Skew Effects On Steel Highway Bridges

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Presentation Outline

- Introduction
- Behavior of Skewed Structures
- Cross Frames and Diaphragms
- Framing Plan
- Analysis
- Case Study
  - Detailing and Fit
  - Deck Placement Considerations
  - Impacts to Pier Design
  - Effects on Bearing Design
  - Expansion Joints
  - Conceptual Erection Sequence
  - Shop Fit-Up
- Summary
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Introduction

- Skew can complicate design, detailing, fabrication, and construction of bridges
- Skew can lead to construction delays and claims if not appropriately accounted for
- Skewed bridges are becoming more prevalent especially in tight urban areas
- We need a plan to address the issues with skew
Introduction

First step is in the planning process try to minimize skew if possible

- Work with roadway designers to adjust the alignment
- Consider lengthening bridge
- Consider integral pier
Introduction

First step is in the planning process try to minimize skew if possible

- Consider retaining wall to allow the use of a non-skewed abutment
Introduction

Recognize skew challenges:
- Introduce torsion in the girders
- Large cross frame forces
- Different thermal movements
- Additional detailing considerations
- Longer substructure elements
Introduction

Next steps to address skew:
- Understand the behavior of skewed structures
- Determine appropriate level of analysis
- Develop optimal framing plan
- Detail skewed bridges properly to mitigate skew effects
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Behavior of Skewed Structures

- Girder differential vertical deflection causes lateral deflections and twist
- Due to the skew and associated framing, skewed girders will deflect vertically, and rotate transversely during deflection
- Shifting of load between girders creates torsion and changes the vertical and horizontal reactions
- Cross-frames attempt to equalize adjacent girder deflections
Behavior of Skewed Structures

- Elastomeric bearings performance
Behavior of Skewed Structures

- Example 1
Behavior of Skewed Structures

- Opposite direction of rotation between span 1 and 2
Behavior of Skewed Structures

- Transverse load paths through cross frames
- “Nuisance Stiffness” Effects
- Lateral reactions develop at the bearings
Behavior of Skewed Structures

- Example 2
Behavior of Skewed Structures

- Effects of Curvature (Radial Piers)
Behavior of Skewed Structures

- Effects of Curvature and Skewed Piers
- Skewed pier leads to longer center span for outside girder
Behavior of Skewed Structures

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Cross Frames and Diaphragms of Skewed Structures

- Straight bridges diaphragms brace compression flanges and transfer wind loads
- For skewed and curved bridges the diaphragms and cross frames members may carry significant load through transverse load paths
- K-type and X-type are utilized based on girder spacing and depth
- Cross frame stiffness is greater than the girder torsional stiffness so the cross frame remains rigid while the girders twist.
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Framing Plan

- The effects of skew on steel I-girder bridges depend on the severity of skew and type of framing
- Integrated system behavior is recognized with framing plan arrangement
- Continuous versus staggered diaphragms
  - Manage Uplift
  - Flange Lateral Bending
Framing Plan - Example 1

- Selectively remove cross-frames near the pier
  - Nuisance stiffness, reduce transverse load paths
- Use full-depth diaphragms at interior pier location
  - Attract load at two distinct locations
- Use staggered cross-frame pattern at skewed ends
  - Eliminate the transverse load paths
Framing Plan - Example 1

- Difference in cross frame member sizes, near skewed pier and typical intermediate
Framing Plan - Example 2

- Based on initial 3D analysis, rearrange cross frames at skewed pier 4
  - Use 3D model to investigate layouts
  - Reduce “nuisance stiffness”
  - Place cross frames along skew
  - No radial frames at skewed pier
  - Omit certain cross frames beyond pier
  - Relieve transverse stiffness & reduce cross frame forces
Framing Plan - Example 2

- Difference in member sizes, near skewed pier and typical intermediate
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Appropriate Analysis

- Level of analysis is based on the configuration of the bridge
  - NCHRP Report 725 introduced a scoring method to assess the accuracy of the analysis method.
  - Based on a skew index that considers the width of the bridge, the skew angle, and the span length

- Various responses considered
  - Major-axis bending
  - Vertical displacements
  - Cross frame forces
  - Flange lateral bending
  - Girder layover at bearings
Appropriate Analysis

- 1D Line Girder Analysis
  - Isolates and analyzes a single girder
  - Loads are distributed to each girder by way of distribution factors
  - Adequate for fairly simple structures with little to no skew angle
Appropriate Analysis

- 2D grid analysis:
  - Begins to address system behavior
  - Girders are modeled with a single line of beam elements
  - Deck is modeled in strips using line elements
  - Limits modeling of cross frames to single line element
  - Generally cannot model warping stiffness

- May produce inaccurate results
  - Cross-frame forces
  - Bearing Reactions
  - Girder displacements
Appropriate Analysis

- 2D grid analysis shortcoming:
  - 2D software only considers St. Venant (pure) torsional stiffness of the girders while neglecting warping torsional stiffness component. Warping torsion produces shear stress and normal stresses in which cross-sections do not remain plane.
  - Significant since I-girders as open, thin-walled sections, primarily carry torsion by warping
  - The lack of torsional stiffness in the I-girder leads to an inability to accept significant load transferred from the cross frames. As a result the 2D model underestimates transverse load paths and cross frame forces in the skewed bridge framing.
Appropriate Analysis

- 3D Finite Element Analysis
  - Girder flanges are modeled with beam elements and webs are modeled using plate or shell elements.
  - Explicitly model all cross-frame members using truss elements for K and X type cross frames and plate or shell elements for the webs of full the depth diaphragms with beam elements for the diaphragm flanges.
  - The deck is typically modeled using brick-type elements or shell elements.

- Benefits
  - Accurate cross-frame forces
  - Properly model girder torsional stiffness and warping stiffness
  - Properly accounts for load shifting between girders
  - Properly capture horizontal and vertical reactions
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Case Study Overview

Exist. WB Bridge:
- 5 simple spans: 471 ft total length
- 60” deep plate girders
- WB fracture critical substructure
- WB no skew counterfort wall abut

Exist. EB Bridge
- 3 continuous spans: 503 ft total length
- 81” deep plate girders
- skewed counterfort wall abut
Case Study Overview

- 70-degree skew
- Two spans @ 280 ft = 560 ft total length
- Deck width: 49’-3” with three lanes
- 6 plate girders
- Webs: 13/16” x 9’-6”
- Flanges: 1.5”x26” to 3”x34”
- X-type intermediate cross-frames
- Full-depth abutment diaphragm along skew
- Full-depth pier diaphragm normal to girders
Case Study Overview

- Stub abutments behind 600 ft long soldier pile walls
- Modular swivel type expansion joints at each abutment
- Multi-column pier supported on 4 rows of battered piles
Case Study Overview
Detailing – End Diaphragm

- Full-depth end diaphragm (length ~ 23.5 ft)
  - Too long for a K-type cross-frame
- Auxiliary stiffeners (back-up stiffeners)
Detailing – End Diaphragm

- Full-depth diaphragm connected to bent stiffener plate
- Bolted jacking stiffener installed after end diaphragm due to conflict
Detailing – Pier Diaphragm

- Detail to avoid interference with fixed bearing at skewed pier
Fit Condition

- Severe skew leads to:
  - Out-of-plumb webs after dead load is applied
  - Excessive bearing rotation
  - Try to control this rotation via detailing

- AASHTO Article 6.7.2
  - Fit condition to be specified in the plans

- 3 choices:
  - No load fit (NLF)
  - Steel dead load fit (SDLF)
  - Total dead load fit (TDLF)
For SDLF and TDLF, the cross-frames are forced into place and the girders are twisted out of plumb during the erection.

Cross-frames connect to girder locations that have different dead load deflections (differential).

Figure courtesy of Ronnie Medlock (High Steel).
Fit Condition

- Steel Dead Load Fit (SDLF) chosen
  - Disc bearing can accommodate rotations
    - Concrete dead load
    - Live load
  - Erection simpler & faster than TDLF
  - Limited construction windows

Fit Condition

- Achieved via girder drops on the shop drawings
  - Drops are the difference in elevation between the top of webs for adjacent girders.
  - Drops are comprised of:
    - differential deflection
    - roadway profile
    - deck cross slope
Deck Placement Analysis

- Girder camber is dependent on the sequence of the deck placement
- Difference between single monolithic deck pour and accumulated deflection due to the deck placement sequence
- Verify deck stresses resulting from pour sequence will not result in cracking
Deck Placement

- Placement of concrete along skew to load girders equally
- Place concrete along bridge skew ahead of paver skew and use retarder to delay set
Deck Placement

- Bridge Paver rails extended to approach
Pier Design

- 49’ wide bridge = 130’ long pier along skew
- 3 segments, each supporting 2 girders
Pier Design
Pier Design: Effect of Skew

- Opposite direction of rotation between span 1 and 2
Pier Design

- Severe skew and fixed bearing condition led to high lateral forces in opposite directions
- Segmented pier:
  o Better accommodate internal thermal force demands
  o Reduce torsion in pier cap
- Circular columns directly under girders to effectively carry vertical reaction
- Intermediate circular columns to effectively resist fixed horizontal bearing reactions
Pier Cap Design

- End Result:
  - Horizontal bearing reactions approximately equal to vertical reactions
- High torsional demand
  - No. 10 bars all around
- Special design considerations at fixed bearing locations
Concrete Anchorage Design

- Specialized approach with seismic-like detailing
  - Supplemental horizontal and vertical stirrups
  - Welded hoop bars
  - Embedded anchor bolts
  - Bar terminators
- Use of parametric tools
  - Clash detection
  - Verify sequence
Pier Cap Detailing

Bar Terminator

Anchorage Reinforcement
Pier

- Welded hoop bars to confine core for anchorage
Pier

Fixed Bearing

Non Guided Expansion Bearing
Bearing Design

- High Load Multi-Rotational Bearings
- Disc bearings were specified (rotation at abutments > 0.05 radians)
Bearing Design

Concrete Placement Hole

Anchor bolts threaded through embedded plate
Swivel Type Modular Expansion Joint

- Multi-directional movement capability
- Detail girders and end diaphragms to accommodate joint
- Special closure pour at joints
  - To minimize movement due to dead load effects (racking)
  - To reduce shrinkage effects
Conceptual Erection Sequence Analysis

- AASHTO LRFD Requirements
  - Article 2.5.3 Constructability
  - “Where the bridge is of unusual complexity, such that it would be unreasonable to expect an experienced contractor to predict and estimate a suitable method of construction while bidding the project, at least one feasible construction method shall be indicated in the contract documents.”
Conceptual Erection Sequence Analysis

- Use LARSA 3D FEM to check:
  - Temporary support structure placement
  - Hold cranes required
  - Girder stresses, deflections, reactions (no uplift)

- Potential issues:
  - Girder buckling capacity greatly reduced due to long unbraced lengths
  - Loading is less than in the final condition, but the girder capacity is also less
Shop Fit-Up
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Summary

- Try to minimize skew in the planning process
- Recognize alternative load paths at skewed supports
- Recognize when a refined 3D analysis is warranted
- Be cognizant of high lateral forces at fixed bearings of a skewed support
- Specify fit condition for the girders and cross-frames
- Consider shop assembly to verify fit-up
- Place deck concrete along skew
- Follow these steps to reduce risk of geometry control issues and construction delays and claims
References

- Chavel, B., Peterman, L., McAtee, C.. (2010).“Design and Construction of the Curved and Severely Skewed Steel I-Girder East-West Connector Bridge over I-88”, International Bridge Conference