mainly in span 2 and near both piers of the deck, 5 to 10 ft (1.5 to 3.1 m) apart along with the bridge length. No cracking was observed within approximately 40 ft (12.2 m) from the east and west abutments with the exception of a longitudinal crack extending from each abutment. Ninety-one percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Crack widths ranged from 0.007 in. (0.178 mm) to 0.020 in. (0.508 mm), with an average of 0.012 in. (0.305 mm).

3.17 BRIDGE 71004 (WITH FIBERS)

Bridge 71004 was constructed in four placements. Placement 1 was constructed on April 21, 2017, Placement 2 was constructed on May 4, 2017, Placement 3 was constructed on June 1, 2017, and Placement 4 was constructed on June 6, 2017. The location of the placements is, however, not known. The bridge carries traffic on T.H. 24 over the Mississippi River in Clearwater, Minnesota. The concrete supplier and the contractor were Hardrives Inc. and Lunda Construction Company, respectively. The bridge has seven spans with lengths of 141 ft-6 in. (43.1 m), 140 ft-7 in. (42.8 m), 178 ft-3 in. (54.3 m), 178 ft (54.3 m), 178 ft (54.3 m), 178 ft (54.3 m), and 180 ft-6 in. (55.0 m), with a total length of 1175 ft (358.1 m). The deck has a 44 ft (13.4 m) wide roadway with a 12 ft (3.7 m) sidewalk on the south side, a 1 ft-8 in. (490 mm) wide barrier on the north side, and a 1 ft-3 in. (380 mm) wide barrier on the south side, for a total deck width of 60 ft-5 in. (17.6 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with no skew. The crack survey was performed at deck ages of 38.6 months for Placement 1, 38.2 months for Placement 2, 37.3 months for Placement 3, and 37.1 months for Placement 4. The crack density of 0.699 m/m^2 was calculated for the entire deck. The crack map is shown in Figure 3.19.



Bridge Number: 71004
Bridge Location: T.H.24 over Mississippi River, Clearwater, MN
Construction Date:
Placement 1: 4/21/2017
Placement 2: 5/4/2017
Placement 3: 6/1/2017
Placement 4: 6/6/2017
Crack Survey Date: 7/9/2020

Bridge Length: 1175.0 ft (358.1 m)
Bridge Width:44.0 ft (13.4 m)
Skew: 0°
Number of Spans: 7
Span 1: 141.5 ft (43.1 m)
Span 2: 140.6 ft (42.8 m)
Span 3: 178.3 ft (54.3 m)
Span 4: 178.0 ft (54.3 m)
Span 5: 178.0 ft (54.3 m)
Span 6: 178.0 ft (54.3 m)
Span 7: 180.6 ft (55.0 m)
Number of Placements: 4

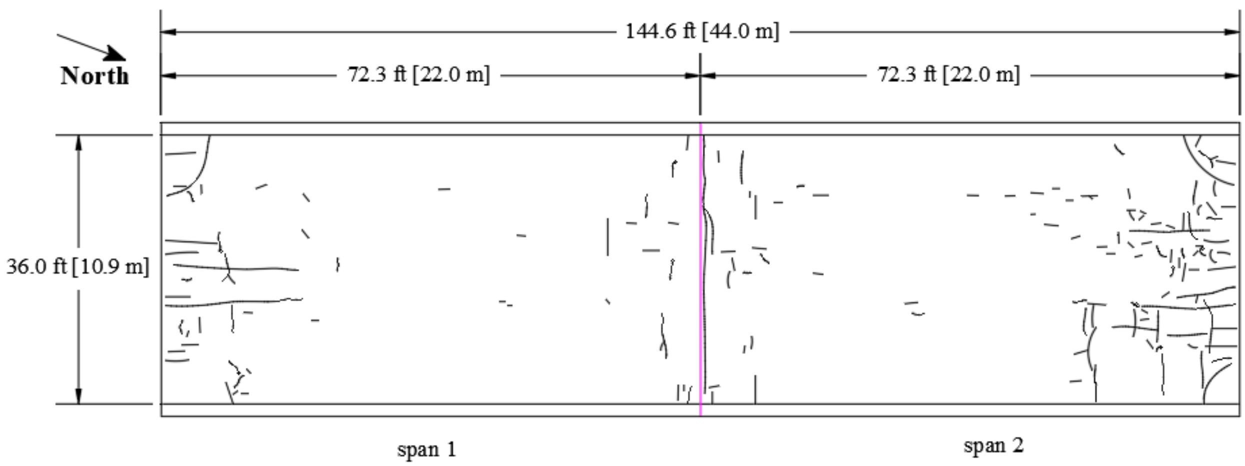
Bridge Age:
Placement 1: 38.6 months
Placement 2: 38.2 months
Placement 3: 37.3 months
Placement 4: 37.1 months
Crack Density: 0.699 m/m^2
Span 1: 0.667 m/m^2
Span 2: 0.752 m/m^2
Span 3: 0.751 m/m^2
Span 4: 0.625 m/m^2
Span 5: 0.722 m/m^2
Span 6: 0.707 m/m^2
Span 7: 0.672 m/m^2

Figure 3.19: Crack survey of bridge 71004

Only the right shoulder and eastbound lane (south end) of the bridge were surveyed due to traffic control limitations. Significant transverse cracking was found throughout the deck. The transverse cracks extend across the entire surveyed width along the full length of the bridge. Some longitudinal cracks were extended from each abutment. Less cracking was observed in spans 6 and 7. Ninety-five percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Crack widths ranged from 0.010 in. (0.254 mm) to 0.030 in. (0.762 mm), with an average of 0.017 in. (0.432 mm).

3.18 BRIDGE 73047 (WITH FIBERS)

Bridge 73047 was constructed in one placement on July 31, 2015. The bridge carries traffic on T.H. 4 over Sauk River in Melrose Township, Minnesota. The concrete supplier and the contractor were Worms Lumber and Ready-Mix Inc. and Robert R. Schroeder Construction Inc., respectively. The bridge has two equal span lengths of 72 ft-4 in. (22.0 m), for a total length of 144 ft-8 in. (44.0 m). The deck has a 36 ft (10.9 m) wide roadway, with a 1 ft-8 in. (490 mm) wide barrier on each side, for a total deck width of 38 ft-4 in. (11.7 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with no skew. The crack survey was performed at a deck age of 59.3 months, and the deck had a crack density of 0.284 m/m^2. The crack map is shown in Figure 3.20.



Bridge Number: 73047
Bridge Location: T.H. 4 over the Sauk River, MN
Construction Date: 7/31/2015
Crack Survey Date: 7/8/2020

Bridge Length: 144.6 ft (44.0 m)
Bridge Width: 36.0 ft (10.9 m)
Skew: 0°
Number of Spans: 2
Span 1: 72.3 ft (22.0 m)
Span 2: 72.3 ft (22.0 m)
Number of Placements: 1

Bridge Age: 59.3 months
Crack Density: 0.284 m/m^2
Span 1: 0.193 m/m^2
Span 2: 0.374 m/m^2

Figure 3.20: Crack survey of bridge 73047

The majority of the cracks were longitudinal, extending from the abutments, possibly due to restraint from the abutments in the transverse direction (Schmitt and Darwin 1995, Miller and Darwin 2000). A long transverse crack formed near the central pier, with a crack length of approximately 33 ft (9.8 m). A few transverse cracks were also observed around the negative moment region of the deck near the pier. The use of fibers did not seem effective in limiting crack formation, as shown in Figure 3.21. Eighty-six percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Crack widths ranged from 0.006 in. (0.152 mm) to 0.025 in. (0.635 mm), with an average of 0.014 in. (0.356 mm).

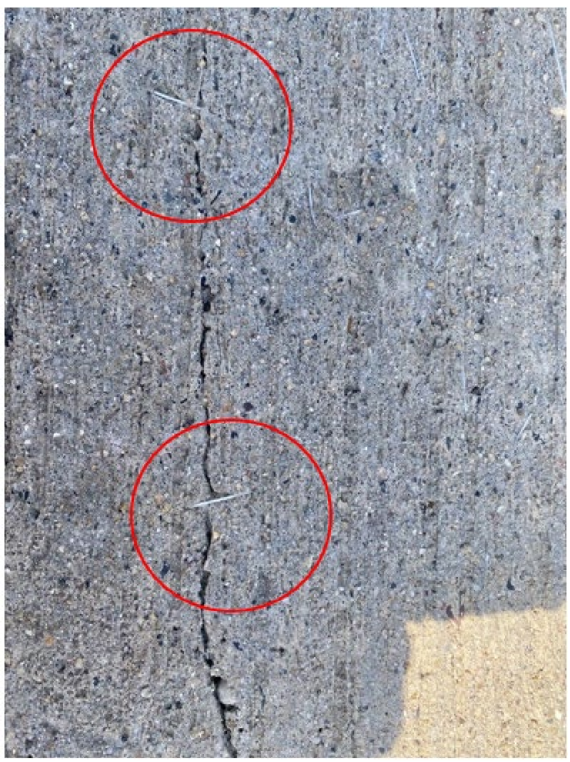
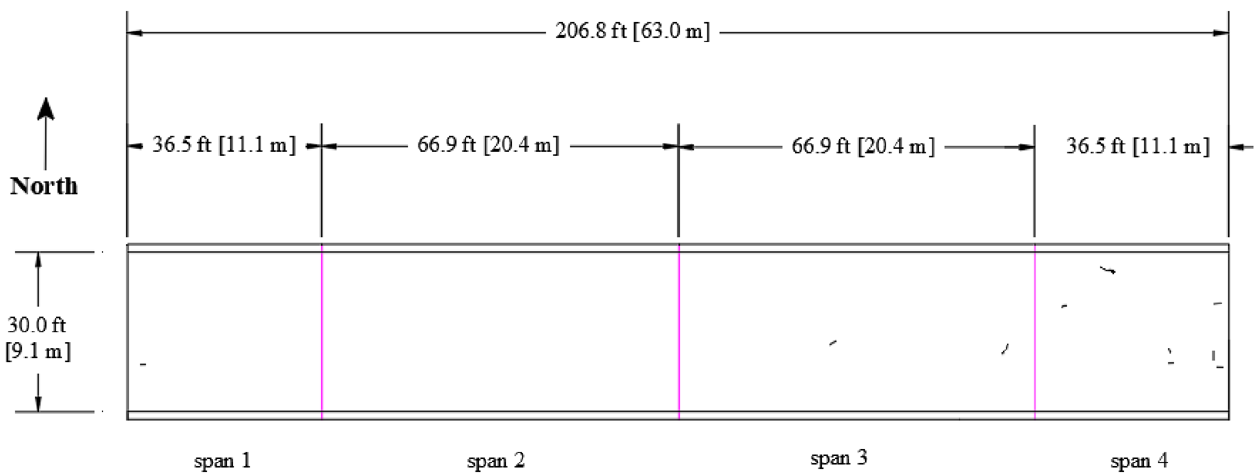


Figure 3.21: Crack propagation in the presence of fibers

3.19 BRIDGE 74805 (WITHOUT FIBERS)

Bridge 74805 was constructed in one placement on October 4, 2017. The bridge carries southbound traffic on C.S.A.H. 31 over I-35 in Owatonna, Minnesota. The concrete supplier and the contractor were Cemstone Products Company and Redstone Construction Company, respectively. The bridge has four spans with lengths of 36 ft-6 ⅛ in. (11.1 m), 66 ft-11 ¾ in. (20.4 m), 66 ft-10 ⅛ in. (20.4 m), and 36 ft-5 in. (11.1 m), with a total length of 206 ft-9 in. (63.0 m). The deck has a 30 ft (9.1 m) wide roadway and a 1 ft-6 in. (460 m) wide barrier on each side, for a total deck width of 33 ft (10.1 m). The nominal deck thickness is 9 in. (230 mm). The bridge deck is supported by prestressed concrete girders with no skew. The crack survey was performed at a deck age of 33.9 months. The crack map is shown in Figure 3.22.



Bridge Number: 74805
Bridge Location: C.S.A.H 31 over I-35, Owatonna, MN
Construction Date: 10/4/2017
Crack Survey Date: 8/3/2020

Bridge Length: 206.8 ft (63.0 m)
Bridge Width: 30 ft (9.1 m)
Skew: 0°
Number of Spans: 4
Span 1: 36.5 ft (11.1 m)
Span 2: 66.9 ft (20.4 m)
Span 3: 66.9 ft (20.4 m)
Span 4: 36.5 ft (11.1 m)
Number of Placements: 1

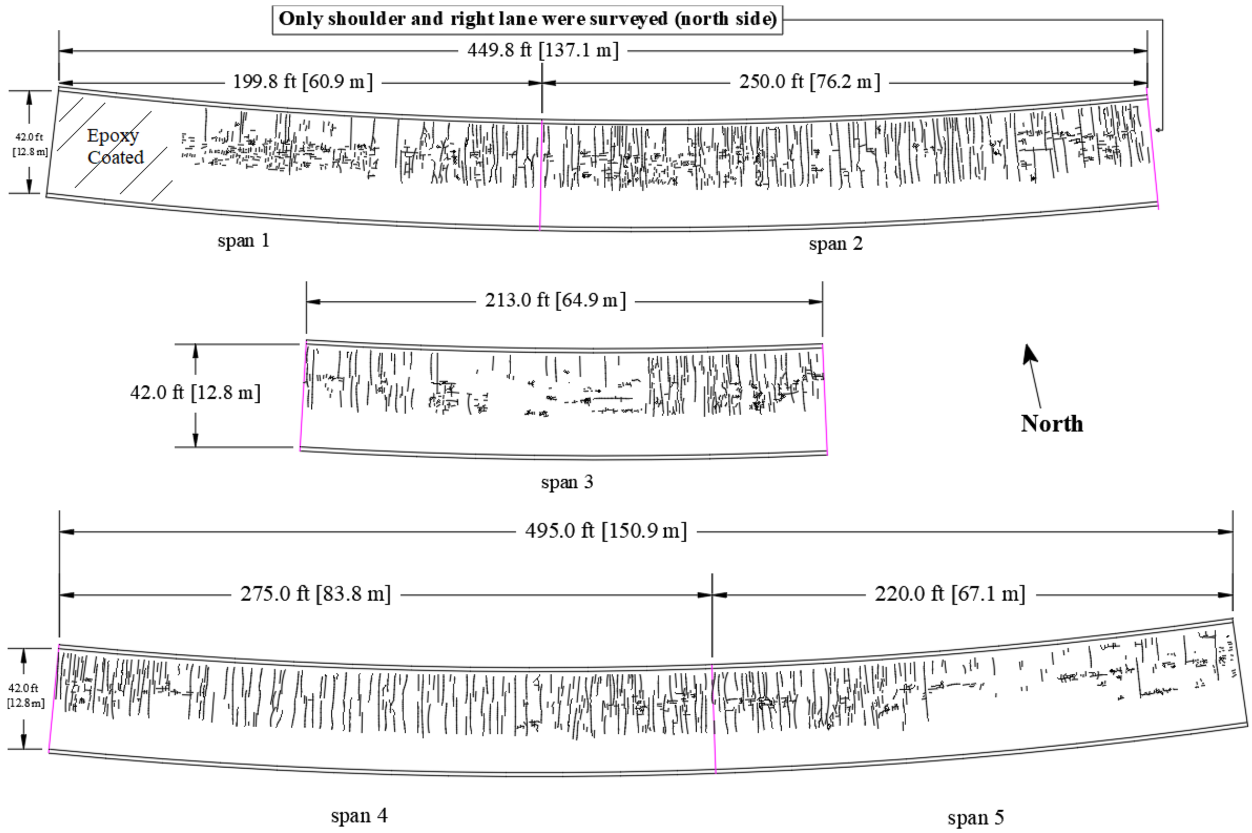
Bridge Age: 33.9 months
Crack Density: 0.007 m/m^2
Span 1: 0.002 m/m^2
Span 2: 0.000 m/m^2
Span 3: 0.005 m/m^2
Span 4: 0.030 m/m^2

Figure 3.22: Crack survey of bridge 74805

The majority of cracks were randomly positioned, distributed mainly over span 3 and span 4 of the bridge. A few longitudinal cracks were located near the east abutment. No cracks were observed in span 2. One short longitudinal crack (crack length below 1 ft [305 mm]) was observed near the west abutment. Seventy percent of the cracks had lengths greater than or equal to 1 ft (305 mm). Crack widths ranged from 0.003 in. (0.076 mm) to 0.009 in. (0.229 mm), with an average of 0.006 in. (0.152 mm).

3.20 BRIDGE 85849 (WITHOUT FIBERS)

Bridge 85849 was constructed in four placements. Placement 1 was constructed on August 14, 2015, Placement 2 was constructed on August 18, 2015, Placement 3 was constructed on August 24, 2015, and Placement 4 was constructed on August 27, 2015. The concrete placement locations, however, are not known. The bridge carries westbound traffic on T.H. 90 WB over T.H. 61 NB in Dresbach Township. The concrete supplier and the contractor were Croell and Ames Construction, respectively. The slightly curved bridge has five spans. The nominal lengths of the spans are 199 ft-9 ⅝ in. (60.9 m), 250 ft (76.2 m), 213 ft (64.9 m), 275 ft (83.8 m), and 220 ft (67.1 m), with a total length of 1157 ft-9 ⅝ in. (352.9 m). The deck is 42 ft (12.8 m) wide with a 1 ft-8 in. (490 mm) wide barrier on each side, for a total deck width of 45 ft-4 in. (13.8 m). The nominal deck thickness is 10 in. (255 mm). The bridge deck is supported by steel girders with a skew ranging from -0º 39’21” to 0º 39’21”. The crack survey was performed at a deck age of 59.7 months for Placement 1, 59.6 months for Placement 2, 59.4 months for Placement 3, and 59.3 months for Placement 4. The crack map is shown in Figure 3.23.



Bridge Number: 85849
Bridge Location: WB T.H.90 over NB T.H. 61, Dresbach TWP, MN
Construction Date:
Placement 1: 8/14/2016
Placement 2: 8/18/2016
Placement 3: 8/24/2016
Placement 4: 8/27/2016
Crack Survey Date: 8/5/2020

Bridge Length: 1157.8 ft (352.9 m)
Bridge Width: 42.0 ft (12.8 m)

Number of Spans: 5
Span 1: 199.8 ft (60.9 m)
Span 2: 250.0 ft (76.2 m)
Span 3: 213.0 ft (64.9 m)
Span 4: 275.0 ft (83.8 m)
Span 5: 220.0 ft (67.1 m)
Number of Placements: 4

Bridge Age:
Placement 1: 59.7 months
Placement 2: 59.6 months
Placement 3: 59.4 months
Placement 4: 59.3 months
Crack Density: 0.976 m/m^2
Span 1: 0.761 m/m^2
Span 2: 1.328 m/m^2
Span 3: 0.822 m/m^2
Span 4: 1.090 m/m^2
Span 5: 0.777 m/m^2

Figure 3.23: Crack survey of bridge 85849

Only one shoulder and roadway lane located at the north side of the bridge were surveyed due to limitations in traffic control. The deck surface had received an epoxy overlay within approximately 50 ft (15.2 m) of the west abutment, and thus, this section could not be surveyed. With a crack density of 0.976 m/m^2, this bridge had the highest crack density in this study. Significant transverse cracking was found throughout the deck. The transverse cracks extended across the entire surveyed width along the full length of the bridge. Some short longitudinal cracks had formed throughout the deck. Less cracking was observed in spans 3 and 5. Due to the high number of cracks on the deck, only a range for crack widths was recorded during the survey. Crack widths ranged from 0.003 in. (0.076 mm) to 0.025 in. (0.635 mm).

3.21 CRACK DENSITIES AND CRACK WIDTH RESULTS

Table 3.1 summarizes the crack survey results, including crack densities, crack widths range, and average crack widths for the 20 bridge decks covered in this report. Individual crack width measurements are provided in Appendix B. Since the information on the different placements for the decks on bridges 62729, 71004, and 85849 is not available, the age for these decks is assumed to be the average of the individual placement ages. The date of construction for bridge 21803 is not available. Crack widths for decks with fibers ranged from 0.002 in. (0.051 mm) to 0.030 in. (0.762 mm), with an average of 0.011 in. (0.279 mm); crack widths for decks without fibers ranged from 0.002 in. (0.051 mm) to 0.025 in. (0.635 mm), with an average of 0.007 in. (0.178 mm).

Table 3.1: Crack survey results

Bridge Number	Technology	Type of Girder	Age (months)	Crack Density (m/m^2)	Crack Width Range (in.)	Avg. Crack Width (in.)
27W06	Fibers	Prestressed	26.7	0.066	0.002 to 0.005	0.003
07051	Fibers	Prestressed	35.3	0.139	0.003 to 0.013	0.008
9691	Fibers	Steel	46.8	0.779	0.004 to 0.030	0.012
21802	No Fibers	Prestressed	33.6	0.103	0.004 to 0.009	0.005
21803	No Fibers	Prestressed	-[a]	0.009	0.004	0.004
21804	No Fibers	Prestressed	34.1	0.206	0.004 to 0.012	0.006
55009	Fibers	Steel	47.1	0.293	0.003 to 0.013	0.008
58821	No Fibers	Prestressed	46.1	0.071	0.009 to 0.020	0.015
58824	Fibers	Prestressed	25.5	0.141	0.006 to 0.020	0.016
62729[b]	Fibers	Prestressed	46.3	0.238	0.005 to 0.016	0.010
62731	Fibers	Prestressed	47.4	0.120	0.004 to 0.010	0.006
62831	Fibers	Steel	57.6	0.567	0.009 to 0.025	0.019
62873	No Fibers	Prestressed	48.3	0.207	0.003 to 0.020	0.010
3062890	No Fibers	Prestressed	57.3	0.060	0.002 to 0.010	0.004
69137	Fibers	Prestressed	23.5	0.026	0.007 to 0.009	0.008
69839	Fibers	Steel	22.8	0.374	0.007 to 0.020	0.012
71004[b]	Fibers	Prestressed	37.8	0.699	0.010 to 0.030	0.017
73047	Fibers	Prestressed	59.3	0.284	0.006 to 0.025	0.014
74805	Fibers	Prestressed	33.9	0.007	0.003 to 0.009	0.006
85849[b]	No Fibers	Steel	59.5	0.976	0.003 to 0.025	-[c]

[a] Data is not available
[b] Deck age is average of placement ages
[c] Not available
Note: 1 in. = 25.4 mm.

3.22 CRACK DENSITIES AS A FUNCTION OF CRACK LENGTH

Figures 3.24 and 3.25 compare crack densities based on (1) total cracking, (2) cracks with lengths ≥ 1 ft (305 mm), and (3) cracks with lengths ≥ 6 in. (150 mm), for decks with and without fibers, respectively. As shown in the figures, the vast majority of the cracks that contribute to crack density have lengths ≥ 1 ft (305 mm) for most of the bridges.

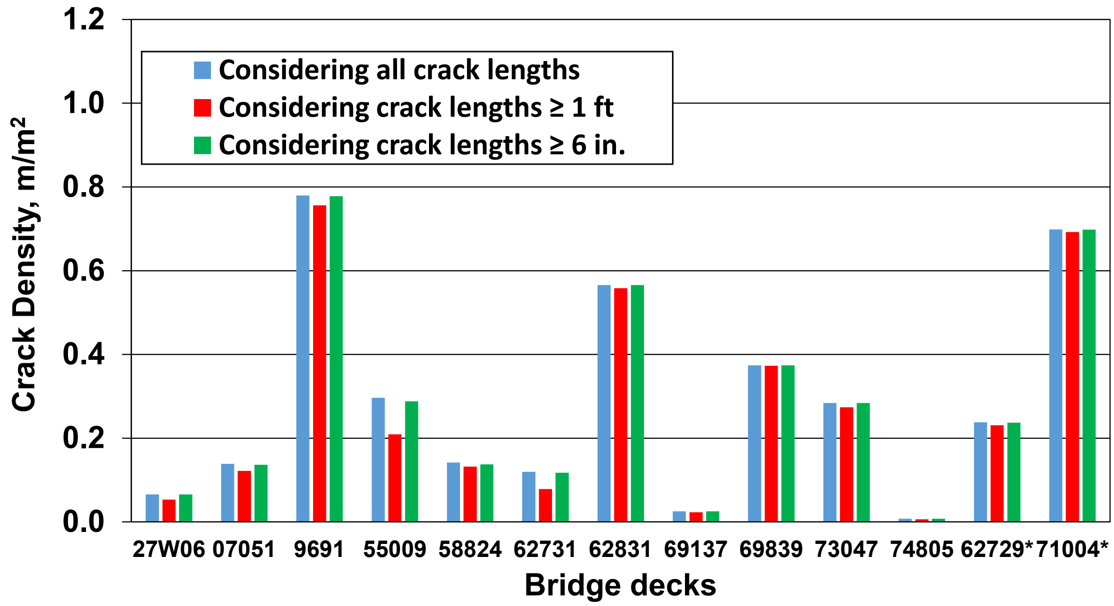


Figure 3.24: Comparison of crack densities, total, cracks with lengths ≥ 1 ft (305 mm), and cracks with lengths ≥ 6 in. (150 mm), for decks containing fibers

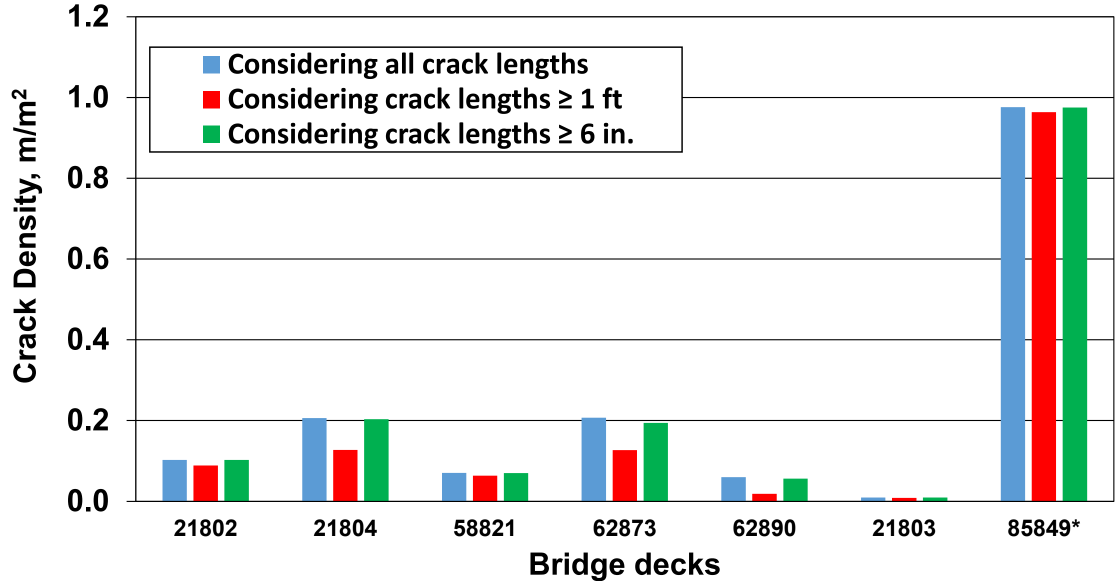


Figure 3.25: Comparison of crack densities, total, cracks with lengths ≥ 1 ft (305 mm), and cracks with lengths ≥ 6 in. (150 mm), for decks not containing fibers

CHAPTER 4: CRACK DENSITY ESTIMATION AT 36 MONTHS

The crack density of bridge decks increases over time. While the 20 bridge decks surveyed in this study were constructed between 2015 and 2018, a fair comparison is not possible unless the crack densities are compared at the same deck age. In studies that are performed over many years, estimating a crack density for a given bridge deck at a given age usually involves simple interpolation. In the present study, however, another approach is necessary, which is based on rates of change in crack density observed for multiple bridge decks from previous studies. The procedure, described in Appendix C, is used to estimate the crack densities of the bridges in this study at an age of 36 months, as shown in Table 4.1. The bridge decks have been categorized into four groups: bridge decks supported by prestressed concrete girders incorporating nonmetallic fibers are labeled as PS-F; bridge decks supported by precast prestressed concrete girders without a crack-reducing technology are labeled as PS; bridge decks supported by steel girders incorporating nonmetallic fibers are labeled as S-F; and bridge decks supported by steel girders without a crack-reducing technology are labeled as S.

As illustrated in Table 4.1, the 36-month estimated crack densities range from 0.010 to 0.696 m/m^2 for the PS-F decks, from 0.028 to 0.211 m/m^2 for the PS decks, and from 0.260 to 0.763 m/m^2 for the S-F decks. The 36-month crack density was 0.942 m/m^2 for the single S deck. The *p* values obtained in the Student's t-test between the average 36-month estimated crack densities of the bridge decks are shown in Table 4.2. Student's t-test was not performed for the single S deck.

Table 4.1: Estimated crack densities at an age of 36-months for decks surveyed for this report

Bridge Number	Category[c]	Deck Age (Month)	Paste Content (%)	Measured Crack Density (m/m^2)	36-Month Estimated Crack Density (m/m^2)
27W06	PS-F	26.7	27.1	0.066	0.083
07051	PS-F	35.3	26.6	0.139	0.141
58824	PS-F	25.5	26.8	0.141	0.166
62729[b]	PS-F	46.3	26.4	0.238	0.210
62731	PS-F	47.4	26.8	0.12	0.098
69137	PS-F	23.5	26.5	0.026	0.046
71004[b]	PS-F	37.8	29.6	0.699	0.696
73047	PS-F	59.3	26.2	0.284	0.220
74805	PS-F	33.9	26.9	0.007	0.010
21802	PS	33.6	24.0	0.103	0.108
21803	PS	-[a]	24.0	0.009	-[a]
21804	PS	34.1	24.0	0.206	0.211
58821	PS	46.1	26.8	0.071	0.054
62873	PS	48.3	25.3	0.207	0.177
62890	PS	57.3	26.4	0.06	0.028
9691	S-F	46.8	23.9	0.779	0.763
55009	S-F	47.1	25.8	0.293	0.260
62831	S-F	57.6	25.9	0.567	0.472
69839	S-F	22.8	26.5	0.374	0.428
85849[b]	S	59.5	25.8	0.976	0.942

[a] Data is not available
[b] Deck age is average of placement ages
[c] PS = prestressed; PS-F = prestressed girders with fibers; S = steel; S-F = steel girders with fibers

As shown in Table 4.1, the deck for bridge 71004, which incorporated fibers (PS-F), has the highest crack density among decks supported by prestressed concrete girders. As will be discussed in Chapter 5, this performance is likely related to the fact that this deck had the highest paste content (29.6%) of the decks in this study. Many studies have indicated that cracking will increase as the paste content of the concrete mixture exceeds a threshold value of approximately 27%, regardless of incorporated crack-reducing technologies. An increase in cracking has also been correlated with poor construction procedures (Khajehdehi and Darwin 2018, Feng and Darwin 2020, Lafikes et al. 2020). This may be the case for the decks on bridges 85849, 9691, 62831, and 69839, all supported by steel girders, that have crack densities above 0.4 m/m^2.

Table 4.2: *p*-values obtained in Student's t-test for comparing the 36-month estimated crack density

Bridges	Group	PS-F	PS	S-F	S
Group	**Ave. of 36-month estimated crack density (m/m^2)**	0.186	0.116	0.481	0.942
PS-F	0.186		0.482	0.035	-[a]
PS	0.116			0.008	-[a]
S-F	0.481				-[a]
S	0.942				

[a] Inadequate data to perform Student's t-test

As shown in Table 4.2, the difference in the average 36-month estimated crack densities of the PS-F and PS decks is not statistically significant (*p*-value of 0.482), indicating that incorporating fibers did not affect the extent of cracking for the prestressed concrete girders. The difference in the average 36-month estimated crack density of the PS-F and S-F decks is statistically significant (*p*-value of 0.035), indicating that the type of girder (steel or prestressed concrete girders) has an effect on the extent of cracking, as has been demonstrated before (*Durability* 1970).

CHAPTER 5: BRIDGE DECKS USED FOR COMPARISON WITH SURVEYED DECKS

Crack survey results from 74 monolithic (one-coarse) bridge deck placements in Kansas, Virginia, and Indiana are used to help evaluate the 20 bridge decks surveyed in this study. The earlier survey results are based on research at the University of Kansas (KU) dating back to the early 1990s. Over that period, KU surveyors have performed more than 665 field surveys on nearly 227 bridge deck placements. Previous studies have shown that although many factors are involved in bridge deck cracking, the primary factors are a function of the concrete material properties and construction procedures. The primary variables considered include paste content, ranging from 22.8 to 29.4%, crack-reducing technology, such as use of low-cracking high-performance concrete (LC-HPC) specifications, internal curing (IC), fiber reinforcement (FRC), shrinkage-reducing admixtures (SRA), girder type (steel, prestressed concrete, or box girders), and construction procedures (of the 74 decks, 62 were constructed with good construction procedures and 12 with poor construction procedures). Each placement is treated as a different deck and analyzed separately. The procedure described in Appendix D is used to calculate the crack densities of the 74 monolithic bridge decks in this chapter at an age of 36 months, as shown in Tables 5.8 and 5.9. The bridge decks have been categorized into eight groups as described in the following sections. Discussion and results are provided in Chapter 6.

5.1 BRIDGE DECKS WITH GOOD CONSTRUCTION PROCEDURES

The 62 bridge deck placements with no construction issues are organized into seven groups. Each group includes decks with at least two surveys at different ages. The decks in each group have the same type of deck, girders, and crack-reducing technologies.

Group 1 includes 43 bridge deck placements with the decks supported by steel girders without the use of a crack-reducing technology with the exception that some decks were constructed following low-cracking high-performance concrete (LC-HPC) specifications. Surveys on 24 of the placements are reported by Schmitt and Darwin (1995), Miller and Darwin (2000), and Lindquist et al. (2005) on decks constructed following Standard Kansas Department of Transportation (KDOT) specifications. Surveys on 12 of the placements are reported by Lindquist et al. (2008), McLeod et al. (2009), Yuan et al. (2011), Pendergrass and Darwin (2014), Bohaty et al. (2013), and Alhmood et al. (2015) on decks constructed in Kansas as part of a 13-year two-phase Pooled-Fund study at KU following low-cracking high-performance concrete specifications. Surveys on two of the decks are reported by Harley et al. (2011) and Shrestha et al. (2013). These bridges are located on highway US-59 south of Lawrence, Kansas and are referred to as the US-59 decks. Surveys on three of the decks, referred to as Control, are reported by Feng and Darwin (2020). These bridges are located on highway K-10 south of Lawrence, Kansas. Surveys on one deck, referred to as VA Control, constructed near Fredericksburg, Virginia, are reported by Polley et al. (2015) and Feng and Darwin (2020), and surveys on one deck, referred to as Extra Control, constructed in 2005 in Kansas, is described Khajehdehi and Darwin (2018). The bridge deck placements in Group 1 are labeled S. The decks in this group had paste contents ranging from 23.4 to 29.4% of the concrete volume, as shown in Table 5.1.

Table 5.1: Paste contents of the bridge decks in Group 1, (S)

Bridge Deck Placement	Paste Content (%)	Bridge Deck Placement	Paste Content (%)
Conv*. 3-046 Ctr. Deck (S)	25.7	Conv. 99-076 North (West Ln.) (S)	28.7
Conv. 3-045 E. Ctr. Deck (S)	26.4	Conv. 99-076 p4 (S)	28.7
Conv. 70-095 Deck (S)	27.2	LC-HPC 1 p1 (S)	24.6
Conv. 70-104 Deck (S)	27.2	LC-HPC 1 p2 (S)	24.6
Conv. 70-103 Left (S)	27.2	LC-HPC 2 (S)	24.6
Conv. 70-103 Right (S)	27.2	LC-HPC 4 p2 (S)	23.4
Conv. 3-045 East Deck (S)	26.4	LC-HPC 5 (S)	23.9
Conv. 3-045 Ctr. Deck (S)	26.4	LC-HPC 6 (S)	24.4
Conv. 3-046 East Deck (S)	26.4	LC-HPC 7 (S)	24.6
Conv. 99-076 North (East Ln.) (S)	28.7	LC-HPC 9 (S)	24.2
Conv. 56-148 Deck (S)	27.2	LC-HPC 11 (North Ln.) (S)	23.4
Conv. 75-044 Deck (S)	27.9	LC-HPC 15 (S)	22.8
Conv. 3-045 West Deck (S)	26.4	LC-HPC 16 (S)	22.8
Conv. 3-045 W. Ctr. Deck (S)	26.4	LC-HPC 17 (S)	24.6
Conv. 3-046 West Deck (S)	26.4	US 59 1 (S)	24.0
Conv. 70-107 Deck (S)	27.2	US 59 2 (S)	24.0
Conv. 56-142 N. Pier (S)	26.5	Control 5 (Eastbound) (S)	24.7
Conv. 56-142 + Moment (S)	26.5	Control 6 (Eastbound) (S)	24.6
Conv. 89-208 Deck (S)	27.1	Control 7 (Eastbound) (S)	24.6
Conv. 89-204 Deck (S)	28.8	VA Control (S)	29.4
Conv. 99-076 p3** (S)	27.9	Extra Control (S)	25.7
Conv. 99-076 p5 (S)	28.7		

* Conv. = Conventional deck
** p = placement

Group 2 consists of six monolithic bridge deck placements incorporating fibers supported by steel girders (Feng and Darwin 2020). The bridges are located in Wyandotte, Shawnee, and Douglas Counties in Kansas. The paste contents of these decks ranged from just 23.8 to 24.7% of the concrete volume. The bridge deck placements in Group 2 are labeled S-F. The paste contents of the bridge decks in Group 2 are shown in Table 5.2.

Table 5.2: Paste contents of the bridge decks in Group 2, (S-F)

Bridge Deck Placement	Paste Content (%)
Fiber 1 NB p1* (S-F)	23.8
Fiber 1 NB p2 (S-F)	23.8
Fiber 2 SB p1 (S-F)	23.8
Fiber 5 WB (S-F)	24.7
Fiber 6 WB (S-F)	24.6
Fiber 7 WB (S-F)	24.6

* p = placement

Group 3 consists of four monolithic bridge deck placements incorporating internal curing (IC) water technology supported by steel girders. The bridge deck placements (identified as IN-HPC-IC) are located in two districts, Seymour and Vincennes, in Indiana (Lafikes et al. 2020). Bridge deck placements in Group 3 are labeled S-IC. The paste contents of these decks ranged from 25.3 to 26.0% of the concrete volume, as shown in Table 5.3.

Table 5.3: Paste contents of the bridge decks in Group 3, (S-IC)

Bridge Deck Placement	Paste Content (%)
IN-HPC-IC-2 (S-IC)	25.3
IN-HPC-IC-3 (S-IC)	25.9
IN-HPC-IC-4 p1* (S-IC)	25.7
IN-HPC-IC-4 p2 (S-IC)	26.0

* p = placement

Group 4 consists of two monolithic bridge deck placements incorporating shrinkage-reducing admixtures (SRAs) supported by steel girders. The bridge decks (VA-SRA) are located in Staunton and Fredericksburg, Virginia (Polley et al. 2015, Feng and Darwin 2020). Bridge deck placements included in Group 4 are labeled S-SRA. The paste contents of these decks were 27.0 or 27.3%, as shown in Table 5.4.

Table 5.4: Paste contents of the bridge decks in Group 4, (S-SRA)

Bridge Deck Placement	Paste Content (%)
VA-SRA 4 (S-SRA)	27.0
VA-SRA 8 (S-SRA)	27.3

Group 5 consists of three monolithic bridge deck placements without a crack-reducing technology supported by prestressed concrete girders. The decks were constructed as part of a 13-year Pooled-Fund program at KU, two following (LC-HPC) specifications and one deck (Control 8/10) constructed following KDOT specifications (Lindquist et al. 2008, McLeod et al. 2009, Yuan et al. 2011, Pendergrass and Darwin 2014, Bohaty et al. 2013, Alhmood et al. 2015). Bridge decks included in Group 5 are labeled PS. The paste contents of these decks ranged from 23.4 to 26.0%, as shown in Table 5.5.

Table 5.5: Paste contents of the bridge decks in Group 5, (PS)

Bridge Deck Placement	Paste Content (%)
LC-HPC 8 (PS)	23.4
LC-HPC 10 (PS)	23.4
Control 8/10 (PS)	26.0

Group 6 consists of two monolithic bridge deck placements incorporating fibers supported by prestressed concrete girders located on US-59 south of Lawrence, Kansas (Harley et al. 2011, Shrestha et al. 2013). Bridge decks included in Group 6 are labeled as PS-F. Both decks had a paste content of 26.4% by volume of concrete, as shown in Table 5.6.

Table 5.6: Paste contents of the bridge decks in Group 6, (PS-F)

Bridge Deck Placement	Paste Content (%)
US-59 10 (PS-F)	26.4
US-59 12 (PS-F)	26.4

Group 7 consists of two monolithic bridge deck placements supported by prestressed box girders. The bridges are located near Seymour, Indiana. One deck (IN-Control) incorporated no crack-reducing technology and the other (IN-IC) incorporated internal curing (Lafikes et al. 2020). The bridge decks included in Group are labeled as PS Box and PS Box-IC, respectively. Both decks had a paste content of 27.6% by volume of concrete (Table 5.7).

Table 5.7: Paste contents of the bridge decks in Group 7, (PS-Box/PS-Box-IC)

Bridge Deck Placement	Paste Content (%)
IN-Control (PS Box)	27.6
IN-IC (PS Box-IC)	27.6

The 36-month crack densities of the bridge decks used for comparison in this study are shown in Table 5.8. The procedures used to calculate these values are presented in Section C.1 of Appendix C,. The detailed crack survey results are documented by Lindquist et al. (2006) and Khajehdehi and Darwin (2018) for the Conventional decks and the extra control deck constructed in Kansas; by Darwin et al. (2016) for the LC-HPC decks constructed in Kansas; by Shrestha et al. (2013) for the south of Lawrence bridge decks; by Polley et al. (2015) for the decks in Virginia containing SRAs, Feng and Darwin (2020) for the decks in Kansas containing fiber reinforcement and by Lafikes et al. (2020) for the Indiana decks with and without IC technology.

Table 5.8: Crack density of bridge decks used for comparison at 36 months of age

Bridge Deck Placement	Crack Density (m/m^2)	Bridge Deck Placement	Crack Density (m/m^2)
*Conv. 3-046 Ctr. Deck (S)	0.042	LC-HPC 8 (PS)	0.358
Conv. 3-045 E. Ctr. Deck (S)	0.043	LC-HPC 9 (S)	0.325
Conv. 70-095 Deck (S)	0.025	LC-HPC 10 (PS)	0.029
Conv. 70-104 Deck (S)	0.069	LC-HPC 11 (North Ln.) (S)	0.163
Conv. 70-103 Left (S)	0.391	LC-HPC 15 (S)	0.227
Conv. 70-103 Right (S)	0.253	LC-HPC 16 (S)	0.250
Conv. 3-045 East Deck (S)	0.078	LC-HPC 17 (S)	0.283
Conv. 3-045 Ctr. Deck (S)	0.174	US 59 1 (S)	0.391
Conv. 3-046 East Deck (S)	0.392	US 59 2 (S)	0.242
Conv. 99-076 North (East Ln.) (S)	0.412	US 59 10 (PS-F)	0.178
Conv. 56-148 Deck (S)	0.259	US 59 12 (PS-F)	0.047
Conv. 75-044 Deck (S)	0.165	Fiber 1 NB p1 (S-F)	0.112
Conv. 3-045 West Deck (S)	0.074	Fiber 1 NB p2 (S-F)	0.220
Conv. 3-045 W. Ctr. Deck (S)	0.178	Fiber 2 SB p1 (S-F)	0.127
Conv. 3-046 West Deck (S)	0.254	Fiber 5 WB (S-F)	0.061
Conv. 70-107 Deck (S)	0.322	Fiber 6 WB (S-F)	0.011
Conv. 56-142 N. Pier (S)	0.064	Fiber 7 WB (S-F)	0.004
Conv. 56-142 + Moment (S)	0.071	Control 5 (Eastbound) (S)	0.052
Conv. 89-208 Deck (S)	0.009	Control 6 (Eastbound) (S)	0.011
Conv. 89-204 Deck (S)	0.736	Control 7 (Eastbound) (S)	0.033
Conv. 99-076 p3 (S)	0.739	Control 8/10 (PS)	0.136
Conv. 99-076 p5 (S)	0.861	VA Control (S)	0.232
Conv. 99-076 North (West Ln.) (S)	0.801	VA-SRA 4 (S-SRA)	0.083
Conv. 99-076 p4 (S)	0.872	VA-SRA 8 (S-SRA)	0.056
LC-HPC 1 p1** (S)	0.049	IN-IC (PS Box-IC)	0.181
LC-HPC 1 p2 (S)	0.024	IN-Control (PS Box)	0.236
LC-HPC 2 (S)	0.048	IN-HPC-IC-2 (S-IC)	0.003
LC-HPC 4 p2 (S)	0.090	IN-HPC-IC-3 (S-IC)	0.061
LC-HPC 5 (S)	0.154	IN-HPC-IC-4 p1 (S-IC)	0.214
LC-HPC 6 (S)	0.271	IN-HPC-IC-4 p2 (S-IC)	0.032
LC-HPC 7 (S)	0.012	Extra Control (S)	0.215

* Conv. = Conventional deck
** p = placement

5.2 BRIDGE DECKS WITH POOR CONSTRUCTION PROCEDURES

The 12 earlier bridge deck placements (identified as **Group 8**) constructed with documented poor construction procedures were supported by steel girders. Eight placements had no crack-reducing technology (S) and four contained fibers (S-F). Comparing the cracking on these decks with that of the decks surveyed in this study is done to help identify the effects of construction procedures. The 36-month crack densities and concrete properties of the 12 bridge decks with poor construction procedures are provided in Table 5.9.

With reference to Table 5.9, the main issue associated with the construction of LC-HPC 12 p1 and p2, LC-HPC 13, Topeka Control p1 and p2, Topeka Fiber 1, and Topeka Fiber 2 p1 and p2 was the loss of consolidation caused by workers walking through freshly consolidate concrete. The contractor failed to re-consolidate the holes left on the concrete by the workers and merely relied on the finishing machine to cover them, which likely left the concrete susceptible to settlement cracking.

Poor practices were also observed during the construction of LC-HPC-14 and Fiber 2 SB p2. A variety of issues were observed in the construction of LC-HPC 14, including insufficient consolidation, overfinishing of the deck, and late delivery of concrete. As a result, the three placements on LC-HPC 14 exhibited the highest crack density of the LC-HPC decks. Additional details associated with the construction of LC-HPC-12, LC-HPC-13, and LC-HPC-14 are provided by McLeod et al. (2009), Pendergrass and Darwin (2014), and Khajehdehi and Darwin (2018). In addition, based on on-site observation, the contractor of Fiber 2 SB p2 did not follow many aspects of the specifications, resulting in a highly cracked bridge deck.

Table 5.9: 36-month crack density and concrete properties of decks with construction issues

Bridge Deck Placement	Crack Density (m/m^2)	Cement Paste (%)	Air Content (%)	Slump (in.)	28-day Strength (psi)
LC-HPC 12 p1 (S)	0.301	24.3	7.4	2¾	4600
LC-HPC 12 p2 (S)	0.354	24.2	7.8	4¼	4380
LC-HPC 13 (S)	0.344	24.1	8.1	3	4280
LC-HPC 14 p1 (S)	0.543	24.4	8.7	3¾	4440
LC-HPC 14 p2 (S)	1.223	24.4	9.8	4¼	3710
LC-HPC 14 p3 (S)	0.695	24.4	9.9	5¼	3830
Topeka Control p1 (S)	0.766	22.2	5.5	3¼	-[a]
Topeka Control p2 (S)	0.393	22.2	5.7	3¼	5700
Topeka Fiber 1 (S-F)	0.284	22.2	6.5	3¼	5230
Topeka Fiber 2 p1 (S-F)	0.709	22.2	6.5	3	5330
Topeka Fiber 2 p2 (S-F)	0.431	22.2	6.7	3¼	5530
Fiber 2 SB p2 (S-F)	0.456	23.8	5.3	5	5950

[a] Data is not available

CHAPTER 6: COMPARISONS AND DISCUSSION

The effects of material properties, crack-reducing technology (fibers), and construction procedures on cracking of 20 bridge decks surveyed in Minnesota are evaluated using the survey results for the 74 bridge deck placements summarized in Chapter 5. Br.21803, with an unknown date of construction, is excluded from the analysis. Additional analyses were performed to investigate the effects of superstructure attributes such as skew, total deck length, and the number of spans on bridge deck cracking using the 36-month crack densities of the 15 decks that followed good construction procedures that were surveyed in Minnesota (Chapter 4), along with the 54 bridge decks introduced in Chapter 5 (Groups 1, 2, 5, and 6). Such analyses are not the main focus of this report and, thus, are provided in Appendix E.

6.1 EFFECTS OF PASTE CONTENT AND FIBERS

Numerous studies have shown that concrete material properties play a crucial role in the durability and cracking of bridge decks. Cement paste content is the most dominant factor in concrete shrinkage and, consequently, cracking in bridge decks. The effects of paste content on the cracking performance of bridge decks have been addressed in numerous studies (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005, Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2019). In a study performed on 32 monolithic bridge decks, Schmitt and Darwin (1999) observed that concrete decks with a cement paste content greater than 27% (by concrete volume) showed significantly greater cracking than decks with lower paste contents. Based on an evaluation of the cracking performance of 40 monolithic bridge deck placements supported by steel girders at the age of 96 months, Khajehdehi and Darwin (2018) showed that cracking of bridge decks with a paste content greater than 27.2% paste content was significantly higher than that of decks with a paste content of 26.4% or less.

Many other researchers have also demonstrated the greater importance of lower cement paste content than the incorporation of crack-reducing technologies alone, such as fiber-reinforced concrete (FRC), SRAs, and IC water in the construction of bridge decks (Feng and Darwin 2020, Lafikes et al. 2020). A number of studies have reported that incorporating fibers mitigates shrinkage and settlement of concrete (Al-Qassag et al. 2015, Ibrahim et al. 2019). In properly constructed bridge decks with low paste contents, however, the evidence indicates that the addition of fibers cannot further ameliorate cracking performance of bridge decks (Khajehdehi and Darwin 2018, Feng and Darwin 2020). Lafikes et al. (2020) reported that in concrete decks with a paste content higher than 27% incorporating IC water with or without SCMs does not result in lower cracking than in decks constructed with lower paste contents. With this as background, the 20 Minnesota bridge decks surveyed in this study (Chapter 2) have been categorized into two groups: decks without construction issues (15 decks); and decks potentially involving poor construction practices (four decks [85849, 9691, 62831, and 69839]). The reason for classifying the four decks separately is that they had paste contents below 27% but had crack densities above 0.4 m/m^2. In other decks, this has occurred only in cases involving poor construction practices. As a result, these decks are analyzed separately in Section 6.2.

Figure 6.1 shows the 36-month crack density of the 15 Minnesota bridge decks (with good construction procedures) surveyed in this study and those used for comparison with good construction procedures (Section 5.1), as a function of the paste content. In Figure 6.1, the Minnesota decks surveyed in this study (a trailing indicator of "MN" in the legend IDs) have paste contents ranging from 23.9 to 29.6%. As shown in the figure, the decks with paste contents below 27.6% exhibited crack densities below 0.4 m/m^2 (with an average of 0.15 m/m^2) at 36 months. As a general observation, the cracking of bridge decks incorporating crack-reducing technologies such as fibers, SRAs, or IC are comparable to those of the decks without crack-reducing technologies. Once the paste content exceeds 27.6%, cracking tends to increase. Of the nine decks with a paste content greater than or equal to 27.9%, seven decks have crack densities above 0.4 m/m^2 at 36 months. Among the 15 Minnesota decks included in Figure 6.1, the deck of Br. 71004, with a paste content of 29.6% and fibers, exhibited the highest crack density, with a value of 0.696 m/m^2. The other 14 Minnesota decks, all with a paste content of 27.1% or less, had crack densities below 0.27 m/m^2.

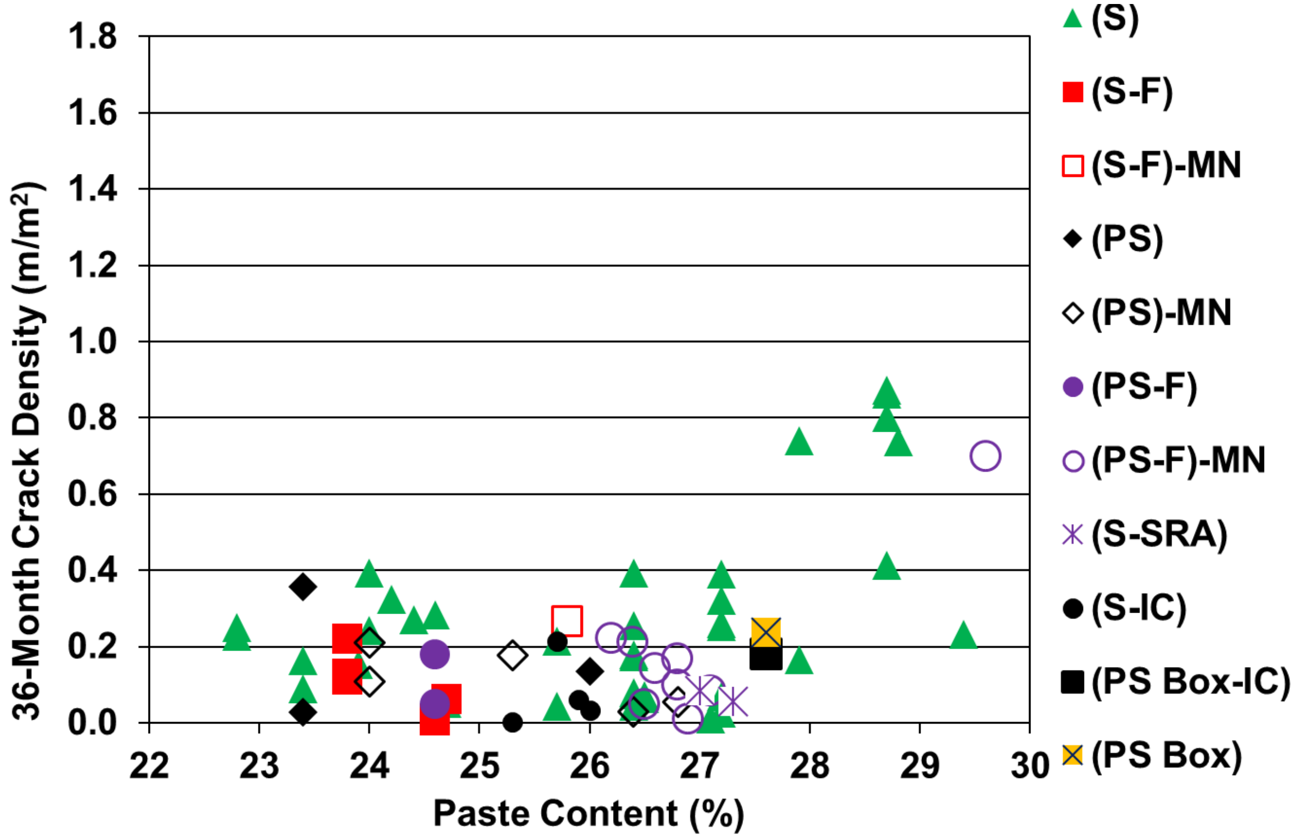


Figure 6.1: Paste content versus 36-month crack density for decks with good construction procedures

Using the results shown in Tables 4.1 and 5.8, the average 36-month crack densities of bridge decks with and without fibers (F) for decks supported by steel (S) and prestressed concrete (PS) girders are compared in Figures 6.2 and 6.3, respectively. A comparison is also made as a function of paste content, such that decks with paste content of 27.2% and lower are categorized as "Low Paste," and decks with paste contents of 27.9% and greater are categorized as "High Paste." Error bars show the ranges of the crack densities for each deck type. The decks supported by steel girders, designated as "(S)," with "Low Paste," contents include 35 placements, with paste contents ranging from 22.8 to 27.2%; decks designated as "(S)" with "High Paste" contents include eight placements, with paste contents ranging from 27.9 to 28.8%; decks designated as "(S-F)" with "Low Paste" contents include six placements, with paste contents ranging from 23.8 to 24.7%; and a single deck designated as "(S-F)-MN" with "Low Paste" content includes one placement, with a paste content of 25.8%. Similarly, decks supported by prestressed concrete girders, designated as "(PS)," with "Low Paste" contents include three placements, with paste contents ranging from 23.4 to 26.0%; decks designated as "(PS)-MN," with "Low Paste" contents include five placements, with paste contents ranging from 24.0 to 26.8%; decks designated as "(PS-F)" with "Low Paste" contents include two placements, each with a paste content of 24.6%; decks designated as "(PS-F)-MN" with "Low Paste" contents include eight placements, with paste contents ranging from 26.2 to 27.1%; and a single deck designated as "(PS-F)-MN" with "High Paste" content includes one placement, with a paste content of 29.6%.

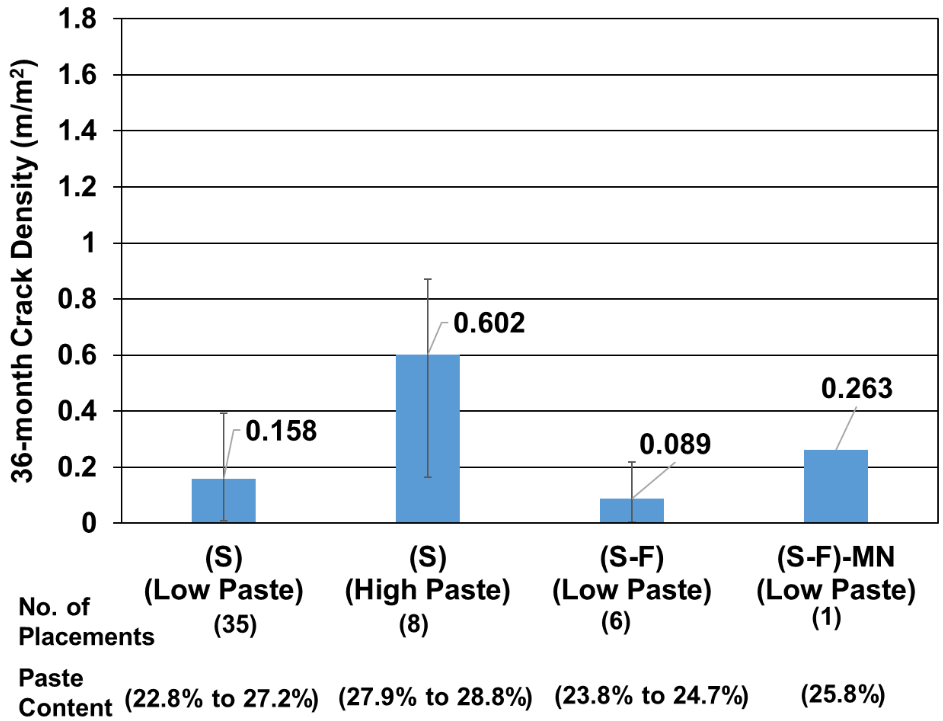


Figure 6.2: 36-month crack densities of decks supported by steel girders with and without fibers

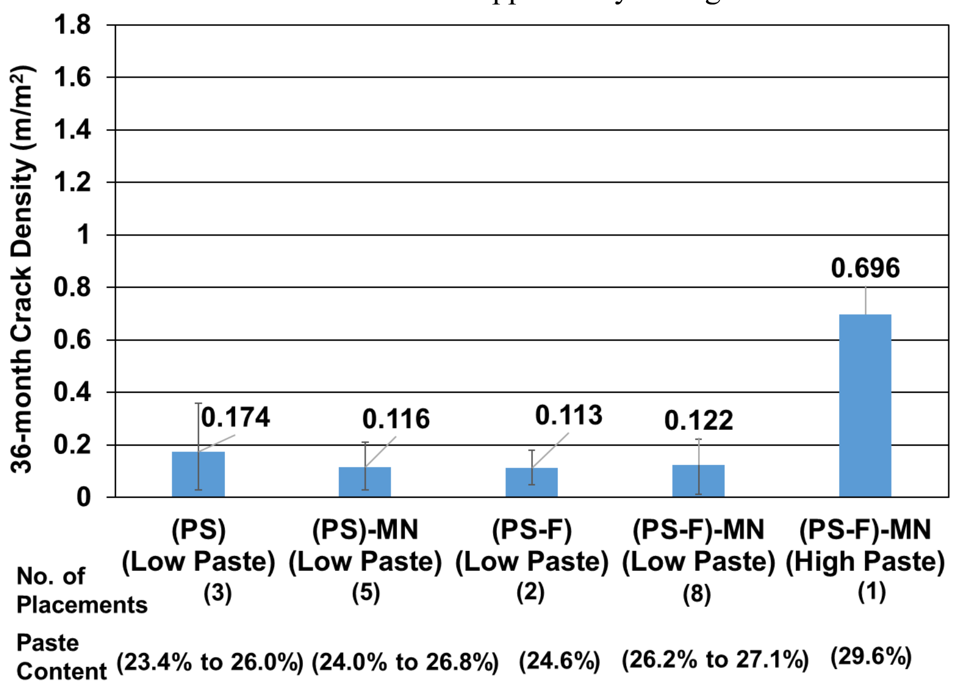


Figure 6.3: 36-month crack densities of decks supported by prestressed concrete girders with and without fibers

Figures 6.2 and 6.3 show that the bridge decks with high paste contents (≥27.9%), supported by either steel or prestressed concrete girders, exhibited noticeably higher crack densities at 36 months than those with paste contents ≤ 27.2%. In decks supported by steel girders, the 36-month crack densities of decks with low paste contents ranged from 0.089 to 0.263 m/m^2, while the average 36-month crack densities of the decks with high paste contents was 0.602 m/m^2. The single steel girder bridge deck with fibers [(S-F)-MN] exhibited the highest crack density at 36 months of age (0.263 m/m^2) of all the decks with low paste contents. Similarly, in decks supported by prestressed concrete girders, the 36-month crack densities of decks with low paste contents ranged from 0.113 to 0.174 m/m^2, while the 36-month crack density of the deck with the highest paste content (29.6%) was 0.696 m/m^2. Tables 6.1 and 6.2 show the Student's t-test results comparing cracking of these decks. To perform such an analysis, at least two data points are needed for each data set. Thus, single deck placements with (S-F)-MN Low Paste and (PS-F)-MN High Paste contents are excluded from the tables.

Table 6.1: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported steel girders with and without fibers

Bridges	**Group**	**(S) Low Paste**	**(S) High Paste**	**(S-F) Low Paste**
Group	**Ave. of 36-month crack density (m/m^2)**	0.158	0.602	0.089
(S) Low Paste	0.158		2.1×10^{-8}	0.197
(S) High Paste	0.602			0.001
(S-F) Low Paste	0.089			

Table 6.2: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported by prestressed girders with and without fibers

Bridges	Group	(PS) Low Paste	(PS)-MN Low Paste	(PS-F) Low Paste	(PS-F)-MN Low Paste
Group	**Ave. of 36-month crack density (m/m^2)**	0.174	0.116	0.113	0.122
(PS) Low Paste	0.174		0.514	0.677	0.472
(PS)-MN Low Paste	0.116			0.966	0.891
(PS-F) Low Paste	0.113				0.886
(PS-F)-MN Low Paste	0.122				

As shown in Tables 6.1 and 6.2, paste content is the dominant factor in the cracking of bridge decks. In decks supported by steel girders, the difference between the crack density of decks with high paste contents (average of 0.602 m/m^2) and that of the decks with low paste contents with (0.089 m/m^2) or without (0.158 m/m^2) fibers is statistically significant (p = 2.1×10^{-8} and 0.001, respectively). In decks supported by steel girders, the difference between the crack density of decks with low paste contents with (0.089 m/m^2) or without (0.158 m/m^2) fibers, however, is not statistically significant (p = 0.197). In decks supported by prestressed concrete girders with low paste contents, the difference between the cracking of decks with fibers and that of the deck without fibers, also is not statistically significant. (p values greater than 0.05).

Overall, high paste contents correlate with increased cracking while the use of fibers does not result in a statically significant difference in crack density.

6.2 EFFECTS OF POOR CONSTRUCTION PROCEDURES

In this section, the 36-month crack densities of bridge decks with poor construction procedures are provided. As discussed in Section 6.1, four Minnesota decks with crack densities greater than 0.4 m/m^2 are suspected to have had construction issues during their construction. To investigate this hypothesis, Figure 6.4 compares the 36-month crack densities of these four decks (identified with a trailing indicator of "MN" in the legend IDs) with those used for comparison with poor construction procedures (Section 5.2) as a function of the paste content. As previously indicated, given that decks with high paste contents exhibit high crack densities, high cracking of decks of 85849, 9691, 62831, and 69839, which contained low paste contents, is not expected. As shown in Figure 6.4, the average 36-month crack densities of the four decks surveyed in this study are similar to most of the decks that had poor construction procedures (such as insufficient consolidation or overfinishing). As shown in the figure, the average 36-month crack densities of decks with construction issues were 0.470 m/m^2 and above, even when low paste content concretes were used; the average 36-month crack density of the three Minnesota decks with fibers shown in Figure 6.4 is 0.554 m/m^2, while that of the deck without fibers shown in the figure is 0.942 m/m^2. The results of Student's t-test results provided in Table 6.3 show that with the paste contents ranging from 22.2 to 26.5%, the differences in crack density of the poorly constructed decks documented in Section 5.2 with and without fibers (averages of 0.470 and 0.577 m/m^2) and the three Minnesota decks constructed with fibers shown in Figure 6.4 (0.554 m/m^2) are not statistically significant (p = 0.565 and 0.908, respectively). The single deck supported by steel girders [(S)-MN, or 85849] is excluded from the Student's t-test analysis but it did have the highest crack density of any of the 20 decks surveyed. Therefore, in all likelihood, the high crack densities of decks of 85849, 9691, 62831, and 69839 resulted from poor construction practices, and thus, resulted in higher crack densities than other bridge decks surveyed in this study.

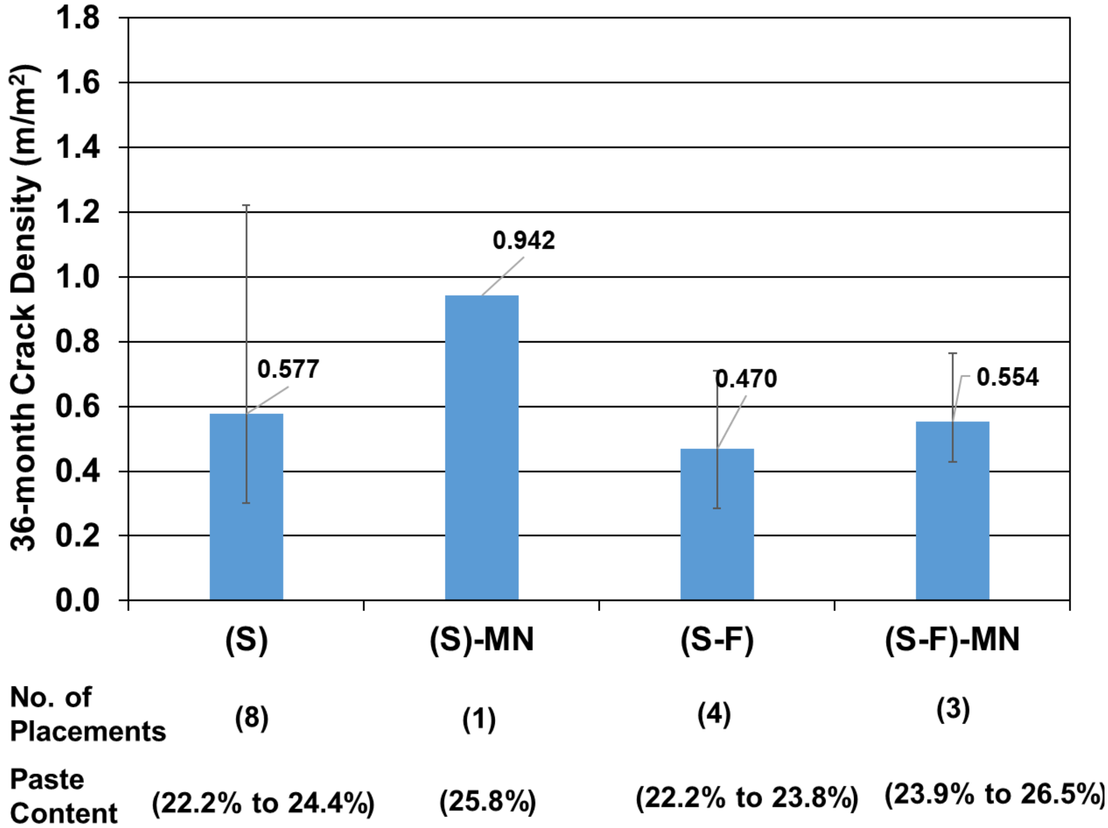


Figure 6.4: Comparing the 36-month crack densities of decks with construction issues

Table 6.3: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported by steel girders, poorly constructed, with and without fibers

Bridges	**Group**	**(S)**	**(S-F)**	**(S-F)-MN**
Group	**Ave. of 36-month crack density (m/m^2)**	0.577	0.470	0.554
(S)	0.577		0.543	0.908
(S-F)	0.470			0.565
(S-F)-MN	0.554			

CHAPTER 7: SUMMARY AND CONCLUSIONS

7.1 SUMMARY

In this study, the Minnesota Department of Transportation (MnDOT) identified 20 monolithic (one-course) bridge decks with and without fibers for cracking surveys. The study investigated the effectiveness of nonmetallic fibers in reducing bridge deck cracking. The crack surveys involved decks constructed between 2015 and 2018, including 13 bridge decks constructed with concrete mixtures containing nonmetallic fibers and seven without fibers. The decks were supported by either steel or precast-prestressed concrete girders. The paste contents (cementitious materials and mixing water as a fraction of concrete volume) ranged from 23.9 to 29.6% for the decks containing fibers and 24.0 to 26.8% for the bridge decks without fibers. The survey results were presented and converted to equivalent crack densities at 36 months of age to allow a fair comparison between decks. The effects of paste content, fibers, and construction procedures on cracking performance of the 20 bridge decks surveyed in this study at 36 months were investigated in comparison with crack surveys of 74 other bridge deck placements with paste contents between 22.8 and 29.4%.

7.2 CONCLUSIONS

The following conclusions are based on the results and analyses presented in this study.

1. For the decks surveyed in this study, the vast majority of cracks that contributed to crack density had lengths greater than 1 ft.
2. For the decks surveyed in this study, there is no apparent correlation between the use of fibers and crack width.
3. Low-cracking bridge decks require the use of concrete with a low paste content (27.1% and below).

4. When the paste content is low, there is no significant difference in the average 36-month crack densities between bridge decks with and without fibers.
5. More generally, good construction practices are needed for low-cracking decks.
6. With poor construction practices, even decks with low paste content, with or without fibers, can exhibit high cracking.

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APPENDIX A: BRIDGE DECK SURVEY SPECIFICATIONS

A.1 DESCRIPTION.

This specification covers the procedures and requirements to perform bridge deck surveys of reinforced concrete bridge decks.

A.2 SURVEY REQUIREMENTS.

A.2.1 Pre-Survey Preparation.

(1) Prior to performing the crack survey, related construction documents need to be gathered to produce a scaled drawing of the bridge deck. The scale must be exactly 1 in. = 10 ft (for use with the scanning software), and the drawing only needs to include the boundaries of the deck surface.

NOTE 1 – In the event that it is not possible to produce a scaled drawing prior to arriving at the bridge deck, a hand-drawn crack map (1 in.= 10 ft) created on engineering paper using measurements taken in the field is acceptable.

(2) The scaled drawing should also include compass and traffic directions in addition to deck stationing. A scaled 5 ft by 5 ft grid is also required to aid in transferring the cracks observed on the bridge deck to the scaled drawing. The grid shall be drawn separately and attached to the underside of the crack map such that the grid can easily be seen through the crack map.

NOTE 2 – Maps created in the field on engineering paper need not include an additional grid.

(3) For curved bridges, the scaled drawing need not be curved, i.e., the curve may be approximated using straight lines.

(4) Coordinate with traffic control so that at least one side (or one lane) of the bridge can be closed during the time that the crack survey is being performed.

A.2.2 Preparation of Surface.

(1) After traffic has been closed, station the bridge in the longitudinal direction at ten feet intervals. The stationing shall be done as close to the centerline as possible. For curved bridges, the stationing shall follow the curve.

(2) Prior to beginning the crack survey, mark a 5 ft by 5 ft grid using lumber crayons or chalk on the portion of the bridge closed to traffic corresponding to the grid on the scaled drawing. Measure and document any drains, repaired areas, unusual cracking, or any other items of interest.

(3) Starting with one end of the closed portion of the deck, using a lumber crayon or chalk, begin tracing cracks that can be seen while bending at the waist. After beginning to trace cracks, continue to the end of the crack, even if this includes portions of the crack that were not initially seen while bending at the waist. Cracks not attached to the crack being traced must not be marked unless they can be seen from waist height. Surveyors must return to the location where they started tracing a crack and continue the survey. Areas covered by sand or other debris need not be surveyed. Trace the cracks using a different color crayon than was used to mark the grid and stationing.

(4) At least one person shall recheck the marked portion of the deck for any additional cracks. The goal is not to mark every crack on the deck, only those cracks that can initially be seen

while bending at the waist.

NOTE 3 – An adequate supply of lumber crayons or chalk should be on hand for the survey. Crayon or chalk colors should be selected to be readily visible when used to mark the concrete.

A.2.3 Weather Limitations.

(1) Surveys are limited to days when the expected temperature during the survey will not be below 60 °F.

(2) Surveys are further limited to days that are forecasted to be at least mostly sunny for a majority of the day.

(3) Regardless of the weather conditions, the bridge deck must be completely dry before the survey can begin.

A.3 BRIDGE SURVEY.

A.3.1 Crack Surveys.

Using the grid as a guide, transfer the cracks from the deck to the scaled drawing. Areas that are not surveyed should be marked on the scaled drawing. Spalls, regions of scaling, and other areas of special interest need not be included on the scale drawings but should be noted.

A.3.2 Delamination Survey.

At any time during or after the crack survey, bridge decks shall be checked for delamination. Any areas of delamination shall be noted and drawn on a separate drawing of the bridge. This second drawing need not be to scale.

A.3.3 Under Deck Survey.

Following the crack and delamination survey, the underside of the deck shall be examined and any unusual or excessive cracking noted.

APPENDIX B: CRACK WIDTH RESULTS

Table B.1: Individual crack-width measurements for decks surveyed in this study ($\times10^{-3}$ in.)

	27W06	07051	9691	21802	21803	21804	55009	58821	58824	62729
1	2	5	7	9	4	6	5	20	6	9
2	2	9	9	4	4	4	7	20	16	9
3	2	5	16	4	4	6	5	9	20	9
4	3	7	4	4	4	4	7	16	16	7
5	3	7	16	6		4	10	20	20	10
6	5	9	12	6		6	9	10	16	13
7	5	5	9	4		4	7	13	20	10
8	2	5	10	6		6	10	7	16	9
9	3	3	9	4		**4**	7	13		16
10	5	13	10	**4**		4	9	16		13
11	3	10	9	6		6	13	10		13
12		9	12	6		7	10	16		9
13		9	25	4		6	9	13		7
14		7	10	4		6	10	10		7
15		7	20			6	7	9		9
16		9	12			6	10	20		9
17		5	20			7	4	20		16
18		9	12			12	3	20		13
19		9	25			12	7	16		16
20		9	16			4	5	16		13
21			20			4	3	16		10
22			4			6	9			10
23			7			4	7			16
24			7			4	7			9
25			20				7			5
26			12				9			9
27			9				13			10
28			30				9			10
29			20				9			5
30			10				13			7
31			9				10			7
32			16				9			
33			20				9			
34			12				7			
35			12				7			
36			20				9			
37			12				13			
38			9				9			
39			9				7			
40			12				7			
41			12				6			
42			9				7			
43			7				7			
44			6				7			
45			6							
46			4							
47			7							

Table B.1: (cont.) Individual crack width measurements for surveyed in this study ($\times 10^{-3}$ in.)

	62731	62831	62873	62890	69137	69839	71004	73047	74805	85849[a]
1	4	16	9	10	9	7	30	20	3	
2	4	16	16	3	7	13	25	20	7	
3	6	16	16	3	7	16	20	20	9	
4	4	25	5	3	9	13	10	16		
5	4	20	20	3	7	13	16	25		
6	10	20	13	3	7	13	13	16		
7	10	9	13	2	7	10	10	6		
8	10	16	13	5	7	16		16		
9	4	16	10	3	7	16		13		
10		20	3	5	9	9		6		
11		16	3	3		13		10		
12		16	3	7		13		13		
13		25	9	3		16		13		
14		20	7	3		20		10		
15		16	3	3		9		7		
16		16	16	5		10		13		
17		16	16	5		10		13		
18		25	16	3		7		13		
19		13	10	3				9		
20		25	4	3				16		
21		25	5	3				9		
22		25	9	3				20		
23			13	3				10		
24			9	3				13		
25				5				16		
26								10		

[a] Not available

APPENDIX C: PROCEDURE FOR ESTIMATING 36-MONTH CRACK DENSITY

C.1 ESTIMATED 36-MONTH CRACK DENSITY

This appendix describes the procedure for estimating the 36-month crack density of the bridge decks surveyed in this study.

C.2 BRIDGE DECK SELECTION

The University of Kansas has been involved in cracking surveys since the 1990s. To estimate the 36-month cracking density of bridge decks surveyed in this study, 62 bridge deck placements with characteristics (such as superstructure and crack-reducing technologies) similar to those surveyed bridge decks in Minnesota were chosen. As described in Section 5.1, the decks included different types of girders (steel, prestressed concrete, and box concrete girders) and crack-reducing technologies (fibers, IC, SRAs) and had been surveyed at least twice. All of the bridges used for analysis had a monolithic (one-coarse) deck. The crack density of all decks increased over time. One deck, LC-HPC 10, which was supported by precast, prestressed girders, exhibited a reduction in crack density between two surveys (the first and second); the crack density of this deck then increased over time, and the initial survey for that deck has been discounted. No decks with issues related to construction were selected.

C.3 CRACKING RATE AND 36-MONTH CRACK DENSITY

The change in crack density as a function of time is referred to as the cracking rate. The process of calculating cracking rates and the associated 36-month crack density of the decks is as follows:

- A trend line is fit to the raw crack density data using a least-squares linear regression (best-fit line) for each bridge deck. The cracking rate is determined as the slope of the best fit line equation.

- Using the best-fit line equation, the 36-month crack density (this differs from the method described in Section D.1) is calculated for each deck.
- The cracking rate and the 36-month crack density are assigned to each bridge deck for further analysis.

The crack density of LC-HPC 17 serves as an example:

1. Determine the best-fit line for the raw data, as shown in Figure C.1.

2. Find the cracking rate and crack density corresponded to 36 months of age using the best-fit line, as shown in Figure C.1.

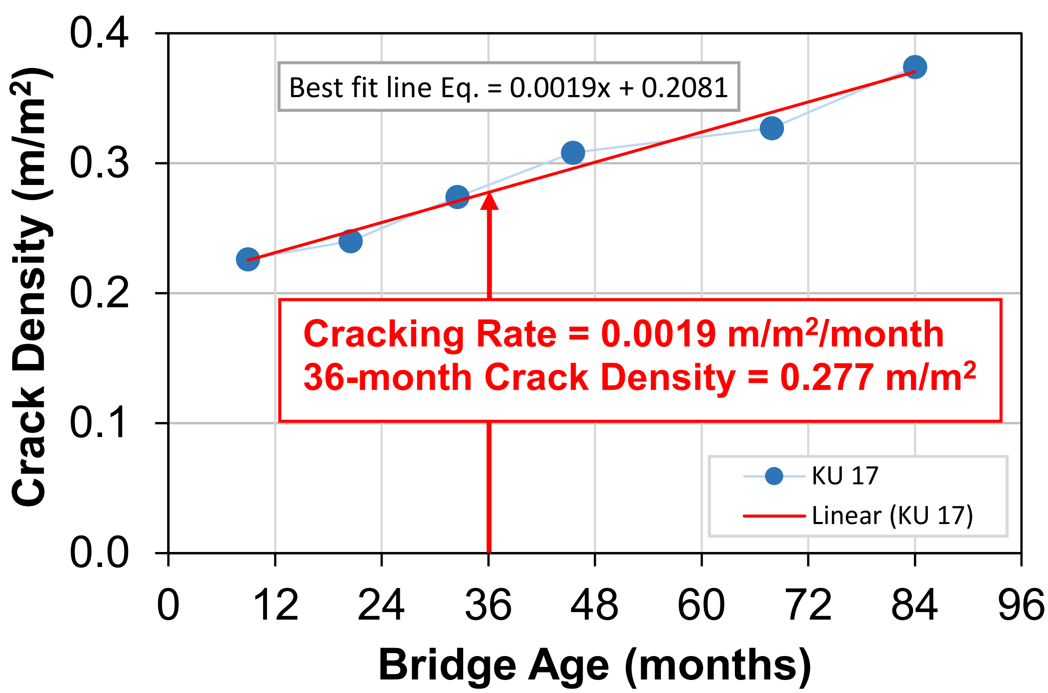

Figure C.1: Cracking Rate and 36-month crack density of LC-HPC 17

The best-fit line, cracking rate, and 36-month crack density assigned to each bridge deck are calculated using this procedure and shown in Table C.1.

Table C.1: Best fit line equation, cracking rate, and 36-month crack density of the decks

Bridge Deck Placement	Best-fit line Equation	Cracking Rate (m/m^2/month)	36-month Crack Density (m/m^2)
Conv. * 3-046 Ctr. Deck (S)	y = 0.0017x - 0.0179	0.0017	0.043
Conv. 3-045 E. Ctr. Deck (S)	y = 0.0016x - 0.0133	0.0016	0.044
Conv. 70-095 Deck (S)	y = 0.0006x + 0.002	0.0006	0.024
Conv. 70-104 Deck (S)	y = 0.0002x + 0.062	0.0002	0.069
Conv. 70-103 Left (S)	y = 0.0025x + 0.2998	0.0025	0.390
Conv. 70-103 Right (S)	y = 0.0022x + 0.1753	0.0022	0.255
Conv. 3-045 East Deck (S)	y = 0.0015x + 0.0225	0.0015	0.077
Conv. 3-045 Ctr. Deck (S)	y = 0.0005x + 0.1549	0.0005	0.173
Conv. 3-046 East Deck (S)	y = 0.0001x + 0.3869	0.0001	0.391
Conv. 99-076 North (East Ln.) (S)	y = 0.0022x + 0.3203	0.0022	0.400
Conv. 56-148 Deck (S)	y = 0.0024x + 0.1744	0.0024	0.261
Conv. 75-044 Deck (S)	y = 0.0012x + 0.1229	0.0012	0.166
Conv. 3-045 West Deck (S)	y = 0.0006x + 0.0514	0.0006	0.073
Conv. 3-045 W. Ctr. Deck (S)	y = 0.0001x + 0.1729	0.0001	0.177
Conv. 3-046 West Deck (S)	y = 0.0016x + 0.1948	0.0016	0.252
Conv. 70-107 Deck (S)	y = 0.004x + 0.1874	0.0040	0.331
Conv. 56-142 N. Pier (S)	y = 0.0006x + 0.0411	0.0006	0.063
Conv. 56-142 + Moment (S)	y = 0.0008x + 0.0405	0.0008	0.069
Conv. 89-208 Deck (S)	y = 0.0026x - 0.0854	0.0026	0.008
Conv. 89-204 Deck (S)	y = 0.002x + 0.6647	0.0020	0.737
Conv. 99-076 p3 (S)	y = 0.0012x + 0.6901	0.0012	0.733
Conv. 99-076 p5 (S)	y = 0.0016x + 0.7947	0.0016	0.852
Conv. 99-076 North (West Ln.) (S)	y = 0.0012x + 0.7495	0.0012	0.793
Conv. 99-076 p4 (S)	y = 0.0012x + 0.8199	0.0012	0.863
LC-HPC 1 p1** (S)	y = 0.0002x + 0.0367	0.0002	0.044
LC-HPC 1 p2 (S)	y = 0.0003x + 0.0269	0.0003	0.038
LC-HPC 2 (S)	y = 0.0019x + 0.0053	0.0019	0.074
LC-HPC 4 p2 (S)	y = 0.0019x + 0.0108	0.0019	0.079
LC-HPC 5 (S)	y = 0.0018x + 0.0686	0.0018	0.133
LC-HPC 6 (S)	y = 0.003x + 0.1343	0.0030	0.242
LC-HPC 7 (S)	y = 0.0007x - 0.0038	0.0007	0.021
LC-HPC 8 (S)	y = 0.0019x + 0.274	0.0019	0.342
LC-HPC 9 (S)	y = 0.0033x + 0.163	0.0033	0.282
LC-HPC 10 (PS)	y = 0.0009x + 0.0343	0.0009	0.067
LC-HPC 11 (North Ln.) (S)	y = 0.0052x - 0.0329	0.0052	0.154
LC-HPC 15 (S)	y = 0.002x + 0.165	0.002	0.237
LC-HPC 16 (S)	y = 0.0032x + 0.1379	0.0032	0.253

Table C.1: (cont.) Best fit line equation, cracking rate, and 36-month crack density of the decks

Bridge Deck Placement	Best fit line Equation	Cracking Rate (m/m^2/month)	36-month Crack Density (m/m^2)
LC-HPC 17 (S)	y = 0.0019x + 0.2081	0.0019	0.277
US 59 1 (S)	y = 0.0039x + 0.232	0.0039	0.372
US 59 2 (S)	y = 0.0034x + 0.1066	0.0034	0.229
US 59 10 (PS-F)	y = 0.004x + 0.039	0.0040	0.183
US 59 12 (PS-F)	y = 0.0011x + 0.0058	0.0011	0.045
Fiber 1 NB p1 (S-F)	y = 0.0014x + 0.0582	0.0014	0.109
Fiber 1 NB p2 (S-F)	y = 0.0055x - 0.0264	0.0055	0.172
Fiber 2 SB p1 (S-F)	y = 0.0035x - 0.0178	0.0035	0.108
Fiber 5 WB (S-F)	y = 0.0032x - 0.0515	0.0032	0.061
Fiber 6 WB (S-F)	y = 0.0006x - 0.0078	0.0006	0.011
Fiber 7 WB (S-F)	y = 0.0002x - 0.0029	0.0002	0.004
Control 5 (Eastbound) (S)	y = 0.0027x - 0.0438	0.0027	0.053
Control 6 (Eastbound) (S)	y = 0.0006x - 0.0095	0.0006	0.011
Control 7 (Eastbound) (S)	y = 0.0014x - 0.0189	0.0014	0.032
Control 8/10 (PS)	y = 0.0067x + 0.0498	0.0067	0.291
VA Control (S)	y = 0.0019x + 0.163	0.0019	0.231
VA-SRA 4 (S-SRA)	y = 0.0024x + 0.0019	0.0024	0.088
VA-SRA 8 (S-SRA)	y = 0.0013x + 0.0111	0.0013	0.058
IN-IC (PS Box-IC)	y = 0.0047x + 0.0124	0.0047	0.182
IN-Control (PS Box)	y = 0.0076x - 0.0384	0.0076	0.235
IN-HPC-IC-2 (S-IC)	y = 0.0014x - 0.0445	0.0014	0.006
IN-HPC-IC-3 (S-IC)	y = 0.0032x - 0.0521	0.0032	0.063
IN-HPC-IC-4 p1 (S-IC)	y = 0.0097x - 0.1311	0.0097	0.218
IN-HPC-IC-4 p2 (S-IC)	y = 0.0012x - 0.0077	0.0012	0.036
Extra Control (S)	y = 0.0032x + 0.1035	0.0032	0.219

* Conv. = Conventional deck
** p = placement

C.3.1 Estimated Cracking Rate at 36 months

As the final step for estimating the 36-month crack density of the bridge decks surveyed in this study, the cracking rates and 36-month crack densities of the decks (shown in Table C.1) are plotted in Figure C.2.

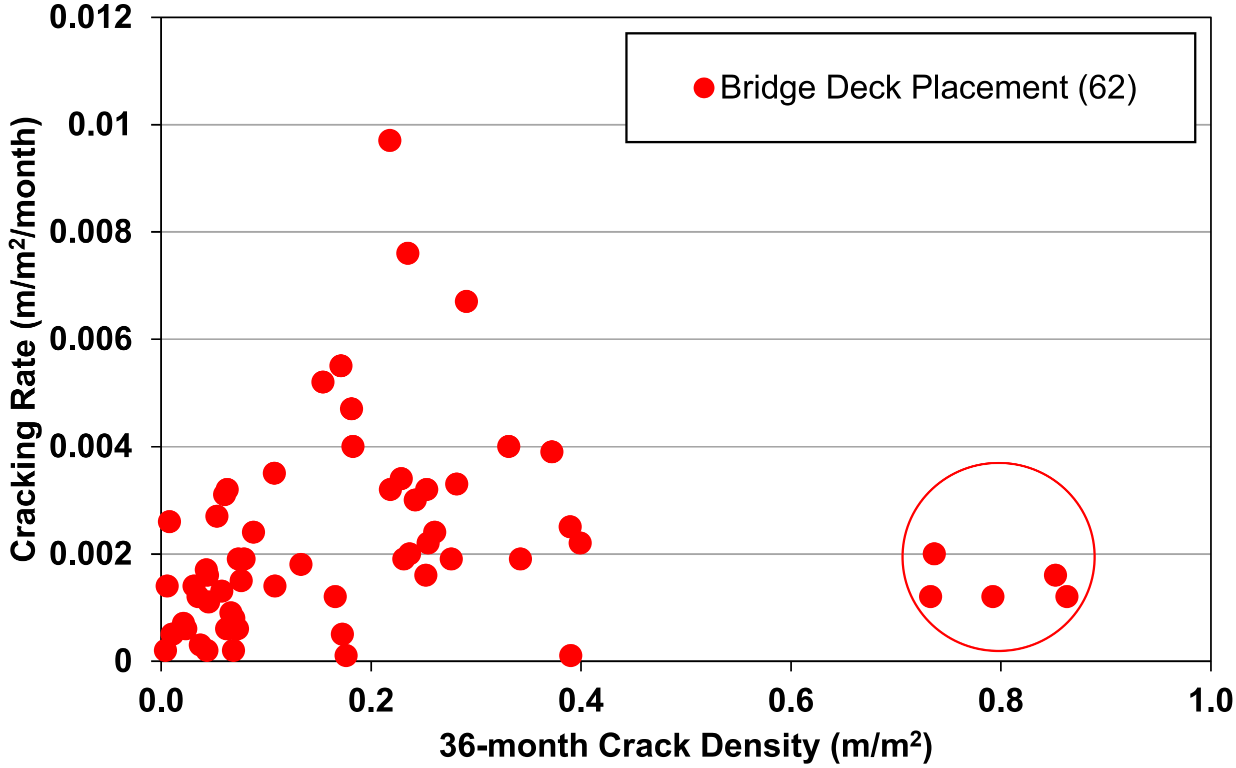

Figure C.2: Cracking rate versus 36-month crack density of 62 deck placements

As shown in Figure C.2, while most of the placements exhibited low to moderate cracking (below 0.4 m/m^2) at the age of 36 months, five placements (shown in a red circle) exhibited high initial crack densities during their first survey (greater than 0.7 m/m^2), with generally low cracking rates, ranging from 0.0012 to 0.0020 m/m^2/months. For decks with a high initial crack density, these results indicate that the cracking rate is likely to remain low, independent of deck age. One explanation for this low cracking rate may be that the concrete in bridge decks with high initial crack densities have built-in stress relief and additional volume changes will not induce stresses that are high enough to induce significant additional cracking.

In contrast to the decks with high initial crack densities, bridge decks with initial crack densities between 0 and 0.4 m/m^2, for the most part, exhibit a tendency to have a higher cracking rate as the 36-month crack density increases.

To account for the differences in behavior of decks with high and lower initial cracking, the deck placements were divided into two categories, as shown in Figure C.3. In this figure, the dashed lines represent the 95% confidence intervals, which define the range of values (upper and lower) with 95% certainty containing the population's true mean.

Category 1 consists of the five deck placements with 36-month crack densities greater than 0.7 m/m^2 (Conv. 89-204 Deck (S), Conv. 99-076 p3 (S), Conv. 99-076 p5 (S), Conv. 99-076 North (West Ln.) (S) and Conv. 99-076 p4 (S)). Category 2 consists of other 57 deck placements. These two categories were used to estimate the 36-month crack densities of the decks surveyed in this study (except for bridge 21803, whose construction date was not available).

Cracking rate as a function of 36-month crack density formula was obtained for each category as follows:

For Category 1, the $\text{Cracking Rate}_{\text{Cat.1}}$ is set equal to the average of cracking rates obtained for the five bridge decks included in this category, as shown in Eq. (C.1).

$$\text{Cracking Rate}_{\text{Cat.1}} = 0.00144 \tag{C.1}$$

where the cracking rate is expressed in m/m^2/month.

For Category 2, the $\text{Cracking Rate}_{\text{Cat.2}}$ is a function of the crack density at 36 months $\text{CD}_{@36\text{ months}}$ obtained using a trend line fitted to the cracking rate data for the Category 2 placements. The cracking rate of Group 2 is calculated using Eq, (C.2).

$$\text{Cracking Rate}_{\text{Cat.2}} = 0.0066 \times (\text{CD}_{@36\text{ months}}) + 0.0013 \tag{C.2}$$

where the crack density CD is expressed in m/m^2.

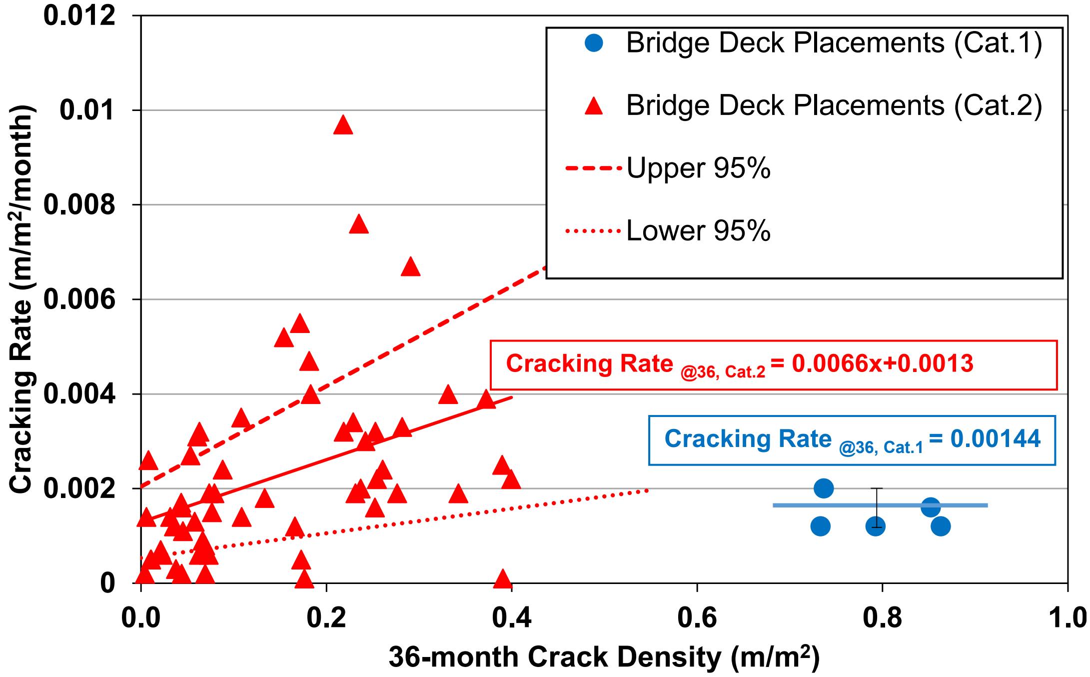

Figure C.3: Cracking rate as a function of 36-month crack density of the decks in Categories of 1 and 2

C.3.2 Estimated 36-Month Crack Density for 19 of the Decks Surveyed in this Study

Based on the process described above, an expression for estimating the 36-month crack density $CD_{@36\text{ months}}$ of the decks surveyed in this study is shown in Eq. (C.3).

$$CD_{\text{Actual}} = CD_{@36\text{ months}} + (\text{Cracking Rate}_{@36\text{ months}}) \times (\text{Age-36}) \qquad \text{(C.3)}$$

where CD $_{\text{Actual}}$ is the measured crack density at Age, the deck age at which the deck was surveyed.

To estimate the 36-month crack density of the decks surveyed in this study, the decks were divided into two groups, which correspond to Categories 1 and 2, in Eq. (C.1) and C.2), respectively, and shown in Figure C.3. Group 1 consists of the three decks with crack densities greater than or equal to 0.699 m/m^2 (71004, 85849, and 9691) while Group 2 includes the other decks.

For the decks in Group 1, the estimated 36-month crack density ($CD_{@36\text{ months}}$) is

$$CD_{@36\ months} = CD_{Actual} - 0.00144 \times (\ Age\text{-}36\ ) \tag{C.4}$$

For the decks in Group 2, the estimated 36-month crack density ($CD_{@36\ months}$) is

$$CD_{@36\ months} = CD_{Actual} - (0.0066 \times CD_{@36\ months} + 0.0013) \times (\ Age\text{-}36\ ) \tag{C.5}$$

The estimated 36-month crack densities for Groups 1 and 2 based on Eq. (C.4) and (C.5), respectively, are shown in Table C.2. As shown in the table, the 36-month estimated crack densities range from 0.010 to 0.696 m/m^2 for the PS-F decks, from 0.028 to 0.211 m/m^2 for the PS decks, and from 0.260 to 0.763 m/m^2 for the S-F decks. The 36-month crack density for the single S deck is 0.942 m/m^2.

Table C.2: The estimated crack densities at the age of 36 months

Bridge Number	Group	Category[c]	Estimated 36-Month Crack Density (m/m^2)
71004[b]	1	PS-F	0.696
85849[b]		S	0.942
9691		S-F	0.763
27W06	2	PS-F	0.083
07051		PS-F	0.141
21802		PS	0.108
21803		PS	-[a]
21804		PS	0.211
55009		S-F	0.260
58821		PS	0.054
58824		PS-F	0.166
62729[b]		PS-F	0.210
62731		PS-F	0.098
62831		S-F	0.472
62873		PS	0.177
62890		PS	0.028
69137		PS-F	0.046
69839		S-F	0.428
73047		PS-F	0.220
74805		PS-F	0.010

[a] Data is not available; [b] Deck age is average of placement ages
[c] PS = prestressed; PS-F = prestressed girders with fibers; S = steel; S-F = steel girders with fibers

APPENDIX D: CRACK SURVEY RESULTS FOR CHAPTER 5

D.1 Crack Densities at 36 Months

The crack density of bridge decks increases over time (Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2019 to name just a few). To eliminate the variable of age and compare bridge deck cracking on an equal-age basis, the crack density at 36 months after construction is chosen for the analyses in this study. An age of 36-month is selected because the tendency to exhibit cracking over the long term becomes apparent at this age (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014).

The primary assumption made in determining the 36-month crack density based on previous survey data is that a linear relationship exists between crack density and deck age. For bridge decks with survey data available at dates both before and after 36 months, the 36-month crack density is determined by linearly interpolating between the two data points. If the latest survey data of a deck was obtained before 36 but no earlier than 30 months of age, the last survey data point is taken as an approximation of the 36-month crack density. Similarly, if the earliest survey data of a deck was obtained after 36 but no later than 42 months, the first survey data point is taken as an approximation for the 36-month crack density. In bridge decks with the first available survey data point taken after 42 months of age or with the latest available survey data point taken before 30 months of age, the 36-month crack density is linearly extrapolated using the two available consecutive survey data points nearest to 36 months.

Exceptions for Fiber 1 NB (p1 and p2), Fiber 2 SB (p1 and p2) decks (Table 5.2) were made due to a reduction in the measurable crack density caused by scaling of the deck. For these decks, the crack densities obtained in the third cracking survey (at ages of 33.7 and 31.7, and 34 and 32.4, respectively) are treated as the crack densities at 36 months.

The crack survey results of the two available consecutive survey data points, used in calculation of 36-month crack densities of the 74 deck placements described in Chapter 5 are presented in Tables D.1 through D5.

Table D.1: Crack Densities at the Time of Survey and Crack Densities Used for Analysis for Fiber, Control, and SRA Decks

Bridge Deck	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
Fiber 1 NB p1	33.7	0.112	-	-	0.112
Fiber 1 NB p2	31.7	0.220	-	-	0.220
Fiber 2 SB p1	34.0	0.127	-	-	0.127
Fiber 2 SB p2	32.4	0.456	-	-	0.456
Topeka Fiber 1	26.8	0.272	37.8	0.287	0.284
Topeka Fiber 2 p1	24.0	0.300	33.6	0.709	0.709
Topeka Fiber 2 p2	24.0	0.645	33.4	0.431	0.431
Topeka Control p1	27.0	0.725	35.8	0.766	0.766
Topeka Control p2	27.0	0.411	35.6	0.393	0.393
Fiber 5 WB	31.1	0.044	44.7	0.091	0.061
Control 5 (Eastbound)	31.2	0.038	44.8	0.077	0.052
Fiber 6 WB	25.0	0.005	38.6	0.013	0.011
Control 6 (Eastbound)	25.3	0.002	38.9	0.013	0.011
Fiber 7 WB	24.6	0.001	38.0	0.005	0.004
Control 7 (Eastbound)	25.8	0.014	38.3	0.037	0.033
VA-SRA 4	10.5	0.027	33.9	0.083	0.083
VA-SRA 8	10.5	0.025	34.0	0.056	0.056
VA Control	31.0	0.222	54.1	0.266	0.232

Table D.2: Crack Densities at the Time of Survey and Crack Densities Used for Analysis for IC and Control Decks in Indiana

Placements	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
IN-Control	71.6	0.507	93.0	0.670	0.236
IN-IC	71.6	0.347	93.0	0.447	0.181
IN-IC-HPC-2	34.8	0.003	56.8	0.033	0.003
IN-IC-HPC-3	21.6	0.016	43.8	0.086	0.061
IN-IC-HPC-4 p1	15.6	0.021	35.4	0.214	0.214
IN-IC-HPC-4 p2	10.5	0.005	32.8	0.032	0.032

Table D.3: Crack Densities at the Time of Survey and Crack Densities Used for Analysis for Conventional Decks in Kansas

Placements	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
Conv. 3-046 East Deck	102	0.402	210	0.418	0.392
Conv. 3-046 West Deck	102	0.362	210	0.539	0.254
Conv. 3-046 Ctr. Deck	102	0.153	210	0.334	0.042
Conv. 75-044 Deck	48	0.179	155	0.304	0.165
Conv. 89-204 Deck	34	0.732	82	0.825	0.736
Conv. 3-045 West Deck	112	0.122	223	0.192	0.074
Conv. 3-045 East Deck	112	0.196	223	0.368	0.078
Conv. 3-045 W. Ctr. Deck	112	0.188	223	0.203	0.178
Conv. 3-045 Ctr. Deck	112	0.215	220	0.273	0.174
Conv. 3-045 E. Ctr. Deck	112	0.163	220	0.333	0.043
Conv. 56-142 Pos. Moment	80	0.108	189	0.200	0.071
Conv. 56-142 Neg. Moment	80	0.093	188	0.163	0.064
Conv. 56-148 Deck	36	0.259	133	0.486	0.259
Conv. 70-095 Deck	106	0.069	212	0.136	0.025
Conv. 70-103 Right	102	0.395	219	0.647	0.253
Conv. 70-103 Left	102	0.557	219	0.852	0.391
Conv. 70-104 Deck	106	0.083	212	0.104	0.069
Conv. 70-107 Deck	34	0.322	82	0.417	0.322
Conv. 99-076 p4	42	0.872	163	1.022	0.872
Conv. 99-076 p5	42	0.861	163	1.052	0.861
Conv. 99-076 North (West Ln.)	42	0.801	161	0.947	0.801
Conv. 99-076 North (East Ln.)	42	0.412	157	0.663	0.412
Conv. 99-076 p3	42	0.739	164	0.881	0.739
Conv. 89-208 Deck	36	0.009	73	0.106	0.009

Table D.4: Crack densities at the Time of Survey and Crack Densities Used for Analysis for LC-HPC Decks, Control 8/10, and Extra Control

Placements	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
LC-HPC 1 p1	32.1	0.044	44.1	0.060	0.049
LC-HPC 1 p2	31.5	0.024	55.0	0.023	0.024
LC-HPC 2	21.2	0.028	44.5	0.059	0.048
LC-HPC 4 p2	32.7	0.094	44.9	0.080	0.090
LC-HPC 5	31.1	0.128	43.0	0.190	0.154
LC-HPC 6	31.4	0.231	43.4	0.336	0.271
LC-HPC 7	24.2	0.019	34.8	0.012	0.012
LC-HPC 8	31.8	0.348	45.0	0.380	0.358
LC-HPC 9	26.5	0.248	38.3	0.344	0.325
LC-HPC 10	36.2	0.029	49.6	0.088	0.029
LC-HPC 11	36.2	0.165	48.4	0.269	0.163
LC-HPC 12 p1	26.8	0.256	38.8	0.313	0.300
LC-HPC 12 p2	27.3	0.268	38.1	0.375	0.354
LC-HPC 13	24.8	0.129	37.1	0.364	0.344
LC-HPC 14 p1	30.0	0.502	42.2	0.585	0.543
LC-HPC 14 p2	25.5	0.727	37.7	1.304	1.223
LC-HPC 14 p3	24.9	0.871	37.1	0.678	0.695
LC-HPC 15	30.8	0.161	43.0	0.316	0.227
LC-HPC 16	31.2	0.211	43.5	0.311	0.250
LC-HPC 17	32.5	0.274	45.5	0.308	0.283
Control 8/10	25.5	0.127	37.2	0.137	0.136
Extra Control	37.0	0.219	48.0	0.265	0.215

Table D.5: Crack densities at the Time of Survey and Crack Densities Used for Analysis for US-59 Decks

Placements	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
US-59 1	31.0	0.385	45.0	0.403	0.391
US-59 2	32.0	0.217	46.0	0.306	0.242
US-59 10	31.0	0.150	43.0	0.217	0.178
US-59 12	30.0	0.022	42.6	0.075	0.047

APPENDIX E: REGRESSION ANALYSIS AND EFFECTS OF SUPERSTRUCTURE ATTRIBUTES ON CRACKING

E.1 GENERAL

To investigate which factors have the greatest effect on bridge deck cracking, the 36-month crack densities for the 15 decks followed good construction procedures surveyed in Minnesota (Chapter 4), along with 54 bridge decks introduced in Chapter 5 (Groups 1, 2, 5, and 6), are evaluated as a function of paste content and superstructure attributes, specifically, skew, total deck length, and the number of spans. Decks with crack-reducing technologies other than fibers and decks supported by prestressed box girders are removed from the analysis (Groups 3, 4, and 7). Decks with (or suspected to have) construction issues during their construction are also excluded from the analysis, including four Minnesota decks (bridges 85849, 9691, 62831, and 69839) and bridge decks introduced in Chapter 5, Group 8 (with poor construction). Finally, bridge 21803, with an unknown date of construction and paste content, is also excluded.

E.2 REGRESSION ANALYSIS

In the following sections, a linear regression model incorporating multiple variables is used to examine the relative importance of each factor contributing to cracking in bridge decks. The relationship between independent variables can be quantified using a regression model, in this case, paste content, skew, total deck length, and the number of spans as independent variables and 36-month crack density as the dependent variable. Based on the p-value of the t-statistic test of the slope coefficient (b) of the independent variables, it is determined whether the variable contributes to the model. A p-value greater than 0.05 (a commonly accepted limit) would indicate that the independent variable does not contribute to the model, while values of $p \leq 0.05$ indicate that the variable contributes to the model.

An important assumption in regression analysis is that dependent variables and independent variables are linearly related. Therefore, the independent variables cannot be evaluated efficiently if they do not affect the dependent variable linearly. This is the case for the effects of paste content on cracking. In a study that included 40 monolithic bridge decks, Khajehdehi and Darwin (2018) and Khajehdehi et al. (2021) reported that cracking of bridge decks containing more than 27.2% paste was significantly higher than that of the bridge decks with less than 26.4% paste content, but that reductions below 26.4% provided no additional advantage. They observed that the 96-month crack densities of the decks with paste contents ranging from 22.8 to 26.4% appear not to be significantly influenced by the variations in paste contents. They observed, however, that the 96-month crack densities of decks with paste contents greater than 26.4% increased almost linearly as the paste content increased. As described in Chapter 6-Section 6.1, bridge decks with paste content of 27.2% and lower are categorized as "Low Paste," and are, therefore, in this report, assigned a value of 27.2% to account for the nonlinear relationship between paste content and crack density. Absolute values of bridge skew are used in the analysis. Tables E.1 and E.2 summarize the principal variables of the 19 Minnesota bridge decks (bridge 21803 is excluded) surveyed in this study, as well as the 54 bridge decks surveyed in previous studies (Groups 1, 2, 5, and 6) used for analysis.

Table E.1: Principal variables of the 15 bridge decks surveyed in Minnesota

Bridges	Paste Content (Adjusted, %)	Skew (degree)	Total Length (ft)	No. of Spans	36-month Crack Density (m/m^2)
21802	27.2	-33.7	146.9	3	0.108
58821	27.2	-49.5	220	3	0.054
21804	27.2	37.0	156.1	3	0.211
62873	27.2	-7.7	227.2	2	0.177
62890	27.2	-8.5	280.9	2	0.028

Table E.1: (cont.) Principal variables of the 15 bridge decks surveyed in Minnesota

Bridges	Paste Content (Adjusted, %)	Skew (degree)	Total Length (ft)	No. of Spans	36-month Crack Density (m/m^2)
27W06	27.2	0.7	262.6	4	0.083
7051	27.2	45.0	275.6	3	0.141
58824	27.2	0.0	283.5	3	0.166
62729	27.2	50.0	219.4	2	0.21
62731	27.2	0.0	89.7	1	0.098
69137	27.2	10.6	233.8	2	0.046
73047	27.2	0	144.6	2	0.22
74805	27.2	0	206.8	4	0.01
71004	29.6	0	1175	7	0.696
55009	27.2	13.8	301.2	4	0.26
62831	27.2	44.0*	219.4	2	0.472
9691	27.2	40.0	150.7	3	0.763
69839	27.2	36.0**	312	3	0.428
85849	27.2	1.0***	1157.8	5	0.942

* Skew: -33.9 to -43.6º
** Skew: -35.6 to 35.6º
*** Skew: -0.7 to 0.7º

Table E.2: Principal variables of the 54 bridge decks from previous studies

Bridges	Paste Content (Adjusted, %)	Skew (degree)	Total Length (ft)	No. of Spans	36-month Crack Density (m/m^2)
US 59 10 (PS-F)	27.2	0.0	225.5	3	0.178
US 59 12 (PS-F)	27.2	0.0	172.5	3	0.047
LC-HPC 10 (PS)	27.2	21.3	335	4	0.029
LC-HPC 8 (S)	27.2	0.0	303	4	0.358
Control 8/10 (PS)	27.2	0.0	317.7	4	0.136
Fiber 6 (WB) (S-F)	27.2	47.0	284	3	0.011
Fiber 7 (WB) (S-F)	27.2	7.0	293	3	0.004
Fiber 1 NB p1 (S-F)	27.2	7.3	232	3	0.112
Fiber 1 NB p2 (S-F)	27.2	7.3	232	3	0.220
Fiber 2 SB p1 (S-F)	27.2	7.2	232	3	0.127
Fiber 5 (WB) (S-F)	27.2	45.0	354	3	0.061
Conv. 75-044 Deck (S)	27.9	0.0	120	3	0.165

Table E.2: (cont.) Principal variables of the 54 bridge decks from previous studies

Bridges	Paste Content (Adjusted.)	Skew (degree)	Total Length (ft)	No. of Spans	36-month Crack Density (m/m^2)
LC-HPC 11 (North Ln.) (S)	27.2	-0.7	117.8	3	0.163
VA Control (S)	29.4	11.0	129	1	0.232
Conv. 70-107 Deck (S)	27.2	0.0	200	3	0.322
Conv. 99-076 North (West Ln.) (S)	28.7	0.0	258	2	0.801
LC-HPC 2 (S)	27.2	0.0	175.1	2	0.048
LC-HPC 4 p2 (S)	27.2	0.0	267.5	3	0.09
Conv. 70-095 Deck (S)	27.2	0.0	238	3	0.025
Conv. 99-076 North (East Ln.) (S)	28.7	0.0	258	2	0.412
Conv. 56-148 Deck (S)	27.2	0.0	244	3	0.259
LC-HPC 7 (S)	27.2	0.0	278.9	2	0.012
Conv. 70-104 Deck (S)	27.2	21.0	254.7	4	0.069
Conv. 89-204 Deck (S)	28.8	0.0	228	3	0.736
LC-HPC 1 p1 (S)	27.2	5.0	155.2	2	0.049
LC-HPC 1 p2 (S)	27.2	5.0	155.2	2	0.024
Control 7 (Eastbound) (S)	27.2	7.0	293	3	0.033
Conv. 3-045 Ctr. Deck (S)	27.2	45.0	160	2	0.174
Extra Control (S)	27.2	22.0	179.6	4	0.215
Conv. 70-103 Left (S)	27.2	45.0	260	3	0.391
Conv. 70-103 Right (S)	27.2	45.0	260	3	0.253
Control 6 (Eastbound) (S)	27.2	47.0	284	3	0.011
US 59 1 (S)	27.2	45.6	387.9	3	0.391
US 59 2 (S)	27.2	45.6	387.9	3	0.242
Control 5 (Eastbound) (S)	27.2	45.0	354	3	0.052
LC-HPC 5 (S)	27.2	0.0	555.7	4	0.154
LC-HPC 6 (S)	27.2	0.0	593.8	4	0.271
LC-HPC 15 (S)	27.2	0.0	352.5	2	0.227
LC-HPC 16 (S)	27.2	0.0	352.5	2	0.25
LC-HPC 17 (S)	27.2	0.0	302.5	2	0.283
Conv. 89-208 Deck (S)	27.2	0.0	363	3	0.009
LC-HPC 9 (S)	27.2	-27.7	431.9	3	0.325
Conv. 99-076 p3 (S)	27.9	0.0	128	1	0.739
Conv. 99-076 p5 (S)	28.7	0.0	128	1	0.861
Conv. 99-076 p4 (S)	28.7	0.0	130	1	0.872
Conv. 56-142 N. Pier (S)	27.2	22.0	112	1	0.064
Conv. 56-142 + Moment (S)	27.2	22.0	112	1	0.071

Table E.2: (cont.) Principal variables of the 54 bridge decks from previous studies

Bridges	Paste Content (Adjusted.)	Skew (degree)	Total Length (ft)	No. of Spans	36-month Crack Density (m/m^2)
Conv. 3-045 E. Ctr. Deck (S)	27.2	45.0	80	1	0.043
Conv. 3-045 East Deck (S)	27.2	45.0	64	1	0.078
Conv. 3-046 Ctr. Deck (S)	27.2	50.0	120	1	0.042
Conv. 3-046 East Deck (S)	27.2	50.0	100	1	0.392
Conv. 3-045 West Deck (S)	27.2	45.0	64	1	0.074
Conv. 3-045 W. Ctr. Deck (S)	27.2	45.0	80	1	0.178
Conv. 3-046 West Deck (S)	27.2	50.0	100	1	0.254

The regression model parameters considered initially using 54 bridge decks from previous studies (Table E.2) are paste content (27.2 to 29.4%), skew (0 to 50º), total length (64 to 593.8 ft), and the number of spans. The *p*-values of the t-statistics of the slope coefficients, as well as adjusted R-squared (R^2), a modified version of R^2 representing the percentage of variance explained by independent variables in a regression model for a dependent variable, are calculated. After the initial regression analysis was performed, only one out of four variables remained in the model, with a *p*-value of less than 0.05, as provided in Table E.3. The variable producing the smallest value of *p*, 6×10^{-7}, was cement paste, which resulted in an adjusted R^2 value of 0.444 for the model.

Table E.3: Principle variables found in the initial regression analysis

Principal Variable	Slope coefficients, *b*	*p*-values of the t-statistics of the slope Coefficients	Adjusted R^2
Paste content (%)	0.282	$\mathbf{6\times10^{-7}}$	0.444
Skew (degree)	-0.028	0.412	
Total length (ft)	-2×10^{-4}	0.846	
Number of spans	3×10^{-4}	0.267	

Given that paste content was the only independent variable with a *p*-value of less than 0.05, a second regression analysis was performed between the 36-month crack density as the dependent variable and the paste content as the independent variable to finalize the regression model. As shown in Table E.4, the slope coefficient for paste content and the adjusted R^2 of the model increases slightly from 0.282 and 0.444 in the first regression analysis to 0.287 and 0.462, respectively, in the second.

Table E.4: Principle variables found in the second regression analysis

Principal Variable	Slope coefficients, *b*	*p*-values of the t-statistics of the slope Coefficients	Adjusted R^2
Paste content (%)	0.287	**9.5×10^{-9}**	0.462

To investigate the effects of variables other than the dominant variable on cracking, the effects of paste content as the dominant variable must be eliminated from the analysis. By using the slope coefficient of (b = 0.287), the measured (Appendix D) or measured/estimated (Appendix C) 36-month crack densities ($\mathrm{CD}_{@36\text{ month}(\text{measured/estimated})}$) can be converted into equivalent values for a single paste content. The adjustment for this analysis is based on a paste content of 27.2%. For this analysis, the adjustments are made based on a paste content of 27.2%. The calculation is shown in Eq. (E.1).

$$\mathrm{CD}_{\text{Adjusted@36 months}} = \mathrm{CD}_{@36\text{ month (measured/estimated)}} + 0.287\times(\,27.2\%\text{-Paste content}\,) \qquad \text{(E.1)}$$

where $\mathrm{CD}_{\text{Adjusted@36 months}}$ is the adjusted 36-month crack density.

E.3 FACTORS AFFECTING CRACKING

The following sections evaluate the effects of paste content, skew, total length, and the number of spans of bridge decks on cracking. For each section, the independent variable is evaluated based on the girder type (prestressed concrete or steel girders) with or without the incorporation of fibers in the deck. The first portion of each section provides the measured/estimated and adjusted 36-month crack density of the 15 Minnesota decks surveyed in this study (identified with a trailing indicator of "MN" in the legend IDs). In a somewhat broader way, the second portion evaluates the effects of independent variables (described in Section E.2) using both 15 Minnesota decks surveyed in this study and 54 decks surveyed in previous studies (identified with a trailing indicator of "All" in the legend IDs).

E.3.1 Paste Content

The effects of paste content in bridge deck cracking were discussed in detail in Chapter 6-Section 6.1 of this report. Cement paste content is the dominant factor in concrete shrinkage and, consequently, cracking in bridge decks, and thus, low-cracking bridge decks require the use of concrete with a low paste content (27.2% and below).

E.3.2 Skew (θ)

The results show that low cracking can be associated with high or low skew. Figures E.1 to E.3 show the average measured/estimated and adjusted 36-month crack densities for the 15 Minnesota decks surveyed in this study (with good construction). Three categories were defined as decks without skew ($\theta = 0^{o}$), skews greater than 0^{o} and less than 45^{o}, and skews greater than or equal to 45^{o}. As shown in Figure E.1, the average measured/estimated 36-month crack density for prestressed concrete girder decks with fibers decreases from 0.238 to 0.065 m/m^2 when the skew increases from 0 to a greater value but less than 45^{o}; the average measured/estimated 36-month crack density, however, increases from 0.065 to 0.176 m/m^2 when the skew increases more ($\theta \geq 45^{o}$). Although the standard deviation (σ) for Minnesota decks with fibers supported by prestressed concrete girders without skew ($\sigma = 0.239$ m/m^2) was considerably higher than that of the skewed decks ($\sigma = 0.019$ or 0.035 m/m^2), the differences between categories are not statistically significant

(p values ranging from 0.105 to 0.769). Similar observations can be made when the crack densities are adjusted using Eq. (E.1); a decrease from 0.100 to 0.065 m/m^2 when the skew increases from 0 to less than 45°; and an increase from 0.065 to 0.176 m/m^2 when the skew increases more ($\theta \geq$ 45°); these differences, are, again, not statistically significant (p values ranging from 0.105 to 0.639).

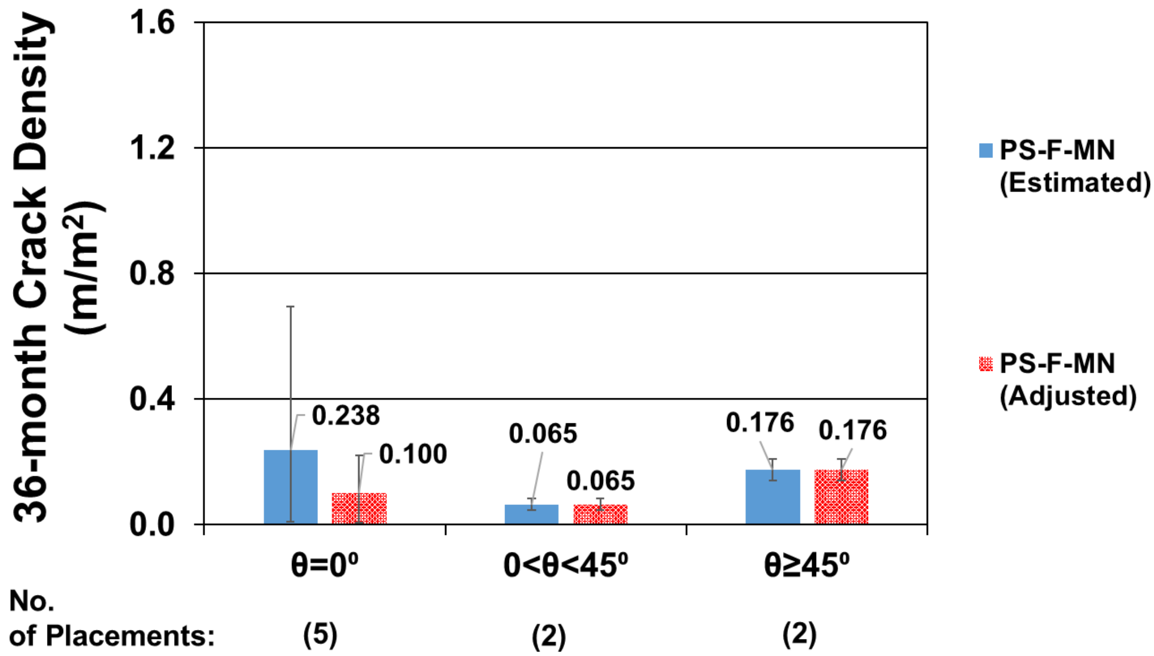

Figure E.1: Average measured/estimated and adjusted 36-month crack densities for Minnesota bridge decks supported by prestressed concrete girders with fibers and different skew

As shown in Figure E.2, the average measured/estimated 36-month crack density for prestressed concrete girder decks without fibers decreases from 0.131 to 0.054 m/m^2 when the skew of the bridge was greater than or equal to 45°. Similar observations can be made when the crack densities are adjusted using Eq. (E.1); these differences, however, are small. The fact that there is no difference between the average measured/estimated and adjusted 36-month crack densities suggests that the paste content alone, regardless of the other variables, has a dominant effect on cracking.

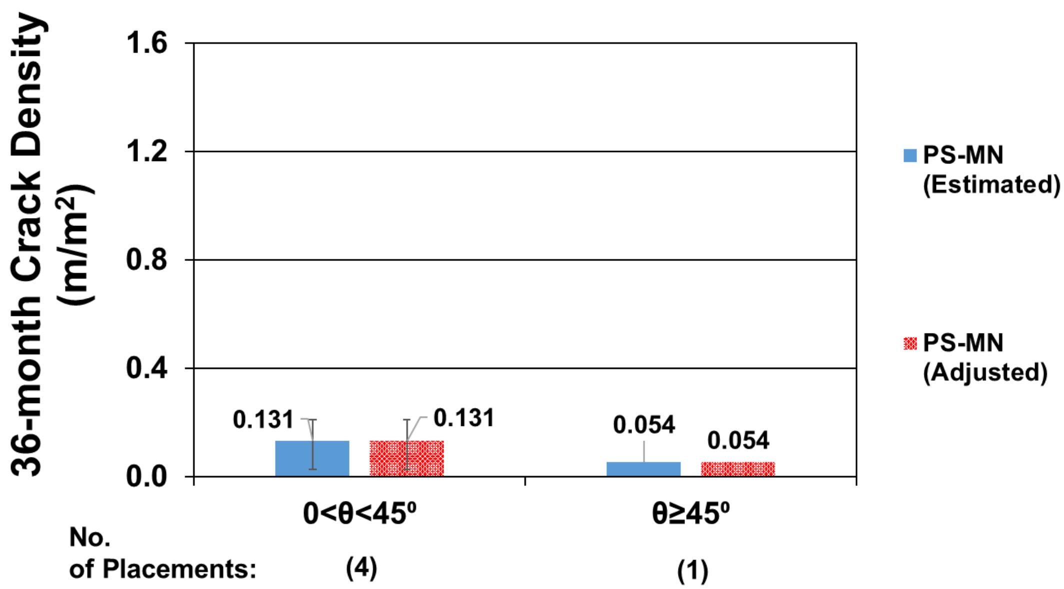

Figure E.2: Average measured/estimated and adjusted 36-month crack densities for Minnesota bridge decks supported by prestressed concrete girders without fibers and different skew

As shown in Figure E.3, a single steel girder bridge deck with fibers [S-F-MN (Estimated)] exhibited average measured/estimated and adjusted crack density of 0.260 m/m^2 at 36 months of age.

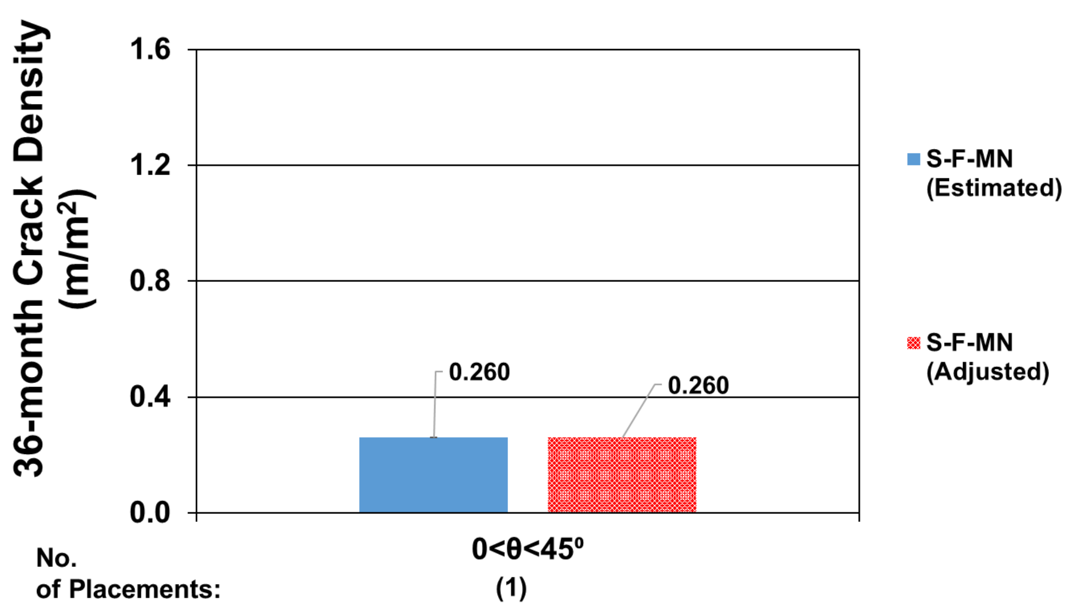

Figure E.3: Average measured/estimated and adjusted 36-month crack densities for a single Minnesota bridge deck supported by steel girders with fibers and a skew less than 45º (θ = 14º)

Figures E.4 to E.7 show the average measured/estimated and adjusted 36-month crack densities for all of the decks described in Section E.1 (with good construction). As shown in Figure E.4 (all but two of these are Minnesota decks), the average measured/estimated 36-month crack density for prestressed concrete girder decks with fibers decreases from 0.202 to 0.065 m/m^2 when the skew increases from 0 to a greater value but less than 45^o; the average measured/estimated 36-month crack density, however, increases from 0.065 to 0.176 m/m^2 when the skew increases more ($\theta \geq 45^o$). Although the standard deviation for decks supported by prestressed concrete girders and fibers without skew (σ = 0.213 m/m^2) was considerably higher than that of the skewed decks (σ = 0.019 or 0.035 m/m^2), no statistically significant differences were observed between the categories (*p* values ranging from 0.105 to 0.881). Similar observations can be made when the crack densities are adjusted using Eq. (E.1); a decrease from 0.104 to 0.065 m/m^2 when the skew increases from 0 to a greater value but less than 45^o; and an increase from 0.065 to 0.176 m/m^2 when the skew increases to $\theta \geq 45^o$; these differences, however, are small and not statistically significant (*p* values ranging from 0.105 to 0.562).

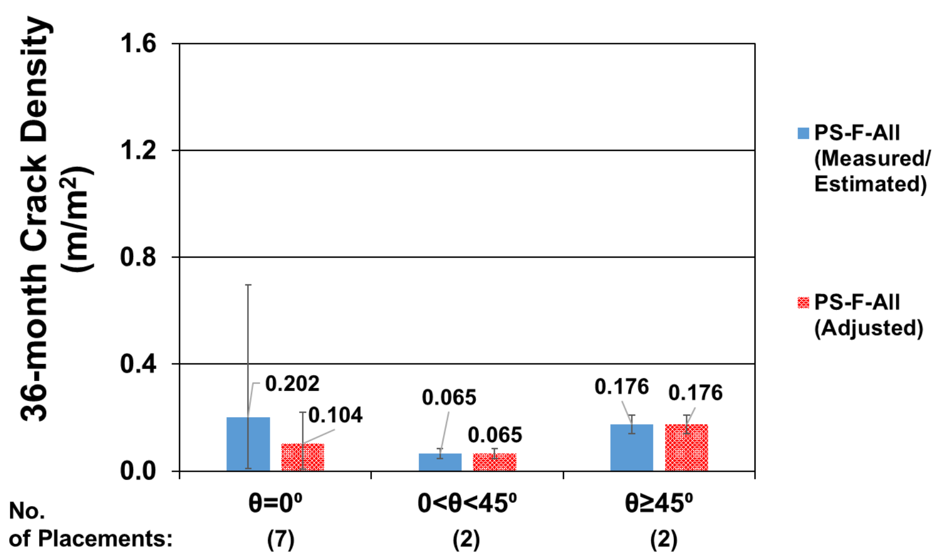

Figure E.4: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by prestressed concrete girders with fibers and different skew

As shown in Figure E.5, the average measured/estimated 36-month crack density for prestressed concrete girder decks without fibers decreases from 0.247 to 0.054 m/m^2 when the skew increases. The lowest 36-month crack density (0.054 m/m^2) is observed for a single deck with a skew greater than or equal to 45° (θ = 49°). Similar observations can be made when the crack densities are adjusted using Eq. (E.1); the difference, however, is not statistically significant (p = 0.173).

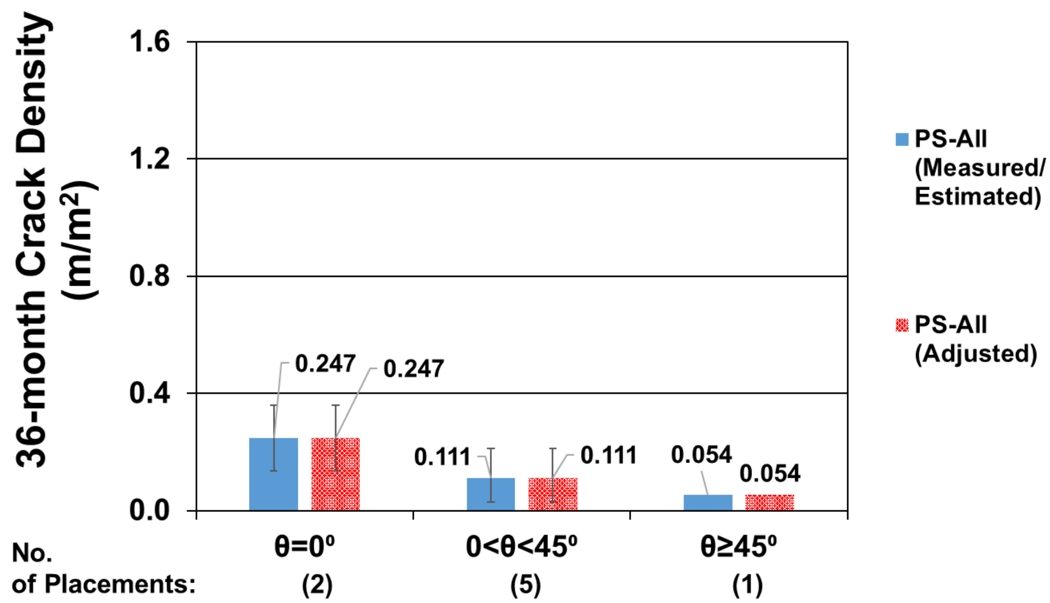

Figure E.5: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by prestressed concrete girders without fibers and different skew

As with Figure E.5, the average measured/estimated 36-month crack density for prestressed concrete girder decks without fibers decreases from 0.145 to 0.036 m/m^2 when the skew increases, as illustrated in Figure E.6. The lowest average 36-month crack density (0.036 m/m^2) is observed for decks with skews greater than or equal to 45°. Similar observations can be made when the crack densities are adjusted using Eq. (E.1); the difference is not statistically significant (p = 0.213).

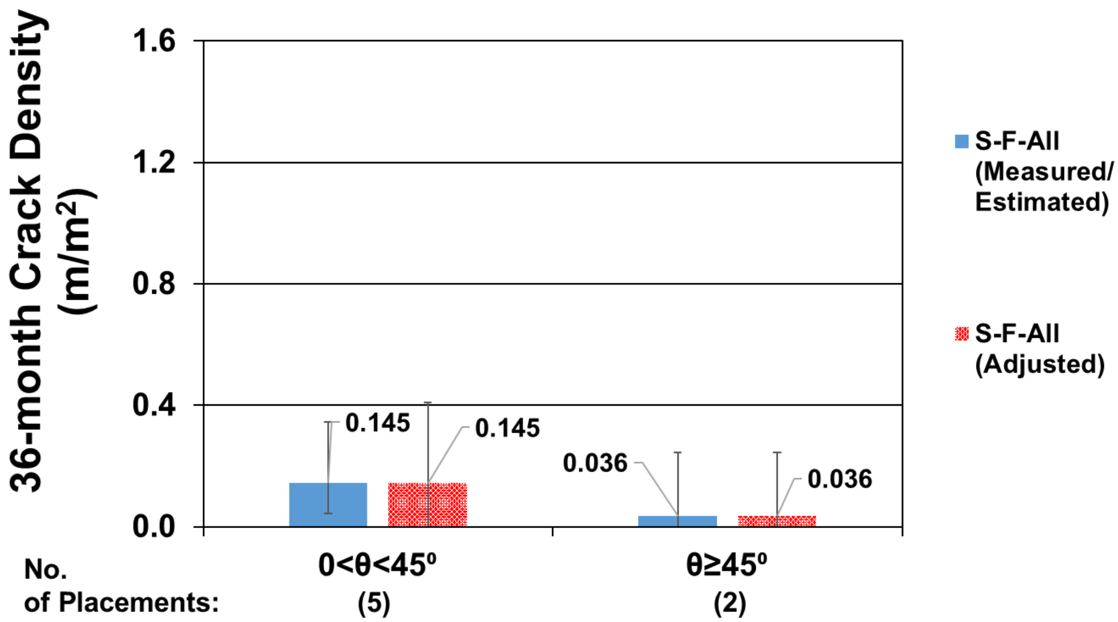

Figure E.6: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by steel girders with fibers and different skew

As shown in Figure E.7, the average measured/estimated 36-month crack density for all steel concrete girder decks without fibers decreases from 0.344 to 0.125 m/m^2 when the skew increases from 0 to less than 45º; the average measured/estimated 36-month crack density, however, increases from 0.125 to 0.184 m/m^2 when the skew increases more ($\theta \geq 45^o$). The standard deviation (σ) for decks supported by steel girders and fibers without skew ($\sigma = 0.294$ m/m^2) is considerably higher than that of the skewed decks ($\sigma = 0.097$ or 0.134 m/m^2), where a statistically significant difference was observed between decks with $\theta = 0^o$ (no skew) and those with $0 \leq \theta < 45^o$ ($p = 0.036$). Similar observations can be made when the crack densities are adjusted using Eq. (E.1); a decrease from 0.208 to 0.061 m/m^2 when the skew increases from 0 to a skew up to 45º; and an increase from 0.061 to 0.184 m/m^2 when the skew increases more ($\theta \geq 45^o$); the difference between the average 36-month crack density of decks with no skew (average of 0.208 m/m^2) and that of the decks with $0 < \theta < 45^o$ (0.061 m/m^2) is statistically significant (p = 0.044); the difference between the average 36-month crack density of decks with no skew or with skews greater than or equal to 45º, however, is not statistically significant (p = 0.673); the difference between the 36-month crack density of decks with 0 < θ < 45º or θ ≥ 45º, also is not statistically significant (p = 0.080).

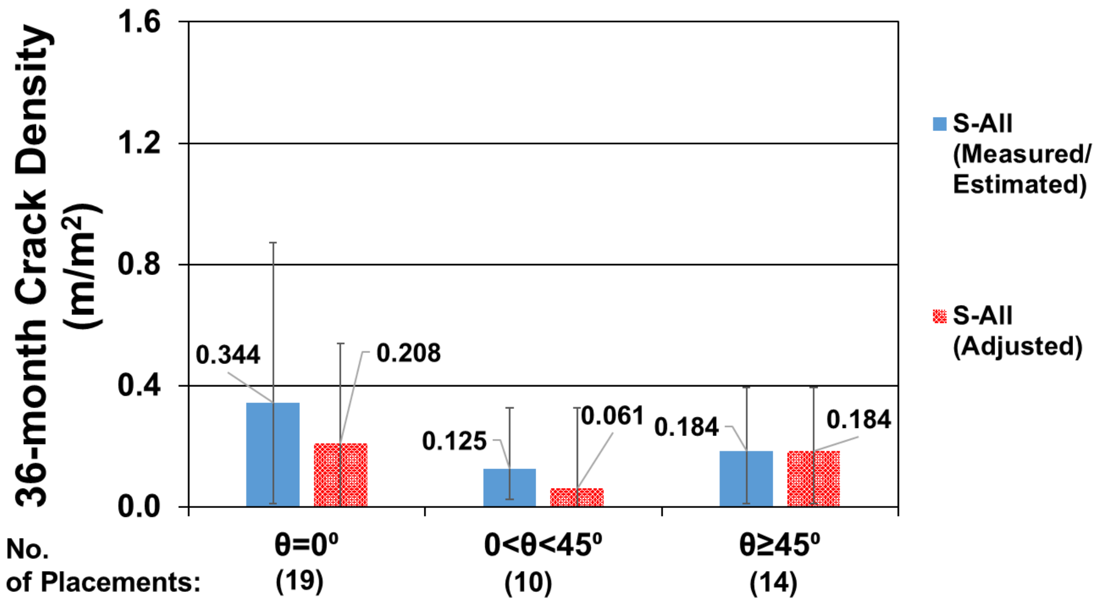

Figure E.7: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by steel girders without fibers and different skew

The results of this section indicate that skew has a small effect on cracking; in most cases in this study, skewed decks exhibit lower cracking than decks without skew, but except for one case, the differences described are not statistically significant. These observations align with the findings dating back two decades ago by Schmitt and Darwin (1995) and Miller and Darwin (2000) who reported that bridge skew has no measurable effect on bridge deck cracking.

E.3.3 Total Deck Length (L)

Results, in general, show that total deck length does not have a statistically significant effect on cracking. Figures E.8 to E.10 show the average measured/estimated and adjusted (using Eq. (E.1)) 36-month crack densities for the 15 Minnesota decks surveyed in this study (with good construction). Three categories were defined as decks with a total length less than 150 ft (L < 150 ft), greater than or equal to 150 ft but less than 300 ft (150 ≤ L< 300 ft), and greater than or equal to 300 ft (L ≥ 300 ft). As shown in Figure E.8, the average measured/estimated 36-month crack density for prestressed concrete girder decks with fibers increases from 0.109 to 0.696 m/m^2 as the total length increases, although the last value is based on a single bridge. Based on both the measured/estimated and adjusted crack densities, the average 36-month crack density increases from 0.109 to 0.159 m/m^2 for total lengths for decks with values less than 150 ft to values between 150 and 300 ft; this difference is not statistically significant (p = 0.464). The measured/estimated crack density increases all the way up to 0.696 m/m^2 for the single bridge with a length greater than 300 ft, 1175 ft for bridge 71004. This apparent effect is, however, deceiving because the concrete in the deck had a paste content of 29.6%, a value expected to lead to significant cracking. When adjusted for paste content, the crack density of the deck on bridge 71004 is just 0.007 m/m^2. Thus, based on these survey results, there is no indication that bridge deck cracking is associated with bridge length.

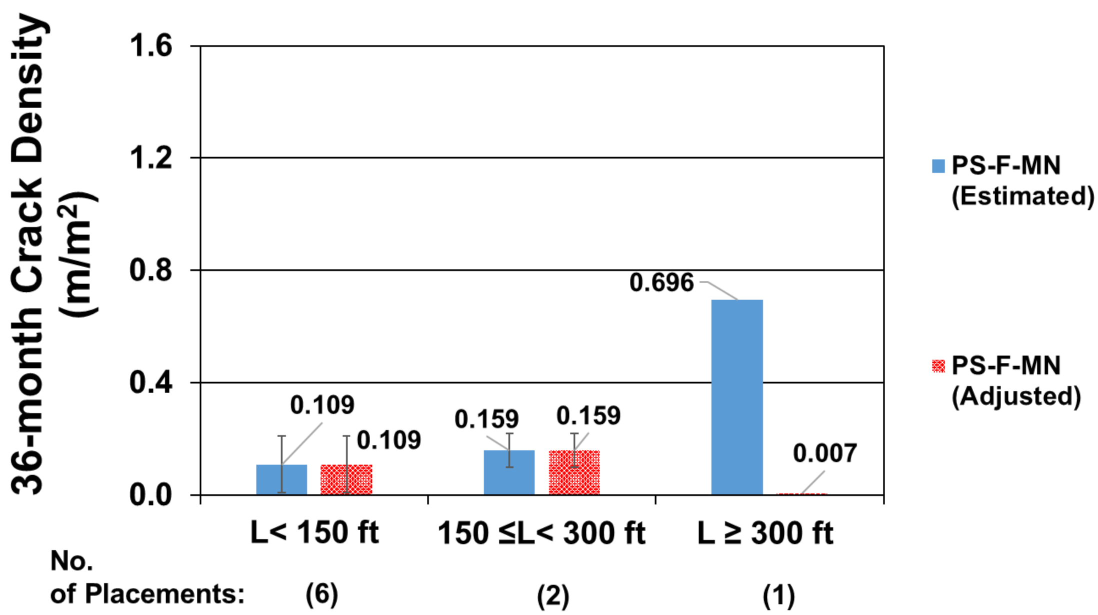

Figure E.8: Average measured/estimated and adjusted 36-month crack densities for Minnesota bridge decks supported by prestressed concrete girders with fibers and different total deck length

As shown in Figure E.9, the average measured/estimated and adjusted 36-month crack density for prestressed concrete girder decks without fibers increases from 0.101 to 0.118 m/m^2 as the total length increases; these differences, however, were small.

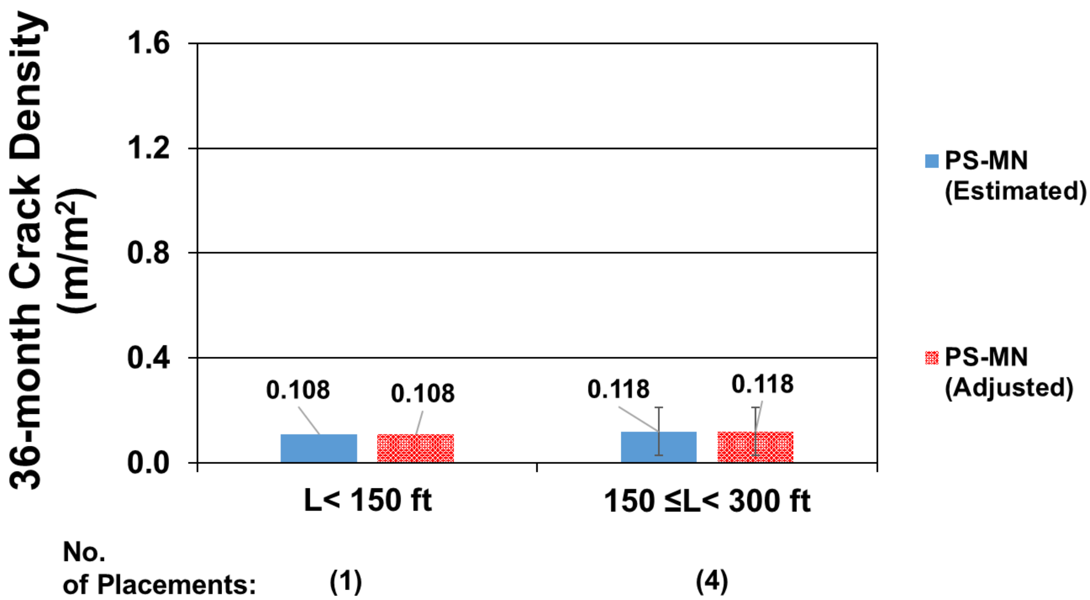

Figure E.9: Average measured/estimated and adjusted 36-month crack densities for Minnesota bridge decks supported by prestressed concrete girders without fibers and different total deck length

As shown in Figure E.10, a single steel girder deck with fibers [S-F-MN (Estimated)] exhibited average measured/estimated and adjusted crack density of 0.260 m/m^2 at 36 months of age.

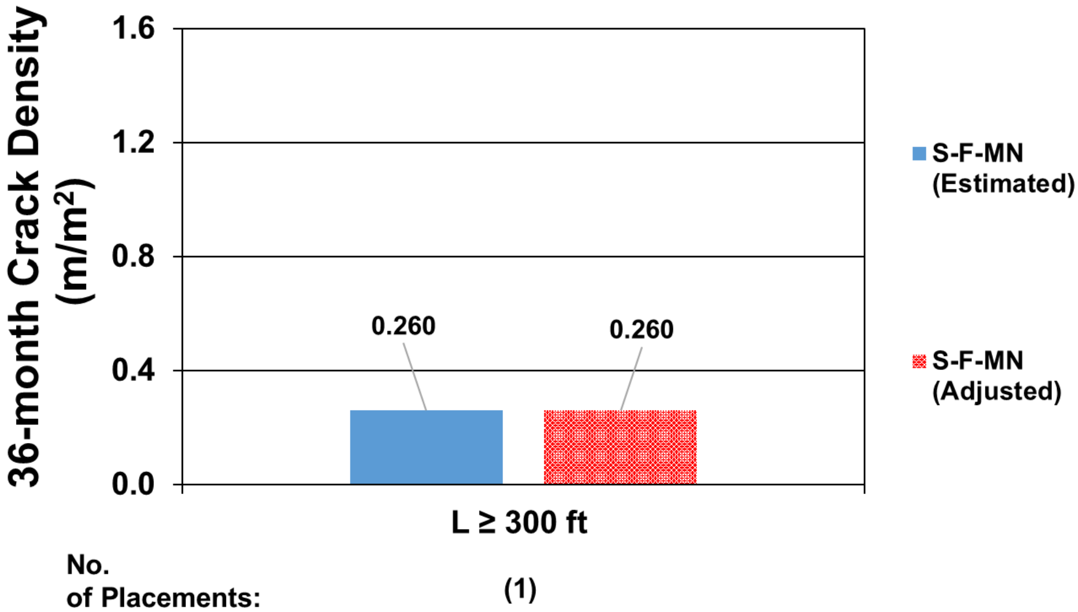

Figure E.10: Average measured/estimated and adjusted 36-month crack densities for a single Minnesota bridge deck supported by steel girders with fibers and a deck length greater than or equal to 300 ft (L = 301.2 ft)

Figures E.11 to E.14 show the average measured/estimated and adjusted 36-month crack densities for all of the decks. As shown in Figure E.11, the average measured/estimated and adjusted 36-month crack density for prestressed concrete girder decks with fibers increases from 0.110 to 0.696 m/m^2 as the total length increases, but as discussed in relation to Figure E .8, the later value results from the high paste content of the concrete in the deck. When the crack densities are adjusted using Eq. (E.1), the average 36-month crack density increases from 0.110 to 0.159 m/m^2 as total deck lengths increase from less than 150 ft increases to values between 150 and 300 ft, with a difference that is not statistically significant (p = 0.433) and drops for the single bridge with a length greater than 300 ft to 0.007 m/m^2.

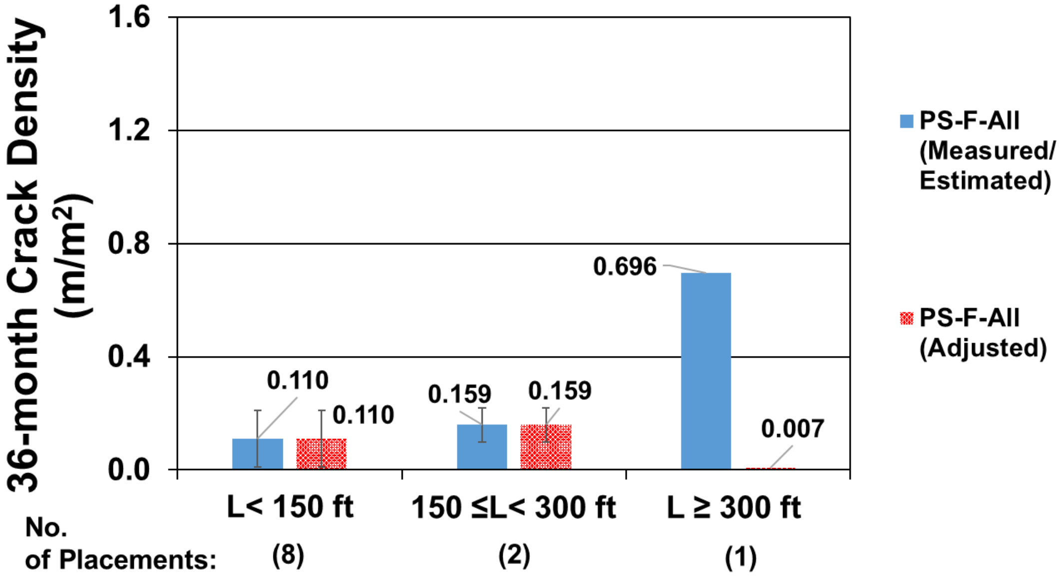

Figure E.11: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by prestressed concrete girders with fibers and different total deck length

As shown in Figure E.12, the average measured/estimated and adjusted 36-month crack density for prestressed concrete girder decks without fibers increases from 0.108 to 0.174 m/m^2 as the total length increases, although the difference between the 36-month crack density of decks with 150 ≤ L < 300 ft and L ≥ 300 ft is not statistically significant (p = 0.583).

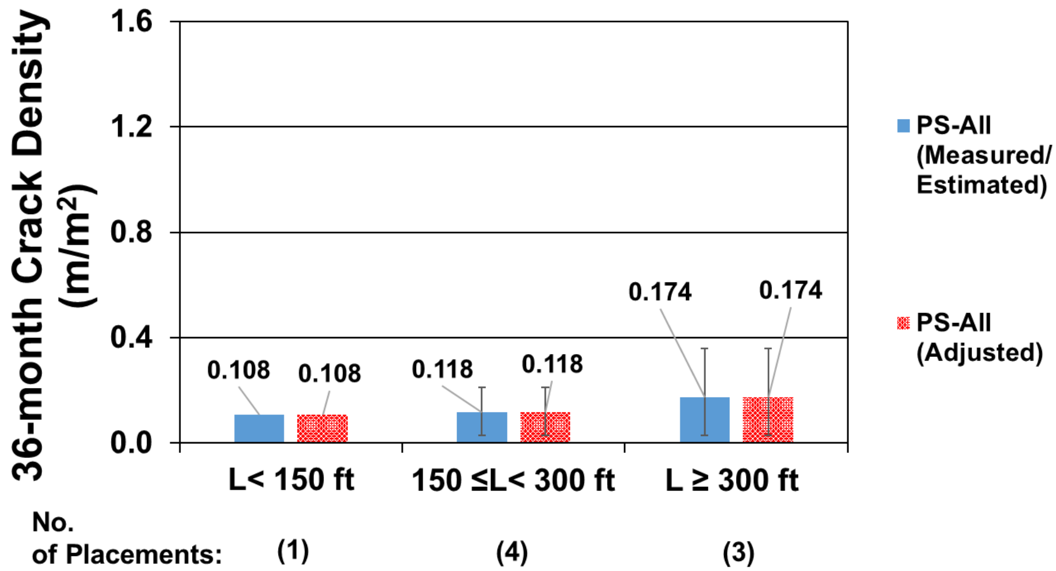

Figure E.12: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by prestressed concrete girders without fibers and different total deck length

Similarly, as shown in Figure E.13, the average measured/estimated and adjusted 36-month crack density for steel girder decks with fibers increases from 0.095 to 0.161 m/m^2 as the total length increases; the difference, however, is not statistically significant ($p = 0.476$).

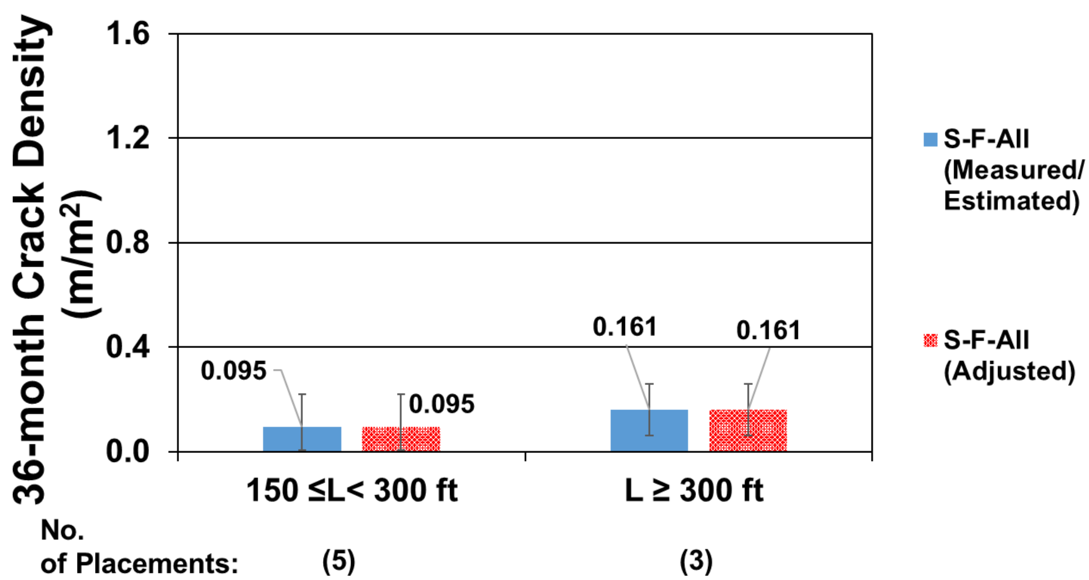

Figure E.13: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by steel girders with fibers and different total deck length

As shown in Figure E.14, the average measured/estimated 36-month crack density for steel concrete girder decks without fibers decreases from 0.282 to 0.218 m/m^2 when the total length increases from L < 150 ft to 150 ≤ L <300 ft and remains essentially unchanged at 0.220 m/m^2 for a total length L ≥ 300 ft. Although the standard deviation (σ) for decks supported by steel girders without fibers with L < 150 ft and 150 ≤ L <300 ft (σ = 0.287 and 0.234 m/m^2, respectively) were considerably higher than that of the decks with L ≥ 300 ft (σ = 0.112 m/m^2), none of the differences are statistically significant (*p* values ranging from 0.500 to 0.976).

Similar observations can be made when the crack densities are adjusted using Eq. (E.1); a decrease from 0.155 to 0.145 m/m^2 when the total length increases from L < 150 ft to 150 ≤ L <300 ft; and an increase from 0.145 to 0.220 m/m^2 when the total length increases from 150 ≤ L <300 ft to L ≥ 300 ft. The standard deviations after the adjustment for paste content reduced from 0.226 to 0.111 m/m^2, where no statistically significant differences were observed between the adjusted 36-month crack density of each category (*p* values ranging from 0.154 to 0.869).

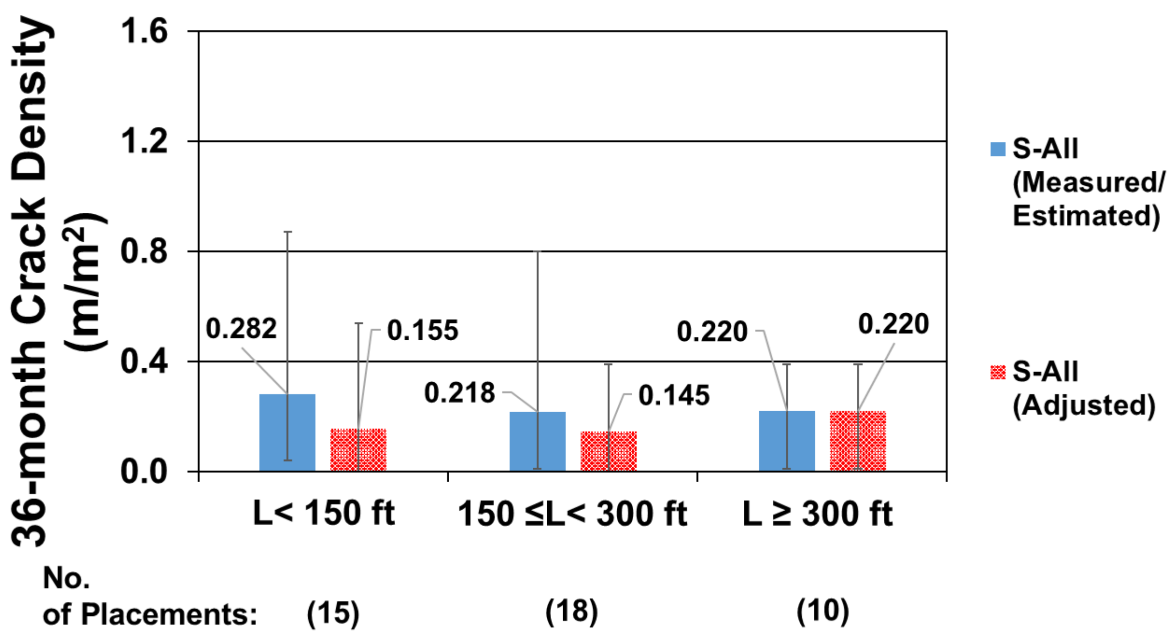

Figure E.14: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by steel girders without fibers and different total length

The results of this section indicate that the total deck length does not have a statistically significant effect on cracking.

E.3.4 Number of Spans (#S)

Figures E.15 to E.17 show the average measured/estimated and adjusted 36-month crack densities for the 15 Minnesota decks surveyed in this study. Three categories were defined as decks with only one span (#S = 1), two spans (#S = 2), and three or more spans (#S $\geq$ 3). As shown in Figure E.15, the average measured/estimated 36-month crack density for prestressed concrete girder decks with fibers increases from 0.098 to 0.219 m/m^2 as the number of spans increases (possibly due to appearance of the negative moment regions in decks with more than one span) with a difference that is not statistically significant between decks with two spans and decks with three or more spans ($p = 0.731$). When the crack densities are adjusted using Eq. (E.1), the average 36-month crack density increases from 0.098 for a single deck with one span to 0.159 m/m^2 for decks with two spans. A decrease from 0.159 to 0.081 m/m^2, however, is observed when the number of spans increases from 2 to values greater than or equal to 3, with a difference that is not statistically significant ($p = 0.245$).

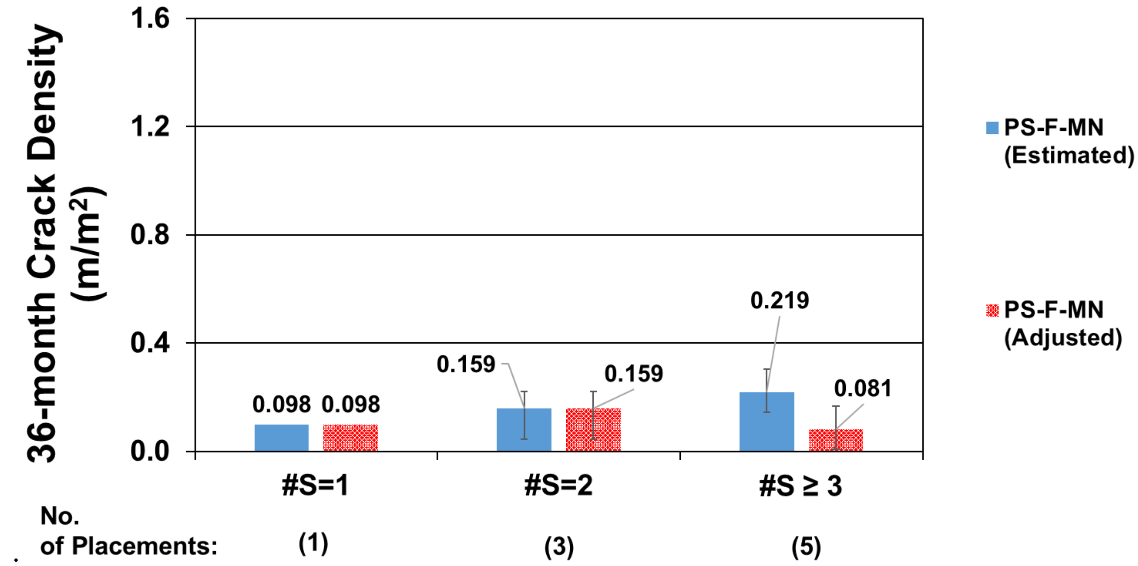

Figure E.15: Average measured/estimated and adjusted 36-month crack densities for Minnesota bridge decks supported by prestressed concrete girders with fibers and different numbers of span

As shown in Figure E.16, the average measured/estimated and adjusted 36-month crack density for prestressed concrete girder decks without fibers increases from 0.103 for decks with two spans to 0.124 m/m^2 for decks with three and more spans; these differences, however, are not statistically significant ($p = 0.805$).

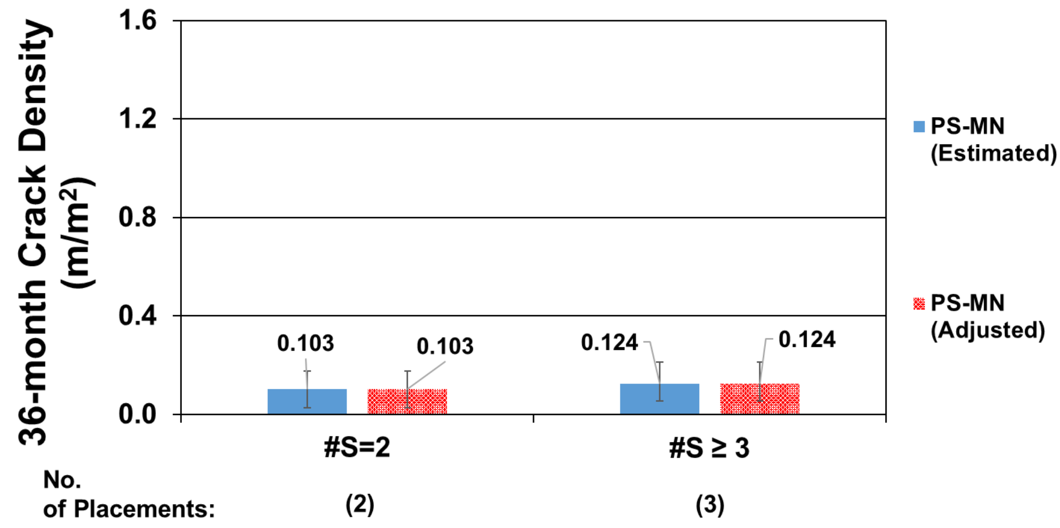

Figure E.16: Average measured/estimated and adjusted 36-month crack densities for Minnesota bridge decks supported by prestressed concrete girders without fibers and different numbers of span

As shown in Figure E.17, a single steel girder bridge deck with fibers [S-F-MN (Estimated)] exhibited an measured/estimated and adjusted crack density of 0.260 m/m^2 at 36 months of age.

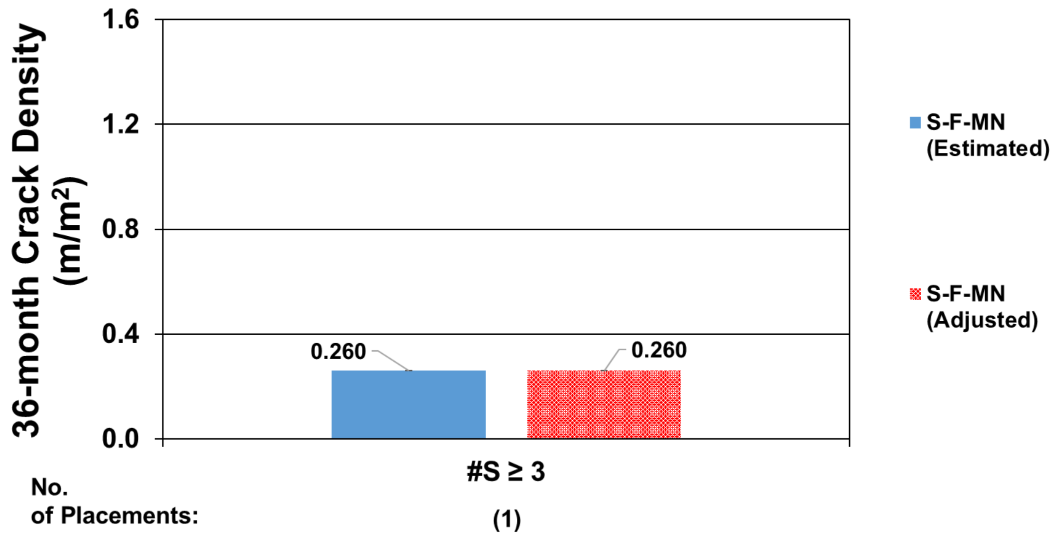

Figure E.17: Average measured/estimated and adjusted 36-month crack densities for a single Minnesota bridge deck supported by steel girders with fibers and four spans (#S ≥ 3)

Figures E.18 to E.21 show the average measured/estimated and adjusted 36-month crack densities for all of the decks. As shown in Figure E.18, the average measured/estimated 36-month crack density for prestressed concrete girder decks with fibers increases from 0.098 to 0.189 m/m^2 as the number of spans increases (possibly due to the negative moment regions in decks with more than one span) with a difference that is, however, not statistically significant (p = 0.838). When the crack densities are adjusted using Eq. (E.1), the average 36-month crack density increases from 0.098 for a single deck with one span to 0.159 m/m^2 for decks with two spans and decreases from 0.159 to 0.090 m/m^2 when the number of spans increases from 2 to 3 or more; the difference is not statistically significant (p = 0.247).

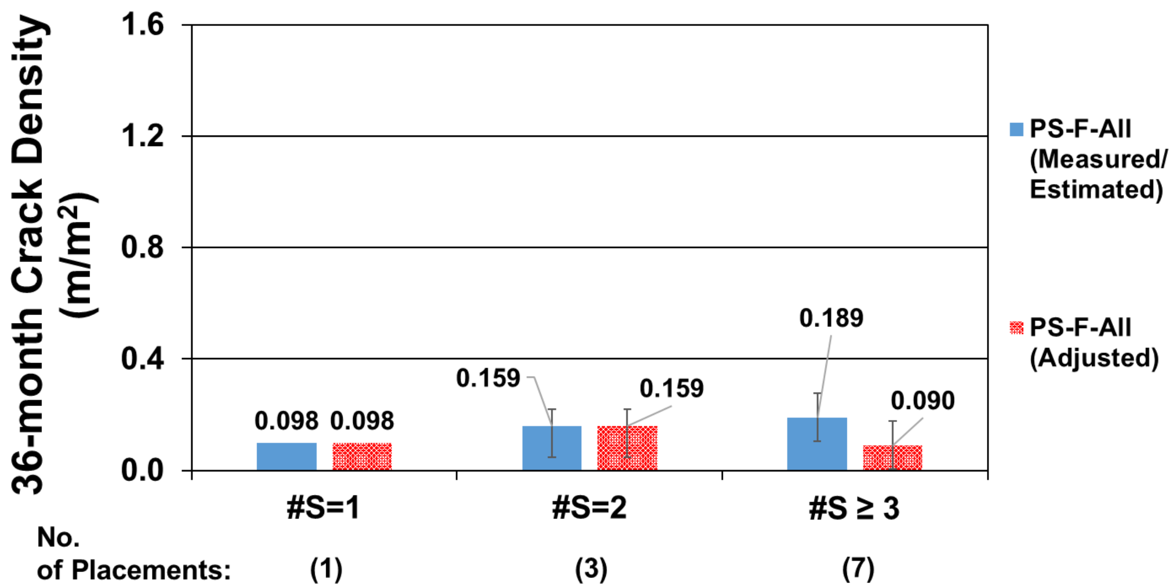

Figure E.18: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by prestressed concrete girders with fibers and different numbers of span

As shown in Figure E.19, the average measured/estimated as well as the adjusted 36-month crack density for prestressed concrete girder decks without fibers increases from 0.103 (for decks with two spans) to 0.149 m/m^2 (for decks with three and more spans); these differences are also not statistically significant (p = 0.645).

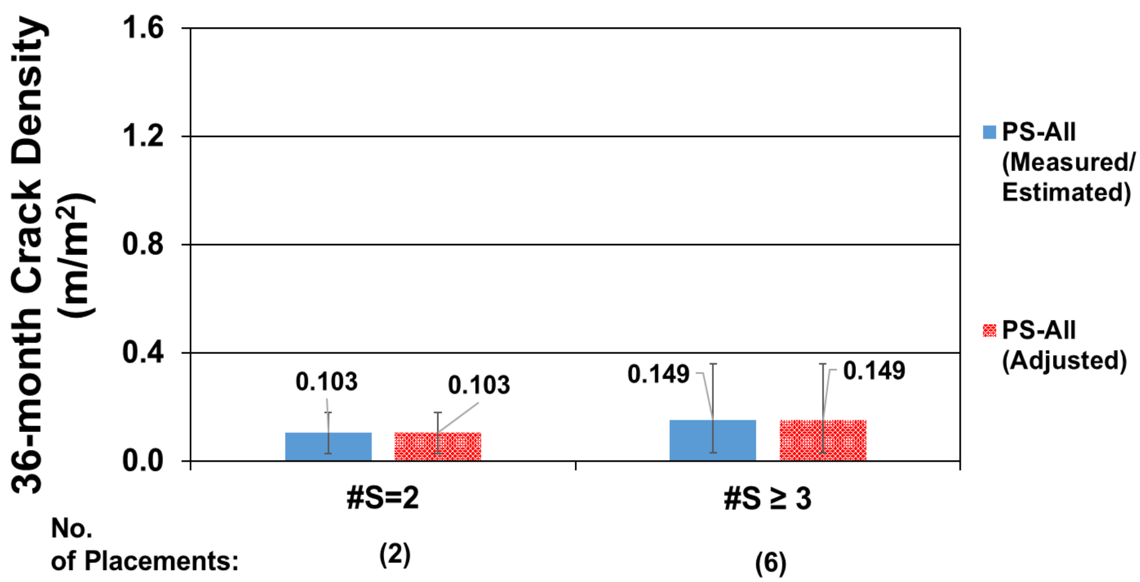

Figure E.19: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by prestressed concrete girders without fibers and different numbers of span

As shown in Figure E.20, the average measured/estimated and adjusted crack density for steel girder decks with fibers was 0.114 m/m^2 at 36 months of age.

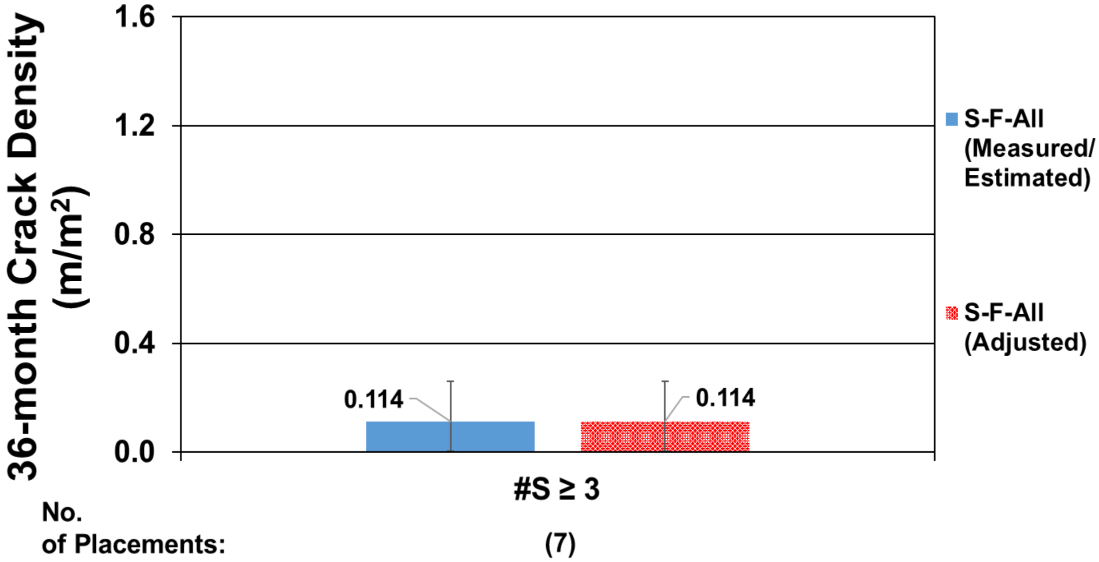

Figure E.20: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by steel girders with fibers and different numbers of span (#S ≥ 3)

As shown in Figure E.21, the average measured/estimated 36-month crack density for steel girder decks without fibers decreases from 0.300 to 0.209 m/m^2 as the number of spans decreases; the differences between categories are not statistically significant (p values ranging from 0.295 to 0.805). When adjusted for paste content using Eq. (E.1), the average 36-month crack density decreases from 0.170 m/m^2 for decks with one span to 0.142 m/m^2 for decks with two spans and increases to 0.176 m/m^2 for decks with three and more spans; the differences between categories are not statistically significant (p values ranging from 0.525 to 0.929).

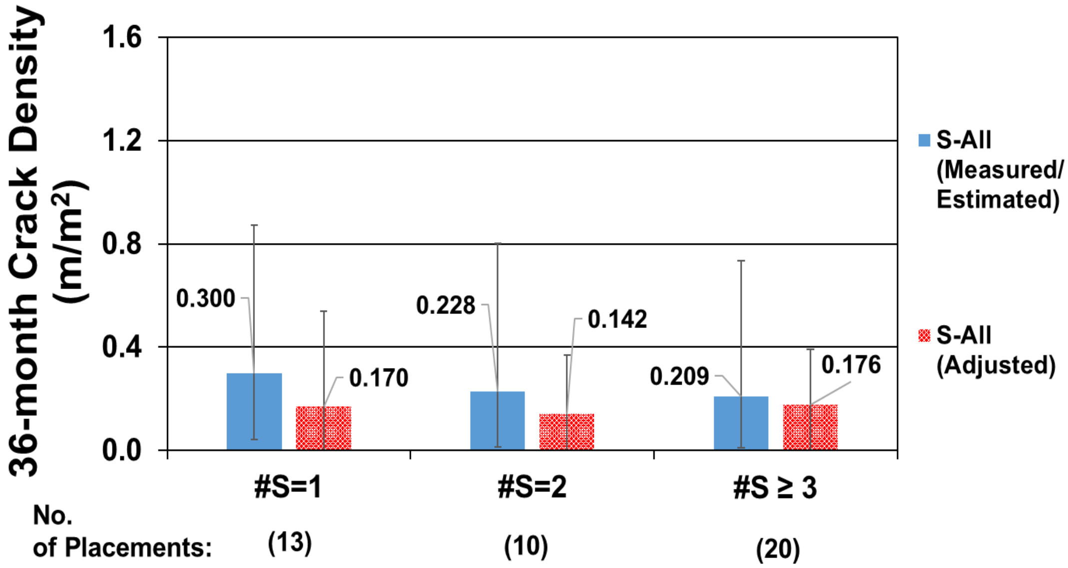

Figure E.21: Average measured/estimated and adjusted 36-month crack densities for all bridge decks supported by steel girders without fibers and different numbers of span

The results of this section indicate that the number of spans does not have a statistically significant effect on cracking.