REVIEW OF SKEW EFFECTS ON PRESTRESSED CONCRETE GIRDER BRIDGES: PROBLEMS AND CURRENT PRACTICES

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ABSTRACT

Atypical load paths in skewed bridges result in stresses larger than the ones experienced by equivalent bridges with no skew. These additional stresses are addressed by the current design codes but only at the strength level, leading to deck cracking, substructure distressing and bearing deterioration under service loads. Given the significant number of skewed bridges particularly in regions with adverse climates, such serviceability problems are of primary importance and require immediate consideration.

This paper provides a review of load path changes and performance problems related to high skew. AASHTO LRFD Bridge Design Specifications (BDS) and State Department of Transportation (DOT) practices related to analysis, design and construction of deck-girder type bridges with large skew are documented. Differences between the AASHTO LRFD BDS and DOT's were highlighted. In addition, results of the inspection of two similar prestressed concrete girder-deck type bridges with high and low skew angles were presented and compared. The paper presents the state of the art of the understanding of bridge skew related problems, and national and state level design and construction practices.

The results show that although state practices are similar, skew angles over which performance is of concern may be different between states, and between states and AASHTO. Bridge inspections demonstrated that not all bridges with skew have performance problems to the same degree, emphasizing the importance of bridge details.

Keywords: Deck Cracking, Temperature, Service Performance, AASHTO Provisions, Assessment and Monitoring, Research.

INTRODUCTION

Bridge engineering community has been aware of the detrimental effects of high skew angles on bridge performance since the early 1900's as documented by Waddell[1] in his book "Bridge Engineering" in 1916. The thirteenth item in Waddell's list of "First Principles of Designing" states that "The building of a skew-bridge should always be avoided when it is practicable". Waddell supports this statement by arguing that skewed bridges have complexities in design and construction, and that the resulting structural behavior is never as good as the one of a straight counterpart. Research and field observations over the years have proven Waddell right.

Problems associated with skew are in fact many. Skew modifies load paths for gravity and temperature loads. Approximate structural analysis procedures developed for simplified live load analyses (1-D or beam-line analyses) may not accurately predict the behavior of high skew bridges. Modified load paths cause non-uniform superstructure deformations and creates additional reactions when these deformations are restrained. Performance problems include distress in substructures, cracking in deck and large movements at bearings.

The goal of this paper is to present analysis and performance issues associated with high skew bridges and their representation in bridge guidelines. This paper has three main sections. It first describes complexities in analysis and issues in performance caused by skew through a detailed literature review. Reasons behind these skew effects were speculated, with an emphasis on superstructure response. When visible, performance issues were also documented by utilizing bridge inspection reports. Secondly, the efforts of bridge design guidelines in mitigating negative effects of skew have been summarized based on AASHTO LRFD Bridge Design Specifications (BDS)[2] and design manuals of several state DOT's. State DOT guidelines were compared to AASHTO LRFD BDS. Finally, inspection results of two similar prestressed concrete girder bridges; one with a high skew and one with no skew, were compared to identify performance issues unique to bridges with skew and to understand bridge characteristics that may help mitigate skew effects.

SKEW EFFECTS ON BRIDGES

High skew angles affects load distribution, performance and constructability through the following ways: 1) by altering internal reaction forces in beams, bearings and bridge ends, 2) by causing horizontal movement of superstructure, resulting in bearing misalignment, 3) by causing deck cracking, 4) by creating constructability issues for steel girders. These factors reduce the accuracy of simple analytical models or cause performance, maintenance or constructability issues. Each of these skew effects is described in this section, together with potential causes. Effects that are visible were also documented through visuals obtained from bridge inspections.

IMPACT ON LOAD PATHS AND ANALYSIS

Beam Internal Forces

In bridges with no skew, load paths follow the longitudinal bridge direction toward the supports as shown in Fig. 1a. In skewed bridges, this load path runs through the area connecting the obtuse corners as forces follow the shortest path to supports as shown in Fig. 1b. Although, this is more pronounced in concrete slab bridges than in deck-beam bridges where beams also serve as load paths toward the supports[3-5], the effects are considerable after 30° of skew[6-9] in deck-beam bridges.

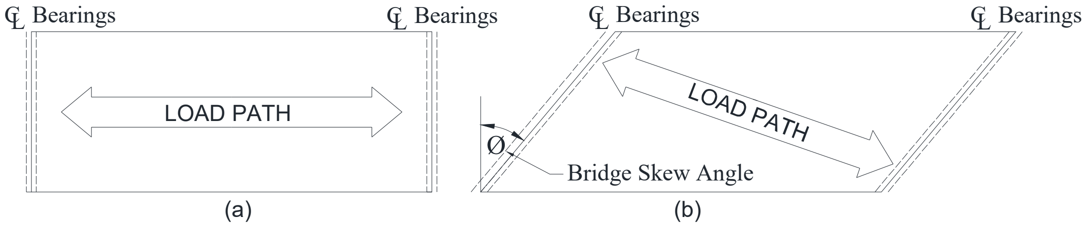

Fig. 1 Load paths in (a) non-skewed and (b) skewed bridges.

Increasing values of bridge skew angle reduces moment in beams along the span and at supports. Shear forces at simply supported[10] and continuous[11] beam ends can increase significantly at obtuse corners with high skew. Shear at simply supported beam ends decrease at acute corners and at interior beams compared to counterparts with smaller skew angles[10]. Analytical studies[12] proposed varying shear forces along the length of beams, as well as varying beam end shears along support lines. A linear decrease of shear from ends to mid-span and from obtuse corner to acute corner was recommended.

Reactions at Bearings

At the abutments of skewed bridges, bearing reactions measured at the obtuse corners were found to be greater than those at the acute corners or at interior bearings[10]. Reactions at pier supports were found to be highly dependent on the ratio of lengths of different spans in a bridge. Support reactions were similar at bearings over a pier for bridges with two equal spans, regardless of the skew angle. For skewed bridges with two unequal continuous spans, increasing skew angles led to greater reactions at exterior beams and smaller reactions at interior beams[11]. Highly skewed bridges with simply supported ends may experience uplift at the acute corners due to decreasing reaction forces.

Negative Moment and Torsion at Bridge Ends

Torsion and negative moments at bridge ends can be induced by high skew angles, even for bridges where bearings are detailed as roller supports[13]. Consistent with the gravity load paths on skewed bridges, bridge ends rotate around an axis parallel to bridge supports as shown in Fig. 2. Unexpected negative moments on top of deck at bridge ends and torsion on beams can be formed.

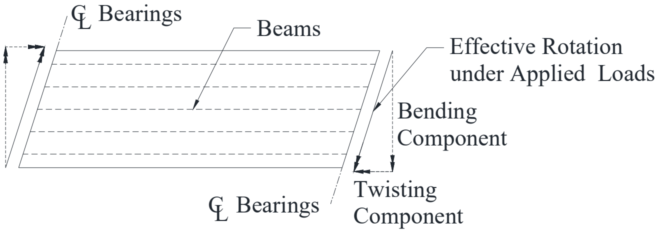

Fig. 2 Effective rotation of beam ends.

IMPACT ON BRIDGE DISPLACEMENTS

Displacements due to skew likely have two main sources[14,15]: 1) thermal expansion and 2) interaction of thermal expansion with certain types of abutments. Skewed bridges expand non-uniformly across their cross section under thermal loads as shown in Fig. 3a, where the largest deformation is along the longest distance, along a line connecting the acute corners. Superstructure and substructure members can be distressed due to thermal expansion, when substructure components provide restraint against expansion.

Thermal expansion between the acute corners causes lateral and longitudinal movements at bridge ends. When skewed bridges have integral or semi-integral abutments, these movements are restrained and additional backfill pressure develops at abutments. Due to skew angle, the resultants of these forces are not collinear and may rotate the bridge further towards the acute corners or counter clockwise direction in Fig. 3b.

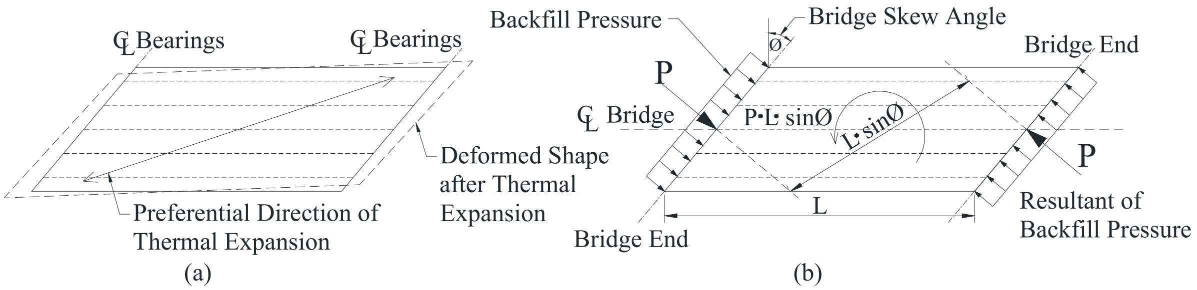

Fig. 3 (a) Thermal expansion, and (b) backfill reactions due to thermal expansion[15].

Horizontal movements are documented in Fig. 4 - Fig. 6. These figures are taken from an inspection of a three-span continuous prestressed concrete deck-girder bridge with a skew angle of 30°, sill abutments with semi-expansion seats and elastomeric bearing pads. Even though bridge skew angle is moderate, displacements of the superstructure is significant. Bridge rotation is documented by cracks in abutments at beam seats in Fig. 4a since the full depth concrete end diaphragm does not allow superstructure to freely rotate. Bridge rotation is also seen through vertical joint opening between adjacent bridges in Fig. 4b, and misalignment of parapet wall over the abutment in Fig. 5. This kind of rotation towards the acute corners could have been caused by thermal expansion.

(a) (b)

Fig. 4 (a) Cracks at beams seats at the acute corner, and (b) open joint between adjacent bridges at the obtuse corner (Source: John Bolka, Wisconsin Department of Transportation (WisDOT)).

(a) (b)

Fig. 5 Misalignment of wingwall and bridge parapet wall at (a) acute, and (b) obtuse corners (Source: John Bolka, WisDOT).

Similarly, Fig. 6 was taken from the inspection of a four-span continuous prestressed concrete deck-girder bridge with a skew angle of 51°, semi-retaining abutments and steel laminated elastomeric bearings. It shows one of the several bearings in the obtuse corner that rotated toward the acute corner, possibly due to thermal expansion and torsion at the obtuse corner.

Fig. 6 Bearing rotation at the obtuse corner (Source: John Bolka, WisDOT).

IMPACT ON DECK PERFORMANCE

Concrete deck diagonal cracks at acute corners are often associated with skewed bridges. They are observed on top and bottom faces of the deck and are oriented orthogonal to the end support lines. Fu et al.[4] concluded that they are mainly caused by thermal loading and shrinkage during concrete hydration, and the restraint at bridge ends on deck by beams and end diaphragms. They also mentioned that moving loads could widen these cracks. Another probable cause is lack of room in acute bridge corners available to place a sufficient amount of reinforcement and develop reinforcing bars. Fig. 7 shows the top and bottom of the deck of the bridges documented in Fig. 6 and Fig. 4 - Fig. 5, respectively.

(a) (b)

Fig. 7 Diagonal cracks on the (a) top and (b) bottom faces of the concrete deck at the acute corners (Source: John Bolka, WisDOT).

CONSTRUCTABILITY OF STEEL GIRDER BRIDGES

Bridge skew angle was also found to affect construction of steel deck-girder bridges[16]. Under non-composite loads, beams are subjected to differential deflections. In the presence of intermediate cross-frames, which are usually perpendicular to beam centerlines and have high in-plane stiffness, differential deflections lead to torsion and flange lateral bending on beams. The use of skewed intermediate cross-frames does not eliminate induced torsion, in spite of connecting points of similar deflection.

Torsion in beams has also been reported at piers and abutments, caused due to end cross-frames resistance to get distorted after the application of non-composite loads. This may result in beams being out-of-plumb during deck pour and compromise strength. In addition, bearings may carry additional lateral forces. Prestressed concrete girders have higher lateral stiffness and require fewer cross-bracings than steel girders. Therefore, they are less susceptible to reaction forces described here.

MITIGATING MEASURES FOR SKEW EFFECTS

The AASHTO LRFD BDS[2] and current bridge design manuals of several State Departments of Transportation (DOT) were reviewed to see if the effects of bridge skewness were acknowledged and included in the design of girder-deck type bridges. The state DOT's whose bridge design practices were reviewed included Wisconsin[17], New York[18], Connecticut[19], Minnesota[20], Ohio[21] , Michigan[22], Vermont[23], Massachusetts[24], New Jersey[25], Indiana[26], New Hampshire[27], Maine[28], Illinois[29], Pennsylvania[30], Rhode Island[31], Texas[32], and Washington[33]. Most of the states were selected to be in the Northeastern region of the US, as these regions have harsh environmental conditions causing faster bridge deterioration. Differences between AASHTO LRFD BDS and DOT practices are reported. For brevity, the review provided here is limited to design practices of prestressed girders and concrete decks. Review of provisions related to bearings, expansion joints and substructures will be published elsewhere.

SKEW RELATED PROVISIONS OF AASHTO LRFD BDS

Provisions Related To Beams

AASHTO LRFD BDS provides live load distribution factors for typical girder-deck type bridges to simplify analysis for typical bridges to 1-D girder-line analyses, largely based on NCHRP 12-26[9] and NCHRP 12-62[34] projects. To account for the altered load paths due to skew, Section 4.6.2.2 provides correction factors to live load distribution factors. AASHTO LRFD BDS C4.6.2.2.3c indicates that large skews produce significant torsional effects that invalidate the use of load distribution factors, i.e. the bridge can no longer be considered "regular".

Section 4.6.2.2.2e allows reduction of girder bending moments due to skew. Correction factors for bending moments may be applied to all beams and throughout the beam length. Skew angles below 30º are treated negligible, except for bridges with box beams. Moments are not reduced further for skew angles above 60º.

Section 4.6.2.2.3c requires an increase in shear forces due to skew. Correction factors for shear are applied to exterior beams at the obtuse corner and the first interior beams only when beams can be assumed to behave as a unit. Otherwise, shear correction factors apply to all interior beams and exterior beams at the obtuse corners. Between the obtuse corner support and mid-span, correction factors can be decreased linearly with a value of 1.0 at mid-span. Requirement that considers the variation of shear along exterior girder span seems to be developed by NCHRP 20-7/Task 107[12]. NCHRP 20-7/Task 107 also recommended a linear decrease of shear correction factor from the obtuse corner to 1.0 at the acute corner, however, this was not included in AASHTO LRFD BDS. Negative values of correction factors can be used to calculate uplift of exterior beams at acute corners due to skew. Correction factors for skew greater than 60º are not available or provided in AASHTO LRFD BDS.

Provisions Related To Concrete Decks

AASHTO LRFD BDS Commentary C4.6.2.1.1 and C4.6.3.2.1 recognize that skewed supports are responsible for a number of detrimental effects such as negative moments at corners, large torsion in the end zones due to differential deflection and significant redistribution of reaction forces. Although consideration of these in design is recommended, no explicit design guidance is provided in this section.

AASHTO LRFD BDS section 9.7.2.5 presents a crack control provision dealing with end zone torsional cracks caused by differential deflections, observed in bridges with skew angles larger than 25º. For skew angles beyond this value, the provision requires the deck reinforcement, as determined by the empirical design method, to be doubled for end zones and in both directions. End zones extend a distance equal to the effective length of the deck per AASHTO LRFD BDS 9.7.2.3.

AASHTO LRFD BDS section 9.7.1.3 states that primary reinforcement of the deck could be placed in the direction of skew for skew angles smaller than 25º. This provision seems to solely facilitate bridge deck construction, as inferred from the commentary to this section, and not to mitigate skew effects.

DIFFERENCES BETWEEN AASHTO LRFD BDS AND STATE DOT PRACTICES

Practices Related To Beams

Review of state practices on beam analysis revealed a general agreement between DOT's and AASHTO LRFD BDS. Table 1 summarizes the differences between DOT practices and AASHTO LRFD BDS. The table also provides additional specifications, if any, given by

DOT's for the analysis of beams for bridges with large skew. Main deviations of DOT's from AASHTO LRFD BDS are highlighted below:

- Even though the reduction in bending moments caused by skew is acknowledged, some DOT's do not reduce moments to be conservative.
- Several DOT's apply correction factors for shear to all beams and across the entire span. Others allow the application of correction factors to shears at the support and reactions at the obtuse corner of only the exterior beams.
- Additional specifications (i.e., not included in AASHTO) consist of limitations of certain types of beams, such as prestressed concrete bulb-tee or I beams, for varying skew angle limits.

Table 1 Deviations of DOT practices from AASHTO LRFD BDS on beams.

State	**Different from AASHTO LRFD BDS**		**Additional Specifications**
	4.6.2.2.2e	**4.6.2.2.3c**	
WI[17]	**17.2.8:** Moment reduction not allowed.	**17.2.8:** Shear correction for all beams, and entire span.	No
NY[18]	No	No	No
CT[19]	No	No	No
MN[20]	No	**4.2.2.1:** Shear correction for all beams, and entire span.	No
OH[21]	No	No	No
MI[22]	No	No	No
VT[23]	No	No	No
MA[24]	No	No	**2.3.5.4:** Northeast bulb-tees and similar beams avoided for skew > 45º.
NJ[25]	No	No	No
IN[26]	No	**406-12.10(01):** For shear at obtuse corner of exterior beams. Below 30º, shear correction disregarded.	No
NH[27]	No	No	No
ME[28]	No	No	No
IL[29]	**3.3.1:** Moment reduction not allowed.	**3.3.1:** Shear correction applied to all beams at non-continuous ends. Optional simplified correction factors proposed.	No
PA[30]	**Structures C4.6.2.2.2e:** Moment reduction not allowed.	**Structures 4.6.2.2.3c:** Shear correction for end shear of exterior beams at the obtuse corner.	**Structures 5.14.1.1:** Prestressed concrete PA bulb-tee and I-beams with a skew limit of 60º.
RI[31]	No	No	No
TX[32]	No	No	No
WA[33]	No	No	**5.6.2:** Prestressed concrete beams not allowed for skew > 45º.

Practices Related To Concrete Deck

State DOT’s also acknowledge the effect of skew angle on bridge decks, in general similar to AASHTO LRFD BDS. Error: Reference source not found presents the differences between DOT practices and AASHTO LRFD BDS for concrete bridge decks and present guidance given by DOT’s in addition to AASHTO LRFD BDS, if any. Main deviations of DOT practices from AASHTO LRFD BDS are as below:

- In relation to the provision on end zone torsional crack control, differences mainly are on the skew angle, beyond which additional reinforcement is required, and the amount, configuration and extension of this reinforcement.
- The skew angle below which primary reinforcement could be placed in the direction of the skew differs from AASHTO LRFD BDS for several DOT’s.
- Guidance provided by DOT’s in addition to AASHTO LRFD BDS include limits for the use of isotropic reinforcement, guidance for edge beam design and deck transverse reinforcement detailing in skewed bridges.

Table 2 Deviations of DOT practices from AASHTO LRFD BDS for concrete decks (rf = reinforcement).

State	**Different from AASHTO LRFD BDS**		**Additional Specifications**
	9.7.1.3	**9.7.2.5**	
WI[17]	**17.5.3.1:** The limit is 20º.	No	No
NY[18]	**5.1.5.1, 5.1.5.2:** The limit is 30º. Traditional deck rf included.	**5.1.5.1:** The limit is 30º. Beam spacing used, instead of effective deck length.	**5.1.5.1:** Traditional instead of isotropic rf for skew > 45º.
CT[19]	**8.1.2.5.1:** The limit is 20º.	**8.1.2.5.1:** The limit is 20º. Additional rf in skew direction only (#5@9”).	No
MN[20]	**9.2.1:** The limit is 20º.	**9.2.1:** No limit given. Additional rf in skew direction (2 #5@5”), radial transverse rf and bent corner bars.	No
OH[21]	**302.2.4.2:** The limit is 15º.	No	No
MI[22]	**7.02.20 E:** The limit is 20º.	No	No
VT[23]	No	No	No
MA[24]	No	No	No
NJ[25]	**20.5:** Main rf ⊥ to beams regardless of skew angle. A portion of it should be	No	No

	fanned extending into the acute deck corner.		
IN[26]	No	No	**404-3.03:** Transverse edge beams should not include top transverse deck steel for skews > 25°.

Table 2 (Continued) Deviations of DOT practices from AASHTO LRFD BDS for concrete decks (rf = reinforcement).

NH[27]	No	No	No
ME[28]	No	No	No
IL[29]	**3.2.3:** The limit is 15°. Additional span length constraint.	No	**3.2.2.1:** Guidance on the design of edge beams, based on skew.
PA[30]	**Structures 9.7.1.3 and C9.7.1.3:** The limit is 15°.	**Structures 9.7.2.5 and C9.7.2.5:** The limit is 15°.	**Appendix G, C1.4.2.5:** Deck transverse rf ⊥ to beams extend inside end-diaphragm and terminate as close as possible to its back face.
RI[31]	**9.6.3:** The limit is 30°.	No	No
TX[32]	**Chapter 3, Section 2 (Pg. 3-4):** The limit is 15°. For skew > 15°, rf should include corner breaks.	No	No
WA[33]	**5.7.2:** Rf is always ⊥ to bridge centerline.	No	No

FIELD INSPECTION OF BRIDGES WITH AND WITHOUT SKEW

Two girder-deck type Wisconsin bridges with prestressed concrete girders were visually inspected to identify performance issues unique to high skew bridges. These bridges were selected so that they were similar in year built, span length, span length to deck width ratio, number of spans, but they had different angles of skew. It was also ensured that the bridges had details that are not outdated in practice. Current common details include elastomeric bearings, semi-retaining abutments and strip seal expansion joints. Error: Reference source not found presents information on the selected bridges. The inspection results of the two bridges are compared to understand performance issues observed in similar bridges with different skew angles.

Table 3 Characteristics of bridges inspected (L=span length, W= deck width).

Girder Type	Skew	L/W	Abutment type	Bearing type	No. Spans	Span length	Year built
70" bulb-tee beam	52°	3.0 – 3.4	Semi-retaining	Steel laminated elastomeric pad (abutments), elastomeric pad (pier)	2	130'– 147'	2001
54" I-beam	0°	3.2 – 3.2				100'– 100'	1995

COMPARISON OF DECK PERFORMANCE

Contrary to the expectations of the research team, no visible cracks were detected in the acute corners of the bridge with 52° skew on the bottom or top surfaces of the deck (Fig. 8a). No cracks were visible on the remaining of the deck surfaces. On the other hand, the bridge with 0° skew, had a significant number of transverse and longitudinal deck top surface cracks, sealed previously. Several longitudinal cracks were spread spaced at 8 ft over abutments as shown in Fig. 8b. In addition, transverse cracks spaced between 1ft and 8 ft were spread between the pier and midspan. No cracks were visible on the deck bottom surface.

(a) (b)

Fig. 8 (a) Lack of cracking on deck bottom surface for 52° skew, and (b) longitudinal cracks for 0° skew near the abutment.

COMPARISON OF BRIDGE DISPLACEMENTS

Bridge movement was inspected by measuring expansion joint openings and bearing pad deformations. Expansion joint openings were measured at an ambient temperature of 31 °F., They were 2.125 in. and 2.50 in. at both abutments and at all corners of the bridges (i.e., the same in all four corners), for the bridge with 52° and 0° skew, respectively. Similarity in expansion joint openings at all corners indicates insignificant racking for both bridges.

Movements of bearings in the direction of girders measured over the two abutments were consistent with ones created by thermal contraction for both bridges. Fig. 9 shows example bearing pad movement in the direction of girders for 52° skew. Bearing pad displacements of the bridge with 0° skew were smaller than the one with 52° skew, likely due to 30% to 50% shorter span lengths in 0° skew bridge.

Fig. 9 Longitudinal displacement of an interior bearing for 52° skew.

In addition to bearing pad movement in the direction of girders, the bridge with 52° skew also had a small (less than 0.25 in.) transverse horizontal movement towards the centerline of the bridge at the obtuse corners of the bridge abutments (Fig. 10a). This could be an indication of bridge rotation toward acute corners. However, similarity in expansion joint openings at all corners contradicts this conclusion. In addition, a rotation around an axis parallel to the bridge centerline was observed on an acute corner bearing (Fig. 10b). This may be attributed to torsion at one end of the bridge. However, this type of bearing movement was not observed on the acute corner at the other bridge end. Although both types of bearing movements shown in Fig. 10 are acknowledged, they were too small to conclude a relationship to skew.

(a) (b)

Fig. 10 (a) Lateral displacement, and (b) rotation of the bearing for 52° skew.

COMPARISON OF SUBSTRUCTURE CONDITIONS

Abutments of both bridges had vertical cracks typically located at the level of beam centerline or beam pedestal edges, some of which ran along the entire abutment height. Fig. 11 compares the abutments of the bridges with 52° (a) and 0° (b) skew. In addition, the bridge with 0° skew had a small area of spall at the concrete diaphragm over the pier.

(a) (b)

Fig. 11 Vertical abutment cracks for bridges with (a) 52° skew, and (b) 0° skew.

OBSERVATIONS FROM THE FIELD INSPECTION

The goal of the field inspection was to compare two similar bridges with and without skew to identify performance problems specific to skew. Contrary to expectations, the comparison showed that condition of the bridge with high skew was not worse than the one with no skew. Although some bearing movements were visible in the bridge with skew, they were not significant or consistent enough to directly relate them to skew. In fact, the deck of the bridge with no skew had significantly more cracking than the one with high skew. These observations show that not all bridges with high skew experience problems with skew to the same degree. Bridge details such as end diaphragm or lack thereof, types and locations of bearings and expansion joints, types of abutments can be selected to alleviate skew effects. The bridge with high skew selected for inspection in this project did not have full depth concrete end diaphragms, had semi-retaining abutments, and elastomeric bearing pads. These details allow bridge movements and may eliminate distress due to skew. In addition, number of spans and ratio of span lengths in a bridge may also have an impact on how much skew affects bridge performance. Bridge details and geometry will be investigated in the future phases of this project.

SUMMARY AND CONCLUSIONS

The goal of this paper is to present analysis, performance and constructability issues related to high skew in bridges, through a review of published literature, AASHTO and State DOT practices, and bridge inspection reports. Literature review on analysis methods of bridges with high skew angles showed that skew alter gravity load paths. Shear, moment and reaction force distribution to girders due to gravity loading are expected to be different for bridges with high skew than the ones with negligible skew. Negative moment and torsion at bridge ends can also be created by high skew. Intermediate and end diaphragms can restrain movement and can cause lateral moment and torsion due to differences in deflections of adjacent beams under gravity loading. Service problems related to high skew angles include deck cracking, bearing movements, and substructure distress. Some of these are created due to temperature loading, when bridge is not allowed to displace freely.

This research reviewed and compared skew related provisions of AASHTO LRFD BDS and several state DOT's. AASHTO LRFD BDS and current DOT practices were found to be in general agreement. Differences between DOT provisions and deviations of DOT provisions from AASHTO LRFD BDS seem to exist mainly due to conservatism and/or DOT bridge maintenance and field experience over the years.

For interior beams, the variation of beam end shears along simply supported and continuous ends suggested by NCHRP 20-7/Task 107[12] implies an increase in end shear due to skew. However, AASHTO 4.6.2.2.3.c does not increase end shear in all interior beams for all girder type and configurations. On the other hand, others observed that end shear in interior beams reduces as skew angle increases. Additional research is needed to understand the impact of skew on interior beam end shear.

The variation of shear correction factors proposed by NCHRP 20-7/Task 107[12] along the beam span is only valid for exterior beams at obtuse corners. AASHTO LRFD BDS 4.6.2.2.3.c, however, recommends using the variation for interior beams as well. Additional analyses focusing on interior girder shear can confirm the validity of this provision.

Diagonal cracks at acute corners of concrete decks of skewed bridges are not directly addressed by AASHTO LRFD BDS. It does not link acute corner cracking with non-mechanical loading (i.e., temperature and shrinkage). Instead, AASHTO LRFD BDS section 9.7.2.5 only considers end zone cracking caused by torsion due to differential deflections.

Finally, field inspections of two prestressed concrete bridges similar in geometry, details and age but different in skew angle concluded that the condition of the high skew bridge was similar or better than the one with no skew. This suggests that skew effects could be reduced or eliminated by appropriate detailing, or by two span bridge configurations. However, further identification of key bridge features capable of mitigating skew effects is necessary to provide definite conclusions.

FUTURE WORK

In the next stages of the research, parametric studies, by means of 3-D finite element modeling, will be performed to investigate bridge details and geometry that may mitigate negative effects of skew. Factors, such as the presence and type of end and intermediate diaphragms, type and configuration of bearing supports, girder material, width-to-span length ratio, number of spans and span length ratio, will be included in parametric studies. In addition, validity of current analysis provisions for large skew bridges will be explored by comparing structural response predicted by 3-D models and by approximate 1-D analyses (i.e., girder-line analysis and skew correction factors). Outcomes of these studies will allow development of recommendations on bridge design and detailing to address the deleterious effects of skew.

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