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Analysis of Bridge Deck Cracking Data

A Review of Mechanisms, Analysis of MnDOT Bridge Construction Data, and Recommendation for Treatment and Prevention

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Cracking of the concrete decks on newly constructed bridges in Minnesota has become a significant concern. Since 2005 MnDOT has been collecting bridge deck construction and early age cracking information on a “Bridge Deck Placement Data Form.” The information collected has been entered into a database, along with early age crack surveys, concrete mix design information and concrete testing information. There currently is information on over 120 bridges stored in the database.

Crack surveys were performed on 20 of the bridges contained in the database. A statistical analysis of the data, including the updated crack surveys, was performed to determine if there were any relationships between variables collected on the forms and crack frequency, type, or time of development.

The analysis showed that, in general, the data collected was not sufficiently consistent to draw significant conclusions. A relationship for temperature restraint cracking for bridges with integral abutments was developed for lineal feet of cracking as a function of bridge deck age, water/cementitious material ratio, and total cementitious content. Recommendations were made for modifications to current construction practices and improving the uniformity of the data collected on the “Bridge Deck Placement Data Form” in the future, so that additional analysis could be performed with more consistent data.

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Executive Summary

Early age bridge deck cracking is a concern in Minnesota and the U.S. in general, and has been the subject of many studies. Previous investigations into the phenomenon have found that most cracking occurs early in the life of the deck (within a few months of construction), but that crack density often increases with time. It has also been noted both by previous investigations and this project that bridge deck overlays tend to exhibit higher crack frequency than full depth bridge decks.

Previous projects conducted by others have identified several potential causes for cracking of concrete bridge decks and deck overlays, which typically occur whenever the tensile stresses (induced by either internal or external sources) exceed the tensile strength of the concrete. The sources of these stresses are many and include: plastic shrinkage, drying shrinkage, settlement, physical tearing, flexure/deflection of the deck, reflection of underlying cracks or joints, and temperature-related mechanisms (thermal expansion/contraction relative to the support system). In addition, bridge design can also impact the development of stresses that cause deck cracking including continuous spans over support structures and integral abutments.

Since 2005, the Minnesota Department of Transportation has been collecting bridge deck placement data on a "Bridge Deck Placement Data Form." The form includes information on the bridge design, abutment type, concrete mixture, placement date(s), placement duration, curing methods, curing conditions, weather, and a preliminary crack survey. The data from these forms has been compiled to a database that is managed by the Mn/DOT Office of Bridges and Structures. This database, as well as additional updated bridge deck crack surveys on a subset of the total number of bridges in the database, was analyzed for this project to identify statistically significant variables that may establish correlations between variables or subsets of variables that may affect the probability of bridge deck cracking.

The results of this analysis showed that there were significant inconsistencies in the data collected on the "Bridge Deck Placement Data Form", as well as with the supplemental information collected and placed in the database. These inconsistencies limited the usefulness of the database as an analysis tool, and thereby limited the statistical relationships that could be derived between cracking and the variables in the database.

Recommendations are included for improving the consistency of the data recorded on the "Bridge Deck Placement Data Form" as well for possible modifications to current Mn/DOT procedures that could be incorporated into either the Mn/DOT construction specifications and to the Bridge Construction Manual.

Chapter 1. Review of Bridge Deck Cracking Mechanisms

Early age bridge deck cracking is a concern in Minnesota and the U.S. in general, and has been the subject of many studies. Previous investigations into the phenomenon have found that most cracking occurs early in the life of the deck (within a few months of construction), but that crack density often increases with time. They also noted that deck overlays tend to have higher crack densities than do monolithic decks [3].

Several sources of cracking for concrete bridge deck overlays have been identified [2, 3, 7]. Concrete bridge decks and deck overlays may develop cracks whenever the tensile stresses (induced by either internal or external sources) exceed the tensile strength of the concrete. The sources of these stresses are many and include: plastic shrinkage, drying shrinkage, settlement, physical tearing, flexure/deflection of the deck, reflection of underlying cracks or joints, and temperature-related mechanisms (thermal expansion/contraction relative to the support system). Service and construction traffic loads may help to activate or accelerate several of these mechanisms (such as deck flexure/deflection and reflection cracking) and can induce fatigue cracking in the longer view. In addition, bridge design can also impact the development of stresses that cause deck cracking (e.g., the presence of continuous spans over support structures, which induce negative moments and flexural tension in the deck, or integral abutments, which provide restraint to deck shrinkage and thermal-induced movements).

Since 2005, the Minnesota Department of Transportation has been collecting bridge deck placement data on a "Bridge Deck Placement Data Form." The form includes information on the bridge design, abutment type, concrete mixture, placement date(s), placement duration, curing methods, curing conditions, weather, and a preliminary crack survey. A copy of the form is in Appendix B. The data from these forms has been compiled to a database that is managed by the MnDOT Office of Bridges and Structures. This database was analyzed for this project to identify statistically significant variables that may establish correlations between variables or subsets of variables that may affect the probability of bridge deck cracking.

1.1 Sources of Bridge Deck Cracking

1.1.1 Plastic Shrinkage

Plastic shrinkage cracks form in unhardened concrete when water is evaporated from the surface more quickly than it can be replaced by bleed water. The resulting change in concrete volume at the surface is restrained by concrete below the surface that has not undergone such volume changes. This causes tensile stresses to develop at the concrete surface before the concrete has sufficient strength to resist them. Low-slump overlays, which typically have low w/c of 0.42 or less, are especially susceptible to this mechanism. This mechanism is particularly critical for thin overlays, which have a high ratio of surface area-to-volume of concrete.

Plastic shrinkage cracking usually manifests as closely spaced parallel cracks that are often oriented approximately perpendicular to the direction of the wind during their time of formation.

Their depth varies with the conditions under which they are formed and can be as deep as 3 inches or more in severe cases (and if they form directly above embedded steel).

Prevention of plastic shrinkage cracking can be accomplished by placing the concrete when the evaporation rate is low (i.e., <0.15 lb/ft^2/hr) and/or preventing the loss of moisture (typically by fogging, misting and/or placing evaporation barriers close behind the finishing operations). Mixture design modifications, such as reducing paste volume (by improving aggregate gradation) are also helpful.

1.1.2 Drying Shrinkage

Almost all concrete contains more water than is necessary for hydration of the cement. Drying shrinkage cracks form in hardened concrete as water not consumed by the hydration process leaves the system, causing the concrete to shrink. The shrinkage is restrained by the underlying concrete, which shrinks less, thereby inducing tensile stresses in the restrained layers above. This loss of moisture (and, therefore, related shrinkage) is greatest at the surface, so stresses are greatest there. Shrinkage may also be restrained by the support system (particularly for thin layers of concrete), by structural features (e.g., integral abutments) or by embedded reinforcing bars.

The pattern and depth of cracking will vary with the source(s) of restraint and the amount of excess water as well. A network of very shallow, tight cracks (sometimes called “crazing”) will form over large areas that are subject to general restraint by underlying concrete and the lowest levels of shrinkage. More significant cracking may develop if more excess water is present, with a more regular, parallel pattern where the orientation of the cracks is perpendicular to the longest placement dimension (similar to the formation of transverse cracks in long pavement panels). Shrinkage crack orientation may also be determined by the orientation of embedded reinforcing (which can serve as a point of restraint and an initiator of cracking).

The prevention of drying shrinkage cracking is mainly a matter of avoiding the use of excess water in the mixture (although reduction of paste content through improved aggregate grading is also helpful). Water demand can be controlled with good aggregate particle size distribution, use of low-absorption aggregate and aggregate with low specific surface characteristics (i.e., more rounded and smooth particles and fewer angular, rough-textured particles). Particle shape and surface texture is particularly important for the fine aggregate in the mixture.

Judicious use of shrinkage-reducing and/or water-reducing admixtures can be helpful as well. The introduction of added water at the job site (either in the truck, beyond allowable amounts, or as a finishing aid) must be avoided.

Finally, it is helpful to avoid over-finishing the concrete. It has been noted that roller screeds tend to bring more paste to the surface than do vibratory screeds, which tends to increase plastic shrinkage cracking [3].

1.1.3 Surface Tears (Finishing)

Low-slump and latex-modified concrete (LMC) overlays are especially susceptible to surface tears caused by finishing and texturing operations. Kuhlmann notes that "(l)atex modified concrete is different from conventional concrete in that a crust, i.e., a relatively firm material caused by the drying of the latex, will form on its surface if exposed too long to the air while in the plastic state. When this crust forms, the working life of the LMC has expired, while underneath, the concrete will be quite plastic until setting time has expired. The difference between these two could be as much as two hours … (t)his surface crust can be torn and cause surface cracks if the finishing operation continues." When a rake is used to impart a grooved surface to the deck, "these tears will appear as short and shallow (typically ½" by 1/8") cracks oriented 90° to the direction of the grooves [6]."

This type of cracking can be relatively deep and potentially harmful, resulting in increased permeability of the bridge deck concrete (see Evaluation and Treatment of Existing Cracks, below). Fortunately, it is also easily avoided by timely finishing and texturing operations and by preventing the surface from drying (i.e., constructing the overlay under conditions when rapid surface drying is unlikely and/or by *misting the area until finishing and texturing are complete*.)

1.1.4 Flexure/Deflection of the Deck

Flexural cracks are structural cracks caused by excessive tensile stresses in the overlay due to flexural movements of the overlay in the negative moment areas (e.g., over the tops of piers and other bridge supports). These cracks are usually oriented transversely to the direction of travel, are relatively straight and are usually spaced 2 – 4 feet apart. They are generally deep (sometimes full-depth) cracks, but they can be effectively sealed if they are addressed before they cause the overlay to delaminate (if an overlay is present).

This type of crack can best be avoided by proper construction timing and staging. It has been suggested placing the overlay after the forms are removed from the structural deck concrete in two-course construction applications, so that the weight of the overlay is born by the underlying concrete rather than by the overlay alone. Virginia and New Jersey studies recommend specific overlay placement sequences to avoid these problems [6].

1.1.5 Reflection of Underlying Cracks and Joints

Whenever a well-bonded bridge deck material is placed over working, moving or otherwise unstable cracks and joints, the overlay can be expected to crack directly over the original crack or joint. The movement may be vertical (i.e., load-related) or horizontal (i.e., temperature- or moisture-related), but the result will be the same either way – a reflective crack. The formation of an uncontrolled crack can be prevented by installing a soft joint in the overlay directly above the working joint or crack at the time of overlay placement.

Similar issues arise when overlaying expansion joints, over which the overlay joint must be formed or blocked out using plastic foam or other suitable material against which the overlay can

be placed. Failure to do this can cause cracking and debonding of the overlay in the vicinity of the expansion joint. After the overlay has been cured, the block-out material can be removed and replaced with the final joint material.

1.1.6 Temperature-Related Mechanisms

Cracks can also result from the placement and curing of the overlay at ambient and/or mixture temperatures that are significantly different from the temperature of the underlying concrete or support structure. If the temperature at which the concrete sets is significantly higher (say, $>30^{o}$F) than that of the underlying concrete, very large tensile stresses may develop after a few days when the two temperatures equilibrate and the resulting thermal contraction in the overlay is resisted by the bond with the underlying material.

Temperature effects are also the likely causes of longitudinal cracking that is sometimes observed near the ends of bridges with integral abutments (rather than hinged end deck supports). In this case, thermal expansion of the deck, restrained at the bridge ends, results in longitudinal compression of the deck and the development of transverse tensile stresses (which can produce longitudinal cracking, similar to the way that loading a concrete cylinder across the diameter produces a crack in the same plane as the load for indirect tensile tests). This type of cracking is referred to as "restraint cracking" throughout this document.

In both cases, the key to preventing this type of cracking is to avoid the differential expansion/contraction between the slab and the support system. Late evening (and sometimes early morning) placements are commonly used for this purpose, particularly in the summer months. This generally offers the added bonus of avoiding high temperature, higher wind and lower humidity conditions that contribute to plastic shrinkage problems.

The use of pinned or hinged joints (rather than integral abutments and continuous bridge designs) reduces the potential for developing transverse cracking at the bridge ends.

Chapter 2. Analysis of Available Data

2.1 Overview of Database

The original project data base consisted of deck placement data forms (completed by project engineers or inspectors), crack sketches on deck plan sheets (color-coded for cracks visible on the top or bottom) that were developed shortly after construction, and representative concrete batch tickets for each project. A large spreadsheet was created to gather the relevant information into a single document that might be useful for statistical analyses and general observations.

This large spreadsheet data base suffered from several deficiencies. First, it did not differentiate between the many different types of cracking (with their different mechanisms and associated design/construction variables), so any correlations and models for "cracking" in general would be weak as there is probably no single variable that correlates well with ***all*** types of cracking. This problem was further complicated by the fact that the crack measurements were observed and collected by many different people, each with different levels of experience and training in accurately and completely identifying and recording all of the different types of cracking on any given bridge. Therefore, the consistency of the cracking data was also somewhat questionable.

In addition to these basic problems in crack type identification and measurement, the original spreadsheet contained many incomplete data sets and many improperly formatted entries that could not be considered numerically. Finally, the spreadsheet also included no detailed mixture design or strength information, and very little useful bridge structure and construction sequencing information.

It became apparent that this data base was going to be of limited usefulness for all of the reasons listed above (and more). As a minimum, another survey effort was required to attempt to differentiate between the different types of cracking that might exist so that the development of these different types of cracks could be addressed independently. A complete up to date copy of the database is available from the MnDOT Bridge Construction Unit.

2.1.1 Inverted T Analysis

While this project was ongoing MnDOT began constructing Inverted T bridge decks. These decks, which are a composite of inverted T beams and a cast in place reinforced concrete deck, are heavily reinforced and have substantial variability in the thickness of the cast in place concrete portion of the deck. Significant cracking of the cast in place decks has been noticed in all of the bridges constructed to date. These bridges were not included in the database analyzed for this project, because the decks are completely different. However, thermal modeling of the cast in place deck of Bridge 25024 was performed to determine if the cracking in that bridge was caused in part due to the concrete mixture used, and if it would be possible to reduce or eliminate the cracking by using a low heat of hydration mix. The analysis is shown in Appendix C.

2.2 Analysis of Trends and Correlations: Twenty Selected Cases

Following a field review of 6 Metro District Bridges, it became apparent that the majority of the cracking evident from the surface of a bridge consisted of relatively high frequency cracking that was limited to the low slump overlay (the vast majority of the bridges in the database were constructed with a low slump overlay), with few of the cracks extending through to the bottom of the structural deck. The project Technical Advisory Panel met to discuss this issue and it was agreed that the purpose of this project was to evaluate bridge deck cracking, not low slump overlay cracking, and that additional crack surveys would be conducted on a subset of the larger dataset and that the surveys would be performed from under the decks so that full depth deck cracking would be observed.

In the fall of 2012, American Engineering Testing, Inc. (AET) staff and MnDOT Bridge Construction Unit personnel selected 20 representative bridges (a subset of the original 150 cases) and conducted a more detailed survey of the cracking that was observable from beneath. It should be noted that, in some cases, these surveys were conducted with binoculars from a significant distance, so some tight cracks without any efflorescence may not have been observed or recorded. Sketches of observed crack patterns were recorded and measurements or estimates of crack lengths were made and summarized into one of two probable source categories: cracking due to deck flexing/deflection, and cracking due to longitudinal restraint. This approach addressed two of the deficiencies noted previously (i.e., differentiation of crack type and consistency of measurements by a single trained observer). Table 2.1 provides a summary of the full data sets associated with these 20 cases. The cracking survey maps are contained in Appendix D.

The original deck placement data forms and cracking maps that were used in preparing the original 150-case spreadsheet were all reviewed and compared with the data entries, and many corrections and revisions of data entries were performed in order to make the spreadsheet more accurate and useful for data analysis. The original cracking sketches were reviewed and used to produce more detailed estimates of the quantities of each of several types of cracking. Batch tickets were used to extract mixture proportions, including as-batched w/(c+p) and total cementitious material content. Data transformations were performed to produce “normalized” cracking data (i.e., values of total observed length of cracking of a particular type per 1000 s.f. of deck area) and other variables that were expected to be more useful in the analyses than those present in the original spreadsheet. Evaporation rates were estimated using reported climate data and mixture temperatures along with the American Concrete Paving Association (ACPA) web application for determining evaporation rates (available at apps.acpa.org and which uses evaporation rate equations which are based on the popular evaporation rate nomograph from ACI 305R, Weather Concreting). There were still some “holes” in this data base (see Figure 2.1), but it was enough of an improvement to make it worthwhile to proceed with some basic statistical analyses.

2.2.1 Correlation Analysis

Based on an understanding of the cracking mechanisms presented previously, a correlation matrix was developed for the two normalized cracking variables (as well as their sum) and the

design and construction variables included in the available data set that were judged to be most likely to show a correlation with the cracking data. The independent variables included in the analysis are:

Cement content (lb/cy)
Total cementitious materials content (lb/cy)
Batched w/(c+p)
Average estimated evaporation rate during placement (lb/sf/hr)
Estimated evaporation at the end of placement (lb/sf/hr)
Maximum time before application of cure (minutes)
Duration of curing (hours)
Longest deck span (ft)
Abutment type
Estimated deck age at fall 2012 AET survey (years)

Variables that might be well-correlated but for which there was not available or sufficient data (e.g., concrete strength and elastic modulus, deck and superstructure (combined) stiffness, etc.) are not included in the analysis. In addition, correlation analyses were not performed for discrete non-numerical data (e.g., abutment type).

Table 2.1: Summary of Structural, Materials and Construction Information for 20 Selected Bridge Decks

Bridge #	Low SP Number	Deck Data Placement Form	Plan View of Crack Survey	Deck Condition Excellent Good Fair Poor	Shrinkage Crack Density (ft/ft²)	Settlement Crack Density (ft/ft²)	End Restraint Crack Density (l.f.)	Other Crack Density (l.f.)	Crack Comments/Pattern (Dates note when crack survey taken)	Pontis Inspection Condition 358 Deck Crack	Pontis Inspection Condition 359 Under Deck	Ready Mix Tickets	Slump, in	Cement Content, lb/cy	SCM Content, lb/cy	Total Cement + SCM	Water Content, lb/cy (design)	Water Content, lb/cy (batched, avg)	w/c (design)	w/c (batched)	Air Content, %	MnDOT Mix Number	District	Person Completing the Form	Bridge Location	Cover Depth, inches	Top Trans Bar Size	Top Trans Bar Spacing, in	Bottom Trans Bar Size & Spacing
02050	0208-123	02050	No Plan							1	1	No Tickets											Metro	Juan Podesta	TH 65 and 121st Ave Blaine		13	5	16 @ 6"
02052		02052	No Plan		0	0	0	0		1	1	No Tickets											Metro	Juan Podesta	TH 65 and 129th Street Blaine		13	6	16 @6.5"
10024	1017-12	10024	10024	Excellent	0	0	0	0	10/26/2006	1	1	10024	3.8/3.7	399/578	171/102	570/680	228/299	221/262	.4/.44	0.39/.385	6.7/7.3	3Y36 AND 3Y43	Metro	Duane Tennison	Cty Rd 112 & TH 212		16	5.5	19-5.5
10039	1017-12	10039	10039	Fair	0	0	30	182	Transverse cracks more significant above pier and at abutments (8-21-06)	1	1	10039	3.5	578	102	680	299	262.5	0.44	0.39	6.8	3Y36A-F	Metro	Duane Tennison	Lyman Blvd & TH 212		13	5.5	16-5.5
10041	1017-12	10041	10041	None	0	0	0	0	4/27/2007	1	1	10041	2.41	578	102	680	299	240	0.44	0.35	5.9	3Y36	Metro	Duane Tennison	Pioneer Trail & TH 212		13	5	13-7
10053	1017-12	10053	10053	None	0	0	0	0	12/14/2007	1	2	10053	3.4	578	102	680	299	255	0.44	0.37	6.2	3Y36A-F	Metro	Duane Tennison	Koehnen Crk & TH 212 WB		19	7	19-7
10054	1017-12	10054	10054	None	0	0	0	0	12/14/2007	1	1	10054	2.72	578	102	680	299	266	0.44	0.39	6.8	3Y36	Metro	Duane Tennison	Koehnen Crk & TH 212 EB		19	7	19-7
19035	1907-68	19035	19035	Excellent	0	0	0	0	Also viewed with HPC tour on 10-1-09 top slab wet, underside 1 crack showing - Excellent	1	1	19035	4	400	170	570	228	214	0.40	0.38	7.4	3Y43HFWC		Harvey Umruh	NA				
27137	1017-12	27137	27137	Excellent	0	0	0	0	6/2/2006	2	1	27137	3.14	578	102	680	299	254	0.44	0.37	7.35	3Y36A-F	Metro	Duane Tennison	Dell Rd & TH 212		16	5.5	16-5.5
33002	3311-10	33002	33002	Excellent	0	0	0	146	10/14/2009	1	1	33002	2.67	575	102	677	297	270.2	0.44	0.40	6.933	303Y36AF	3	Brian Kelley	Snake River, Grasston, MN	1	13	7.5	#13 @ 6"
48030	4801-20	48030	48030	Excellent	0	0	10	0	11/4/2009	1	1	48030	3	580	102	682	300	275	0.44	0.40	6.8	303Y36AF	3	Steve Lynch	TH #23 Milaca	N/A	6	6	#6@6
49037	4912-49037	49037	none	Good	N/A	N/A	N/A	N/A	From photos at S:\Construction..49037 49038 49039 49040 TH 371 Little Falls	3	1	49037	3.25	467	200	667	267	233.6	0.40	0.35	6.9	3Y33HF	3	Vince Pikula	TH 371 over CR 46	N/A	16	5	16 @ 6"
49038	4912-49038	49038	none	Good	N/A	N/A	N/A	N/A	From photos at S:\Construction..49037 49038 49039 49040 TH 371 Little Falls	3	1	49038	3.35	467	200	667	267	234	0.40	0.35	6.2	3Y33HF	3	Tim Nielson	TH 371 NB over CoRd 46		16	5	#16 @ 6"
49040	4912-49040	49040	No plan	Good	N/A	N/A	N/A	N/A	From photos at S:\Construction..49037 49038 49039 49040 TH 371 Little Falls	1	1	49040	3.35	467	200	667	267	232	0.40	0.35	5.82	3Y33HF	3	Tim Nielson	TH 371 NB over TH 115		16	5	#16 @ 6"
82805	8286-64	82805	No Plan		N/A	N/A	N/A	N/A				82805	4	405	135	540	216	208.7	0.40	0.39	7.56	3Y33HP	Metro East	Dan Shogren	SB TH 694 over UPRR		See Plan		See Plan
82806	8286-64	82806	No Plan		N/A	N/A	N/A	N/A				82806	3.33	535	0	535	225	214	0.42	0.40	7.8	3Y33LCHPC	Metro East	Dan Shogren	NB TH 694 over UPRR		See Plan		See Plan
27B34	27-635-25	27B34	27B34	Excellent	0.008726	0	0	0	9/25/2006	2	1	No Tickets											Metro	Mark Mondeel	Portland Ave & Minnehaha Pkwy		13	8	#13, 6.5"
27R30	1017-12	27R30	27R30	None	0	0	0	0	9/26/2006	1	1	27R30	3.48	399	171	570	228	204	0.40	0.36	5.7	3Y43HFWC	Metro	Duane Tennison	Eden Prairie Ped Br & TH 212		13	12	13-12
27R31	1017-12	27R31	27R31	None	0	0	0	0	10/10/2006	1	1	27R31	2.75	578	102	680	299	272	0.44	0.40	6.35	3Y36A-F	Metro	Duane Tennison	WB TH 212 & Riley Crk		13	6	16-6
27R32	1017-12	27R32	27R32	Excellent	0	0	0	0	10/18/2006	1	1	27R32	2.6	578	102	680	299	268	0.44	0.39	6.1	3Y36A-F	Metro	Duane Tennison	EB TH 212 & Riley Crk		13	6	16-6

Table 2.1 (continued): Summary of Structural, Materials and Construction Information for 20 Selected Bridge Decks

Bridge #	Super Type	Abutment Type	Total # Spans	Skew Angle, degrees	Deck Thickness	Deck Width (ft.)	Beam Depth (inches)	Long. Orientation	Beam Spacing, ft	Span Lengths		Total Length	Total (sq. ft.)	Additional Concrete Temp. Readings	Placement Date	Finishing Time			Total # of CuYds Placed	Pour Rate		Average Placement Rate (yds/hr)	Placement Equipment Air Screed or Paving Machine	Start of Placement				Estimated Evaporation Rate (lb/sf/hr) - Start of Placement	End of Placement				Estimated Evaporation Rate (lb/sf/hr) - End of Placement	Average Estimated Evaporation Rate
										List each span	Longest (Worst Case)					Start	Finish	Total (hours)		Sq. Ft. per Hour	Span Per Hour			Conc Temp (F)	Air Temp (F)	Wind Speed (avg.)	Humidity (%)		Conc Temp (F)	Air Temp (F)	Wind Speed (avg.)	Humidity (%)		
02050	601	High/CIP	2	0	7 Dk + 2OL	73 to 87	45	E/W	14	92.5 - 92.5	92.5	190	16501		7/31/2009	8:00	12:30	4.5	403	3667	0.44	89.6	Morrison Screed		64	6	69			72	9	67		
02052	501	High/CIP	2	0	7 Dk + OL	44.83	45	E/W	9.33	92.67 - 92.67	92.67	190	8519		7/17/2009	9:00	12:15	3.25	240	2621	0.63	73.8	Morrison Screed		66	6	77			66	7	78		
10024	501	Parapet	2	9	9	48	72	NS	12	110, 105	110	225	11955	NA	9/14/2006	8:15	16:15	8.00	330	1494	0.28	41.3	Bidwell Machine	74	53	5	83	0.09	71	81	17	45	0.12	0.11
10039	501	HIGH	2	43	9	66	81	EW	9.83	133, 133	133	273	18160	NA	6/13/2006	7:15	13:15	6	510	3027	0.34	85.0	Air Screed	74	64	8	59	0.12	74	84	6	44	0.06	0.09
10041	501	HIGH	2	40	9	66	54	EW	7'-7"	122, 122	122	244	16681	NA	4/18/2007	8:15	17:00	8.75	485	1906	0.24	55.4	Air Screed	66	45	6	67	0.09	70	63	10	38	0.15	0.12
10053	501	INT	1	13	9.5	45	54	EW	13	102	102	102	4650	NA	10/30/2006	11:30	14:30	3	142.5	1550	0.34	47.5	Air Screed	66	59	11	53	0.11	66	68	17	41	0.15	0.13
10054	501	INT	1	10	9.5	45	54	EW	13	102	102	102	4650	NA	10/25/2006	12:00	14:30	2.5	140	1860	0.41	56.0	Air Screed	70	50	7	48	0.12	67	52	13	34	0.19	0.16
19035					9								4598		8/14/2009	6:45	8:45	2	230	2299		115.0			68	0				72	2				
27137	501	Parapet	2	15	9	104	63	N,S	VARIES	106, 116	116	227	23700	NA	5/4/2006	6:20	12:00	5.667	636	4182	0.35	112.2	Air Screed	66	49	10	66	0.12	66	52	10	66	0.11	0.12
33002	Prestr	Integral	3	N/A	7	43'4"	27"	N-S	6.42	71.75, 72.5, 71.75	72.5	217'8"	9432	77,75,77 F	9/17/2009	8:00	12:30	4.5	289	2096	0.67	64.2	Air Screed	77	59	5	60	0.11	77	76	5	60	0.07	0.09
48030	Concrete Beam, Deck	Pile Bent	3	10		70.33	27		11	52.92,53. 67,52.92	54	159.5	11213		9/24/2009	7:40	13:05	5.42	329	2070	0.55	60.7	Mechanical Screed	75	49	3	45	0.09	75	73	0	50	0.03	0.06
49037	501/PCB	Integral	3	11°	9	45.33	45	N/S	12.67, 9.5, 12.67	56, 88, 56	88	198.92	9018	74 @ 9:30 AM	7/27/2005	6:00	9:50	3.83	350.5	2355	0.59	91.5	Paving Machine	76	51	2.5	53	0.08	76	64	10	64	0.15	0.12
49038	501/PCB	Integral	3	11°	9	45.33	45	N/S	12.67, 9.5, 12.67	56, 88, 56	88	196.92	8926	77 @ 5:30AM 84 late pour	7/22/2005	5:30	9:15	3.75	350	2380	0.60	93.3	Paving Machine	78	64	2.5	60	0.07	80	70	2.5	75	0.05	0.06
49040	501/PCB	Integral	3	16°	9	45.33	54"	N/S	12.5	55.90,55	90	202	9169	Not Avail.	7/19/2005	5:45	10:00	4.25	341	2157	0.53	80.2	Paving Machine		50	0	63			71	3.9	61		
82805	See Plan	See Plan	3	See plan		44.5	W27x84	See Plan	See Plan	42.833,57 ,42.833	57	144.66	6438	X	8/10/2010	6:10	9:35	3.4167	223	1884	0.74	65.3	Vibratory screeds with work bridge	76	71	6	83	0.05	78	79	10	72	0.07	0.06
82806	See Plan	See Plan	3	See plan		44	W27x84	See Plan	See Plan	42.833,57 ,42.833	57	144.66	6438	X	5/28/2010	3:01	6:02	3.0167	220	2134	0.85	72.9	Bidwell Screed - 48' with work bridge	60	61	6	64	0.03	61	59	6	67	0.04	0.04
27B34	501	Hinged Wings	1	0	9	84	14	NS	2.41666667	39.25	39	39.66	3438	80	9/6/2006	9:25	12:15	2.8333	101	1213	0.37	35.6	Morrison Screed	80	66	2	59	0.07	80	77	1	56	0.04	0.06
27R30	501	Parapet	2	0	7	14	63	NS	14.5	123,100	123	226	3170	NA	9/6/2006	8:15	13:45	5.5	79	576	0.33	14.4	Air Screed	76	65	3	85	0.05	76	85	4	48	0.05	0.05
27R31	501	Parapet	1	15	9	45	54	EW	9.5	100	100	100	4750	NA	9/28/2006	10:45	12:45	2	123	2375	0.53	61.5	Air Screed	65	51	2	69	0.04	60	54	4	56	0.04	0.04
27R32	501	Parapet	1	15	9	45	54	EW	9.5	100	100	100	4750	NA	9/28/2006	8:00	10:00	2	123	2375	0.53	61.5	Air Screed	63	46	6	78	0.07	65	48	5	75	0.07	0.07

Table 2.1 (continued): Summary of Structural, Materials and Construction Information for 20 Selected Bridge Decks

Bridge #	Color Of Beams	Beam Sunlight Exposure	Beam Temp Prior and During Placement, deg F	Method of Placement	Contractor	Date/Time Burlene/Burlap Applied	Date/Time Burlene/Burlap Removed	Length of Curing Period (hrs)	Curing Material	Was The Surface Kept Continually Wet During Cure? Yes	Was The Surface Kept Continually Wet During Cure? No	Were Temp. Gauges Used Yes	Were Temp. Gauges Used No	Indicate The Deck & Ambient Temp (F) 24 Hrs.	Indicate The Deck & Ambient Temp (F) 48 Hrs.	Weather Conditions During Curing (rain, dry, etc)	Time Elapsed Prior to Placing Curing Maximum Mins	Time Elapsed Prior to Placing Curing Minimum mins	Any Cracks at Time of Deck Form Removal	Date of Deck Form Removal	Date of Crack Survey	Deck Age when Top Surveyed, days	Est age (yrs) in Fall 2012	Flexural or Deflection Cracking, l.f.	Normalized Flexural or Deflection Cracking, l.f./1000 s.f.	Temp. Restraint Cracking, lin.ft.	Normalized Temp Restrain Cracking, l.f./1000s.f.	Total Flex, Defl and Temp Restaint Cracking, l.f.	Normalized Total Flex, Defl and Temp Restaint Cracking, l.f.
02050	White Concrete	Yes		Pump	C.S. McCrossan	7/31/2009 8:30AM	8/8/2009 8:00AM	192	NO	X			X			Dry	30	25	see comments	8/28/2009	10/9/2009	70	3.25	140	8.48	0	0.00	140	8.48
02052	White Concrete	yes		Pump	C.S. McCrossan	7/17/2009 9:15AM	7/25/2009 8:00AM	191	Burlap & Poly	X			X			dry	25	20	No Cracks Noticed on Deck	8/15/2009	9/23/2009	68	3.25	8	0.94	0	0.00	8	0.94
10024	Gray	Partly cloudy	53 prior; 74 during	Pump	Kraemer (ZRC)	9/14; 1 PM	9/21; 8 AM	163	Burlene & Poly	X			X	71	69	Cloudy, below normal temp	360	45 Min.	None Observed	9/25 to 9/27, 10/23 to 10/26	9/21 (top), 10/26 (bot)	7	6.00	18	1.51	0	0.00	18	1.51
10039	Gray (conc brn)	Partly cloudy	60 prior, 71 during	Pump	Kraemer (ZRC)	6/13; 12:30 PM	6/19; 4 PM	148	Burlap & Poly	X			X	100	94	Dry, rain evening of 6/16	315	180	No Comment	7/26 to 8/11	8/14 (bot), 8/21 (top)	62	6.25	293	16.13	25	1.38	318	17.51
10041	Gray	Sunny & clear	47 prior, 71 during	Pump	Kraemer (ZRC)	4/18; 12:30 PM	4/24; 10:30 AM	142	Burlap, Poly, Insul. Blankets				X	81	80	Rain on 4/22, 0.5"	270	120	None Observed	5/1/07 to 5/10/07	4/24/07, 5/17/07 (top), 5/10/07 (bot)	29	2.50	0	0.00	0	0.00	0	0.00
10053	Gray	Sunny	52 prior, 65 during	Pump	Kraemer (ZRC)	10/30; 3 PM	11/6; 3:30 PM	167.5	Burlene, Poly, 2 layers of Insul. Blankets	X		X		86 (top), 77 (bot)	73	Cloudy	210	120	None Observed	1/26/07, 2/13/07	11/9/06 (top), 2/14/07 (bot)	10	6.00	62	13.33	10	2.15	72	15.48
10054	Gray	Sunny	44 prior, 50 during	Pump	Kraemer (ZRC)	10/25; 2 PM	11/1; 10 AM	164	Burlene, Poly, Insul. Blankets, Grnd Heater	X		X		65 (top), 55 (bot)	78	Cloudy	150	120	None Observed	1/24/07 to 2/12/07	11/1/06 (top), 2/4/07 (bot)	7	6.00	0	0.00	10	2.15	10	2.15
19035				Pump Truck	Lunda	8/14/09; 7 AM	8/24/09; 10A	243	Wet Burlap/Poly	x			x	76	75	Varied	25	8	None Observed	9/10/2009	9/1/2009	28	3.25	18	3.91	13	2.83	31	6.74
27137	Gray (conc brn)	Partly sunny 1st hr, cloudy rest	44 prior, 48 during	Pump	Kraemer (ZRC)	5/4; 10:45 AM	5/10; 12:30 PM	148	Burlap & Poly	X			X	84/50(air)	81/53(air)	Partly cloudy, rain on 5/8	270	270	None Observed	5/15 to 6/1	6/2 (bot), 5/10 & 6/13 (top)	6 and 40	6.50	28	1.18	0	0.00	28	1.18
33002	Gray	14 days from setting to deck	62	Concrete Pump and Morrison Screed	Redstone Construction	9/17/2009 12:30PM	9/24/2009 3:00PM	168	Wet Burlap & Plastic	X		X				Dry	30	10	None	10/12/2009	10/14/2009	27	3.00	0	0.00	10	1.06	10	1.06
48030	Gray	None	50	Concrete Pump and Morrison Screed	Redstone Construction	9/24/09, 08:20 - 13:30	10/1/09, 15:00	172	Burlap/Soaker Hoses	X			X	110/65	85/73	Dry 24 hrs, Lt Rain 48 hrs, Rain and cool 72 hrs	30	10		10/26/2009	11/3/2009	40	3.00	104	9.27	0	0.00	104	9.27
49037	Gray	NA	49° East facial, 48° interior	Pump/Screed	Lunda	7/27; 12:50 PM	8/3; unknown	168	White Mem. / Burlene			X		*35	*29	clear, sunny	30	20	No Comment	None listed	None listed	N/A	7.25	20	2.22	22	2.44	42	4.66
49038	Gray	E. Fascia only (Late pour)	69 - 73	Pump	Lunda	7/22; Noon	7/29; unk	168	White Mem. / Burlene	X		X			82	PC/Warm	30	15	No Comment	No Comment	No Comment		7.25	57	6.39	33	3.70	90	10.08
49040	Gray	Not Avail.	Not Avail.	Pump/Screed	Lunda	7/19; 1 PM	7/26; Unkown	168	White Mem. / Burlene	X		X		117, 70	91, 73	PC/Clear	30	15	No Comment	No Comment	No Comment		7.25	214	23.34	48	5.24	262	28.57
82805	brown	X	NA	pump	Lunda	8/10/2010 within 30 mins of final strike off	8/18/2010	192	pre-wetted burlap and white plastic sheeting	X			X	ambient 72-93 deg	ambient 72-92 deg	7days=58-93 F, wind 4-15 mph, total rain 3.9"	30	0		NA			2.25	304	47.22	22	3.42	326	50.64
82806	brown	X	NA	pump	Lunda	5/28/2010 within 10 mins after final strike off	6/12/2010	360	pre-wetted burlap and white plastic sheeting, 2 layers, with soaker hoses daily	X			X	ambient 64-91 deg	ambient 59-81 deg	14 days=51-91 F, wind 5-13mph, total rain 2.60"	14	0		NA			2.50	140	21.75	14	2.17	154	23.92
27B34	Gray	Hazy sunshine	65 prior; 78 sun, 70 shade during	Pump	R. Schroeder Const.	9/6; 2 PM	9/18; 2 PM	288	Burlene		X		X	100/79(air)	75/60(air)	Cooler temp, little wind	120	120	No Comment	9/25/06	9/25/06	19	6.00	260	75.63	0	0.00	260	75.63
27R30	NA	NA	NA	Pump	Kraemer (ZRC)	9/6, 3 PM (spray); 9/7, 6:30 AM (burl)	9/25; 1:30 PM	430.5 hrs	Cure spray applied, Burl.	X	(for 7 days)		X	68 (air)	NA	Cloudy, light mist	420	240	No	9/15/06 to 9/19/06	9/19/06 (bot), 9/26/06 (top)	20	6.00	0	0.00	0	0.00	0	0.00
27R31	Gray	Cloudy	50 prior; 53 during	Pump	Kraemer (ZRC)	9/28/06; 12:45 PM	10/4/06; 7:45 AM	139 hrs	Burlene & Poly	X			X	71	70	Light rain during pour - cloudy	150	120	None Observed	10/6 to 10/10	10/4 (top), 10/10 (bot)	6	6.00	0	0.00	0	0.00	0	0.00
27R32	Gray	Cloudy	44 prior; 47 during	Pump	Kraemer (ZRC)	9/28/06; 10:45 AM	10/3/06; 3 PM	124.25 hrs	Burlene & Poly	X			X	72	70	Light rain day of pour - cloudy	165	120	None Observed	10/10 to 10/17	10/3 (top), 10/18 (bot)	5	6.00	0	0.00	0	0.00	0	0.00

Table 2.1 (continued): Summary of Structural, Materials and Construction Information for 20 Selected Bridge Decks

Bridge #	Comments (discuss delays in placement, concrete problems, etc)	
02050	2 cracks on east of middle of bridge aprox 10 - 20 ft from middle joint on both sides	Need pictures or a sketch of these cracks! Span lengths don't add up. Says no curing material, but kept wet – curing material is water (ponded)? Need to provide better instructions on filling in some entries in the data form - provide an indication of type of expected response - for example is beam sunlight exposure a yes/no or percentage or what?
02052	No cracks noticed on deck	
10024	Started w/ a 3Y43 HFWC mix, adding super plasticizer at pump; a Eucon 37 Breit admixture. Problems getting consistency. 10 trucks to jobsite w/ mix & 5 trucks rejected. At ~10AM we switched to 3Y36 mix. First truck 3Y36 was here at 11AM. Started testing at 8AM & to pour 3Y43 HFWC. Due to problems after ~5 FT into deck pour, sat for 1.5 hrs and started to get a cold joint	
10039		
10041	Footprints in deck on W end due to covering deck too soon. Milled deck, by PCI, on 5/15/07 on W end where foot imprints were made while covering deck after deck pour. No cracks observed.	
10053	QA allowed at least 1 - 9.5 yd load of concrete with a 5.25" slump to be poured in deck. Ground heater set to 170 deg F. Ground heater turned off on 11/4/06.	
10054	For curing used a ground heater also w/ water temp set at 125 deg F. 24 hrs later ground heater was turned up to 170 deg F. Turned off ground heater at 10:30 AM on 10/30/06.	
19035		
27137	1 truckload (9.5 yds) w/ 9.7% air got poured into deck.	
33002	No problems encountered	Original Crack Survey noted 2 cracks above each pier - full deck width (38.5') and one on each side of each pier. Cracks were tight. 9-inch slab includes 7-in deck (1-in cover top and bottom) and 2-in low-slump overlay.
48030		
49037	Clear, no clouds.Nice morning.	Only 1 mix ticket provided out of about 30.Deck and ambient temps look bogus.
49038	Cloudy light winds, excellent conditions during pour - Hot days following the pour.	
49040	Curing Compound in Paving Training(?) (note: 24 hrs under deck 75 degrees F)	
82805		
82806		
27B34	Could not check bottom of deck for cracking, as the bridge is over water.	
27R30	8" slump (.5 yds) got into deck due to QA trying different tests w/ mix & did not have enough time to complete. Inconsistent concrete being delivered w/ first few truck's. Adding Eucon 37 superplasticizer at jobsite, part of the difficulty & why 8" slump got into deck	Lots of mix variability on this job ... blown cement cut-offs, changes in admixture dosage, changes in trim water, etc. Slump was all over the board from start to finish.
27R31	Poured BR 27R31 & 27R32 back to back.	
27R32	Poured BR 27R31 & 27R32 back to back.	Mix got progressively drier with each batch ... from 0.41 to .375 w/c

Table 2.2 presents a summary of the data used in subsequent analyses for the 20 selected cases (a more easily read subset of Table 2.1). Grey-shaded cells indicate missing data; yellow-shaded cells indicate data that the analyst considered to be missing or questionable.

Table 2.2: Summary of Key Data for 20 Selected Cases

Bridge #	Normalized Flexural or Deflection Cracking, l.f./1000 s.f.	Normalized Temp Restraint Cracking, l.f./1000s.f.	Normalized Total Flex, Defl and Temp Restaint Cracking, l.f./1000sf	Age (fall 2012), years	Cement Content, lb/cy	Total Cementitious (lb/cy)	w/(c+p) as batched	Estimated Evaporation Rate - End of Placement (lb/sf/hr)	Length of Curing Period (hrs)	Average Estimated Evaporation Rate (lb/sf/hr)	Max Time to Apply Cure (mins)	Longest Span (ft)	Abutment Type
02050	8.48	0.00	8.48	3.25					192.00		30.00	92.50	High/CiP
02052	0.94	0.00	0.94	3.25					191.00		25.00	92.67	High/CiP
10024	1.51	0.00	1.51	6.00	578	680.00	0.39	0.12	163.00	0.11	360.00	110.00	Parapet
10039	16.13	1.38	17.51	6.25	578	680.00	0.39	0.06	148.00	0.09	315.00	133.00	High
10041	0.00	0.00	0.00	2.50	578	680.00	0.35	0.15	142.00	0.12	270.00	122.00	High
27137	1.18	0.00	1.18	6.50	578	680.00	0.37	0.11	148.00	0.12	270.00	116.00	Parapet
48030	9.27	0.00	9.27	3.00	580	682.00	0.40	0.03	172.00	0.06	30.00	53.67	Pile Bent
49037	2.22	2.44	4.66	7.25	467	667.00	0.35	0.15	168.00	0.12	30.00	88.00	Integral
49038	6.39	3.70	10.08	7.25	467	667.00	0.35	0.05	168.00	0.06	30.00	88.00	Integral
33002	0.00	1.06	1.06	3.00	575	677.00	0.40	0.07	168.00	0.09	30.00	72.50	Integral
10053	13.33	2.15	15.48	6.00	578	680.00	0.37	0.15	167.50	0.13	210.00	102.00	Integral
10054	0.00	2.15	2.15	6.00	578	680.00	0.39	0.19	164.00	0.16	150.00	102.00	Integral
49040	23.34	5.24	28.57	7.25	467	667.00	0.35		168.00		30.00	90.00	Integral
82805	47.22	3.42	50.64	2.25	405	540.00	0.39	0.07	192.00	0.06	30.00	57.00	See Plan
82806	21.75	2.17	23.92	2.50	535	535.00	0.40	0.04	360.00	0.04	14.00	57.00	See Plan
19035	3.91	2.83	6.74	3.25	400	570.00	0.38		243.00		25.00		
27R30	0.00	0.00	0.00	6.00	399	570.00	0.36	0.05	430.50	0.05	420.00	123.00	Parapet
27R31	0.00	0.00	0.00	6.00	578	680.00	0.40	0.04	139.00	0.04	150.00	100.00	Parapet
27R32	0.00	0.00	0.00	6.00	578	680.00	0.39	0.07	124.25	0.07	165.00	100.00	Parapet
27B34	75.63	0.00	75.63	6.00				0.04	288.00	0.06	120.00	39.25	Hinged Wings

Table 2.3 presents the correlation matrix for the numerical data for the 20 selected cases. All correlation values range from zero to $\pm$1.0; values of 0 indicate no correlation whatsoever between the two variables being considered (i.e., a perfect shotgun pattern), while values approaching +1.0 or -1.0 show perfect correlation between the two variables. Positive values indicate positive correlation (i.e., an increase in one variable relates to an increase in the other), while negative values indicate negative correlation (i.e., an increase in one variable relates to a decrease in the other).

The correlation matrix in Table 2.3 shows that most of the selected independent variables are only weakly correlated with the cracking measurements obtained by AET in 2012. Furthermore, many of the weak correlations seem to be in the wrong direction (e.g., increased span length is weakly correlated with decreased deck cracking of both types). All cells that exhibit correlations in the opposite direction of what is expected have been shaded red. Cells containing correlations that are in the expected direction (e.g., increased evaporation rates weakly correlated with increased restraint cracking – as expected) are shaded green.

There are a few cells that contain correlation values that appear to be in the opposite direction as would be expected, but that might actually be surrogates for different relationships. For example, increased cementitious material content is moderately correlated with decreased cracking of both types, and we normally think of increased cementitious material content as being a sign of higher potential shrinkage. However, since the cementitious contents of the cases being considered are confined to a rather small range, the effect of increased cementitious

content on concrete strength (and, therefore, resistance to cracking of all types) may be greater than the impact on shrinkage and volumetric stability. Since we have no strength measurements, this cannot be confirmed, but these cells have been shaded yellow to indicate that they may or may not be of value in modeling the development of cracking. It should be pointed out that some of the other variables that appear to be incorrectly correlated may also be surrogates for (or may be masking) other relationships.

Table 2.3: Correlation Matrix for Cracking and Some Key Variables

	Normalized Flexural or Deflection Cracking, l.f./1000 s.f.	*Normalized Temp Restraint Cracking, l.f./1000s.f.*	*Normalized Total Flex, Defl and Temp Restaint Cracking, l.f./1000sf*	*Age (fall 2012), years*	*w/(c+p) (batched)*	*Cement Content, lb/cy*	*Total Cementitious (lb/cy)*	*Average Estimated Evaporation Rate (lb/sf/hr)*	*Estimated Evaporation Rate - End of Placement (lb/sf/hr)*	*Max Time to Apply Cure (mins)*	*Length of Curing Period (hrs)*	*Longest Span (ft)*
Normalized Flexural or Deflection Cracking, l.f./1000 s.f.	1.0000											
Normalized Temp Restraint Cracking, l.f./1000s.f.	0.1980	1.0000										
Normalized Total Flex, Defl and Temp Restaint Cracking,	0.9968	0.2761	1.0000									
Age (fall 2012), years	-0.0544	0.1872	-0.0380	1.0000								
w/(c+p) (batched)	0.0607	-0.3947	0.0094	-0.4466	1.0000							
Cement Content, lb/cy	-0.3753	-0.5504	-0.4127	0.0347	0.4546	1.0000						
Total Cementitious (lb/cy)	-0.5313	-0.2848	-0.5257	0.4942	-0.0702	0.7091	1.0000					
Average Estimated Evaporation Rate (lb/sf/hr)	-0.3545	0.0802	-0.3454	0.2284	-0.3054	0.3820	0.5486	1.0000				
Estimated Evaporation Rate - End of Placement (lb/sf/hr)	-0.3449	0.1580	-0.3310	0.1943	-0.3998	0.2202	0.3669	0.9400	1.0000			
Max Time to Apply Cure (mins)	-0.2132	-0.4547	-0.2463	0.3516	-0.1199	0.2497	0.2070	0.2589	0.2174	1.0000		
Length of Curing Period (hrs)	0.2797	-0.0381	0.2711	-0.1641	-0.0506	-0.5381	-0.7734	-0.4933	-0.3815	0.1069	1.0000	

One strong correlation that *can* be observed in the data presented in Table 2.2 is that *restraint cracking was observed consistently (and almost exclusively) on bridges with integral abutments*. One "high" abutment bridge (#10039) exhibited a small amount of restraint cracking, and three bridges with unspecified abutment types (#19035, #82805 and #82806) also exhibited restraint cracking (the abutment types on these bridges should be determined). However, none of the parapet or pile bent abutment types and only the one "high" type abutment bridge exhibited restraint cracking, while every one of the bridges with integral abutments had restraint cracking.

2.2.2 Data Plots

Figures 2.1 through 2.4 present plots of flexural and deflection cracking versus deck age, span length, w/(c+p) and cementitious material content, respectively. They help to illustrate the limitations of the current data base in identifying the causes of this type of cracking.

Figure 2.1 examines the development over time of cracks that appear to be due to deck flexure and deflection. It is reasonable to assume that flexure/deflection cracking will either develop during construction due to construction staging and/or the presence of traffic on adjacent lanes during construction, or will develop due to fatigue over time. Figure 2.1 shows that, while there appears to be a general trend of increasing cracking with time (as one might expect), there are a

few outliers (#82805, #82806 and #27B34, which are shown in Figures 2.1 through 2.4 with red data points) where significant cracking developed at a fairly early age. It is these points that are mainly responsible for the low and negative correlation of age with flexural/deflection cracking. A best-fit line plotted through all 20 data points has a slightly negative slope (decreasing cracking with age and not shown in Figure 2.1). Forcing the model for all 20 data points through the origin yields a positive slope, but the standard error of estimate is high (19.74) and the r-squared value is quite low (0.231). Eliminating the three points in question and forcing the best-fit line through the remaining 17 cases (data points shown in blue) provides a stronger model (r-squared = 0.406) with a much lower SEE (6.69 ft/1000 sf).

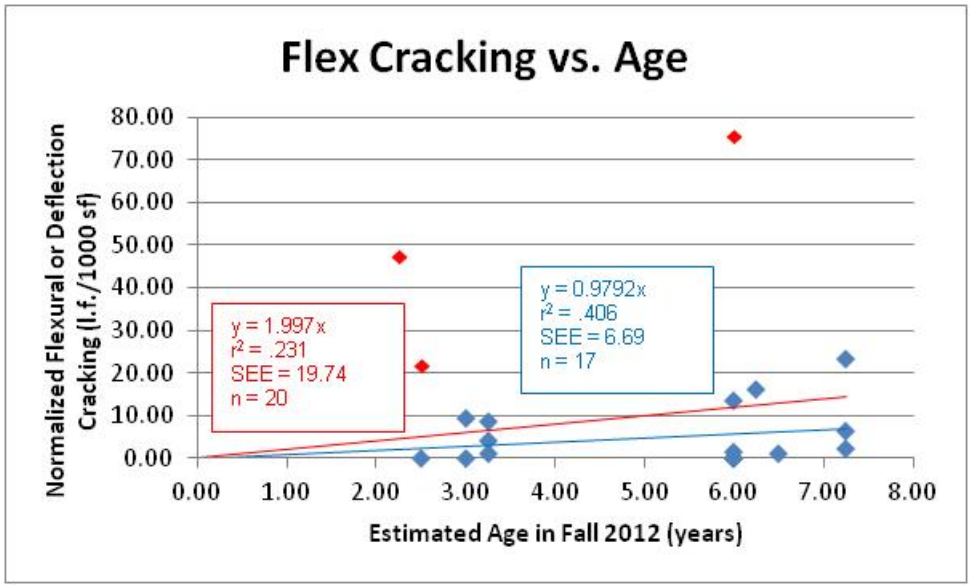

Figure 2.1: Normalized Flexural or Deflection Cracking vs. Age at Time of Survey

The reason(s) for the higher amounts of cracking in the three cases in question are not apparent in the data presented in Table 2.1. Detailed studies should be considered for these three cases to determine the nature of the observed cracking.

It is worth noting at this point that the oldest deck in this study was less than 8 years old at the time of survey. Longer-term performance data may provide clearer indications of causal relationships.

Figure 2.1 presents a plot of normalized flexural/deflection cracking as a function of the length of the longest span. This variable was selected as an available surrogate for unavailable data concerning overall deck and superstructure stiffness and deflection characteristics. From this data plot, it is clear that span length is a poor surrogate for actual stiffness and deflection data. The data generally show a negative relationship (i.e., less flexural cracking with increasing span length). If bridges #82805, #82806 and #27B34 (plotted in red) are eliminated from this graph (eliminating three of the highest cracking points), then the relationship is essentially flat and uncorrelated.

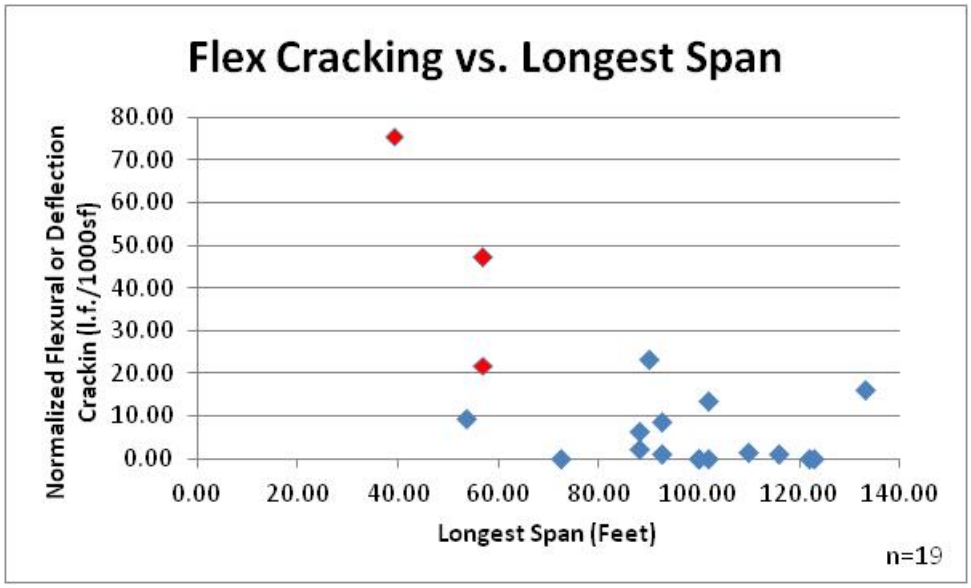

Figure 2.2: Normalized Flexural or Deflection Cracking vs. Maximum Span Length

Clearly the most important structural factors in the development of bridge deck flexural cracking (i.e., deck and superstructure stiffness/deflection characteristics and construction sequencing) are not well-quantified or represented in the current data base, which hinders the ability to accurately determine their impacts on the development of deck cracking.

Figures 2.3 and 2.4 examine the impacts of w/(c+p) and total cementitious material content (c+p) on the development of flexural cracking. While there is little doubt that very high values of w/(c+p) and very low values of cementitious material content would result in the use of weak concrete and higher incidences of cracking, the actual range of available data for both of these variables is fairly tight and the resulting correlations and trends shown in Table 2.2 and Figures 2.3 and 2.4 are negligible (particularly when bridge #82805 is eliminated).

Figures 2.5 through 2.11 present plots of restraint cracking density versus the key variable included in the data base that are most likely related to the development of restraint cracking: deck age, maximum time before cure application, duration of curing, evaporation rate at the end of placement, average evaporation rate during placement, w/(c+p) and cementitious material content, respectively. In all of these graphs, red data points correspond to projects with integral abutments, green data points are projects with high-type, parapet and pile bent abutments, and blue data points are for projects for which the abutment type was not reported.

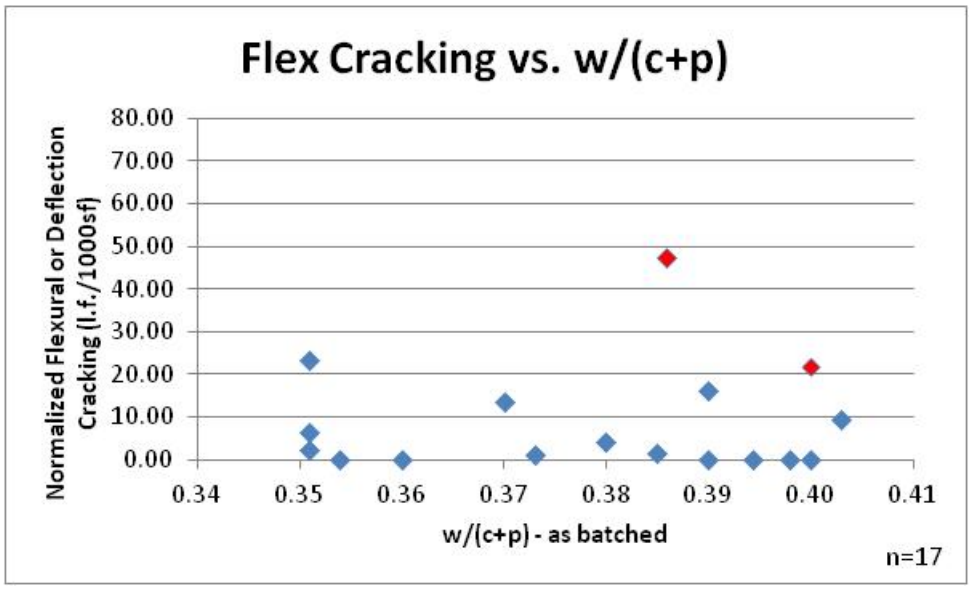

Figure 2.3: Normalized Flexural or Deflection Cracking vs. w/c

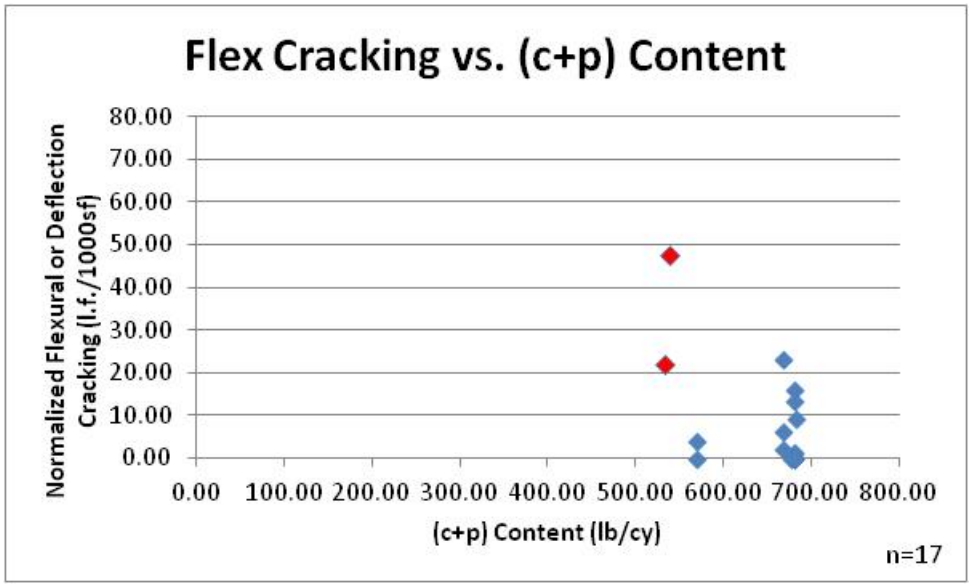

Figure 2.4: Normalized Flexural or Deflection Cracking vs. Cement Content

Figure 2.5 shows the increase in restraint cracking with deck age. The green line represents a best-fit linear model (forced through the origin) that considers all 20 cases. There is a clear trend of increasing restraint cracking with age and the model is reasonably good ($r^2 = 0.43$) for a single variable linear regression!

As noted previously, all of the cases with integral abutments exhibited restraint cracking; when only these cases (the red data points) are considered, the slope of the regression line steepens and the model statistics improve dramatically ($r^2 = 0.91$), although there are only 6 data points considered (2 data points fall on top of each other). Clearly the use of integral abutments is highly associated with restraint-type cracking, with increasing incidence and quantity over time.

There are three additional cases with observed restraint cracking but for which the abutment type is missing from the data base. If these cases (which are plotted in blue) are considered with the integral abutment cases, the slope of the line changes only slightly and the quality of the model doesn't change significantly, so they seem to verify the model for whatever abutment type they represent.

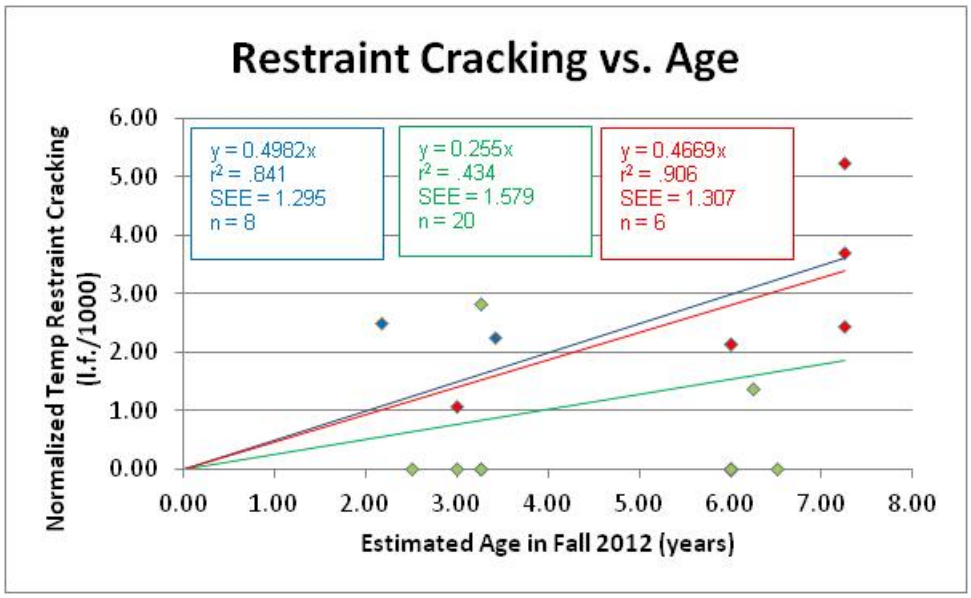

Figure 2.5: Normalized Restraint Cracking vs. Deck Age at Time of Survey

Figure 2.6 plots temperature restraint cracking density versus maximum time to application of curing materials. If we consider only the cases with integral abutments (which are much more restrained than the other types), the data suggest either no real data trends or, at best, a weak trend toward higher amounts of restraint cracking with shorter delays in cure application, which doesn't seem to make much sense. It seems more likely that the data represent a variance in cracking that is unrelated to time before cure application.

Figure 2.7 plots length of curing period against temperature restraint cracking and again shows little relationship between the two, perhaps in part due to the lack of a range of curing periods for the integral abutment cases. There may be a slight trend of decreasing cracking with increased curing for the non-integral abutment cases that exhibited cracking (4 cases), but additional data would be useful to confirm whether this is a real trend or just a representative variance of cracking quantities.

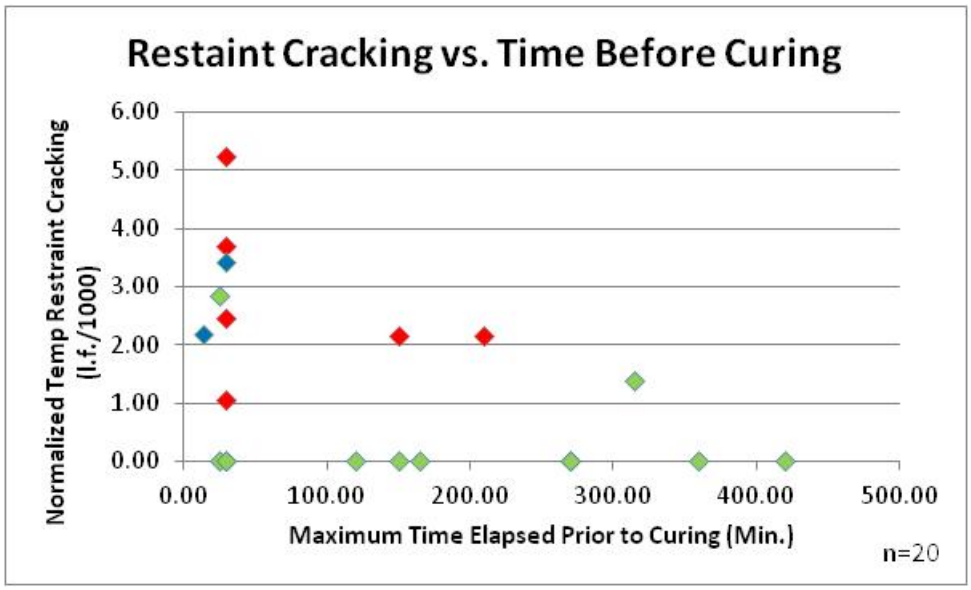

Figure 2.6: Normalized Restraint Cracking vs. Maximum Elapsed Time Before Curing

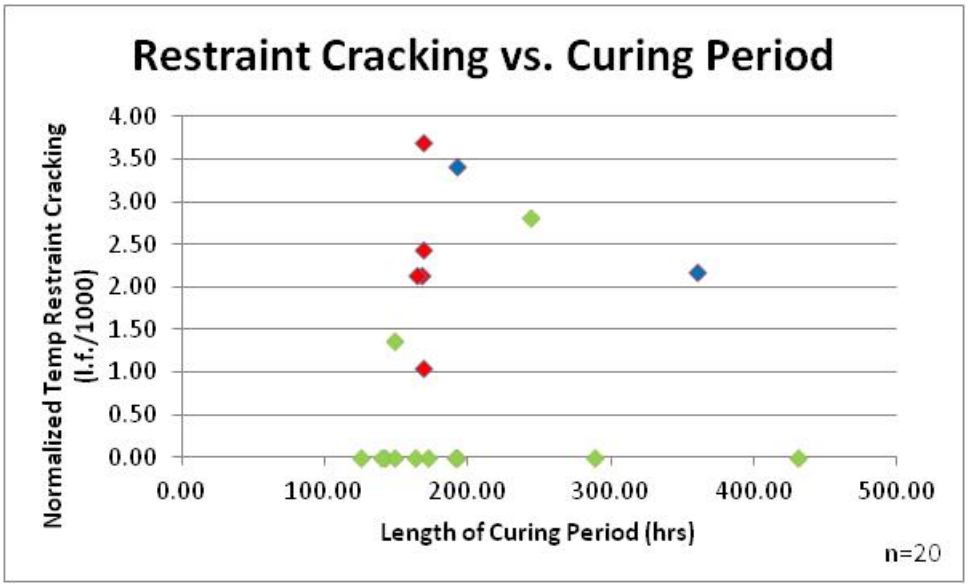

Figure 2.7: Normalized Restraint Cracking vs. Duration of Curing

Figures 2.8 and 2.9 present plots of restraint cracking versus evaporation rate (at the end of placement and average during placement, respectively). These variables almost certainly affect the development of shrinkage cracking, but (as indicated in these figures) appear to have little impact on the development of restraint cracking at the abutments.

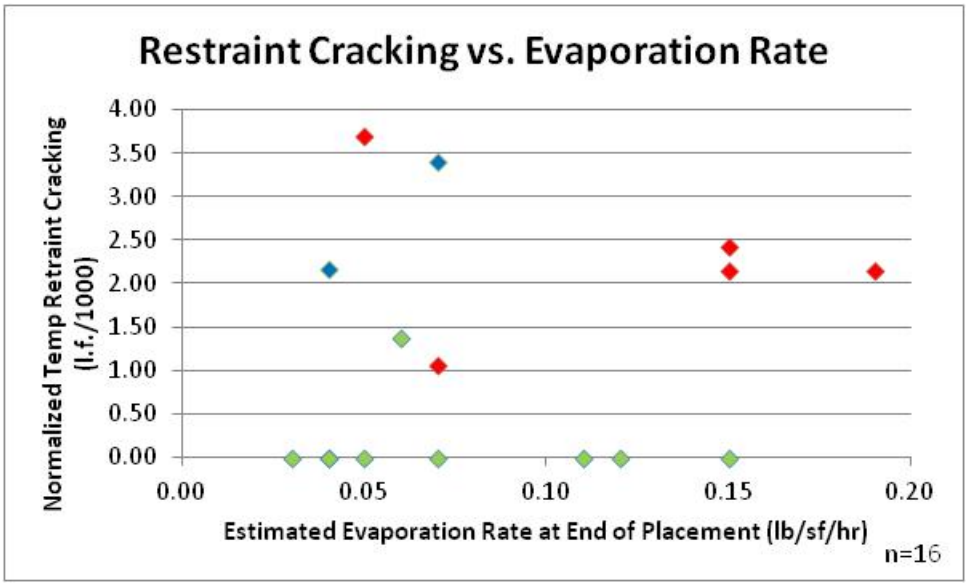

Figure 2.8: Normalized Restraint Cracking vs. Evaporation at End of Placement

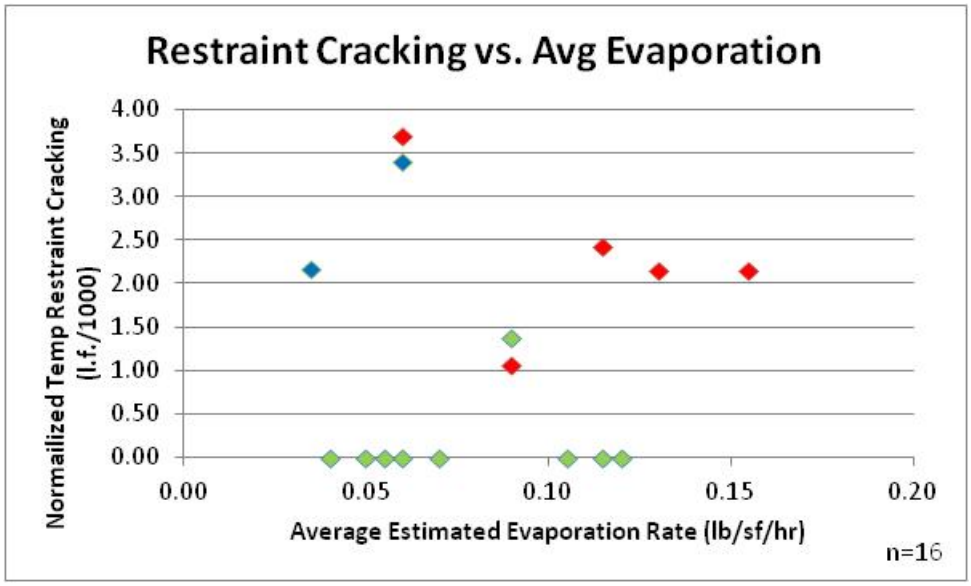

Figure 2.9: Normalized Restraint Cracking vs. Average Evaporation Rate During Curing

Figure 2.10 illustrates the apparent effect of water-to-cementitious ratio on the development of restraint cracking. There does appear to be rather well-defined trend of decreased restraint cracking with increased w/(c+p) for the cases that did exhibit such cracking (mainly the integral abutment and undefined abutment type cases). This trend is consistent with the correlation coefficient of -0.395 shown in Table 2.3, but is the opposite of what one would normally expect (i.e., increased shrinkage potential and restraint cracking with higher w/(c+p)).

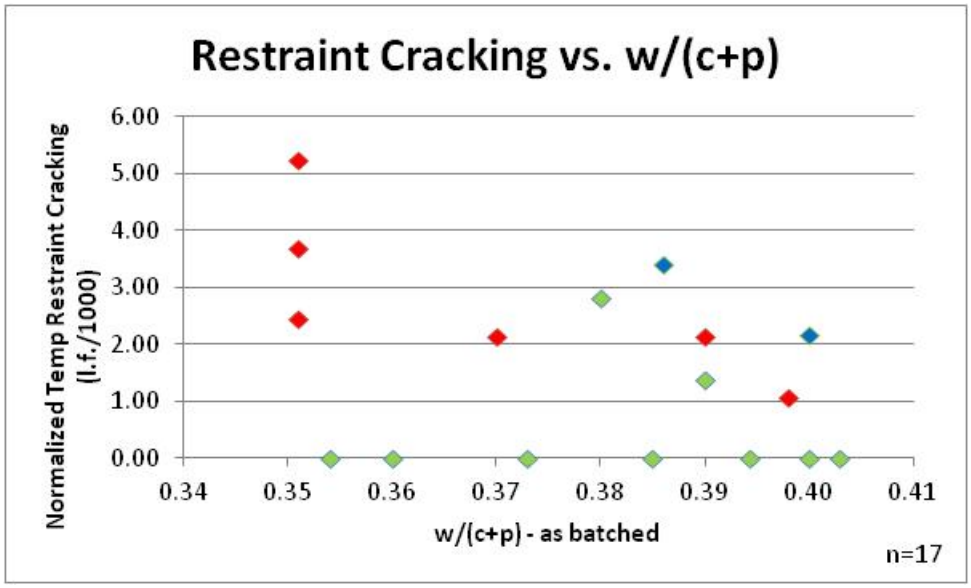

Figure 2.10: Normalized Restraint Cracking vs. w/(c+p)

The range of w/(c+p) represented in this data set is restricted to 0.35 – 0.41. While concrete strength increases typically result from reduced w/(c+p), their effect on reducing restraint cracking may be relatively small over such a small range of w/(c+p). Any strength gain benefits from lower w/(c+p) in this range may be more than offset by mixture sensitivity to loss of water during placement and curing; this may be the effect that we are seeing in this graph, where volumetric changes in the concrete at very low w/(c+p) – in combination with end restraint at the abutments – results in increased levels of restraint cracking.

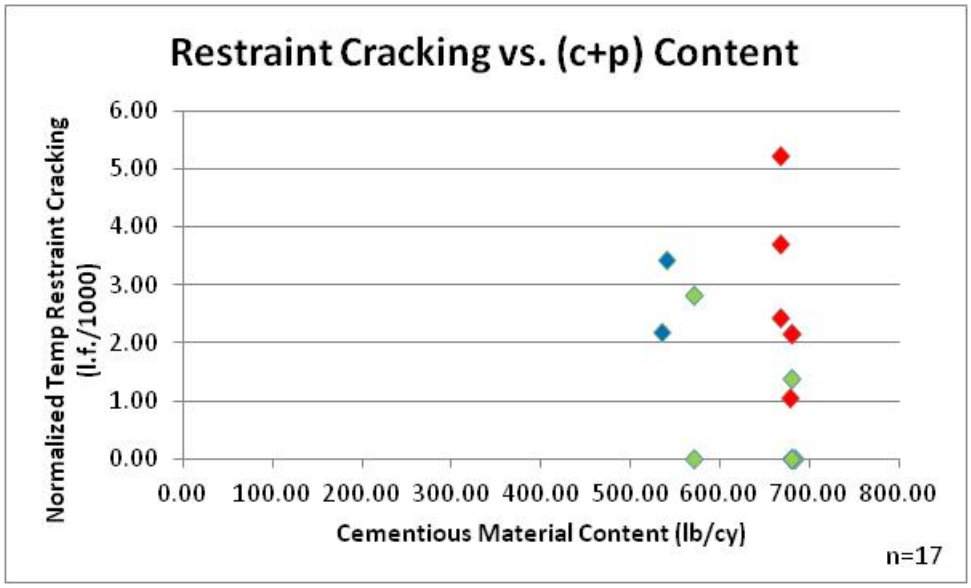

Figure 2.11: Normalized Restraint Cracking vs. Cement Content

Figure 2.11 illustrates the apparent effect of total cementitious content on the development of restraint cracking. There does appear to be slight trend of decreased restraint cracking with increased cementitious content for the cases that did exhibit such cracking (mainly the integral abutment and undefined abutment type cases). This trend (if it actually exists) is the opposite of what one might expect (i.e., increased shrinkage potential and restraint cracking with higher cementitious content), but the potential for shrinkage is reduced by the low w/(c+p) of all of the mixtures (0.35 – 0.40), so the increased strength that accompanies somewhat higher cementitious contents may be coming into play in reducing restraint cracking.

2.2.3 Modeling

The available data set really doesn't present much opportunity for developing useful, realistic models of bridge deck cracking of any sort. Correlations between measured cracking and possible independent variables are generally weak or nonexistent, in part because of the small size and range of the available data set.

The following documents the development of a model of restraint cracking using this limited data set, but it is only for demonstration purposes. It is based on only 9 observations (for the integral abutment and undefined abutment type cases) and is purely a multivariate linear regression analysis that includes only 3 variables. It isn't worth the time to try to squeeze anything more out of this limited data set by using nonlinear regression analysis or other techniques. The purpose here is to simply show that useful and revealing tools might be developed from a more comprehensive data base.

The model developed is:

$$y=24.995+.151(X1)-.0117(X2)-41.401(X3)$$

where:

y = Normalized Restraint Cracking in the selected bridge set (integral abutments and other undefined abutment types), lf/1000 s.f.

X1 = Age of the deck (yrs) at the time of survey

X2 = Total cementitious content of the mixture (lb/c.y.)

X3 = w/(c+p), as batched

Model statistics:

$R^2 = 0.604$

SEE = 1.07 lf/1000 sf

This model suggests that the incidence of restraint cracking increases with age and decreases with increasing w/(c+p) and cementitious content. Like all models, it is only valid within the inference space over which it was developed and it could lead to incorrect conclusions and actions if used to extrapolate performance outside of the data ranges of the cases used in its development.

Figure 2.12 presents a plot of predicted cracking vs measured cracking for the data points used to develop the model. Most points lie near the line of equality, which indicates that the model is reasonably accurate.

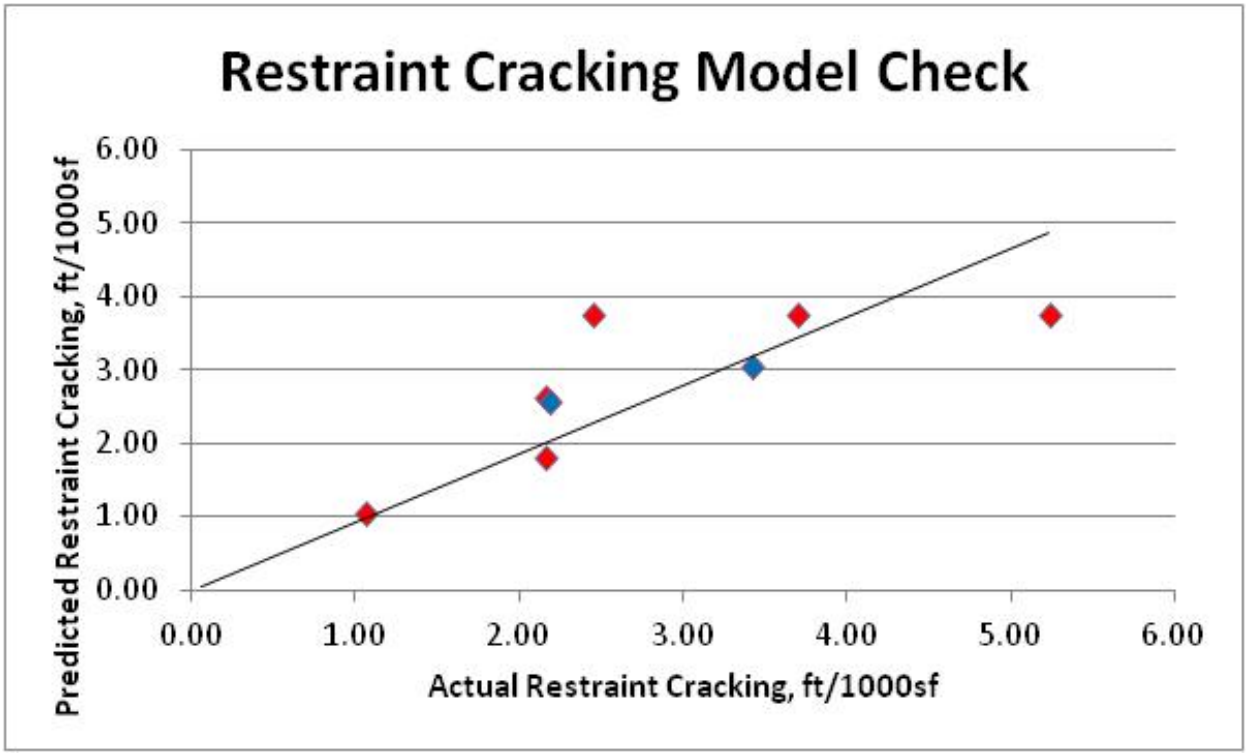

Figure 2.12: Plot of Predicted vs. Actual Restraint Cracking.

Chapter 3. Recommendations for Future Research and Specification Modifications

A wealth of data has been collected and exists in the current database of 150 cases. This database could easily serve as a basis for future research. However, an effort must be made to uniformly and accurately classify and quantify all of the cracking observations in the data base. Sufficient uniformity can be achieved by training one person (or a small team of people) to evaluate the available cracking sketches and extract the required information in a usable format.

It would be also be useful to visit each bridge deck again (or as many as possible or feasible, in consideration of the fact that closures for surveying the top surfaces will be difficult) and do a complete deck crack survey using the best available methods. Previously performed investigations into bridge deck cracking provide recommendations for performing bridge deck cracking surveys; this information should be considered in establishing a standard practice for Minnesota [3].

Finally, even the limited analyses conducted in this study were hampered by missing data that should be easily obtained (e.g., abutment type, weather conditions during placement and curing, etc.). When a key data element is missing, the entire case must be eliminated from use in model development. Therefore, these data elements should be researched and inserted into the data base to make every case as useful as possible.

When the above steps have been taken, the existing data set will represent a much more valuable resource for analysis in determining the sources of early bridge deck cracking in Minnesota.

3.1 Evaluation and Treatment of Existing Cracks

While deck cracking is not desirable, it is important to know what to do about it when it does develop. This requires an understanding of both the nature of the crack (i.e., which mechanism is (or, often, which mechanisms are) at work and to determine what impact (if any) that the cracking is likely to have on the performance of the deck overlay. Just because some cracking is present it should not be assumed that the entire overlay has failed and must be replaced [6].

3.1.1 Evaluation of Existing Cracks

There are three primary factors that will determine both the potential impact of the cracking on future performance as well as the treatment (if any) that should be applied: 1) cracking mechanism, 2) depth, width and extent of cracking, and 3) presence of delamination between the overlay and underlying deck or beams.

Cracking mechanisms were described previously and are not repeated here. However, it should be noted that cracks due to reflection of underlying and moving cracks or joints cannot be effectively repaired unless the mechanism of movement is also addressed and eliminated. In these instances, it may be beneficial to “rout and seal” the cracks in the same manner that is

sometimes done for reflective cracks in highway pavements. If done before the movement of the crack causes spalling or delamination, this repair approach (rout and seal) may prevent the development of spalling and delamination and allow a satisfactory service life for the overlay.

Crack depth and width are best measured by examining cores of the deck. Small diameter (i.e., 2-4 inches) cores are sufficient for making these determinations. Shallow cracks (e.g., 1/8 inch or less) will have no real effect on overlay permeability and expected performance, while deep cracks (1/2 inch or more) may be cause for concern [6]. Deep, wide cracks can provide a conduit for the entry of deicing chemicals, oxygen, water and other materials that can cause corrosion of embedded reinforcing steel. They also *may* allow increased saturation of the concrete and entrapment of water in the deck, both of which can result in scaling, delamination and other forms of freeze-thaw damage. Evaluation of this potential can be evaluated using rapid chloride permeability (RCP) tests (which may dictate the size of core retrieved in the investigation).

Loss of bond between the concrete overlay the underlying layers (e.g., as a result of incomplete removal of deteriorated concrete prior to placing the overlay) may cause cracking, or may be a result of continued deck deterioration after cracking due to other causes. In either case, concrete overlays that have debonded will generally require removal and replacement unless they were designed to perform in this manner. Techniques for assessing bond conditions include both destructive tests (i.e., coring) and nondestructive tests (e.g., "sounding" techniques using a chain drag, rebar or hammer, ground-penetrating radar, and ultrasonic devices).

3.1.2 Bridge Deck Crack Treatments and When They Should Be Used

At least two studies have investigated the effectiveness of different types of materials on sealing and filling plastic shrinkage cracks in bridge decks. Materials evaluated include, low-viscosity epoxy, low-viscosity methacrylate, sodium silicate, latex-cement-sand slurry and latex-cement slurry.

The low-viscosity epoxy and methacrylate materials were effective in penetrating and filling both narrow and wider cracks. There was no evidence that the sodium silicate penetrated or filled the cracks. Previous research noted that the epoxy sealants didn't penetrate as fully as the methacrylate materials near the lower end of their application temperature ranges [8].

The latex-cement-sand slurry tended to bridge cracks and bond to the top surface of the concrete rather than fill the cracks. The latex-cement slurry was of sufficiently low viscosity to penetrate wider cracks, but it did not fill them. Therefore these types of slurry mixes be used only for treatment of shallow tears and cracks [6].

Based on documented experience and laboratory studies, it is recommended that deep cracks (e.g., >1/4 inch) should be sealed using low-viscosity epoxy or methacrylate materials. *There is no evidence that shallow cracks caused by drying shrinkage need to be (or benefit from being) sealed.*

3.1.3 Development of an Objective and Rational Approach to the Treatment of Deck Overlay Cracks

A rational, predictable and justifiable approach to the treatment of deck overlay cracks (and the responsibility for payment for the treatments) must consider the type(s) of cracking (i.e., structural vs. nonstructural), the source of the cracking, the extent of the cracking and the stability of the cracking. This could require three (or more) inspections of the surface by the agency: 1) as soon as the surface is fully visible after placement (after removal of the burlap); 2) after the burlap has been removed and all decking and other sources of dead load are in place, but before opening to live traffic; and 3) at least 7 days after the bridge has been opened to full unrestricted traffic. At each of these times, the project engineer (or inspector) would need to measure the width, length and depth of each crack and establish the locations of the ends of the cracks with respect to permanent reference points. Coring may be deemed necessary if crack depths cannot be inferred from the crack patterns (type of cracking) or accurately determined using a mechanical probe.

A well-trained engineer should determine the type of cracking (structural or nonstructural) and source of cracking (e.g., shrinkage, plastic shrinkage, reflection, etc.) for each crack (or area of cracking).

Structural cracks will generally be (or will become) deep cracks that are a result of structural issues over which the contractor has little or no control (e.g., cracking in negative moment areas of continuous spans over piers, expansion restraint cracking at integral abutments, reflective cracks of underlying joints and seams, etc.). These *should be repaired by an appropriate technique* (e.g., epoxy injection or low-viscosity methacrylate for moment and restraint cracking, rout and seal for reflective cracking) *at the agency's expense*.

Nonstructural cracks (e.g., shrinkage or plastic shrinkage cracking, surface tears, etc.) *that are evidence of defects in materials or contractor workmanship should be evaluated and treated at the contractor's expense*. Because the incidence and density of these types of cracks may vary with concrete batches, changing environmental conditions during placement, etc., it is appropriate to establish "lots" for inspection and treatment. Each lot should be between 100 s.f. (roughly 10' x 10') and 400 s.f. (20' x 20') in area. Lot boundaries can be arbitrary, but should be selected to reflect obvious changes in materials, finishing practices, or other factors that would result in changes in crack patterns.

Appropriate treatments within each lot should reflect both the density of cracking within the lot and the width of individual cracks within the lot. Crack density can be estimated as the sum of the surface areas of each crack (i.e., average crack width multiplied by crack length) divided by the lot area. Crack widths and densities used for determining treatment should be the "final" measurements obtained after the deck has been opened to service loads. The table below represents an example of the type of table that could be developed to provide guidance in the appropriate treatment of nonstructural deck cracking.

Table 3.1: Example Treatment Table for Bridge Deck Cracking

<table>
<tr><td></td><td colspan="4">Cracking Density Within Lot</td></tr>
<tr><td>Average Crack Width Range, inches[1]</td><td>Isolated (<0.005%)</td><td>Occasional (0.005% to <0.017%)</td><td>Moderate (0.017% to <0.029%)</td><td>Extensive (>0.029%)</td></tr>
<tr><td><0.004</td><td rowspan="4">No Treatment</td><td rowspan="2">No Treatment</td><td>No Treatment</td><td>MM</td></tr>
<tr><td>0.004 to <0.008</td><td rowspan="2">Epoxy or MM</td><td rowspan="3">Investigate[2]</td></tr>
<tr><td>0.008 to <0.012</td><td rowspan="2">Epoxy or MM</td></tr>
<tr><td>0.012 to <0.016</td><td rowspan="4">Investigate[2]</td></tr>
<tr><td>0.016 to <0.020</td><td>Epoxy or MM</td><td rowspan="4">Investigate[2]</td></tr>
<tr><td>0.020 to <0.024</td><td>Epoxy</td><td rowspan="3">Remove and Replace</td></tr>
<tr><td>0.024 to <0.028</td><td>Epoxy</td></tr>
<tr><td>≥0.028</td><td>Investigate[2]</td></tr>
</table>

[1]Average Crack Width to be determined as the average of 3 representative measures
[2]Investigation should consider the nature and stability of cracking and the probability that repair techniques will effectively prevent future surface deterioration and delamination. *Removal and replacement should be required only when there is a significant probability that all other options will lead to premature failure of the deck*.

3.2 Improving MnDOT Bridge Deck Specifications and Cracking Policies – Points for Consideration

Appendix A contains a summary of the most significant factors that are believed to influence the development of cracks in bridge deck overlays. Based on this summary and the preceding discussion, the following issues should be considered in discussions of possible changes to MnDOT policies and specifications to reduce the incidence of cracking bridge deck overlays:

- Structural Design
  - For skewed structures, additional reinforcement should be considered in corners to resist thermal and shrinkage stresses.
- Deck Preparation Prior to Overlay Placement
  - Consider adding emphasis to the importance of deck preparation prior to overlay placement, particularly concerning techniques for ensuring the complete removal of unsound and deteriorated concrete (e.g., hydrodemolition and sounding techniques). Delamination of deck overlays due to inadequate removal of deteriorated concrete almost always results in overlay cracking and premature failure.
- Mixture Design
  - Limit paste volume to 27 percent or less [3,7]
  - Optimize w/c – hold between 0.38 and 0.42. Lower w/c may be more susceptible to autogenous plastic shrinkage and may not have sufficient bleed water to resist initial plastic shrinkage. Higher w/c may be susceptible to drying shrinkage cracking.
  - Use Type I, IP, IS or II Cement; consider reducing total cementitious contents to reduce overall concrete shrinkage). Do not use Type III cement unless necessary

for more rapid strength gain when traffic will be using other portions of the bridge during placement.
    - Consider reducing the "brittleness" of the deck overlay by reducing the design compressive strength to 4000 psi or less and by limiting actual compressive strength to <6000 psi
    - Consider specifying/allowing a higher minimum air content to take advantage of the added workability afforded by entrained air.
    - Consider using the largest practical aggregate size and grade aggregate as required in order to reduce paste (and cementitious material) requirements.
    - Avoid the use of aggregate (especially sands) that increase water demand due to particle shape; use rounded and smooth (rather than angular and coarse-textured [e.g., manufactured]) fine aggregate to reduce water demand for a given slump.
    - When using Type I or II cements, consider allowing the use of higher quantities of pozzolans as replacement for cement to control hydration and early temperatures, in both bridge decks and low slump overlays; consider the addition of 1 – 2% shrinkage-reducing admixture (although this may increase susceptibility to scaling)
    - Investigate the possibility of internal curing to reduce plastic and drying shrinkage problems
- Restrict Placement Conditions
    - Evaporation Rate <0.10 lb/s.f./hr – see ACI Recommended practices for Hot Weather Concreting for evaporation chart.
    - Avoid placement during high winds (>15 mph)
    - Maintain air temperature range at placement to 45 – 85F
    - Consider limiting daily temperature swing<50F, and girder-deck differential temperature <22F for at least 24 hours.
    - When possible, reroute or slow traffic on adjacent portions of the bridge.
- Finishing
    - When used, roller finishers should be operated in a manner that minimizes excess mortar at the deck surface (or avoid this type of finisher completely).
- Curing
    - *Apply mist water or evaporation retarder film immediately after screeding/finishing.* Poly film (if used) should be white to minimize solar heat gain, which might otherwise raise temperature of the fresh concrete too quickly.
- Construction Sequencing
    - Recognize that construction sequencing may have an effect on the incidence of deck cracking and consider modifying construction sequencing (e.g., multiple placements in specific lanes and moment regions of the deck, with appropriate delays between placements), when appropriate, to minimize the potential for certain types of structural cracking and deflection-related cracking due to traffic on adjacent lanes.
- Assessment of Deck Cracking and Determination of Appropriate Treatments
    - Training – consider the development and implementation of a training program for inspectors and contractors to assist them in:
        1. better recognizing the probable sources of cracking (e.g., structural vs. materials/workmanship issues) based on observed cracking patterns;

2. accurately measuring the length, depth and extent of cracking; and
3. assessing the risk of deterioration or loss of service life from observed cracking.

- Standardized crack measurement procedures – consider developing standard procedures for measuring the depth, width, length and extent of deck cracking so that all trained technicians and contractors arrive at comparable assessments of deck cracking.
- Treatment schedule - consider developing a standard treatment schedule for deck cracking that calls for treatments of deck cracking that accurately reflect the type, severity and extent of any cracking observed, as well as who should pay for the treatment. For example, reflective cracking of underlying joints and cracks that are beyond the contractor's control might be routed and sealed at the agency's expense, while the treatment of a specific density of plastic shrinkage cracking caused by workmanship problems might require sealing the affected area of the deck with methacrylate at the contractor's expense.

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Appendix A: Summary of Factors that Affect the Development of Bridge Deck Overlay Cracking

- Bridge Deck Type (monolithic vs overlays)
- Material Effects
  - Cement Type – Type II cement has been found to reduce thermal stresses and related deck cracking and Type K (shrinkage compensating cement) can be effective in reducing cracking [7]
  - Aggregate type, size and volume
    - Effects on shrinkage and absorption (due to water required to achieve desired workability)
    - Effects on Coefficient of Thermal Expansion (COTE)
  - Use of Admixtures
    - Mineral admixtures can reduce early temperature rise, decrease early strength, lower permeability, etc.
    - Chemical admixtures
      - Water reducers can reduce shrinkage when used to reduce water demand
      - Shrinkage reducing admixtures can reduce shrinkage (but can also decrease scaling resistance)
      - Set-retarders can delay hydration process and affect early temperature rise
  - Mixture Proportions
    - Higher water content tends to yield more cracking
    - Higher cement content tends to yield more cracking
    - Greater volume of cement paste (combined volume of water and cement) yields more cracking (no surprise, since paste content controls shrinkage).
    - Water-cementitious ratio has historically been strongly correlated with cracking
      - Too low and autogenous shrinkage increases
      - Too high and plastic/drying shrinkage increases
      - Best range seems to be 0.38 to 0.42
    - Increased air content can decrease drying shrinkage
  - Compressive Strength
    - Too much strength and too high elastic modulus results in more cracking as concrete can accommodate less strain (brittle concrete). Effect is particularly strong for monolithic decks, less so for overlays.
    - Creep (permanent deformation over time) can reduce stresses that develop due to restraint.
- Girder End Condition – Integral abutments tend to result in increased deck cracking in end regions (generally oriented perpendicular to the abutments). Crack densities may be 2 – 3 times the density in the end regions of pin-ended decks.
- Date of Construction - changes in materials and construction processes over time (Darwin, et al. 2004)
  - Example: increased use of pumps, which require higher paste contents
  - Example: increased use of roller screeds, which move more paste to the surface than vibrating screeds
  - Example: improved curing materials and techniques, which should reduce cracking
- Environmental Conditions

- Air temperature, relative humidity, precipitation, solar radiation, wind speed and other factors affect evaporation rates, concrete temperatures during curing, plastic shrinkage, and built-in thermal stresses.

- Construction Practices
  - Curing – maintenance of proper temperature and moisture conditions during hardening
    - Need timely application and effective application
    - Key factor in reducing shrinkage cracking
    - Control of hydration (curing) temperature has been suggested because it can be measured and influenced (if not controlled) through mix design, batching and curing processes
  - Deck construction sequence
    - Formwork deflection/sag can induce flexural stresses; VA and NJ have recommended specific pouring sequences.
- Design Issues
  - Restraint of the deck relative to girders, parapet, abutments, etc. is the most significant design factor relative to deck cracking.
    - Girder type affects restraint – simply supported girders are less susceptible, multi-span continuous girders are more susceptible. Various conclusions about steel girders vs. prestressed concrete girders
  - Deck thickness
    - Thin decks have higher drying shrinkage (moistures) gradients; thick decks have higher temperature gradients.
  - Reinforcing bar alignment can create weakened planes if top and bottom bars are aligned.

Appendix B: Bridge Deck Placement Data Form

MnDOT Form BR4789 (1/10)

Bridge Deck Placement Data Form

Name of person completing this form: _____ Phone number: _____

Bridge Data

Low SP No. _____ Mn/DOT Mix No. _____
Br. No. _____ Br. Location: _____ District: _____
Top Trans. Bar Size & Spacing: _____ Bot. Trans. Bar Size & Spacing: _____
Superstructure Type: _____ Abutment Type: _____ No. Spans: _____
Skew Angle: _____ Deck Width (ft): _____ Beam Depth: _____ (in) Orientation: _____
Beam Spacing: _____ Span Lengths: _____ Total Length: _____

Deck Placement Data

Attach copies of batch tickets from all loads that were tested for slump, air, strength, temperature.
Include ALL test results on the batch ticket (air content, slump, cylinder #, conc temperature).
Additional conc temp readings: _____
Placement Date: _____ Fin. Start Time: _____ Fin. End Time: _____
Total no. of cubic yards placed: _____ Avg. Placement Rate (yds/hr): _____
Placement equip: ☐ Air Screed ☐ Paving Machine ☐ Other: _____
Air temp at start of placement: _____ Wind speed: _____ Humidity: _____
Air temp at end of placement: _____ Wind speed: _____ Humidity: _____
Color of Beams: _____ Beam Sunlight Exposure: _____
Beam temp prior and during placement: _____
Method of Placement (pump, conveyor, bucket, etc.): _____
Contractor: _____

Curing Data

Date/Time burlap applied: _____ Date/Time burlap removed: _____
Length of curing period: _____ (hrs,) Curing Material: _____
Was the surface kept continually wet during curing? ☐ Yes ☐ No
Were temperature gauges installed in the deck? ☐ Yes ☐ No (If yes, submit temperature data, if no
indicate the deck & ambient temp at 24 & 48 hrs. after placement: 24 hrs: _____ 48 hrs: _____
Weather conditions during curing (rain, dry, windy, etc): _____
Indicate the maximum and minimum time that elapsed prior to placing curing: _____

Crack Survey

Indicate any visible cracking on an attached framing plan. Use red for bottom of deck cracks, use blue for top of deck cracks.
Complete the crack survey at time of deck form removal.
Date of deck form removal: _____ Date of crack survey: _____
A follow up survey will be conducted within one year.
Comments (discuss delays in placement, concrete problems, etc.): _____

Submit Questions, Completed Form, Batch Tickets, etc. to:
Mark Spafford, MnDOT Bridge Office, MS 610, 3485 Hadley Ave. North, Oakdale, MN 55128 (651) 366-4564

Appendix C: Analysis of Cracking, Inverted T Bridge Deck, Bridge No.25024

This report was prepared to document the results of thermal analysis of the cast in place deck supported on precast inverted Tee sections. The analysis was prompted to determine the likely cause of the observed longitudinal cracking. The review included a thermal model of the slab and void section along the bottom of the stem and between the stems. In addition to this analysis the modeling was repeated using a low heat of hydration concrete typically used in Minnesota for mass elements less than 10 feet thick.

As Built Analysis

The construction records reviewed included the ambient temperature conditions at the time of construction, the drawings and some temperature data from the actual construction. Based on the temperature records and experience with similar mixtures, the heat of hydration was modeled as follows:

Time (hours)	Heat of Hydration (W/m3)
0-24	600
24-36	350
36-100	120
>100	10

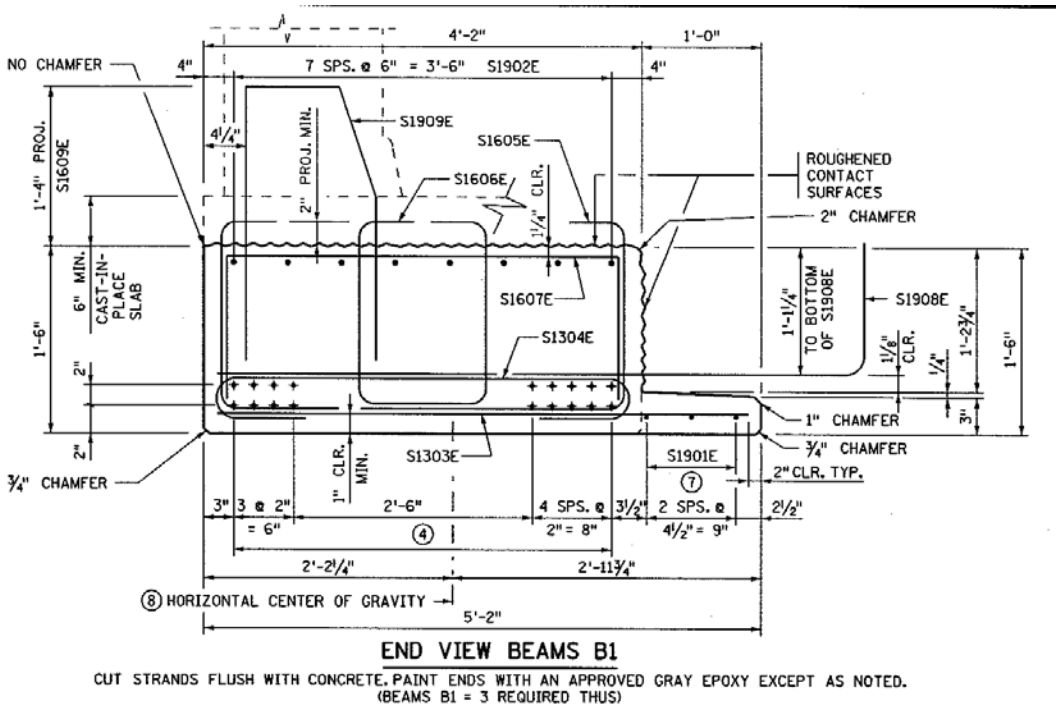
The model employed was a finite difference model with an assumed incoming concrete temperature of 72 degrees Fahrenheit. Ambient conditions were assumed as shown on the figures below. Figure C.1 presents the section showing the precast beam, void space and proposed deck thickness. At the void section the concrete thickness is 1.8 feet. At the stem section the concrete thickness is 0.5 feet. Figures C.2 and C.3 respectively show the temperature conditions in each section.

The differential temperature for the void segment of the T is high but likely would not cause cracking except that the concrete is bonded to the Pre-cast inverted T below. As such there is no allowable expansion and the restraint does not allow any relief and the restraint factor used to compute the stresses should be set to 1.0.

Some more information regarding strength gain with time for the actual concrete in use would assist in calculating the actual stresses in the slab at the transition from stem base to void section. Based on some data for early age concrete of similar performance the stresses can be calculated.

Figure C.4 presents the differential temperature at a depth of 4 inches. This differential exists over a short distance approximately 1 foot. Due to their stiff nature of the inverted T there is very little relief of the restraint and there is no reduction in the resulting stress estimate. Assuming a strength at 24 hours of 1500 psi and a coefficient of thermal expansion of 6x10-6 F-1 the tensile stress exceeds the strength of the concrete at approximately 24 hours.

As a result would be expected structures will crack along the line of the stem of the T. It is understood that this type of cracking in fact has been observed in the field.



END VIEW BEAMS B1

CUT STRANDS FLUSH WITH CONCRETE. PAINT ENDS WITH AN APPROVED GRAY EPOXY EXCEPT AS NOTED.
(BEAMS B1 = 3 REQUIRED THUS)

Figure C.1. End View Beams, Bridge No. 25024

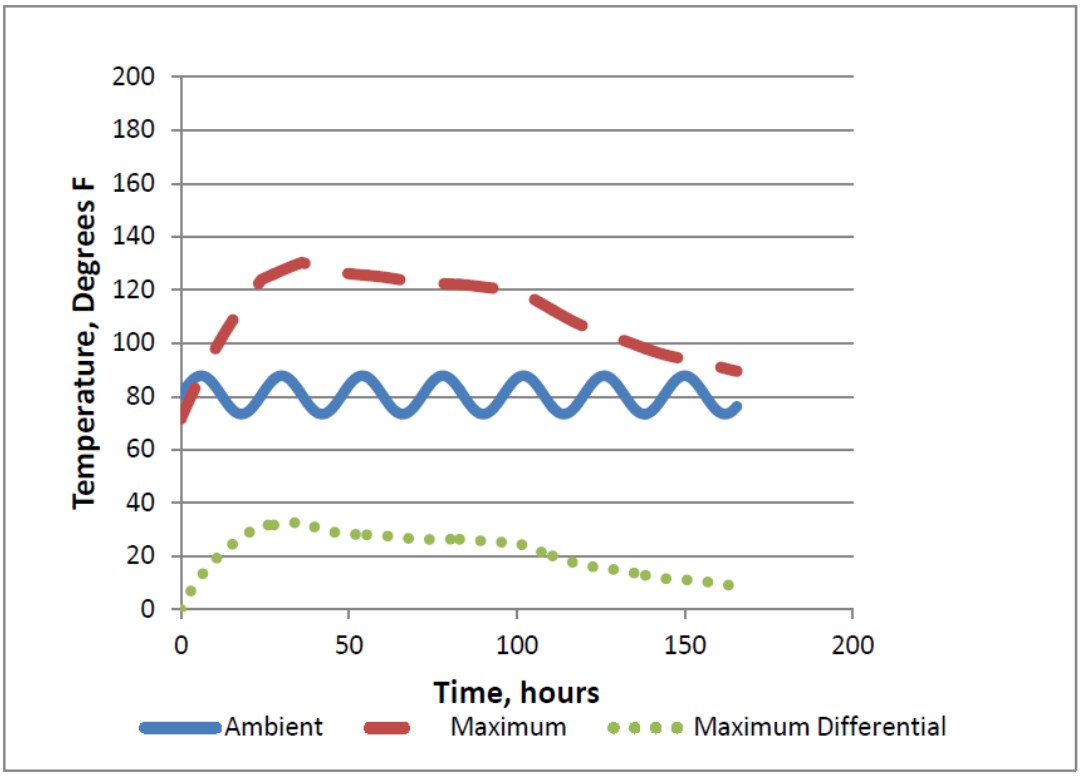


Figure C.2: Predicted Temperatures for 21 inch Thick Void Section

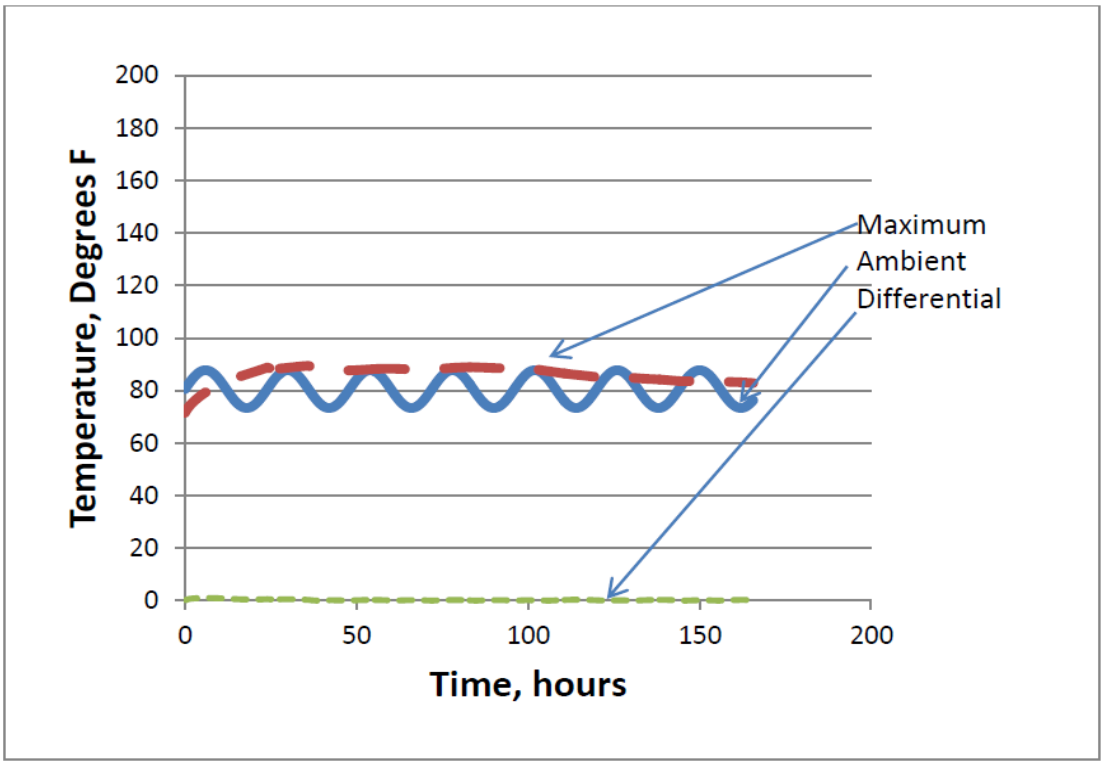


Figure C.3: Predicted Temperatures, 6 inch Slab Section

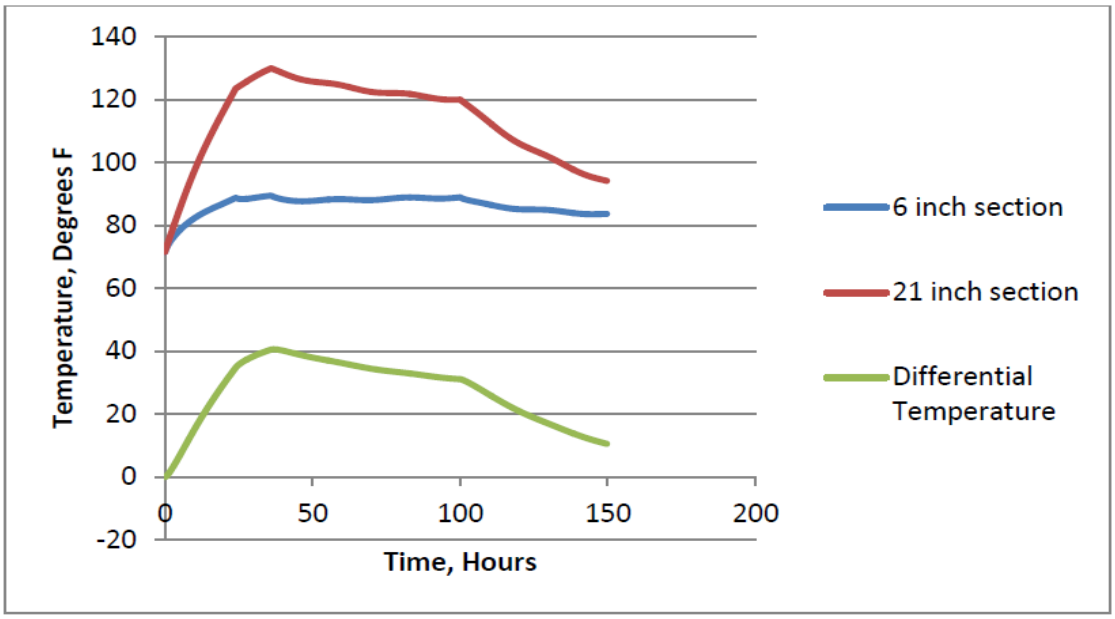


Figure C.4: Temperature and Temperature Difference at a Depth of 3 Inches as Constructed

Low Heat of Hydration Mixture Analysis

As an alternative to the concrete used as constructed, the model was rerun assuming a concrete with the heat of hydration shown below:

Time (hours)	Heat of Hydration (W/m3)
0-24	360
24-36	300
36-100	75
>100	10

This heat of hydration is typical for moderately sized (less than 10 feet) bridge members in Minnesota. These mixes are typically proportioned using large quantities of pozzolanic materials such as fly ash and slag. Figure C.5 presents the temperature versus time for the condition where the inverted T structure shown in Figure C.1 uses a low heat of hydration concrete.

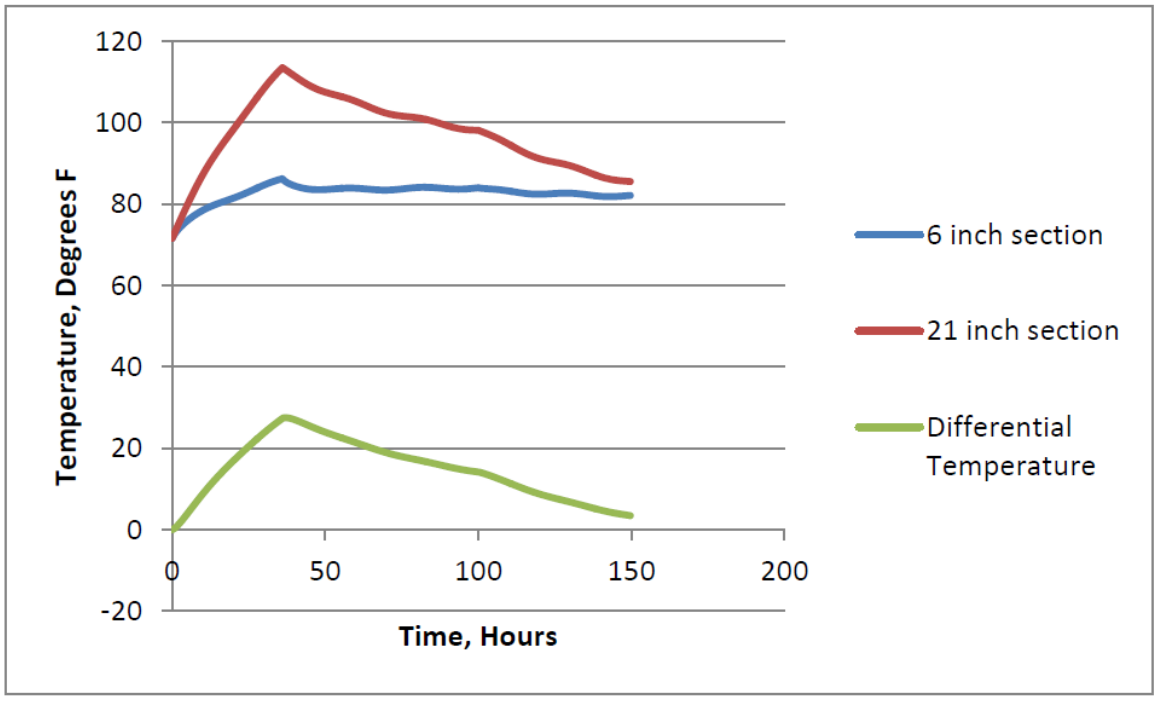


Figure C.5: Temperature and Temperature Difference at a Depth of 3 Inches as Constructed

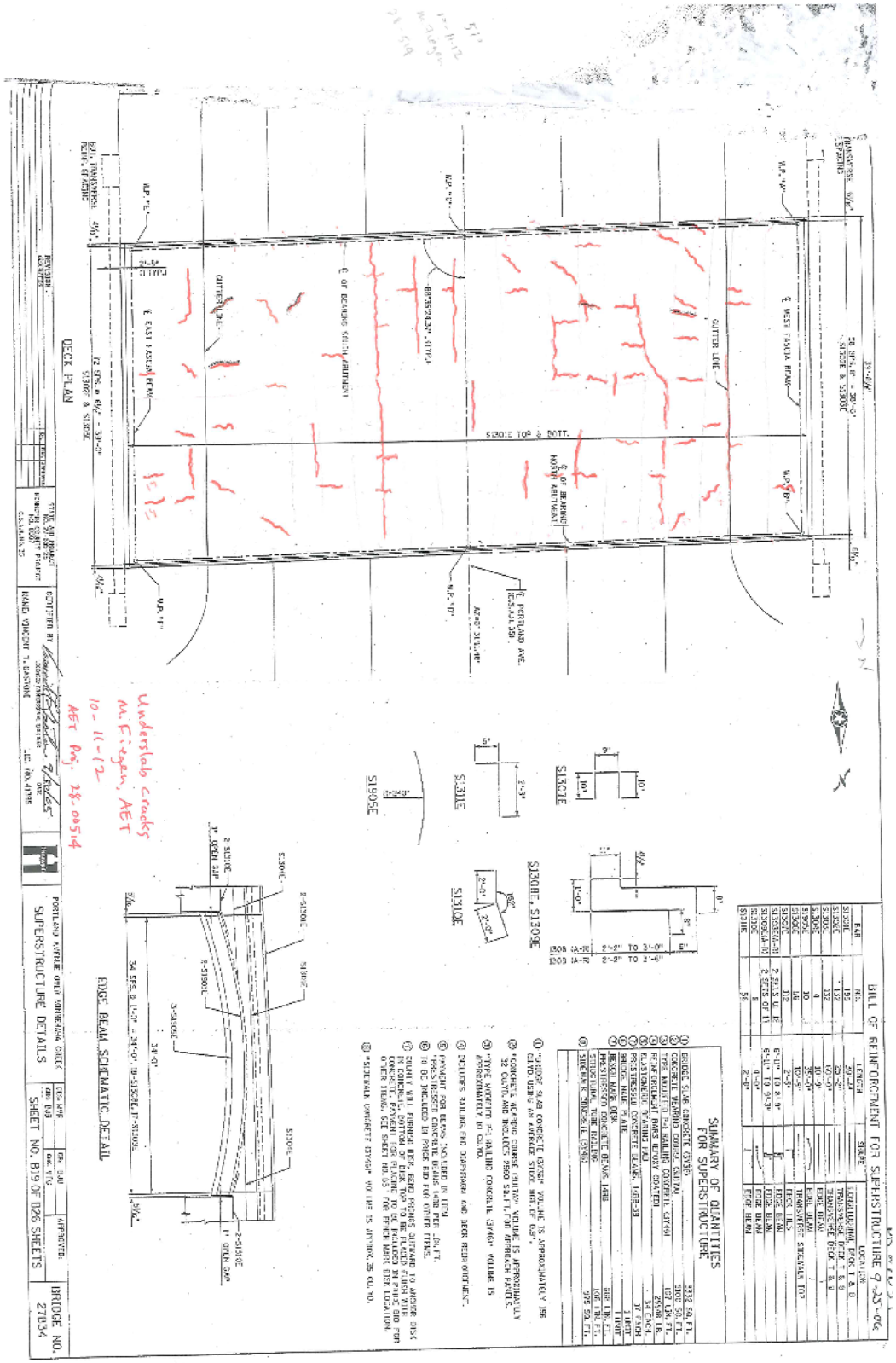
The required level of expansion would need to be set for each individual structure. Testing would need to be performed to ensure that the concrete in situ does expand. Guidance to the use of shrinkage compensating concrete and respect is given in the American Concrete Institute's Committee 223 report on Shrinkage Compensating Concrete.

Conclusions

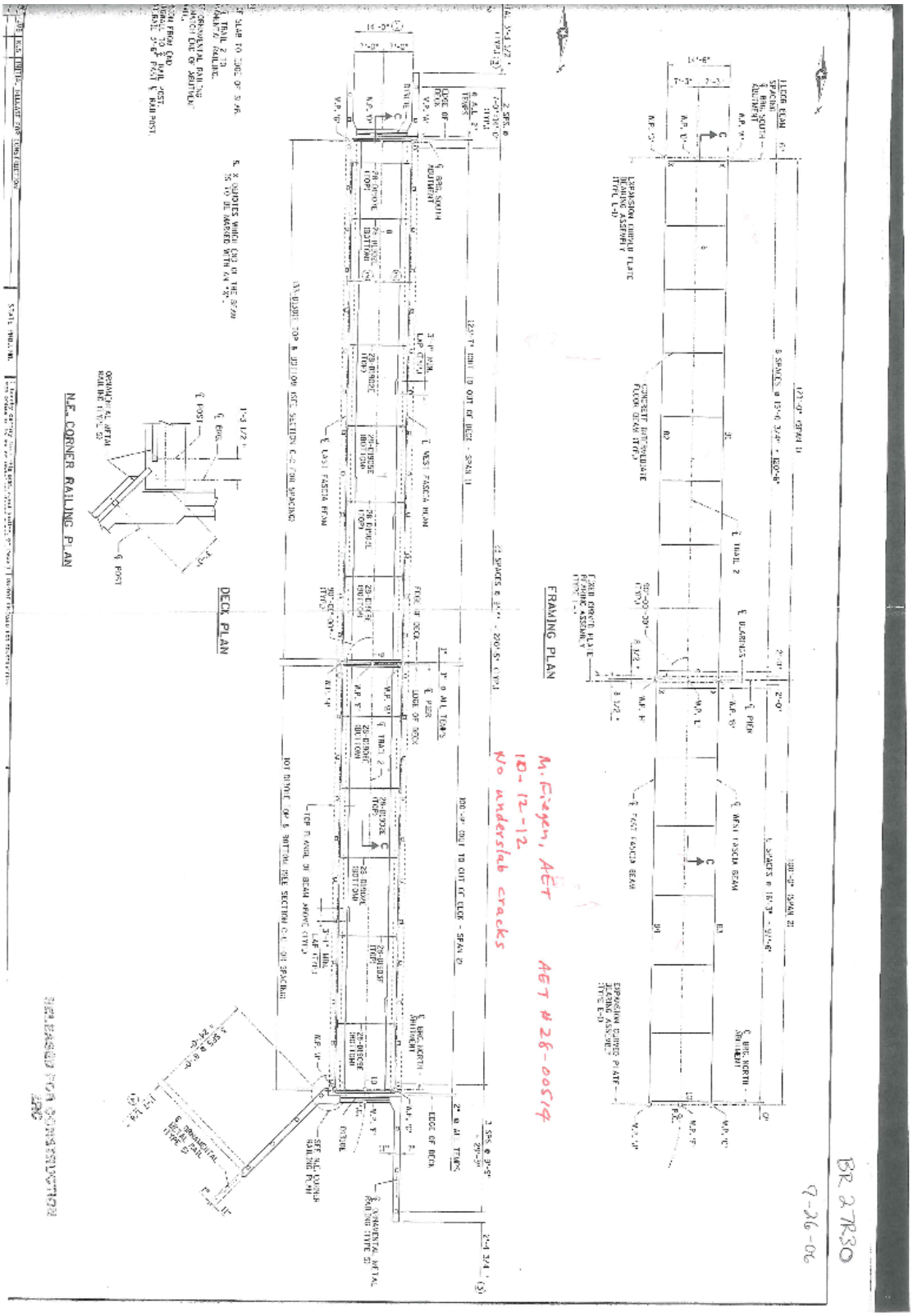
Based on the analyses performed it is our opinion that the use of a low heat of hydration concrete would reduce, but not eliminate, the presence of transverse cracking at the T stems. One alternative to eliminate this cracking would be the use of shrinkage compensating concrete, which will act to "chemically prestress" the mild reinforcement and the inverted T. This approach would require extensive laboratory testing prior to field implementation.

Appendix D: Bridge Deck Cracking Map

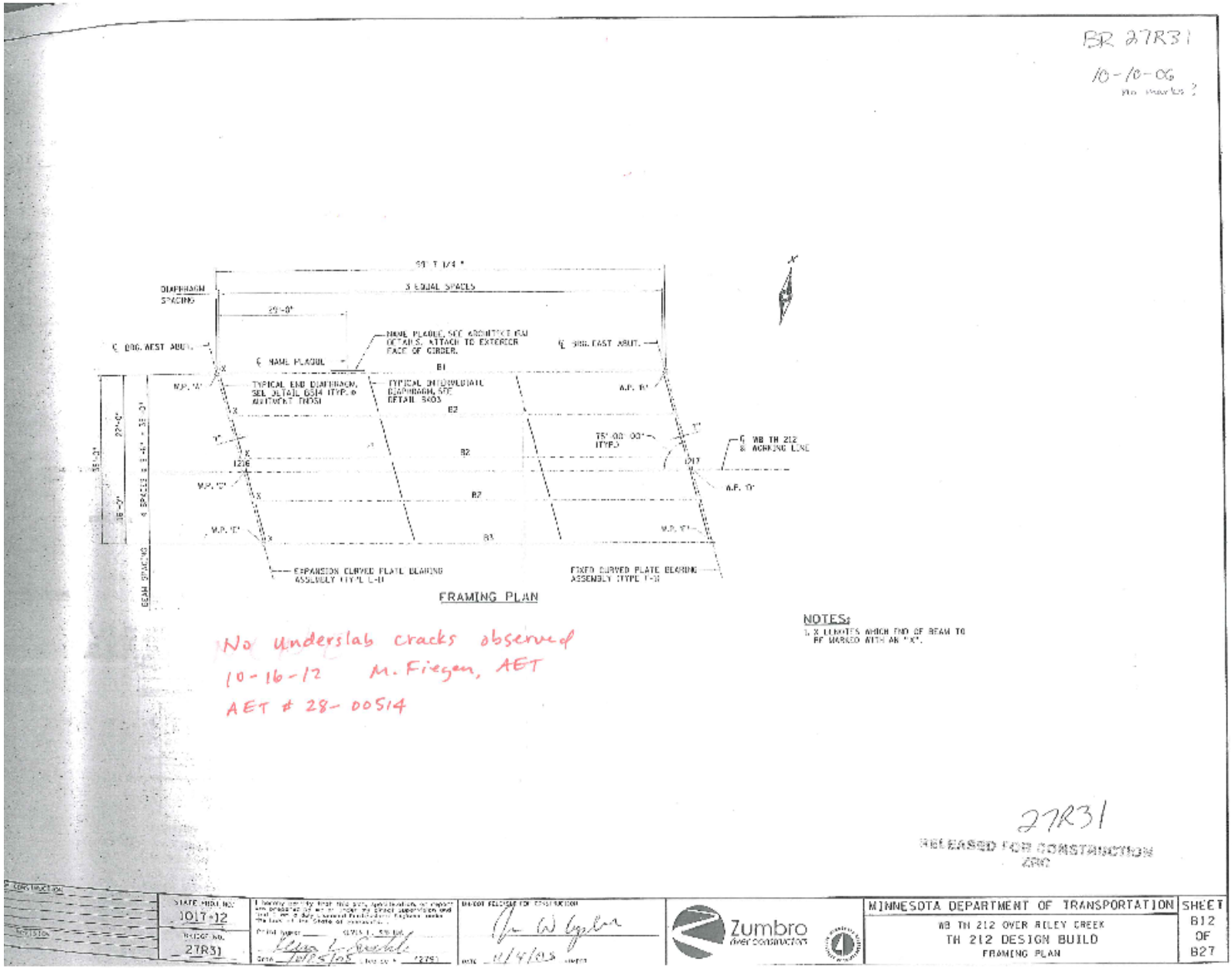
Bridge 27B34



Bridge 27R30

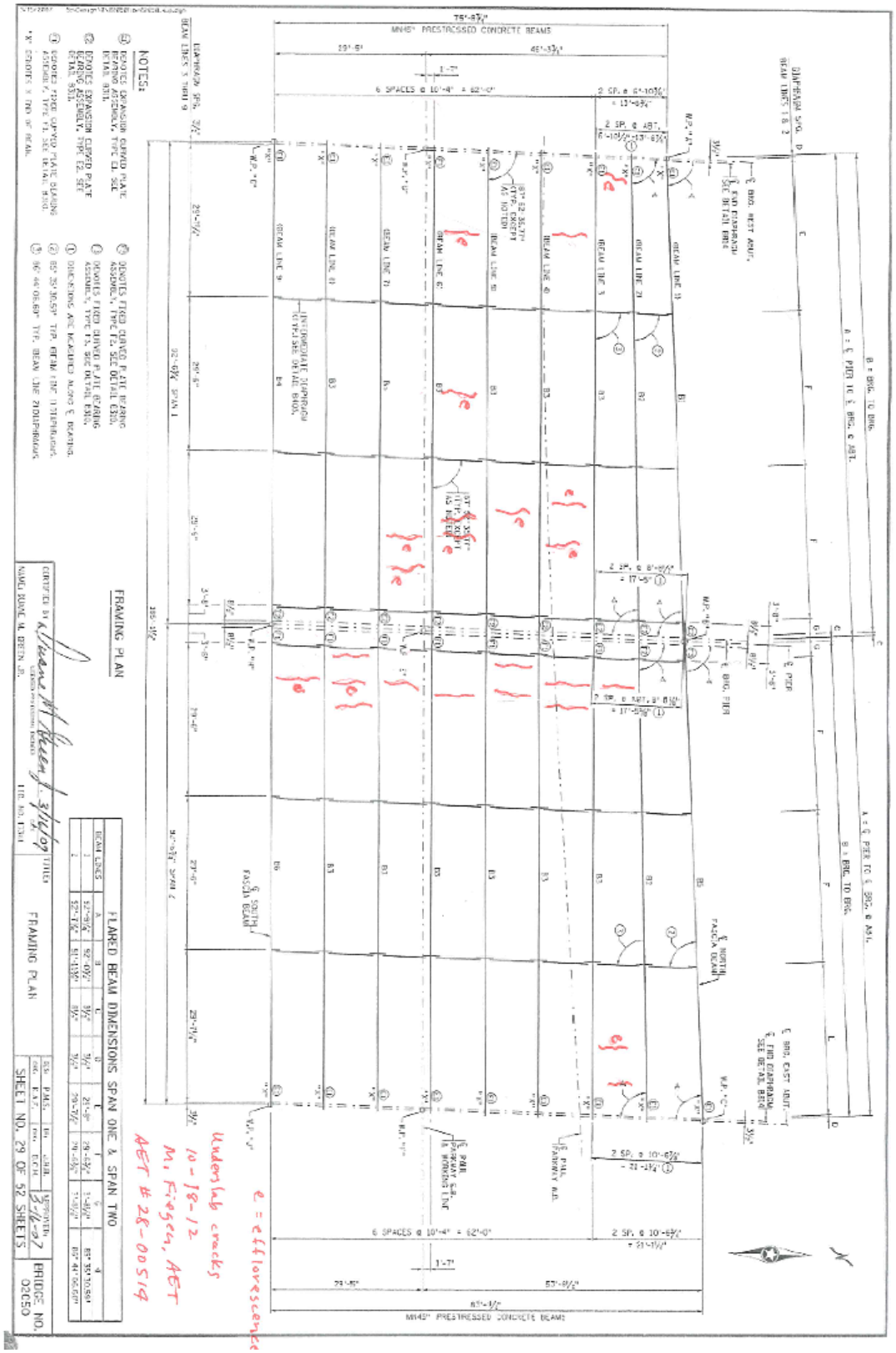


Bridge 27R31

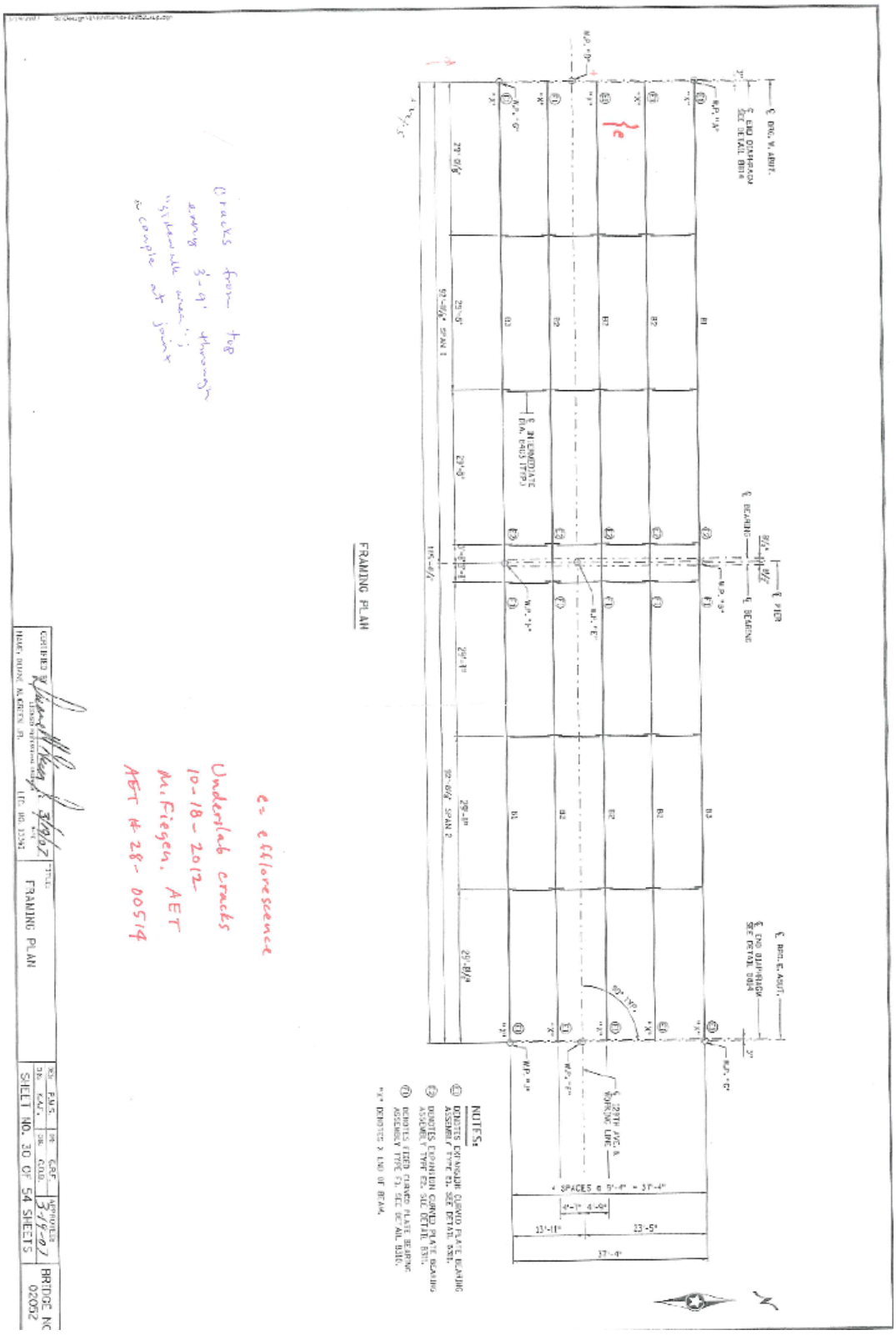


Bridge 27R32

Bridge 02050



Bridge 02052



cracks from top
bearing 3'-9" thickness
reinforcement not
a complete set joint

c = efflorescence

Underslab cracks
10-18-2017
Mr. Fiegen, AET
AET # 28-00514

DESIGNED BY	DETAILED BY	CHECKED BY	QUANTITIES BY	APPROVED	
HDR, INC.	HDR, INC.	HDR, INC.	HDR, INC.		
3/30/07					
DATE					

TITLE: FRAMING PLAN

DES. EAF.	DET. EAF.	CHK. EAF.	QUAN. EAF.	APPROVED 3/30/07

SHEET NO. 30 OF 54 SHEETS

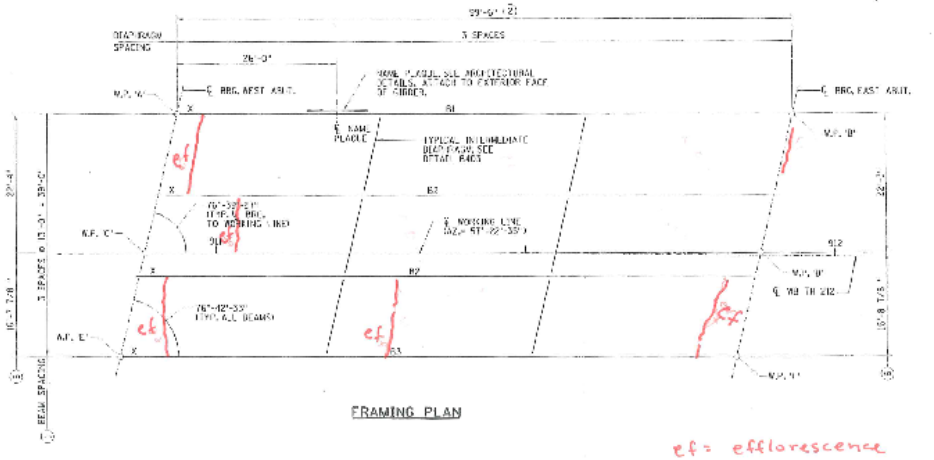
BRIDGE NO. 02052

Bridge 10024

Bridge 10039

Bridge 10041

BR 10053
2-14-0.



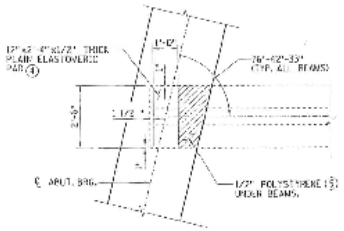
FRAMING PLAN

ef = efflorescence

Underlab cracks
10-16-12
M. Fiegen, AET
AET # 28-00514

NOTES:

1. DIMENSIONS PERPENDICULAR TO ℄ OF BEAMS.
2. DIMENSION PARALLEL TO BEAMS.
3. X DENOTES WHICH END OF THE BEAM TO BE MARKED WITH AN "X".
4. ELASTOMERIC MATERIAL & PAD CONSTRUCTION SHALL COMPLY WITH SPEC. 3141.
5. POLYSTYRENE MATERIAL SHALL COMPLY WITH SPEC. 3760.
6. DIMENSIONS PERPENDICULAR TO WORKING LINE.

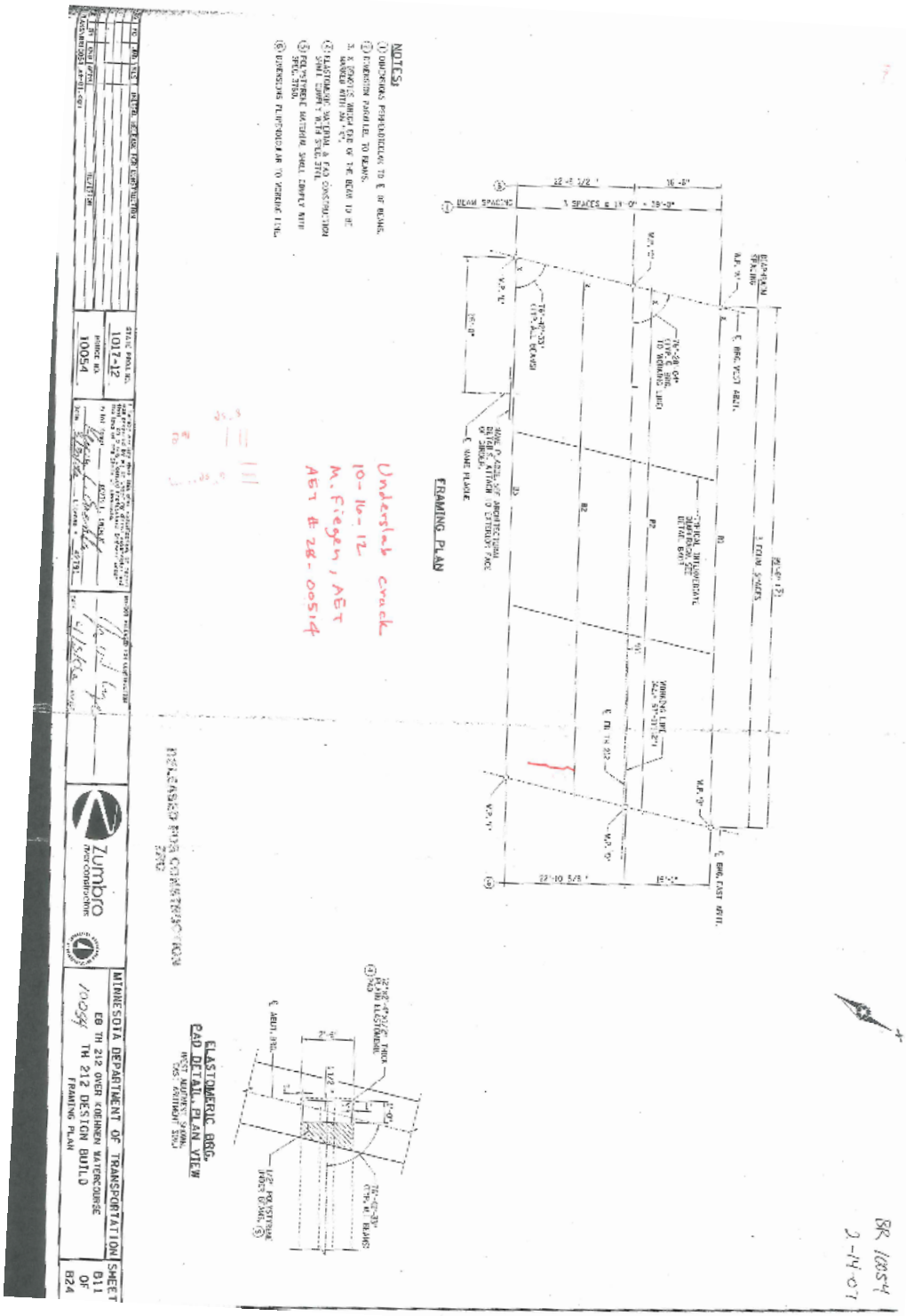


ELASTOMERIC BRG. PAD DETAIL, PLAN VIEW
(WEST ABUTMENT SHOWN, EAST ABUTMENT SIMILAR)

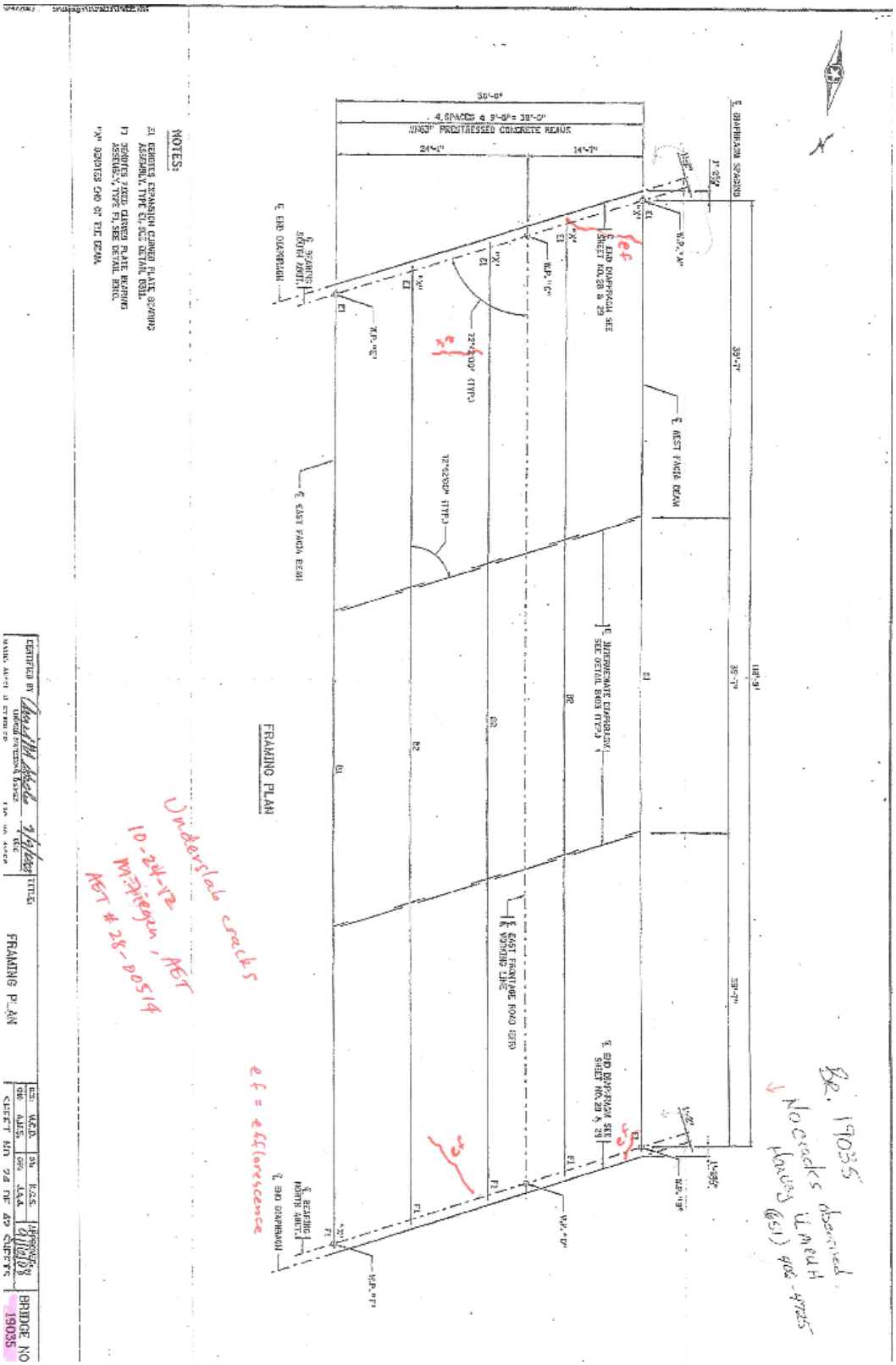
RELEASED FOR CONSTRUCTION
ZM

DESIGN	PO	INIT.	D.S.	INITIAL RELEASE FOR CONSTRUCTION	STATE PROJ. NO. 1017-12		Zumbro river constructors	MINNESOTA DEPARTMENT OF TRANSPORTATION	SHEET B12
DATE	SY	DDR	ZMB	REVISION	BRIDGE NO. 10053			MB TH 212 OVER KOEHNEN WATERCOURSE 10053 TH 212 DESIGN BUILD FRAMING PLAN	OF B25
ALL_PLANS\BR10053_sht01.dgn									

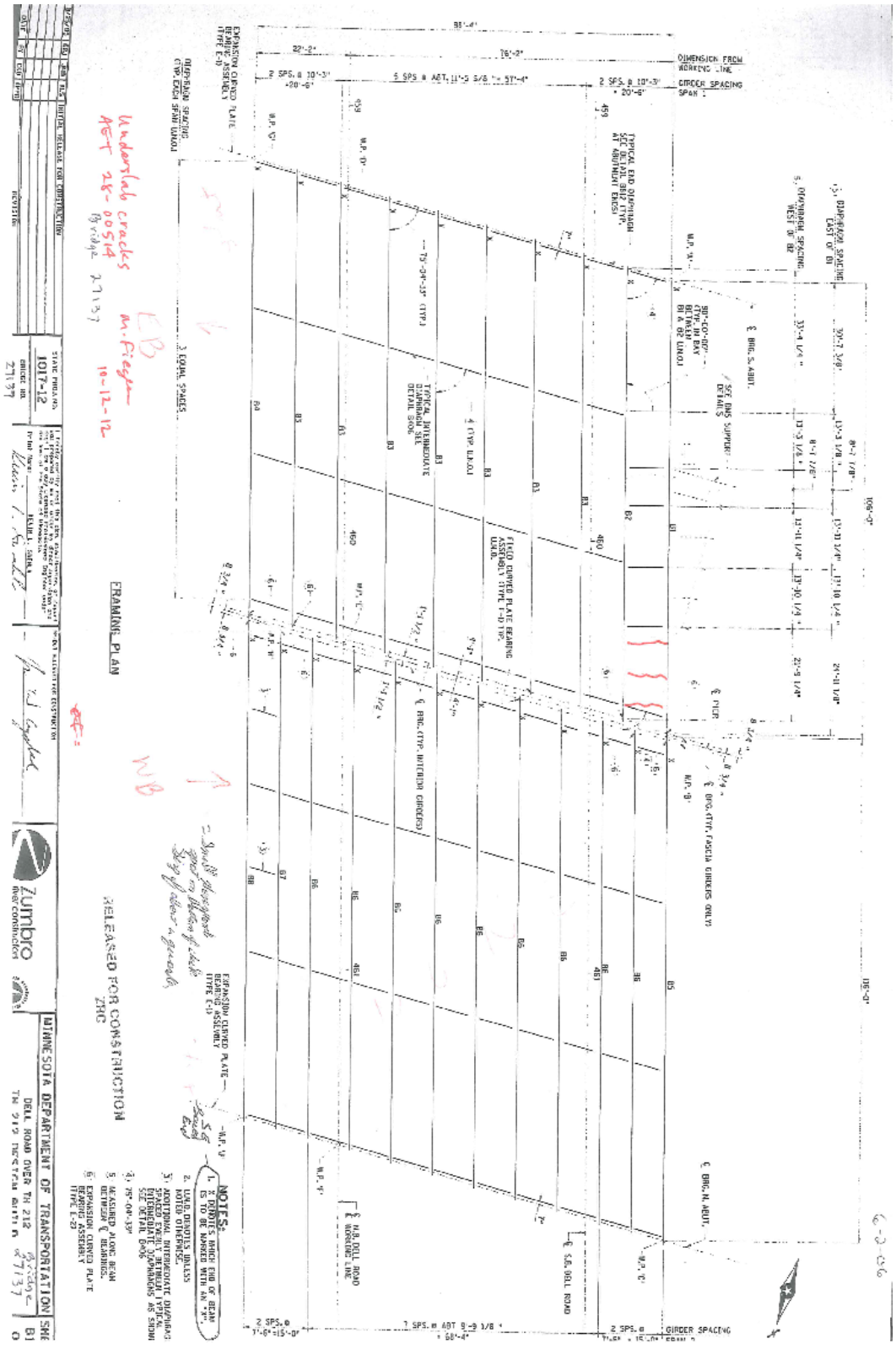
Bridge 10054



Bridge 19035



Bridge 27137



Bridge 33002

Bridge 48030

Westwood

Solutions for your Success

JOB Milaca Bridge #48030 SHEET NO. 2 of 2

MADE BY STL DATE 11/04/2009 JOB NO. 4801-20

CHECKED BY _____ DATE _____ SEC. SHT. NO. _____

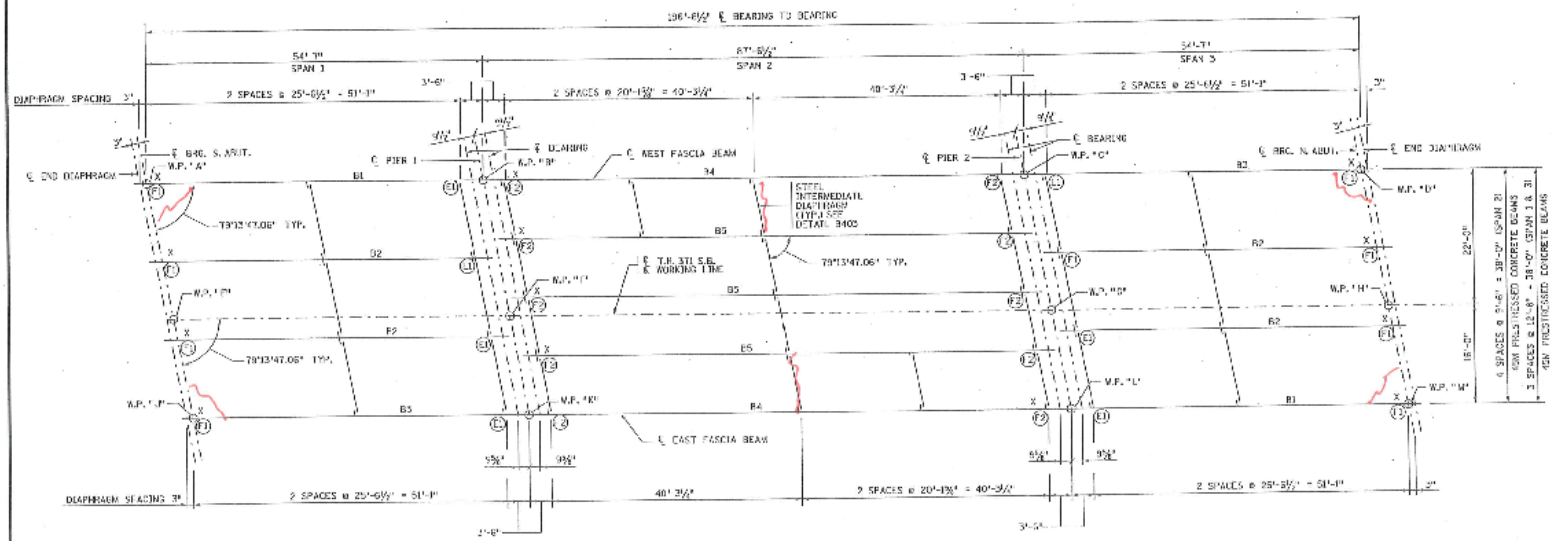
CALCULATIONS FOR CRACK SURVEY, DECK

M Fiegen
10-18-12

e = efflorescence

Underslab cracks
10-18-12
M. Fiegen, AET
AET # 28-00514

Bridge 49037



bridge 49037

FRAMING PLAN

Underslab cracks
10-18-12 M. Fiegen, AET
AET # 28-00514

NOTES:

(F1) DENOTES ELASTOMERIC BEARING PAD, TYPE F1, SEE DETAIL B305
(F2) DENOTES PTFE CURVED PLATE BEARING ASSEMBLY TYPE F1, SEE DETAIL B310.
(E1) DENOTES EXPANSION CURVED PLATE BEARING ASSEMBLY TYPE E1, SEE DETAIL B311.
X DENOTES "X" END OF BEAM.

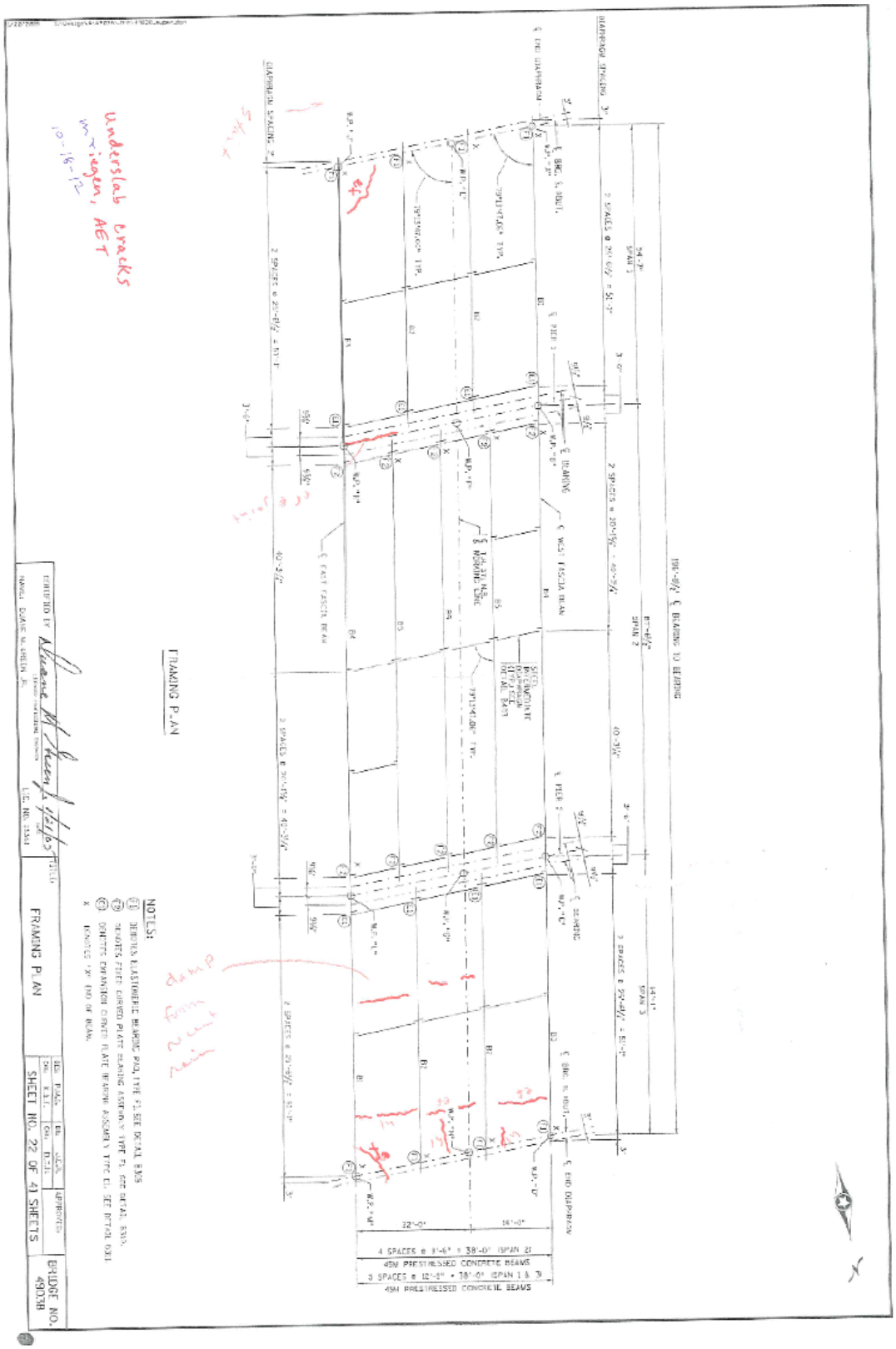
CERTIFIED BY: Duane M. Swenson 12/15/05 TITLE: FRAMING PLAN

DES. P.W.S.	DR. J.C.R.	APPROVED:
CHK. K.A.F.	CHK. D.C.H.	

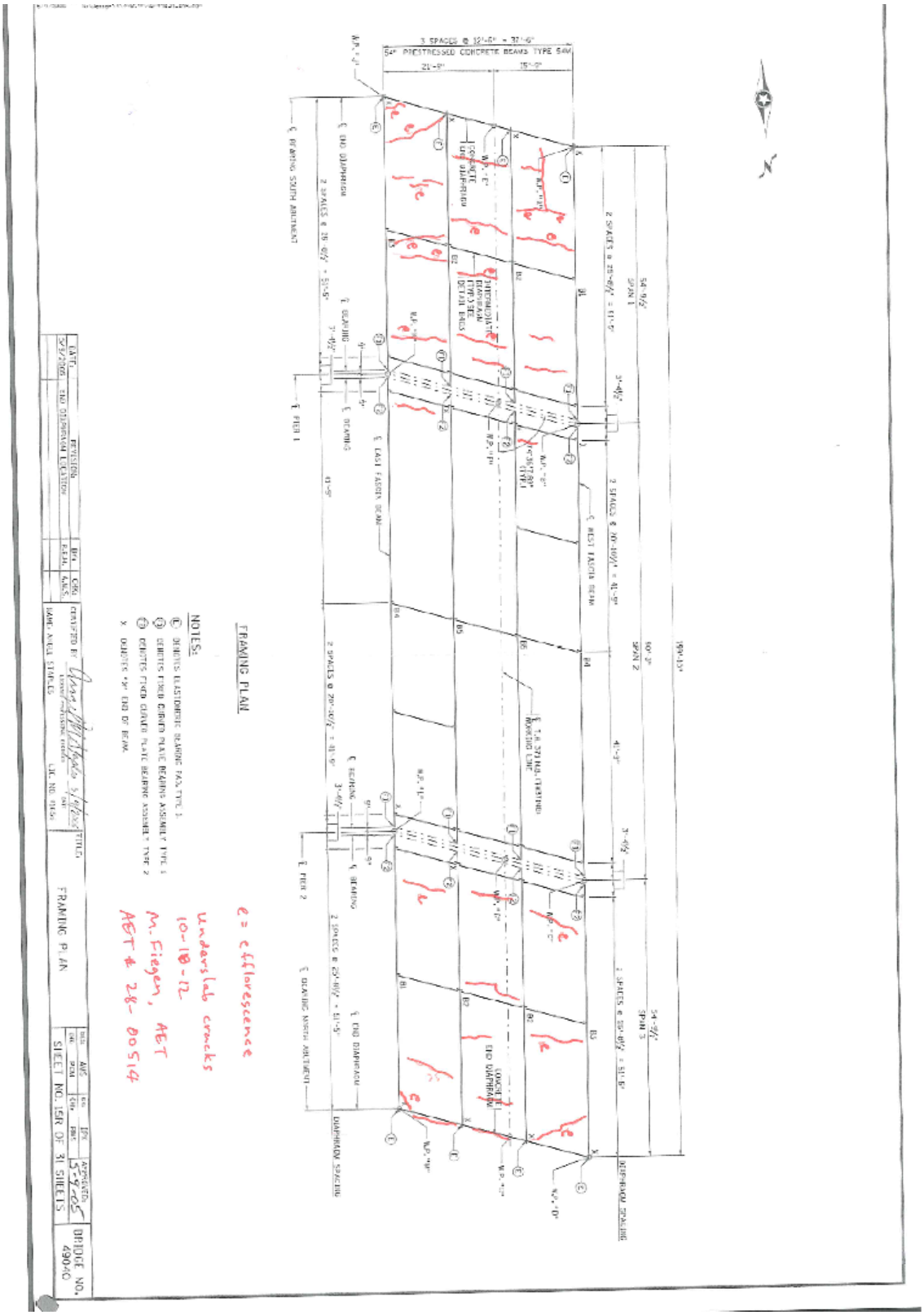
BRIDGE NO. 49037

BRIDGE 49037 (2005)

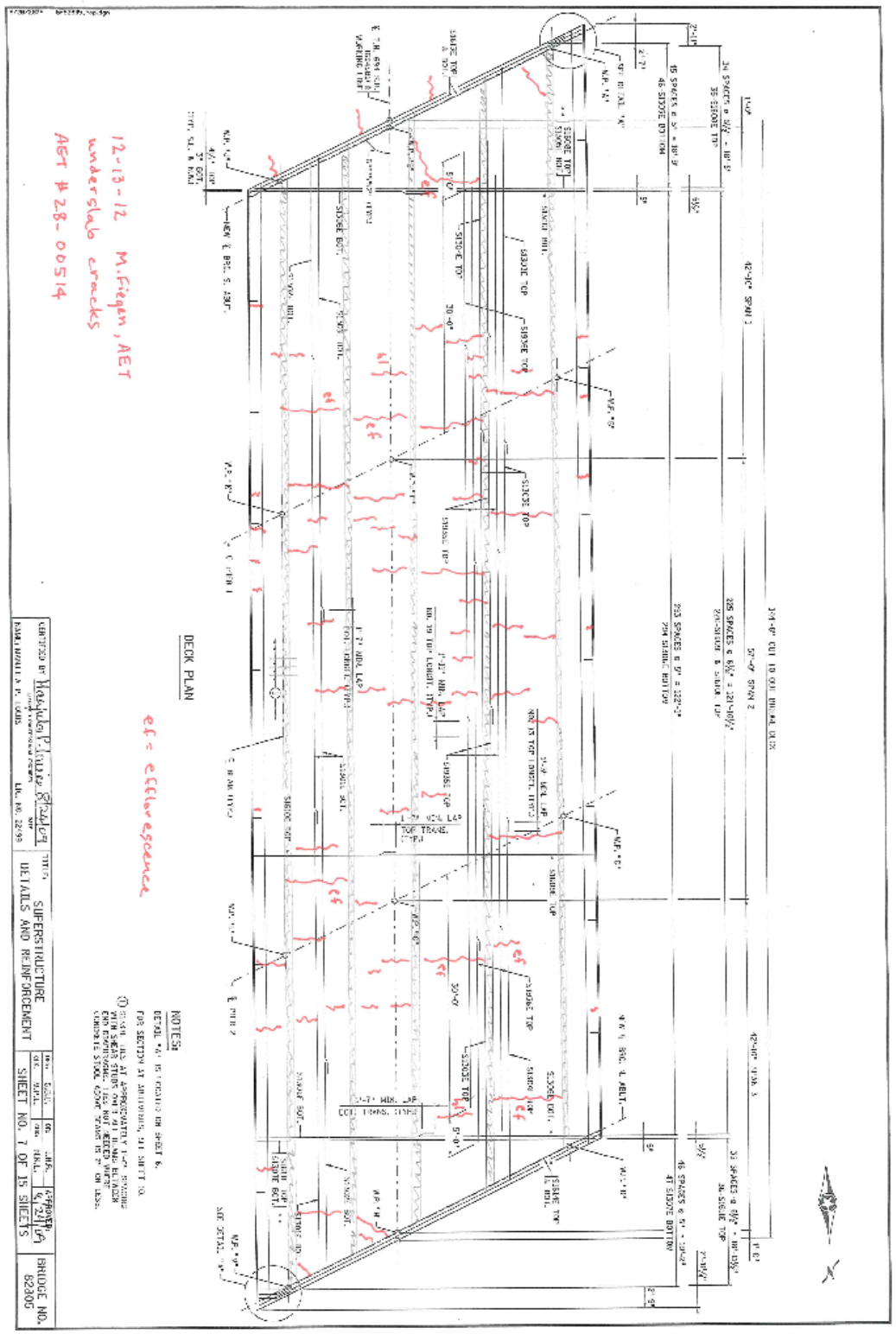
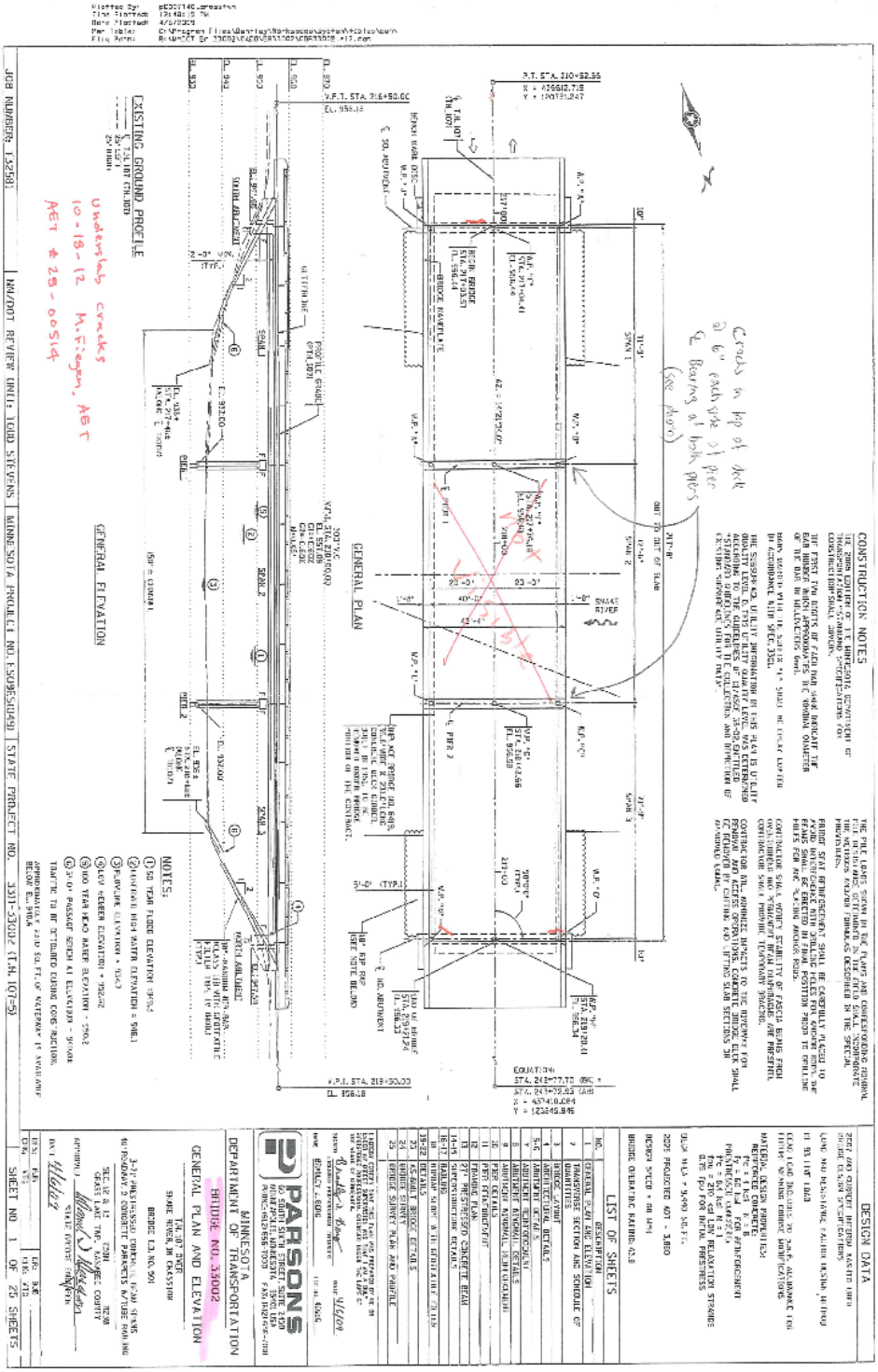
Bridge 49038



Bridge 49040



Bridge 82085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