TTI: 0-6955

# Development of a Strategy to Address Load Posted Bridges through Reduction in Uncertainty in Load Ratings: TxDOT Workshop

Product 0-6955-P1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

sponsored by the
Federal Highway Administration and the
Texas Department of Transportation
https://tti.tamu.edu/documents/0-6955-P1.pdf

TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

Texas A&M Transportation Institute

# TxDOT Project 0-6955:
# Development of a Strategy to Address Load Posted Bridges Through Reduction in Uncertainty in Load Ratings

TxDOT Workshop

*October 7, 2019 – Austin, TX*

Texas Department of Transportation

# Workshop Agenda

| Time | Description |
| --- | --- |
| 9:00 - 9:20 am | • Welcome and Introductions<br>• Workshop Overview<br>• Project Motivation and Objectives<br>• Texas Load-Posted Bridge Inventory |
| 9:20 – 9:45 am | • Basic Load Rating Analysis<br>• Areas of Opportunity |
| 9:45 – 10:15 am | • Refined Analysis of Selected Typical Bridges<br>• Areas of Opportunity |
| 10:15 – 10:30 am | • Break |
| 10:30 – 11:10 am | • Load Testing<br>• Model Updating<br>• Impact on Rating Factors |
| 11:10 am – 12:00 pm | • Refined Load Rating Guidelines and Examples<br>• Summary, Conclusions, and Recommendations<br>• Questions and Discussion |
| 12:00 pm | • Adjourn |

# Introductions – TAMU/TTI Project Team

- Mary Beth Hueste – RS
- Stefan Hurlebaus
- John Mander
- Stephanie Paal
- Tevfik Terzioglu
- Graduate Students
  - Matthew Stieglitz
  - Nuzhat Kabir

# Introductions – TxDOT Project Team

- James Kuhr– Project Manager
- Graham Bettis
- Jesus Alvarez
- Jonathan Boleware
- Aaron Garza
- Andrew Lee
- Courtney Holle
- Curtis Rokicki

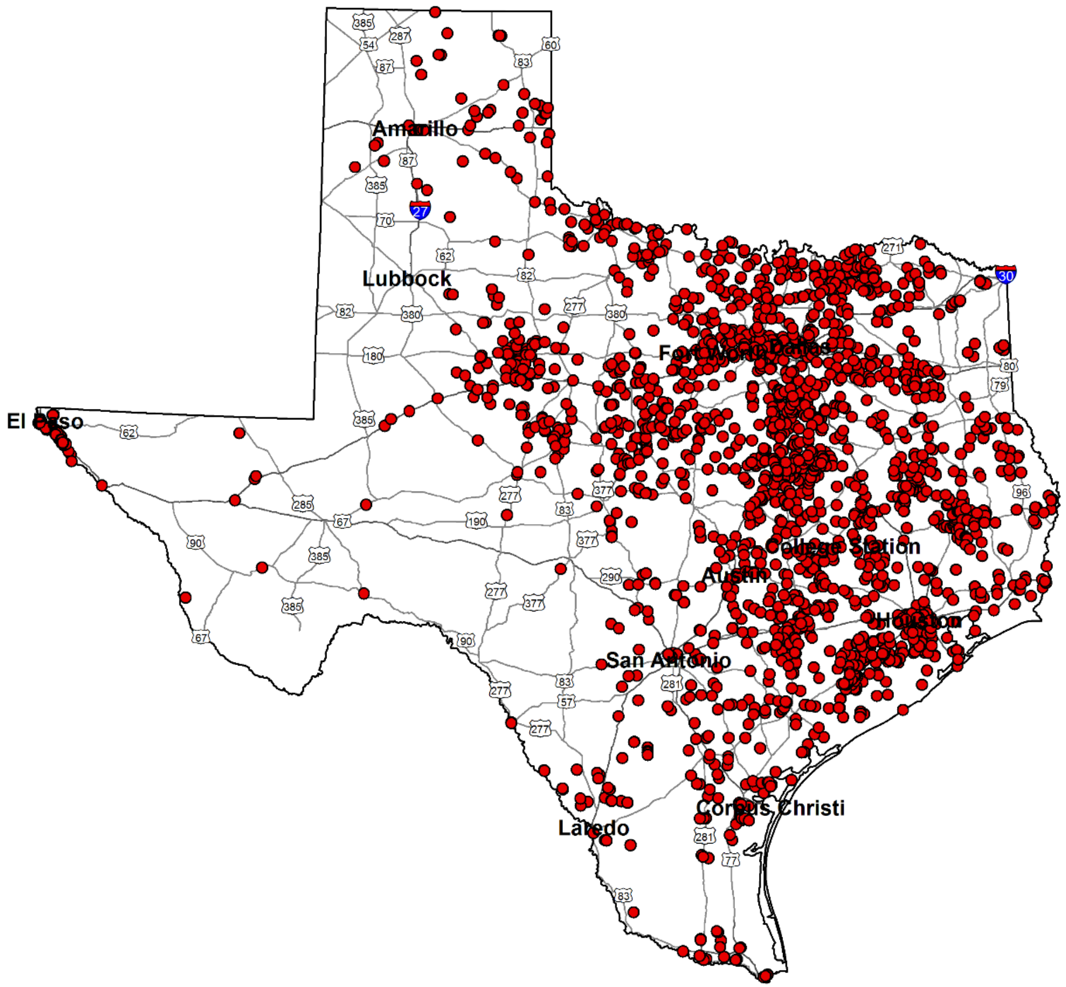
# Workshop Overview

- Project Motivation and Objectives
- Texas Load-Posted Bridge Inventory
- Basic Load Rating and Identification of Areas of Opportunity
- Refined Analysis of Selected Typical Bridges
- Load Testing, Model Updating and Impact on Load Rating
- Refined Load Rating Guidelines
- Refined Load Rating Examples
- Summary and Conclusions

# Project Motivation and Objectives

# Load Posted Bridges

- Management of aging bridge assets
  - DOTs rely on the load rating process
  - Post load restrictions if the capacity is below current legal loads
- Load posted bridges in Texas:
  - Over 2100 bridges below the legal limit (NBI 2016)




*Load posted bridges in Texas (2111)*

TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

# Motivation

Impact on freight movement and economic vitality

- Commerce, traffic, and emergency egress issues
- Removing load postings is always of interest

Challenges

- No clear cut solution for removing postings
  - Varied geometries and materials
  - Built in different eras and environments
- AASHTO Manual for Bridge Evaluation (MBE) allows for refined rating
  - Does not address how to identify appropriate structures
  - Gives procedures to conduct non-destructive load testing, but does not provide procedures for refined analysis


**4.4—ACCEPTABLE METHODS OF STRUCTURAL ANALYSIS**

Any method of analysis that satisfies the requirements of equilibrium and compatibility and utilizes stress-strain relationships for the proposed materials may be used.

Texas Department of Transportation

Texas A&M Transportation Institute

# Project Objectives

*TxDOT Project 0-6955: Development of a Strategy to Address Load Posted Steel Multi-Girder Bridges Through Reduction in Uncertainty in Load Ratings*

- Overall objective:
  - *Determine appropriate strategies to remove load postings for Texas bridges posted at load levels below the legal limit.*
- Specific objectives:
  - **Quantify and characterize** the population of load posted bridges in Texas.
  - Identify **areas of opportunity**, including more accurate material properties and information from bridge inspections, refined modeling for less conservative load distribution modeling, and proof testing for verification of acceptable load levels.
  - Determine whether load rating calculations using **refined information and techniques** can eliminate load postings in some cases or increase the allowable loads on load posted bridges.
  - Develop refined load rating guidelines and examples.

# Project Scope

*TxDOT Project 0-6955: Development of a Strategy to Address Load Posted Steel Multi-Girder Bridges Through Reduction in Uncertainty in Load Ratings*

- ✓ Reduce uncertainty in a safe and appropriate manner.
- ✓ Target specific details of the bridge and load rating easiest to adjust.
- ✓ Review and synthesize population of load posted bridges.
- ✓ Conduct basic load rating analysis to identify the controlling limit states.
- ✓ Perform load testing and refined analysis to identify areas of opportunity.
- ✓ Assess benefits of refined ratings.
- ✓ Develop implementation approach including refined load rating guidelines and examples.

# Development of Load Rating Procedures

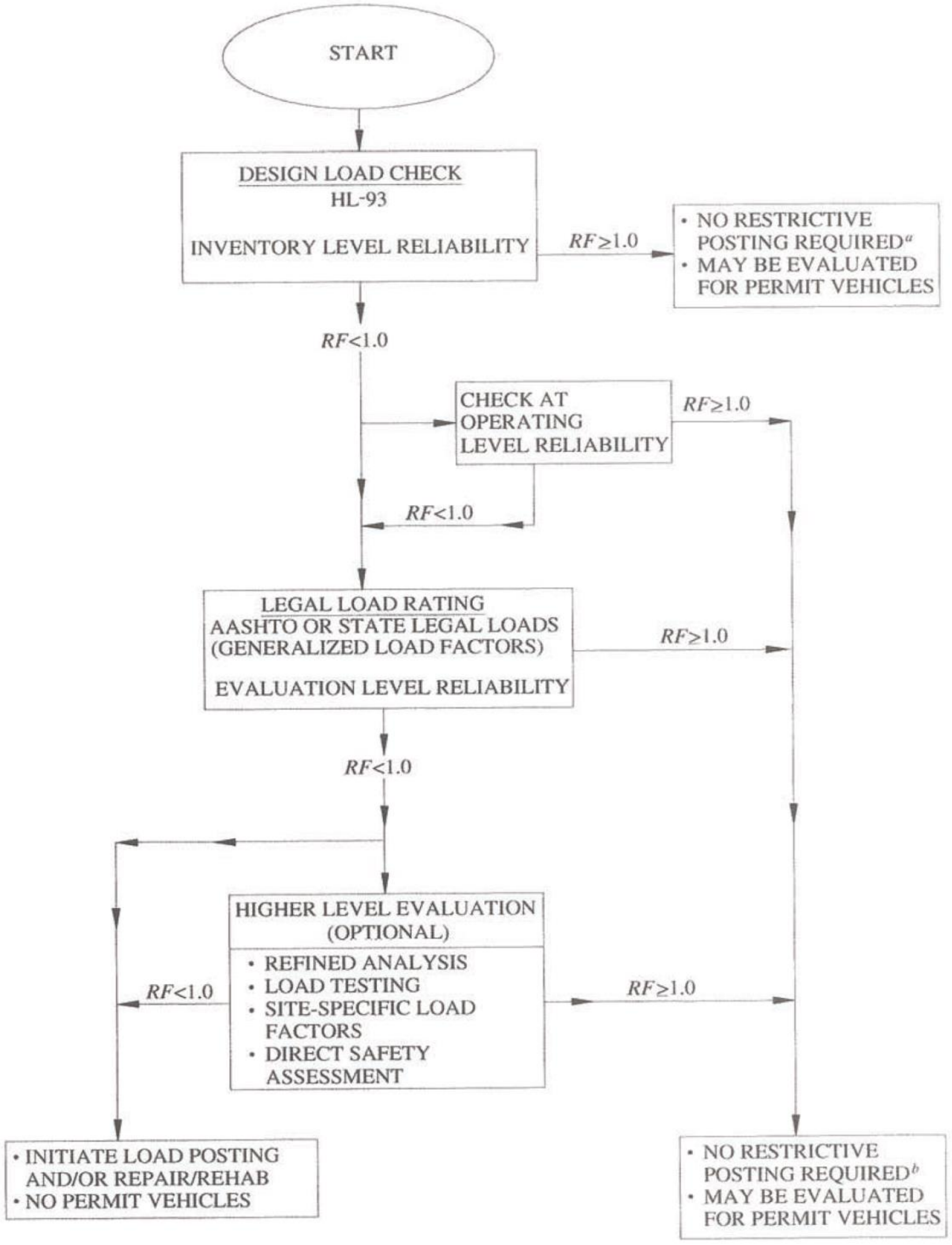
- 1967 — Silver Bridge Collapse
- 1968 — Federal Highway Act of 1968
- 1970 — 1st AASHO Inspection Manual
- 1973 — AASHO becomes AASHTO
- 1974 — LFR for Steel Bridges
- 1978 — Push towards LFR
- 1983 — Manual for Maintenance Inspection of Bridges
- 1987 — NCHRP Reports 292 and 301 help push LRFR
- 1994 — MCE released – complete rewrite of evaluation manual
- 2001 — NCHRP Project 12-46 tasked with development of LRFR manual
- 2003 — MCE and LRFR of Highway Bridges
- 2005 — 1st edition MBE
- 2011 — 2nd edition MBE
- 2018 — 3rd edition MBE

# Allowable Stress Rating (ASR) and Load Factor Rating (LFR)

**ASR and LFR** → Evaluation of live load models at two levels of reliability

- **Inventory Rating (IR)**
  - Specifies the multiple of design truck that can pass over the bridge such that the bridge can be used safely for an indefinite period of time

- **Operating Rating (OR)**
  - Specifies the multiple of design truck that is the absolute maximum that can pass over the bridge




# AASHTO MBE LRFR Procedure

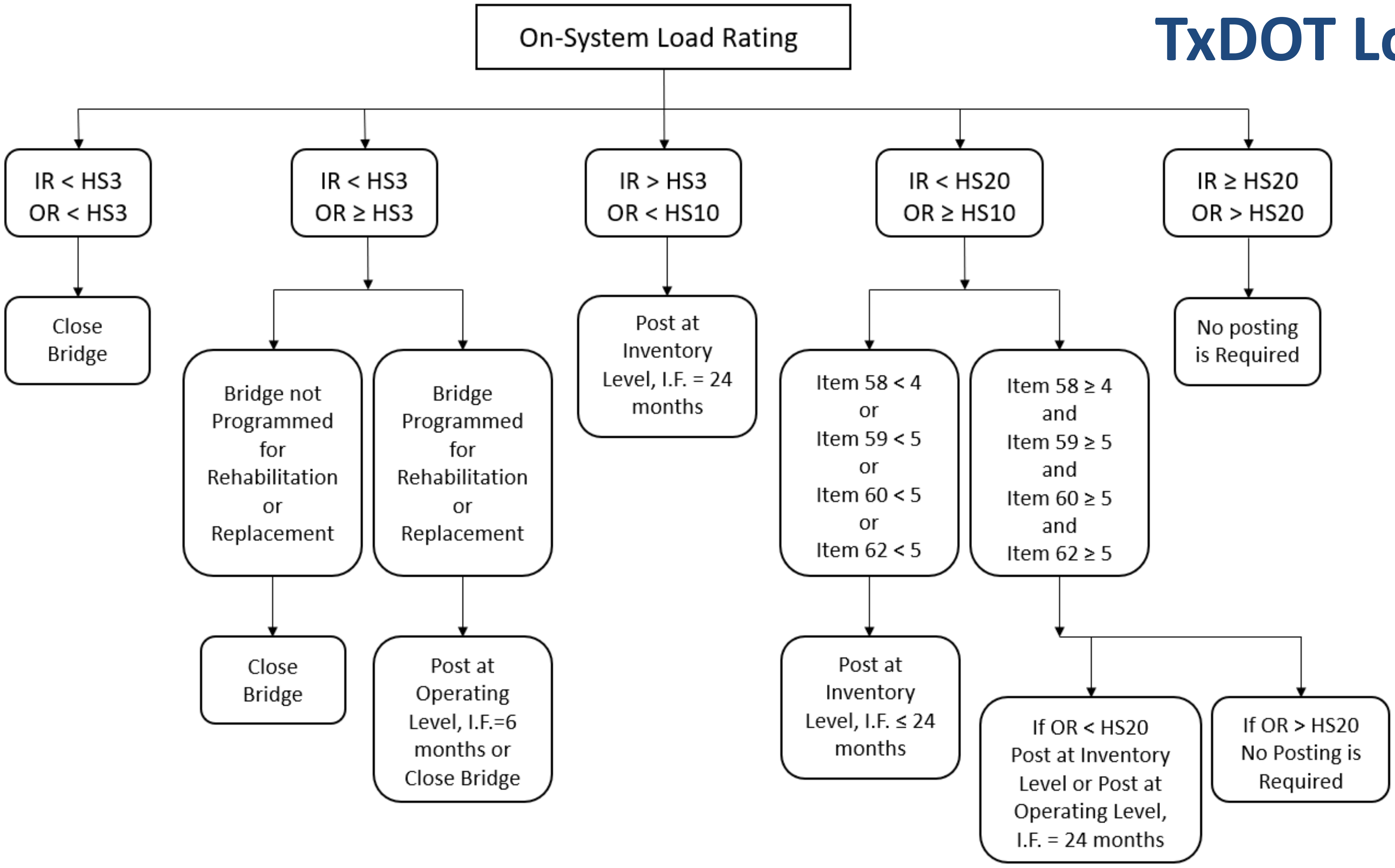
## Evaluation Live Load Models

1. **Design Load Rating**
   - HL-93 loading and LRFD design standards
   - Strength limit state at the LRFD design level of reliability (inventory rating)
   - If the RF ≥ 1 at the Inventory level → satisfactory for all legal loads
   - Evaluation at a second lower level of reliability (operating rating) is also an option
2. **Legal Load Rating**
   - Provides a single safe load capacity (for a given truck configuration) applicable to AASHTO and State legal loads
3. **Permit Load Rating**
   - For the passage of vehicles above the legally established weight limitations
   - Applied only to bridges having sufficient capacity for AASHTO legal loads

Texas A&M Transportation Institute

# TxDOT Load Rating Specifics

## On-System Bridges




*Adapted from TxDOT Bridge Inspection Manual, 2018*

9: Excellent Condition
8: Very Good Condition
7: Good Condition
6: Satisfactory Condition
5: Fair Condition
4: Poor Condition
3: Serious Condition
2: Critical Condition
1: "Imminent" Failure Condition
0: Failed Condition

Item 58: Deck condition rating
Item 59: Superstructure condition rating
Item 60: Substructure condition rating
Item 62: Culvert condition rating

# AASHTO MBE
## Rating Factor Equations

**Rating factor equation for ASR and LFR:**

$$RF = \frac{C - A_1 D}{A_2 L(1 + I)}$$

- Capacity *C* is found using either ASD or LFD procedures
- Live load effects are calculated for truck loading (H or HS) only

**Rating factor equation for LRFR:**

$$RF = \frac{C - (\gamma_{\mathrm{DC}})(DC) - (\gamma_{DW})(DW) \pm (\gamma_P)(P)}{(\gamma_{LL})(LL + IM)}$$

- Capacity *C* is found using LRFD procedures
- Live load effects are calculated for HL93 loading

# Texas Load-Posted Bridge Inventory

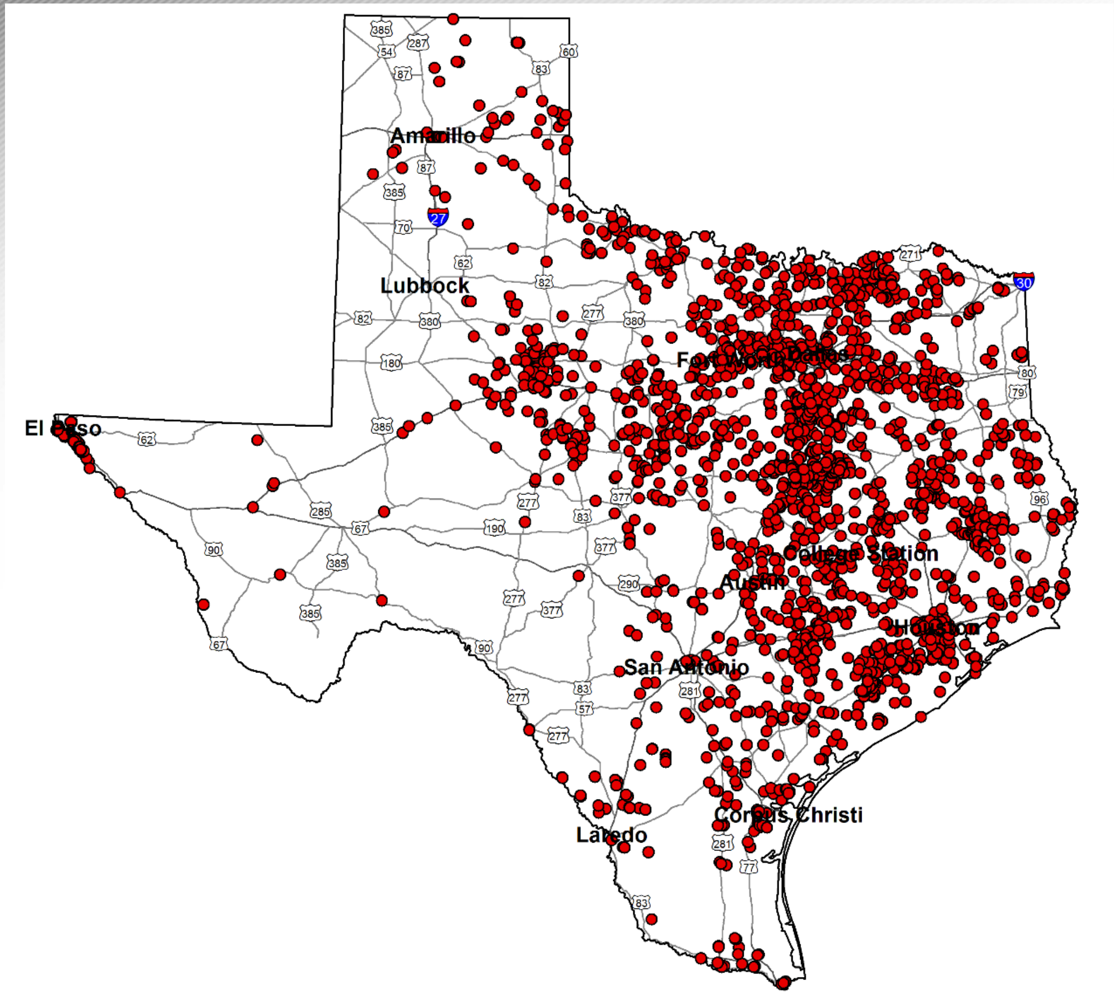
# Introduction

- **Texas has 2111 load posted bridges (NBI 2016)**
  - Evaluated based on kind of material, type of construction, age, maximum span length, width, operating rating

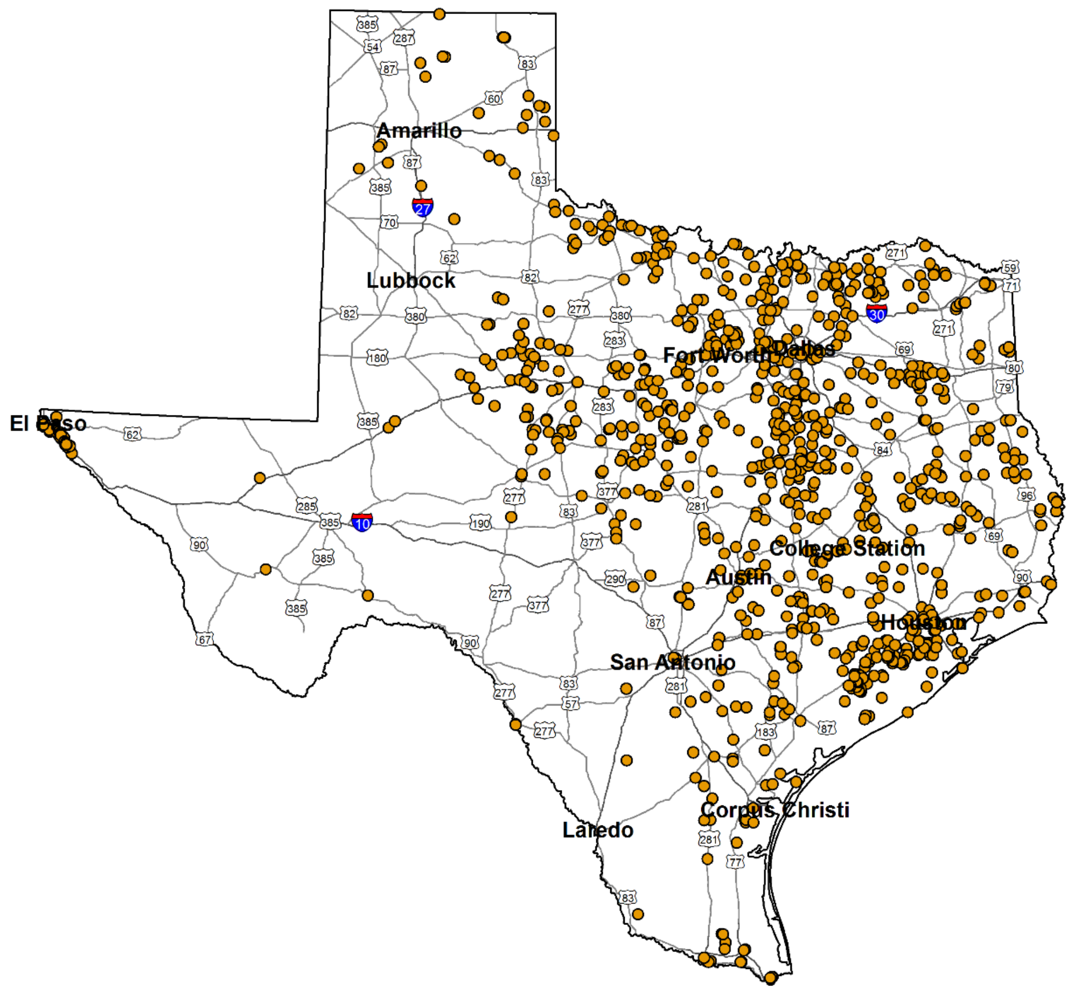
| Condition Classification | On-System | Off-System | Total |
|---|---|---|---|
| Structurally Deficient (SD) | 39 | 473 | 512 |
| Functionally Obsolete (FO) | 58 | 572 | 630 |
| Sub-standard for Load Only (SSLO) | 78 | 891 | 969 |
| Total | 175 | 1936 | 2111 |

- It is more likely to remove load postings for **SSLO** bridges using more accurate information and refined analysis.

# Geographic Locations

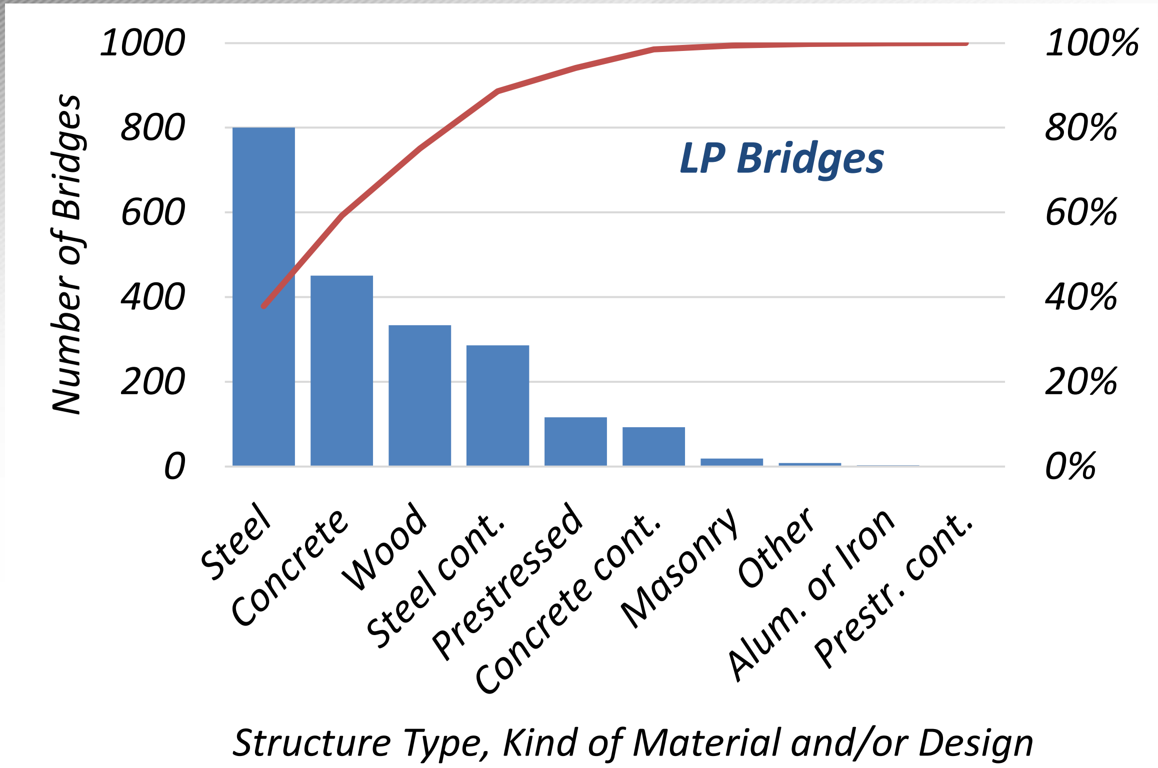


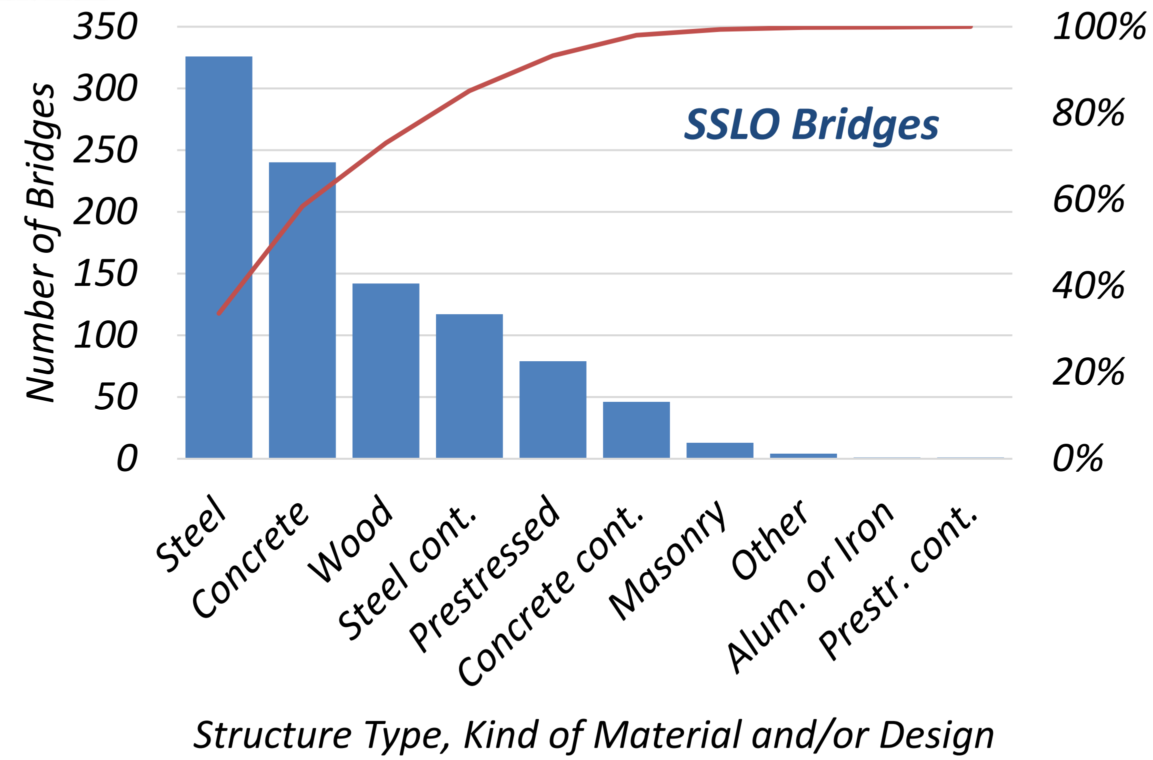

*All LP bridges in Texas (2111 bridges)*




*All SSLO bridges in Texas (969 bridges)*

# Distribution of Load Posted Bridges



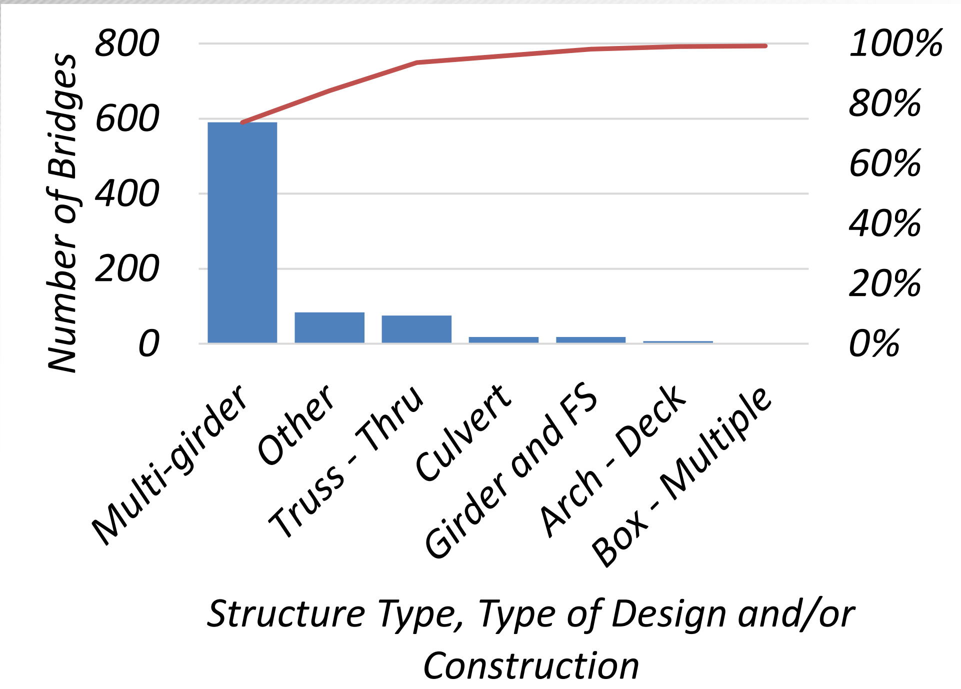




| Kind of Material/Design | No. of Bridges | Percentage |
|---|---|---|
| Steel | 800 | 38% |
| Concrete | 451 | 21% |
| Wood | 334 | 16% |
| Steel cont. | 286 | 14% |
| Prestressed | 116 | 5% |

| Kind of Material/Design | No. of Bridges | Percentage |
|---|---|---|
| Steel | 326 | 34% |
| Concrete | 240 | 25% |
| Wood | 142 | 15% |
| Steel cont. | 117 | 12% |
| Prestressed | 79 | 8% |

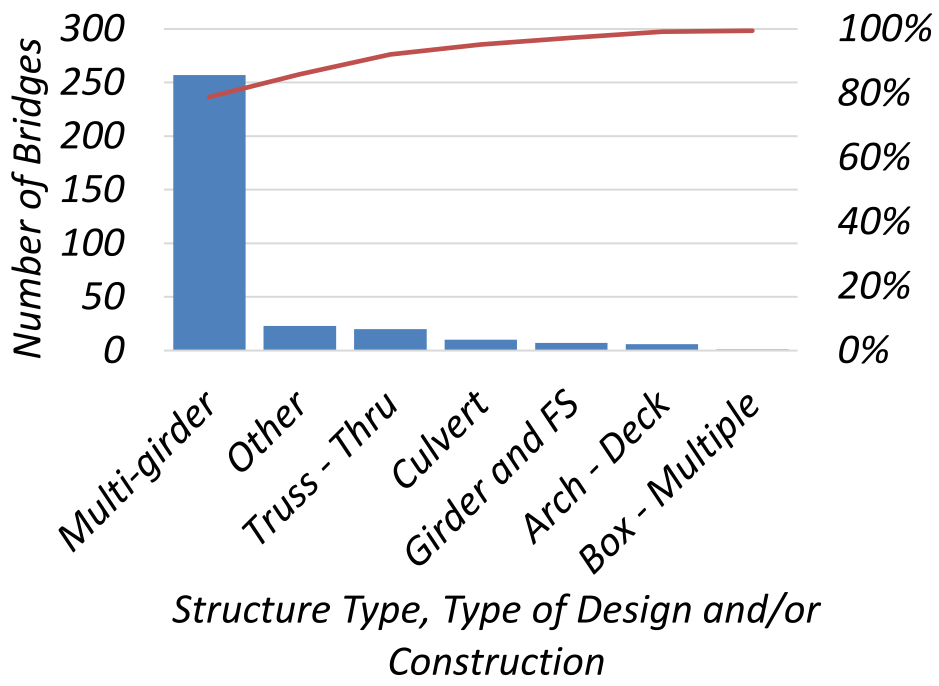
# Distribution of Steel Bridges

## Load Posted Bridges




| Type of Design/Construction | No. of Bridges | Percentage |
|---|---|---|
| Multi-girder | 590 | 74% |
| Other | 84 | 11% |
| Truss - Thru | 75 | 9% |
| Culvert | 18 | 2% |

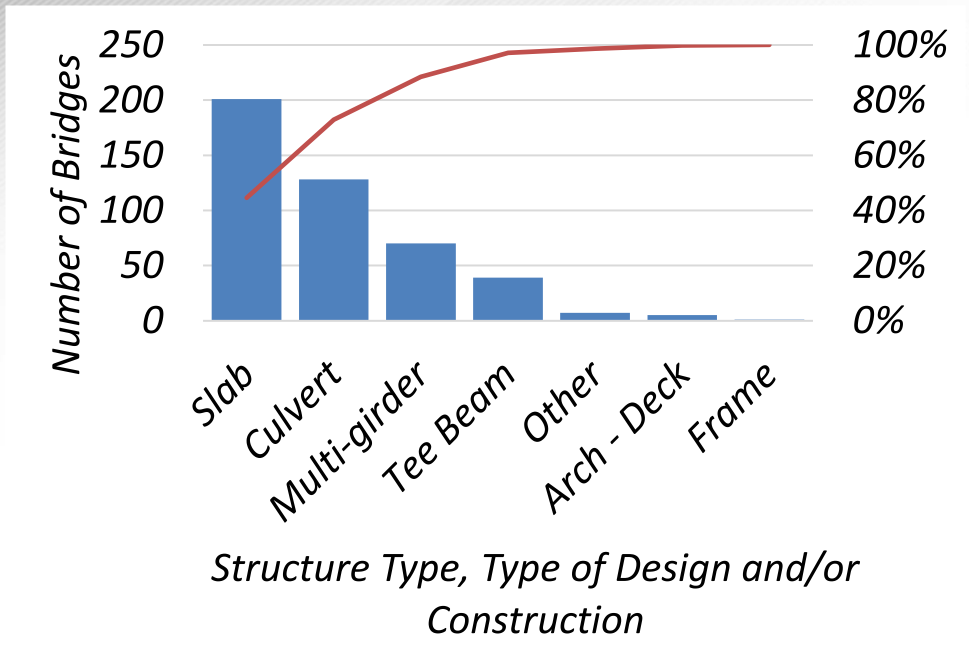
## SSLO Bridges




| Type of Design/Construction | No. of Bridges | Percentage |
|---|---|---|
| Multi-girder | 257 | 79% |
| Other | 23 | 7% |
| Truss - Thru | 20 | 6% |
| Culvert | 10 | 3% |

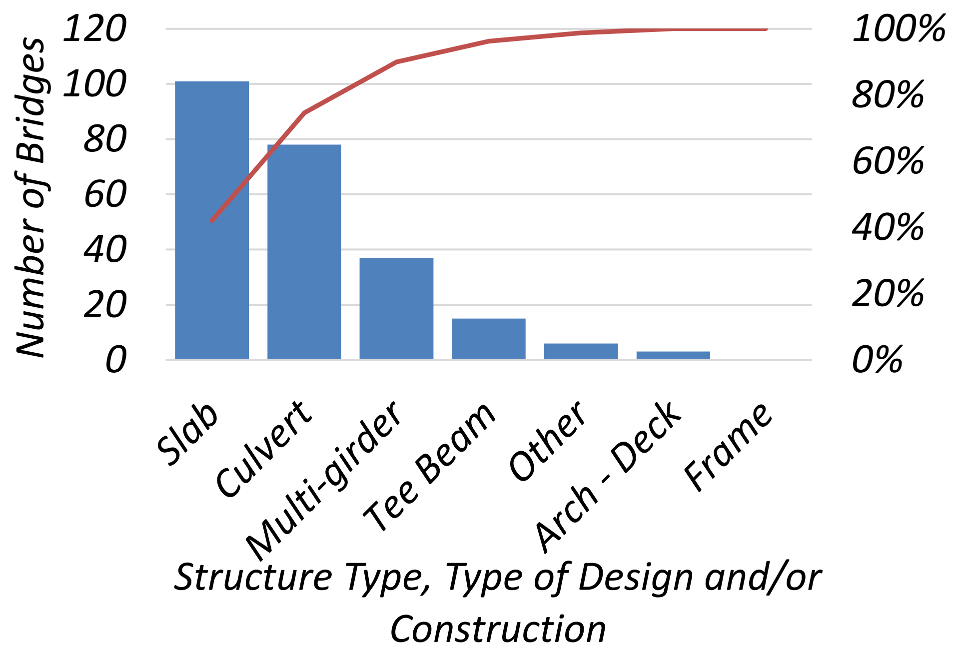
# Distribution of Concrete Bridges

## Load Posted Bridges




| Type of Design/Construction | No. of Bridges | Percentage |
|---|---|---|
| Slab | 201 | 45% |
| Culvert | 128 | 28% |
| Multi-girder | 70 | 16% |
| Tee Beam | 39 | 9% |

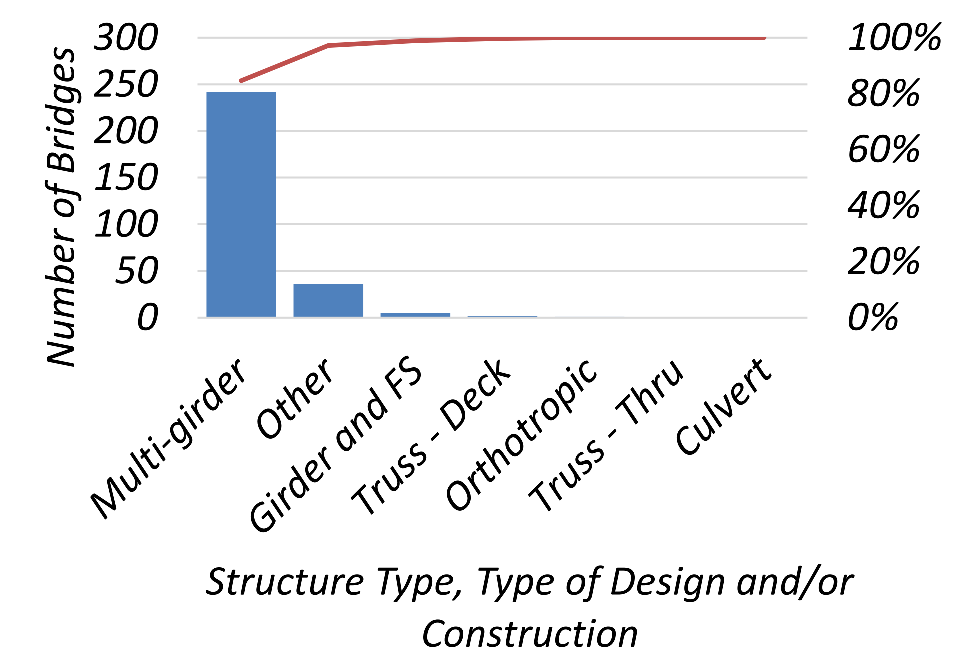
## SSLO Bridges



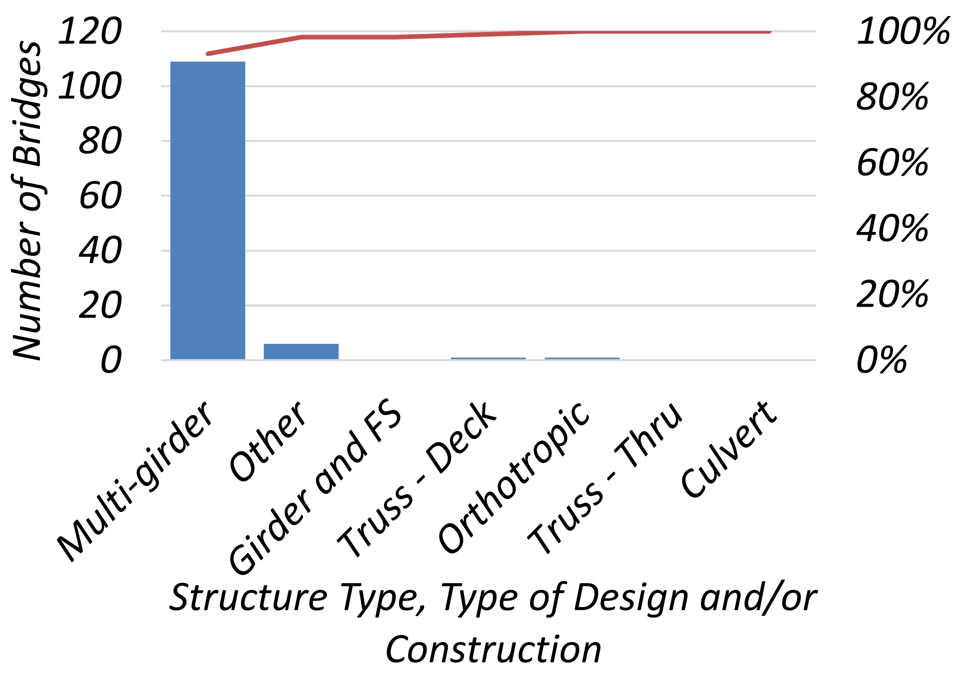

| Type of Design/Construction | No. of Bridges | Percentage |
|---|---|---|
| Slab | 101 | 42% |
| Culvert | 78 | 33% |
| Multi-girder | 37 | 15% |
| Tee Beam | 15 | 6% |

# Distribution of Steel Continuous Bridges

## Load Posted Bridges




## SSLO Bridges




| Type of Design/Construction | No. of Bridges | Percentage |
|---|---|---|
| Multi-girder | 242 | 85% |
| Other | 36 | 13% |

| Type of Design/Construction | No. of Bridges | Percentage |
|---|---|---|
| Multi-girder | 109 | 93% |
| Other | 6 | 5% |

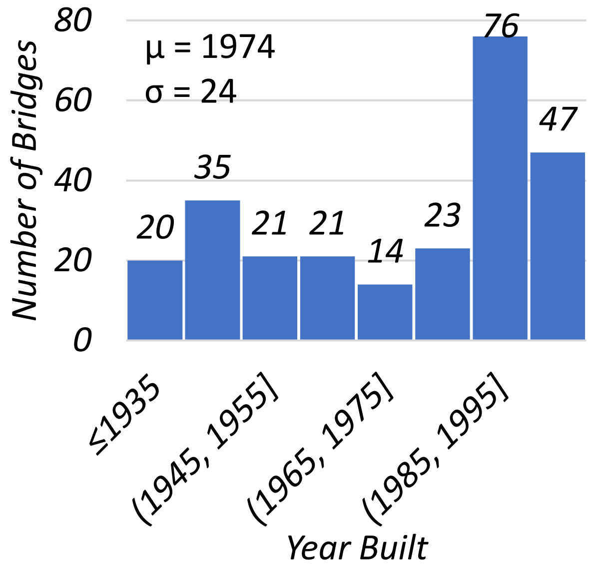
# Texas SSLO Bridges by Type

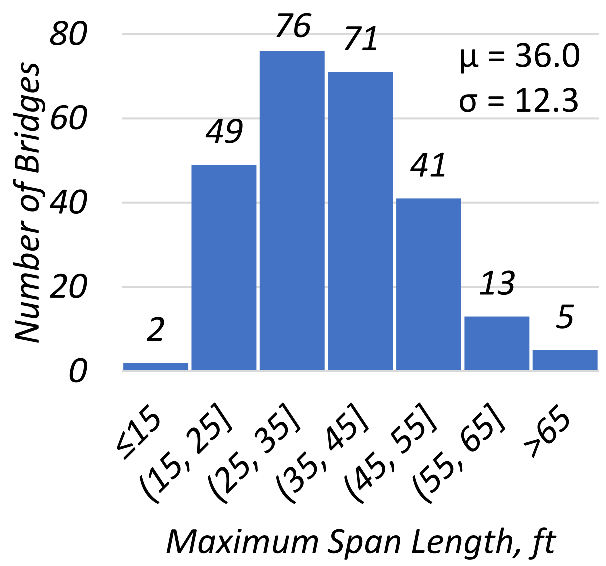
| Material/Design | Bridge Type | No. of Bridges | | |
|---|---|---|---|---|
| | | On System | Off System | Total |
| Steel | Stringer/Multi-beam or Girder | 14 | 243 | 257 |
| Concrete | Slab | 42 | 59 | 101 |
| Concrete | Stringer/Multi-beam or Girder | 2 | 35 | 37 |
| Steel Continuous | Stringer/Multi-beam or Girder | 6 | 103 | 109 |
| Prestressed | Other | 0 | 68 | 68 |
| Concrete Continuous | Slab | 4 | 38 | 42 |

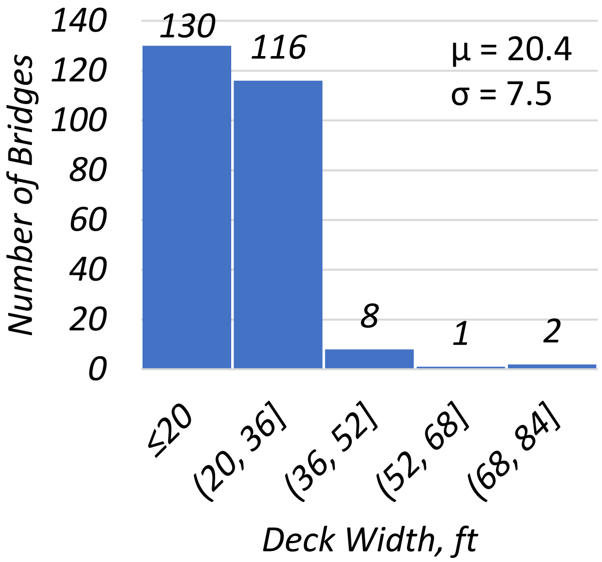
Of the 969 SSLO bridges:
- 27% are steel multi-girder
- 11% are steel continuous multi-girder
- 10% are concrete slab
- 4% are concrete multi-girder

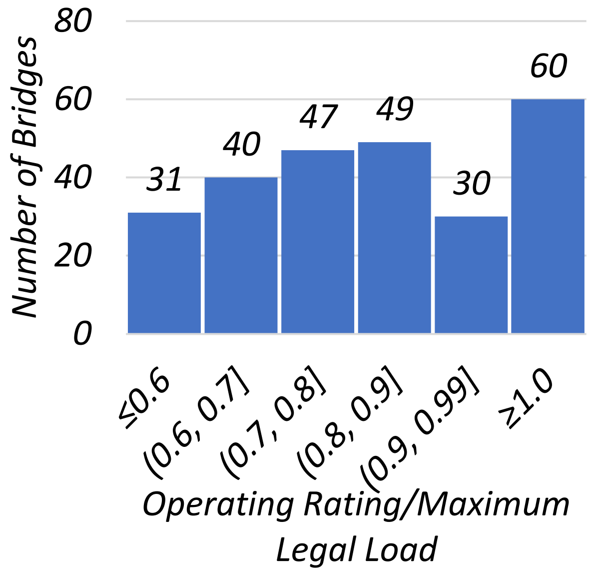
# SSLO Steel Multi-Girder Bridges

All SSLO

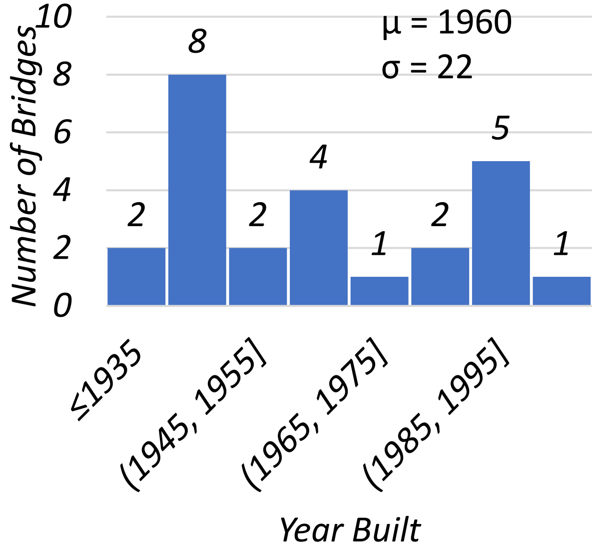


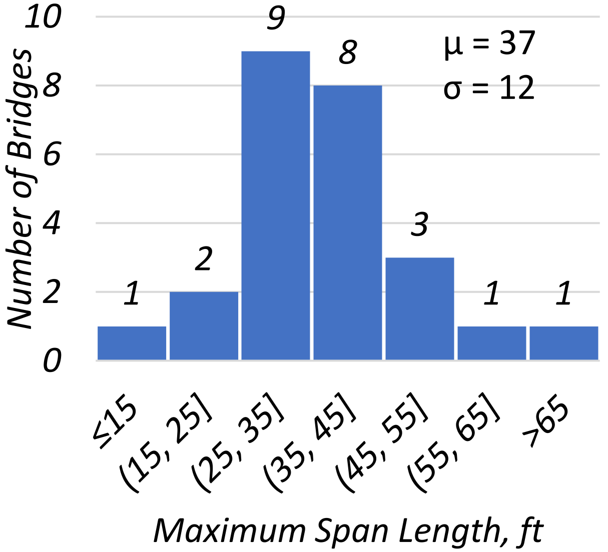



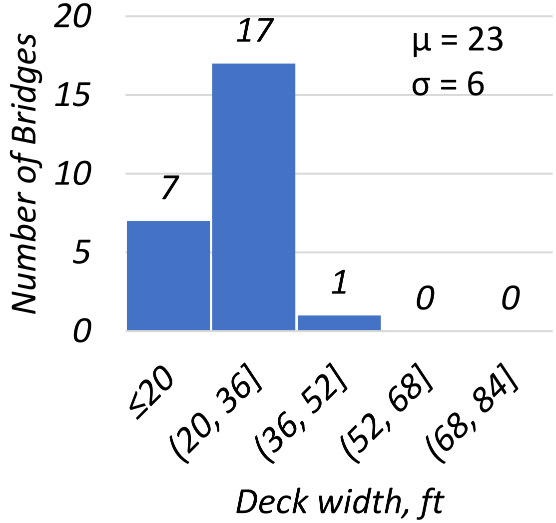



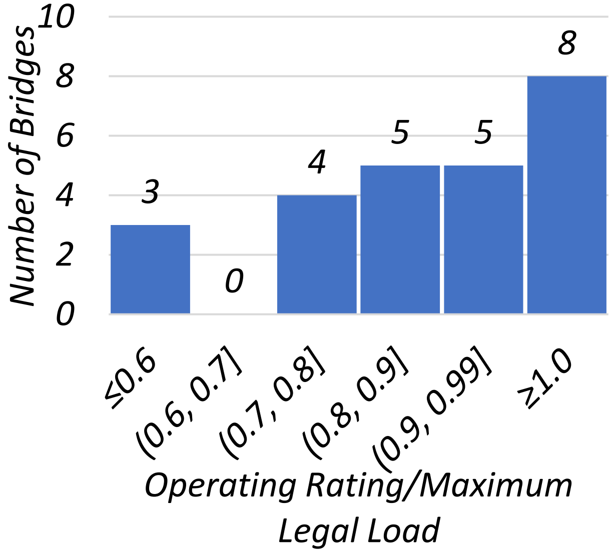




Selected

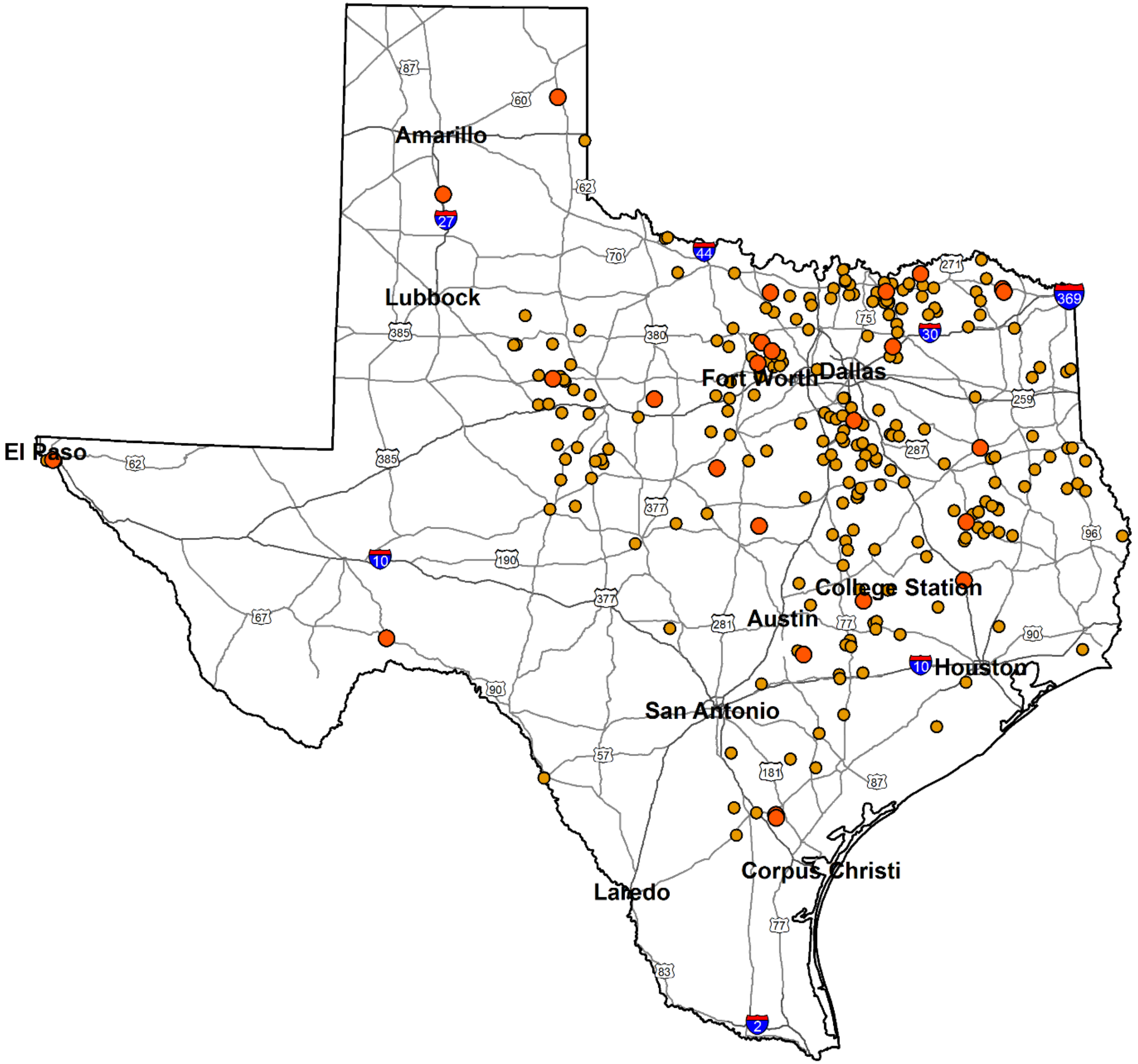


# Location of Selected SSLO Steel Multi-Girder Bridges




- *Yellow Placemark*
  - *Full dataset of SSLO steel multi-girder bridges (257 bridges)*
- *Orange Placemark*
  - *Selected subset of SSLO steel multi-girder bridges (25 bridges)*

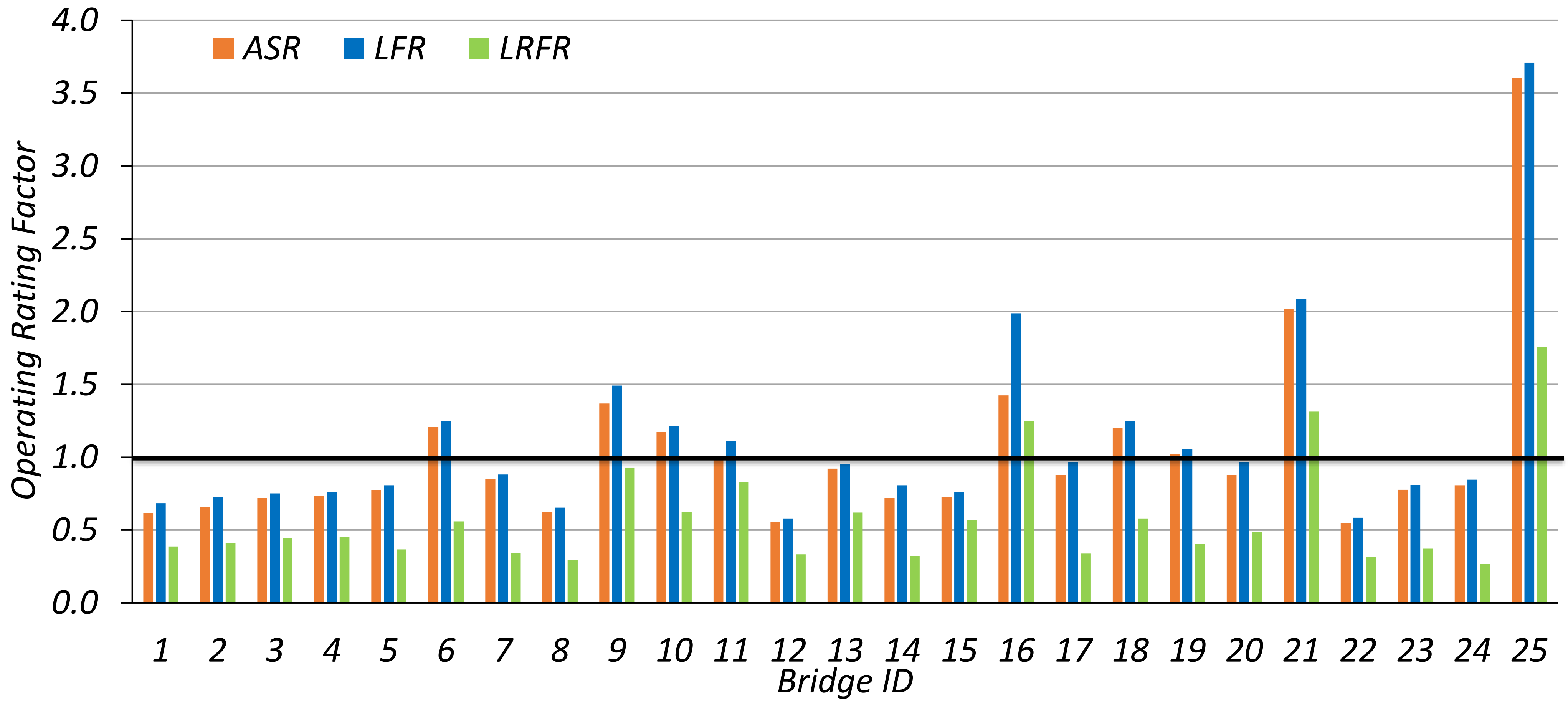
# Basic Load Rating and Identification of Areas of Opportunity

# Steel Multi-Girder (SM) Bridges

## Subset for Basic Load Rating Analysis

- **25** steel simple span bridges were selected to conduct basic load ratings
  - 9 on-system, 16 off-system
- Year built ranges from **1931 to 2000**
- Maximum span length ranges from **14 to 69 ft**
- Deck width ranges from **14 to 46 ft**

# SM Interior Girder Flexure Operating RFs



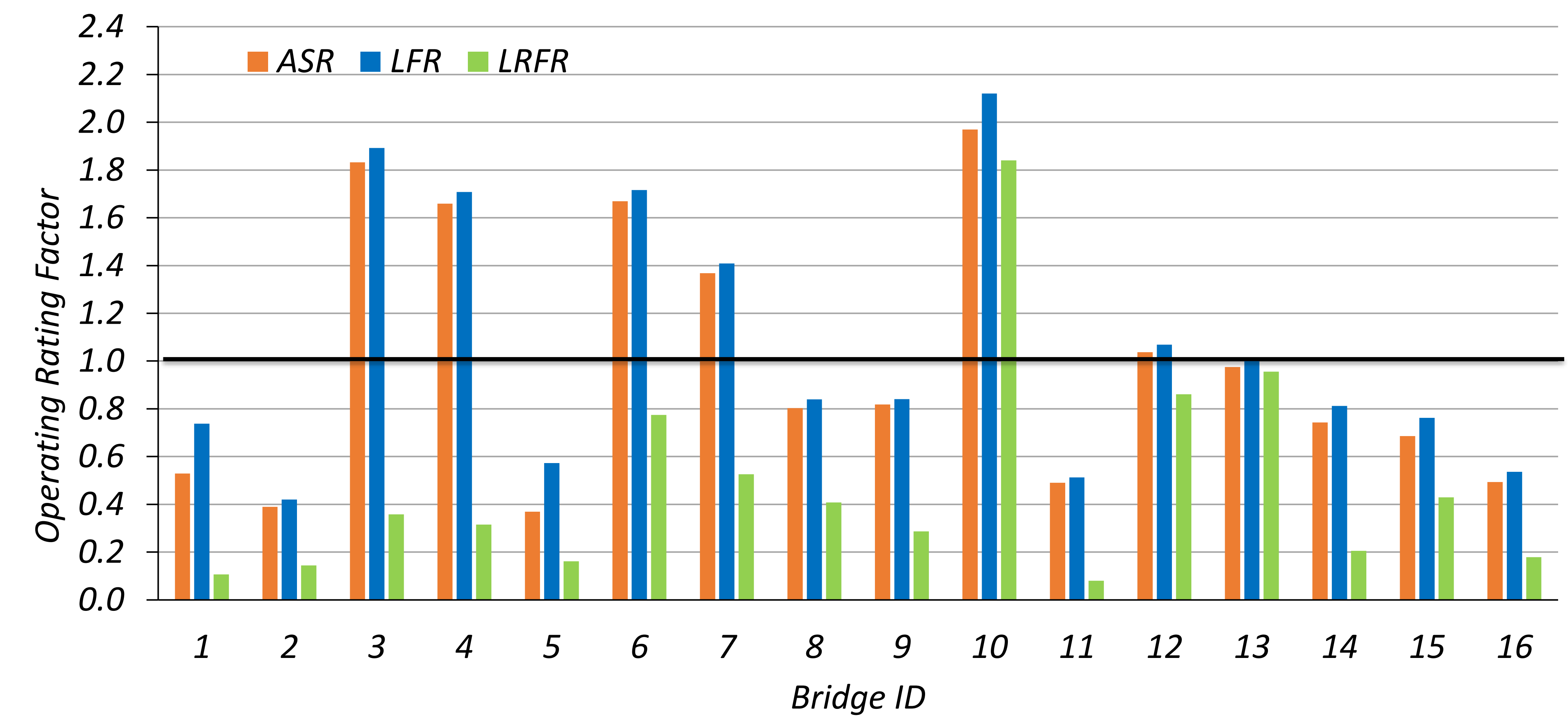

- LFR produced higher Operating RFs than ASR
- LRFR resulted in lowest RFs for all analyzed bridges

# Continuous Steel Multi-Girder (SC) Bridges

## Subset for Basic Load Rating Analysis

- **16** steel continuous bridges were selected to conduct basic load ratings
  - 4 on-system bridges, 12 off-system bridges
- Year built ranges from **1910 to 1999**
- Bridge length ranges from **22 to 2723 ft**
- Maximum span length ranges from **11 to 152 ft**
- Deck width ranges from **14 to 34 ft**

# SC Interior Girder Flexure Operating RFs



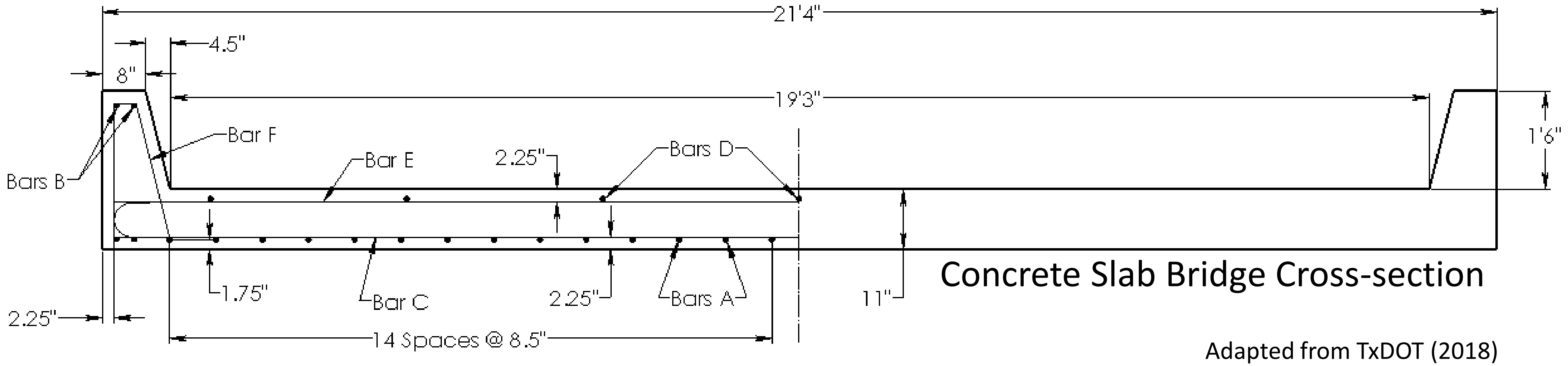

- LFR method consistently provided higher RFs than ASR
- LRFR method tends to give much lower RFs

# Simple Span Concrete Slab Bridges

## Subset for Basic Load Rating Analysis

- **23** out of 101 SSLO simple span concrete slab (CS) bridges selected
  - 14 on-system bridges, 9 off-system bridges
- Year built ranges from **1920 to 1970**
- Maximum span length ranges from **18 to 25 ft**
- Deck width ranges from **21 to 46 ft**

Bridge CS-9




Concrete Slab Bridge Cross-section

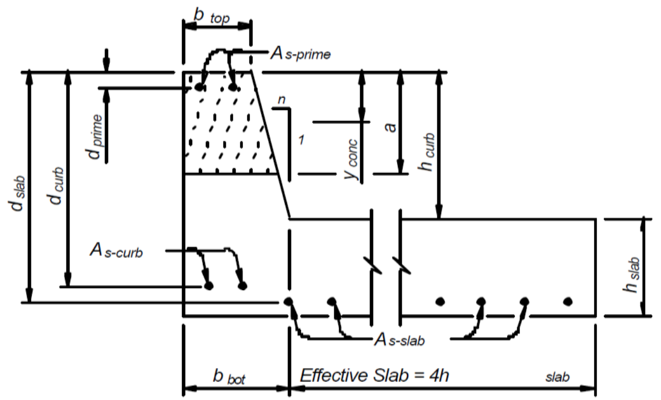
Adapted from TxDOT (2018)

# Concrete Slab Bridge Types

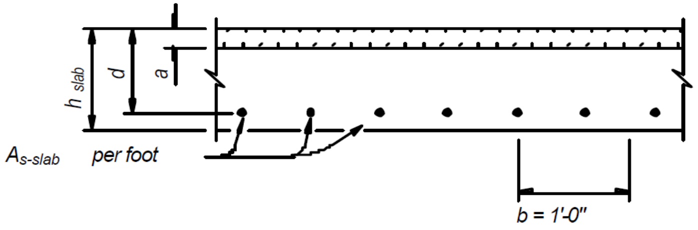
- Concrete Slab Bridges
  - Without integral curbs
    - Rated using equivalent strip approach
  - With integral curbs/beams - Flat Slab (FS)
    - Rated using Illinois Bulletin 346 approach
  - 15 of 23 selected bridges

# Analysis of Concrete Slab Bridges with Integral Curbs

- Illinois Bulletin 346
  - Developed in 1943
  - Provide empirical formula for curb and slab moment demands
  - Currently used by TxDOT to load rate concrete slab bridges with integral curbs (also called FS (Farm Service Road) Bridges in TxDOT Drawings)
- Amer et al. (1999)
  - 27 bridges investigated using grillage analogy
  - Increasing edge beam depth increase in equivalent width
  - $E = 6.89 + 0.23L \leq \frac{W}{N_L}$
  - $C_{edge} = 1.0 + 0.5\left(\frac{d_1}{3.28} - 0.15\right) \geq 1.0$



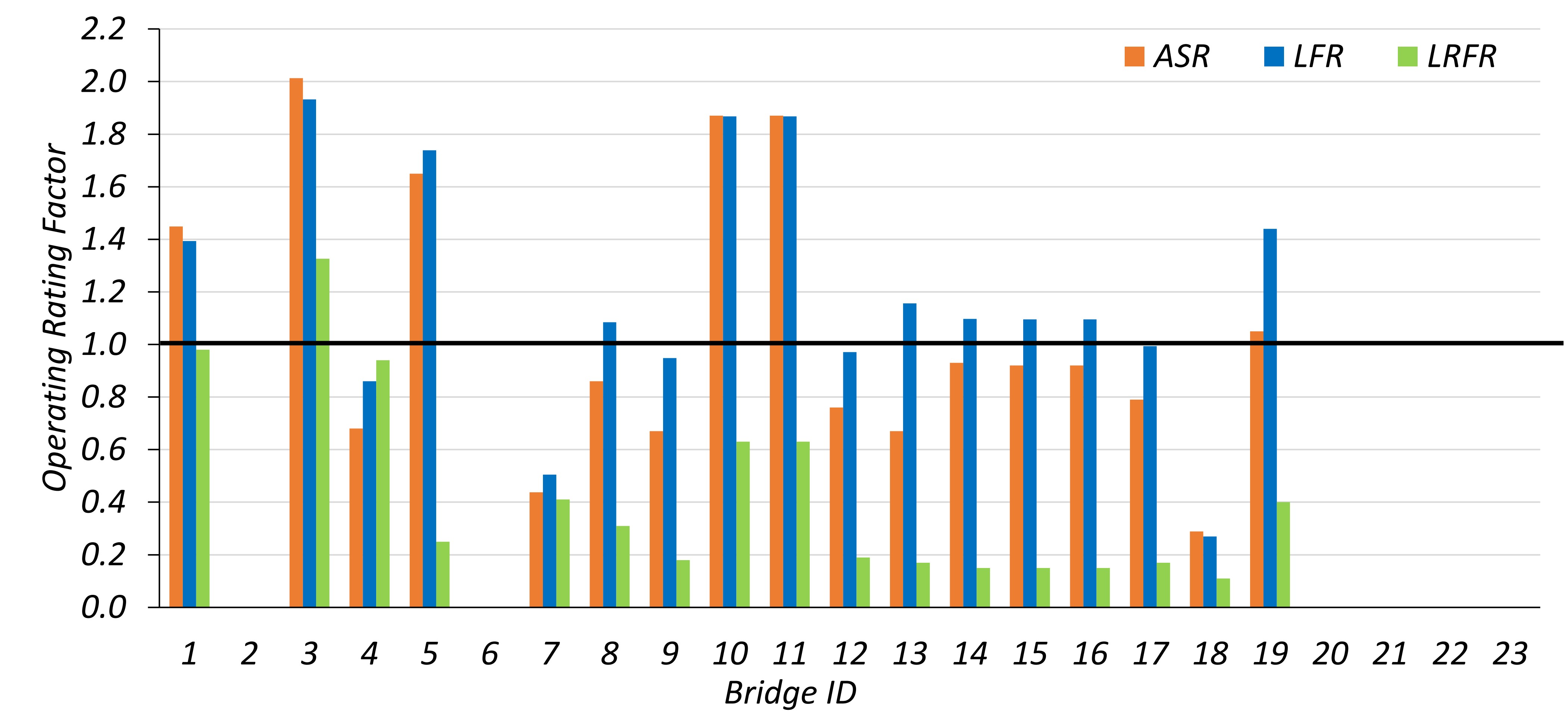

L-curb component




Interior slab

Adapted from TxDOT (2001)

# CS Bridge Flexure Operating RFs

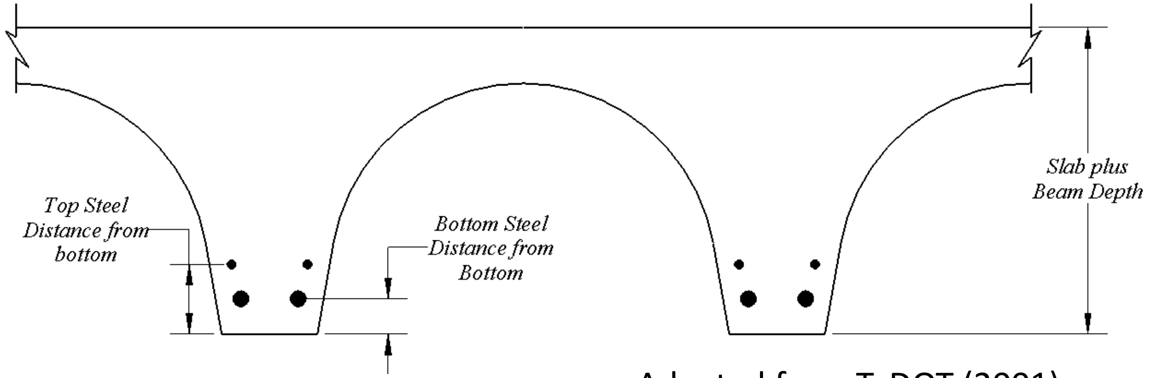



- LRFR provided low flexure RFs than ASR and LFR except for Bridge CS-4

# Simple Span Concrete Multi-Girder Bridges

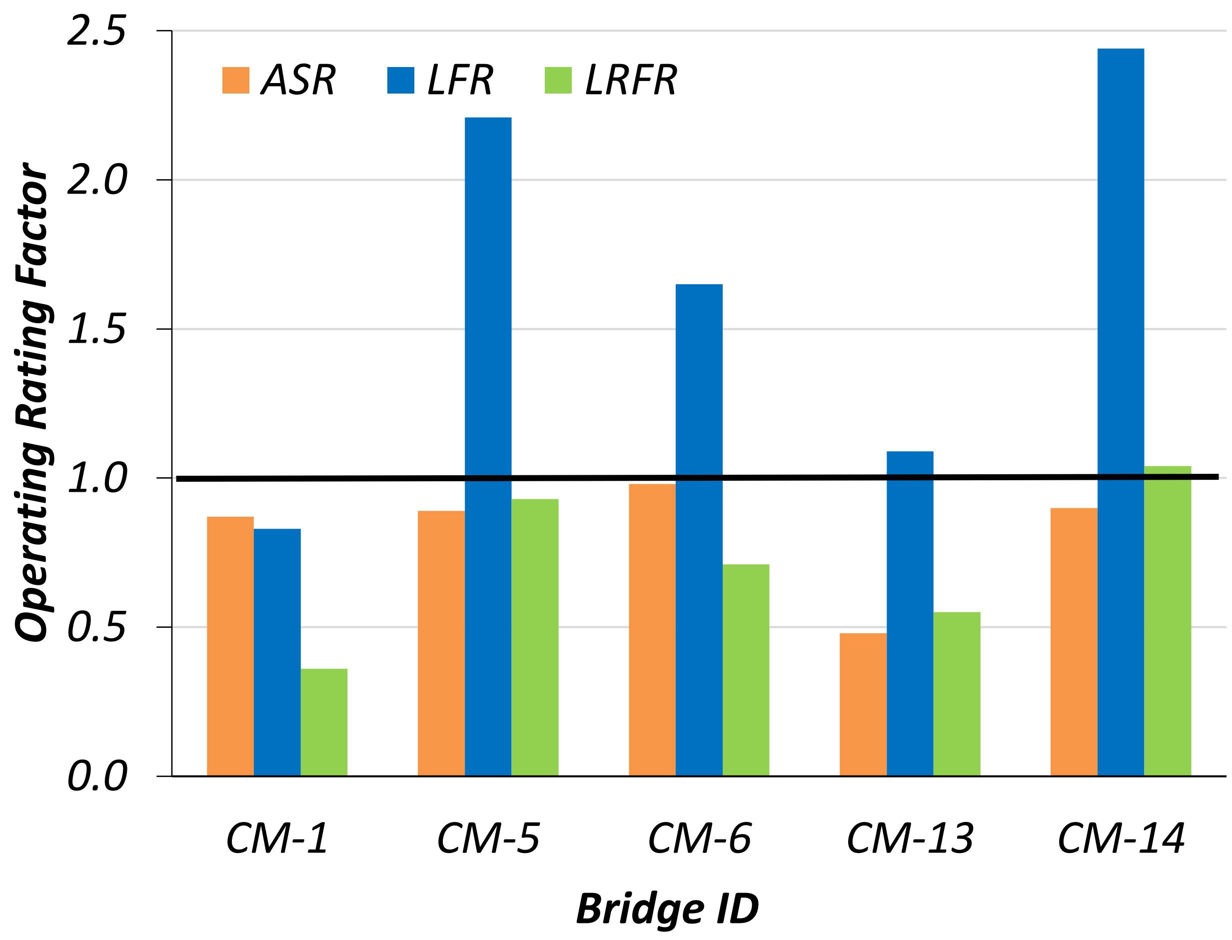
## Subset for Basic Load Rating Analysis

- **14** out of 37 SSLO simple span concrete multi-girder (CM) bridges selected
  - 2 on-system bridges, 12 off-system bridges
- **5** bridges had sufficient information for load rating
  - Year built ranges from **1940 to 2000**
  - Maximum span length ranges from **29 to 40 ft**
  - Deck width ranges from **21 to 35 ft**




Adapted from TxDOT (2001)

# CM Bridge Calculated Flexure RFs




- LFR provided high flexure RFs than ASR and LRFR except for Bridge CM-1

# Possible Areas for Opportunity to Improve Load Ratings

- Partial Composite Action (for steel bridges)
- Live Load Distribution Factors
- Updated Material Properties
- Partial Fixity at Supports
- Refined Analysis Models

# Refined Analysis of Selected Typical Bridges

# Steel Multi-Girder Bridge

## Bridge SM-5

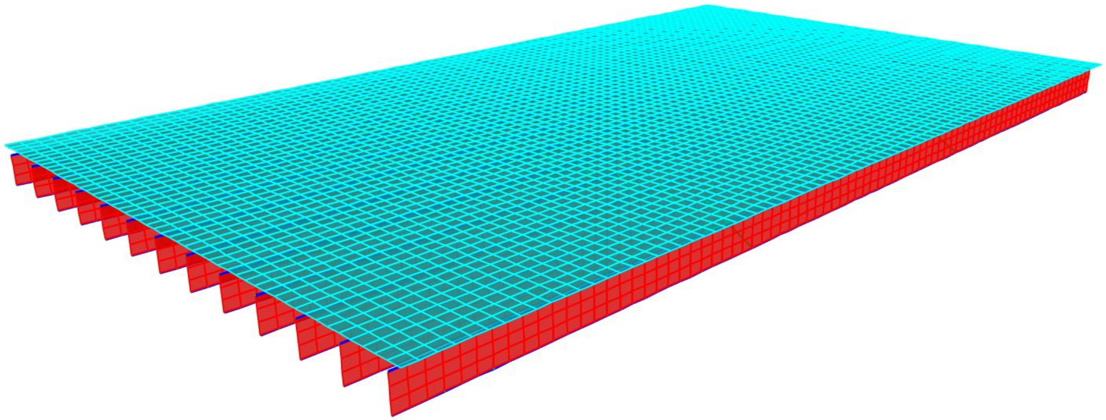
| ID | Route Prefix | Year Built | ADT | Max. Span Length (ft) | Deck Width (ft) | Girder Spacing (ft-in.) | Condition Rating | | | Operating HS20 Rating Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Deck | Superstructure | Substructure | |
| Avg. | - | 1974 | - | 36 | 20 | 4'-3" | 6 (satisfactory) | 6 (satisfactory) | 6 (satisfactory) | 0.83 |
| SM-5 | 3 (On-system) | 1938 | 300 | 41 | 24 | 1'-11" | 7 (good) | 6 (satisfactory) | 7 (good) | 0.79 |

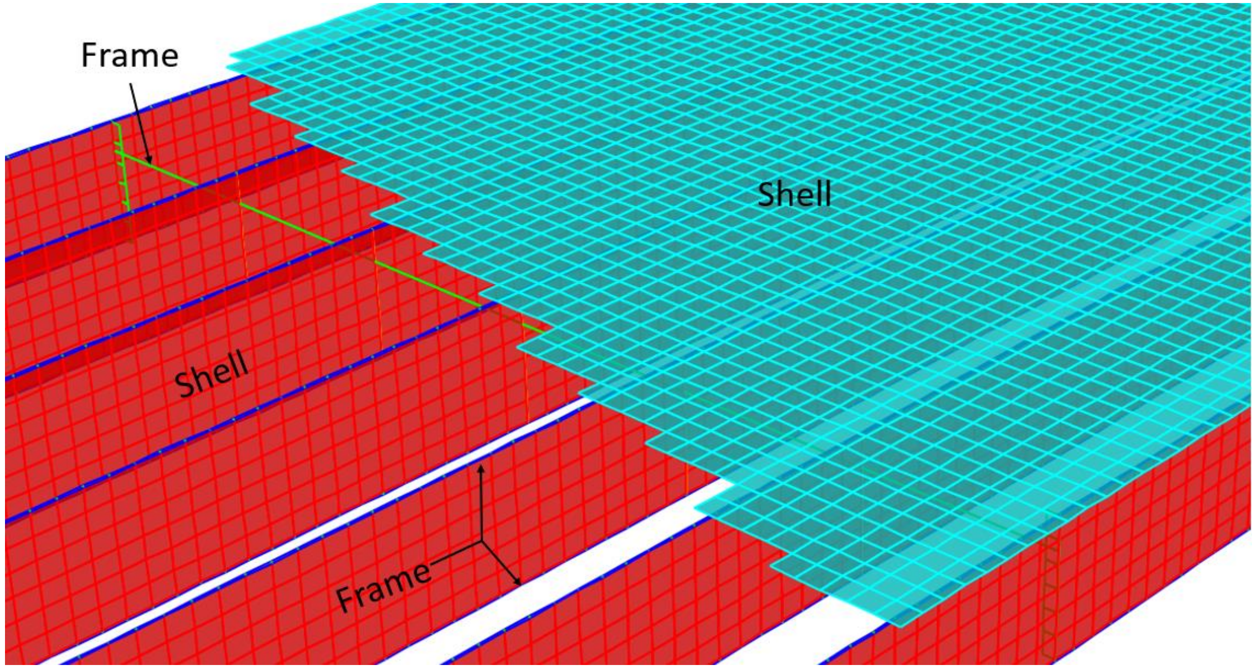
Carries PR 40 and traverses Big Chinquapin Creek near Huntsville, approximately 1.0 mi southwest of I-45

# Model Development

## Bridge SM-5

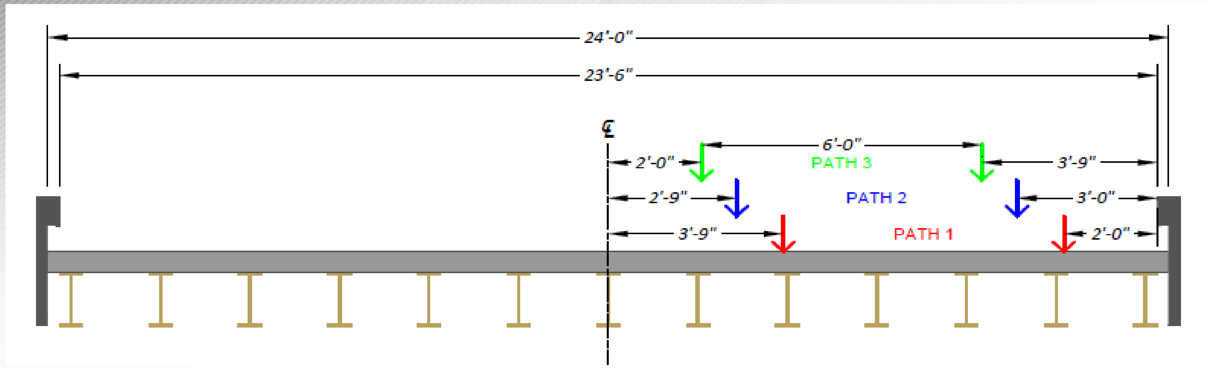
- SM-5 was modeled using the commercial software CSiBridge
- Mesh sensitivity analysis was conducted, and a maximum mesh size of 6 in. was used
- Model was verified by comparing midspan moments and end shears to expected values from structural analysis



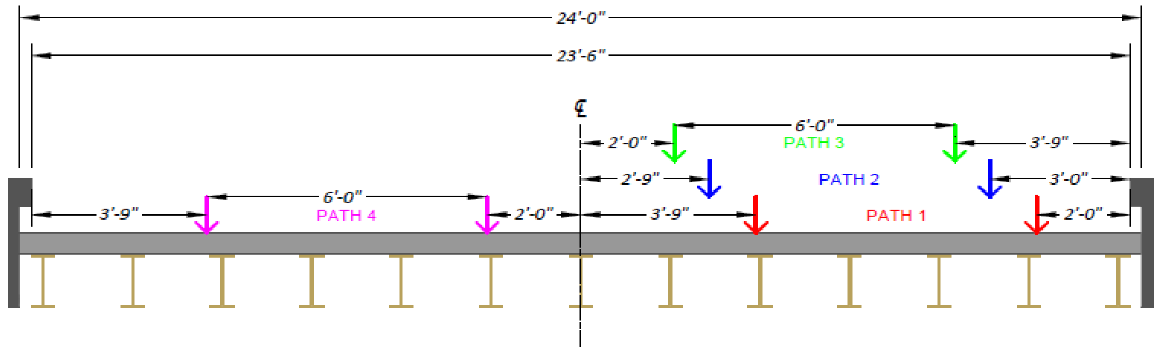


# Load Paths

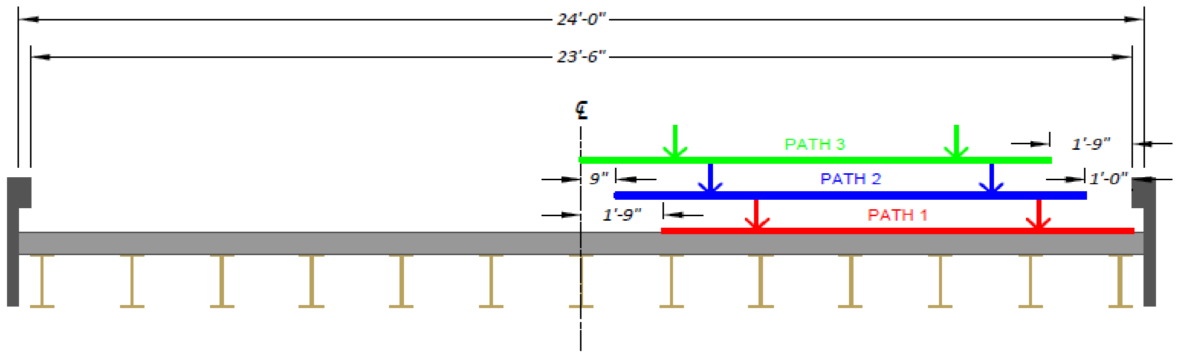
## Bridge SM-5



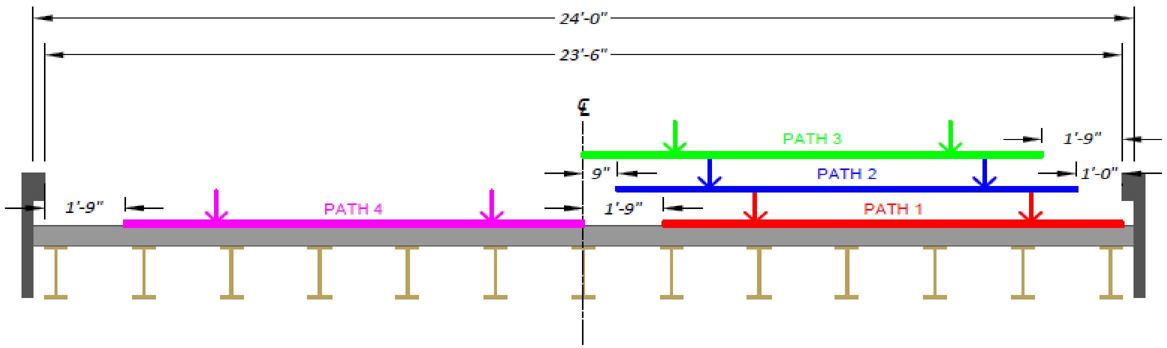

One-Lane HS20




Two-Lane HS20




One-Lane HL93




Two-Lane HL93

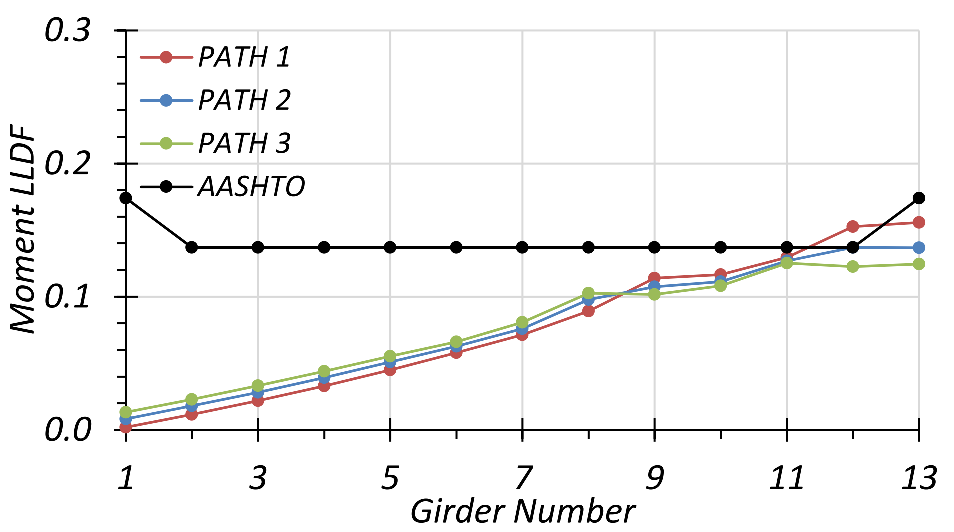
$$LLDF = \frac{M_i}{\sum M_i}$$

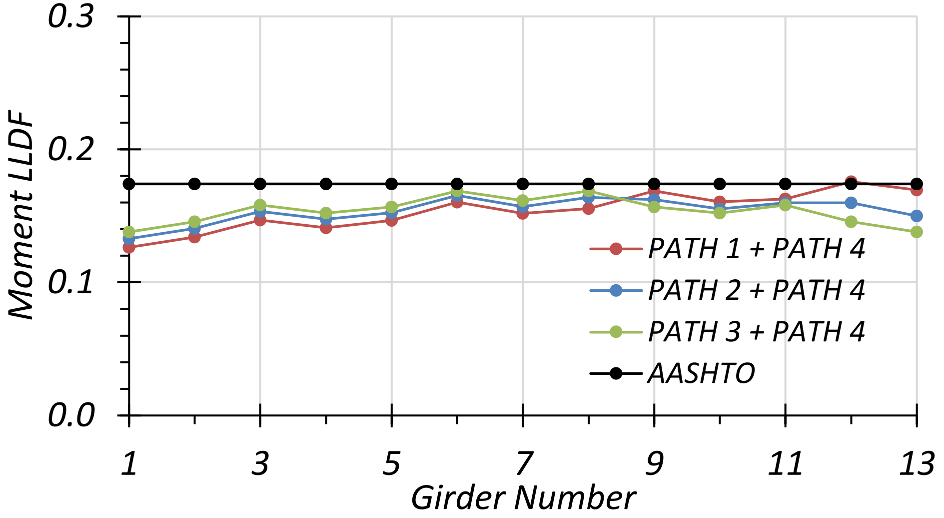
# HS20 Moment LLDFs

## Bridge SM-5

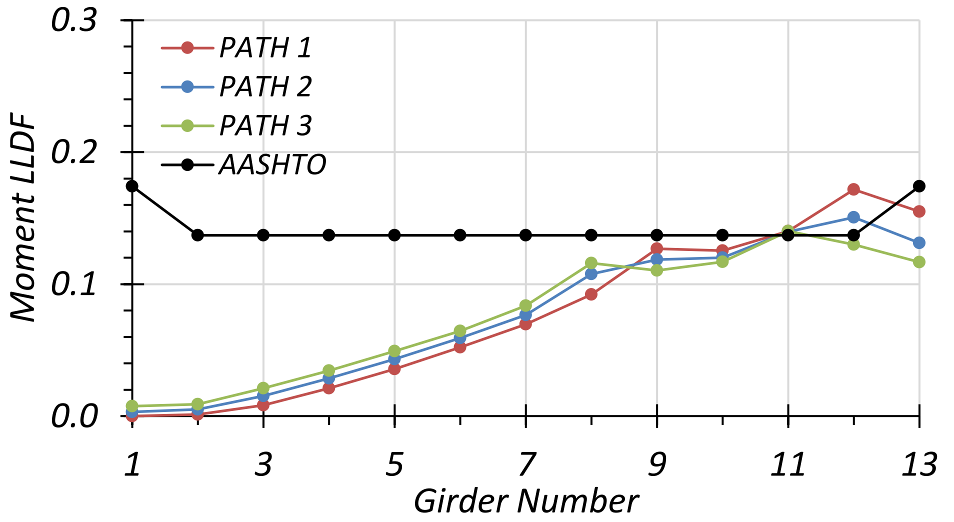
**One-Lane** **Two-Lane**

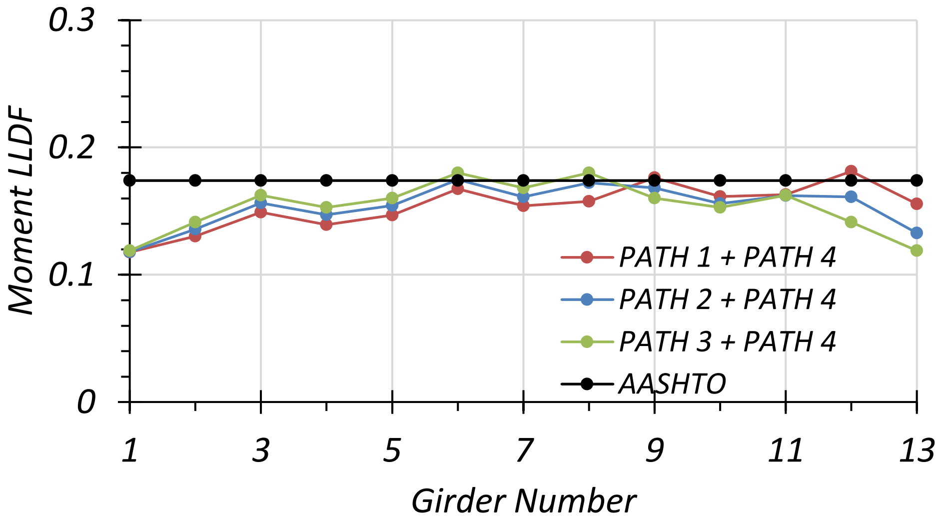
**Non-Composite**




**Composite**




Texas Department of Transportation

AASHTO Standard Specifications provide a good estimate of the maximum LLDFs from the analysis.

Texas A&M Transportation Institute

TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

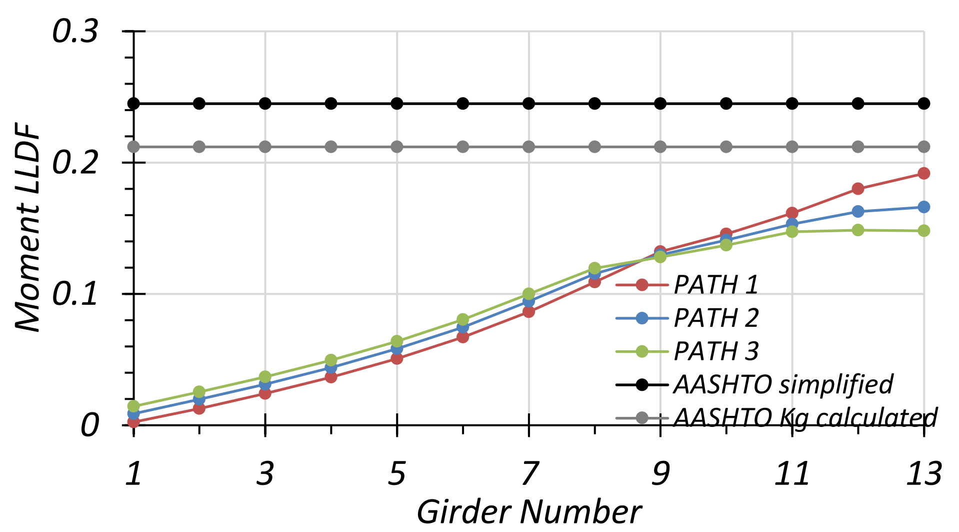
$$LLDF = \frac{M_i}{\sum M_i}$$

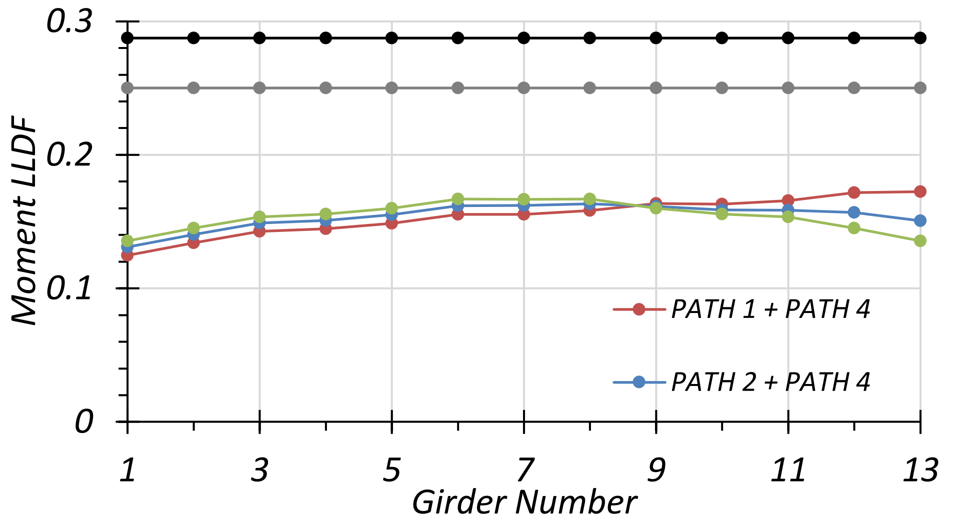
# HL93 Moment LLDFs

## Bridge SM-5

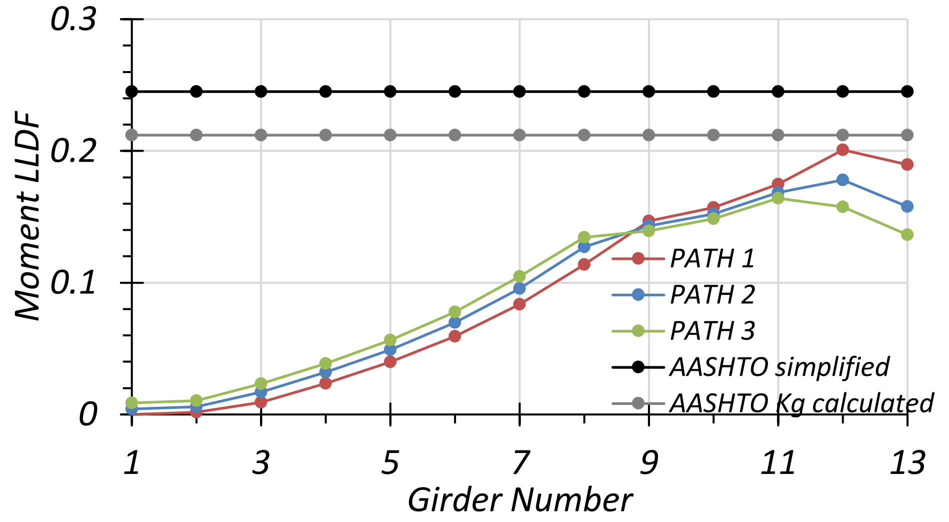
**One-Lane** | **Two-Lane**

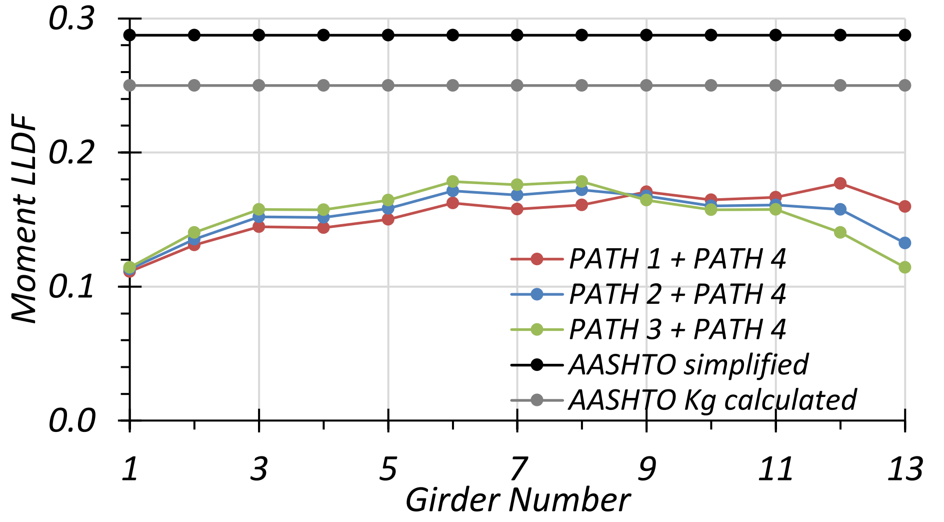
**Non-Composite**




**Composite**




AASHTO LRFD Specifications give conservative LLDFs, especially for two-lane loading

Texas Department of Transportation

Texas A&M Transportation Institute

# Steel Continuous Multi-Girder Bridge

## Bridge SC-12

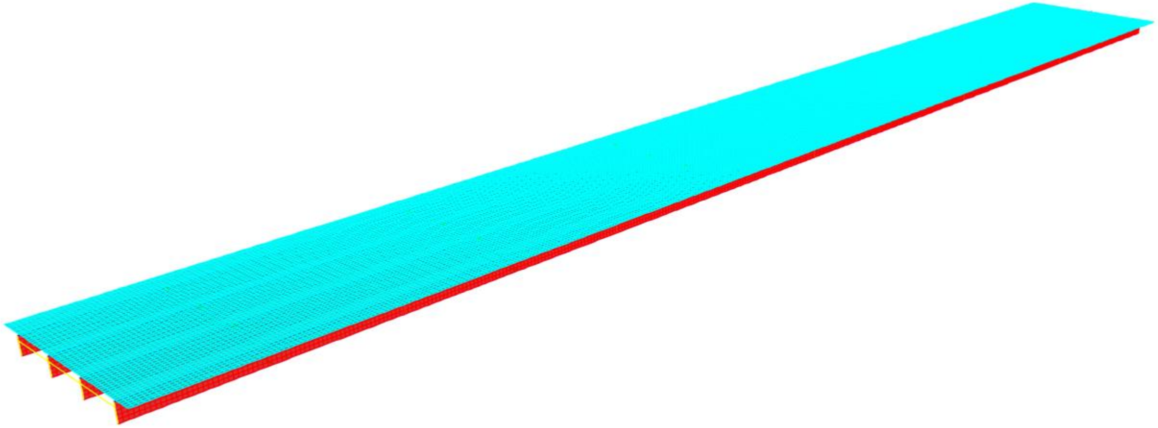
| ID | Route Prefix | Year Built | ADT | Max. Span Length (ft) | Deck Width (ft) | Girder Spacing (ft-in.) | Condition Rating | | | Operating HS20 Rating Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Deck | Super-structure | Sub-structure | |
| Avg. | - | 1962 | - | 25 | 20 | 3'-9" | 6 (Satisfactory) | 6 (Satisfactory) | 6 (Satisfactory) | 0.85 |
| SC-12 | 3 (On-System) | 1959 | 260 | 75 | 26 | 6'-8" | 6 (Satisfactory) | 7 (Good) | 7 (Good) | 0.93 |

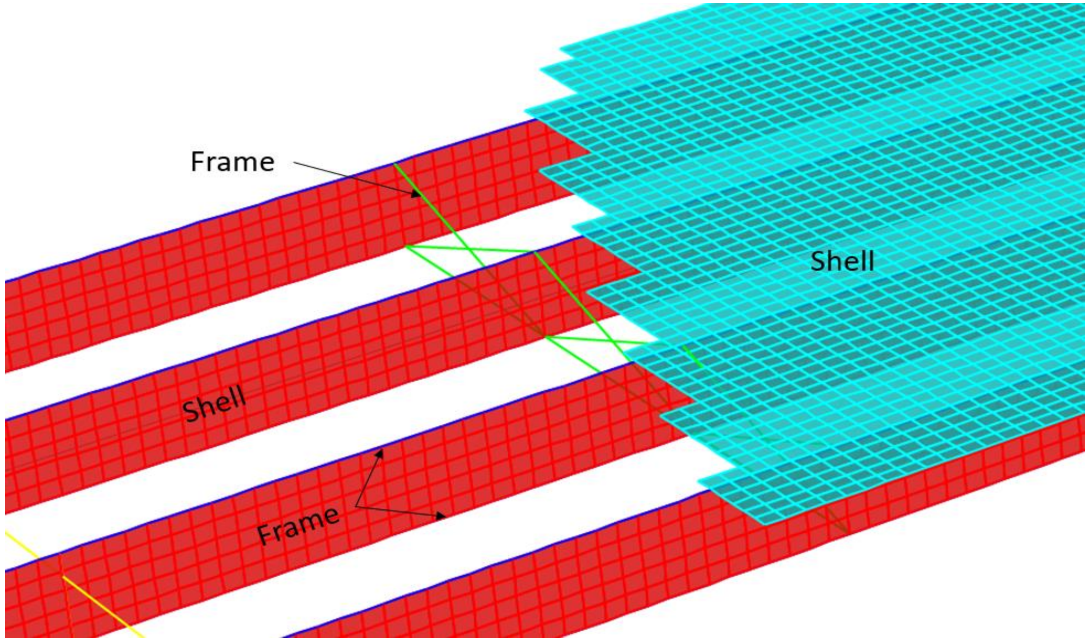
Carries FM 1047 and traverses Simms Creek near Lometa, approximately 0.9 miles northwest of FM 581

# Model Development

## Bridge SC-12

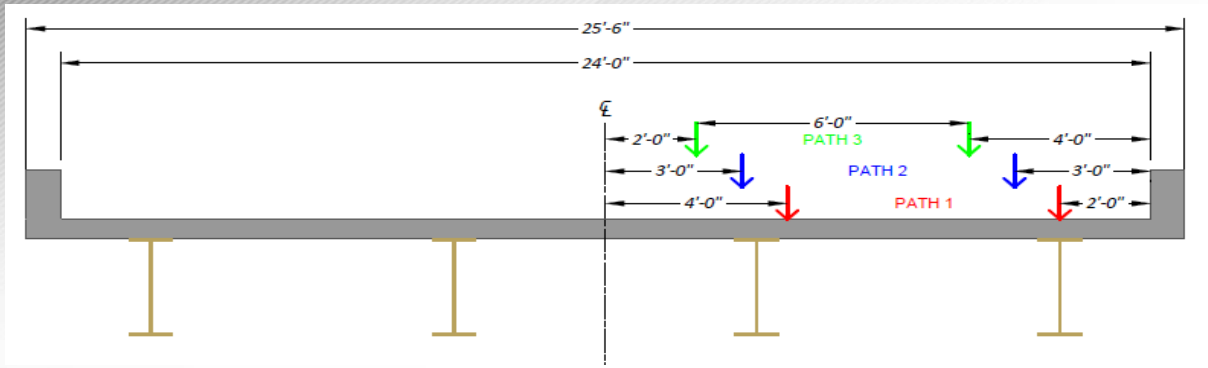
- SC-12 was modeled using the commercial software CSiBridge
- A maximum mesh size of 6 in. was used based on the mesh sensitivity analysis performed for Bridge SM-5
- Models were verified by comparing midspan moments and end shears to expected values from structural analysis



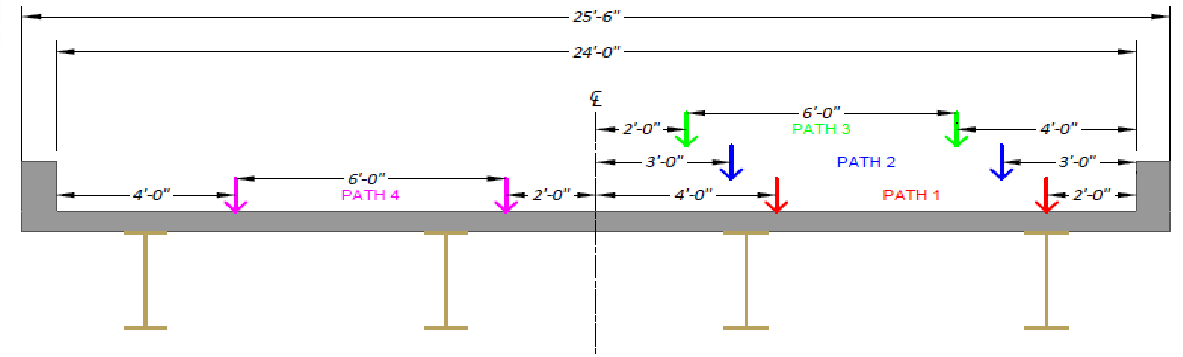


# Load Paths

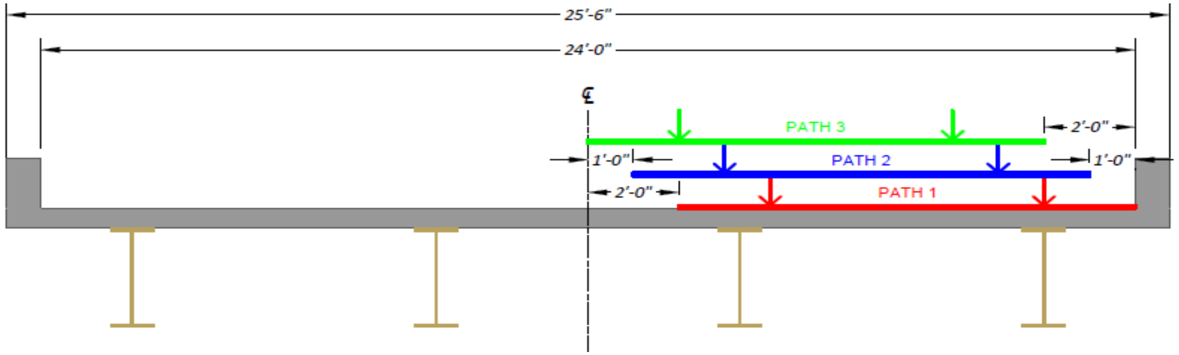
## Bridge SC-12



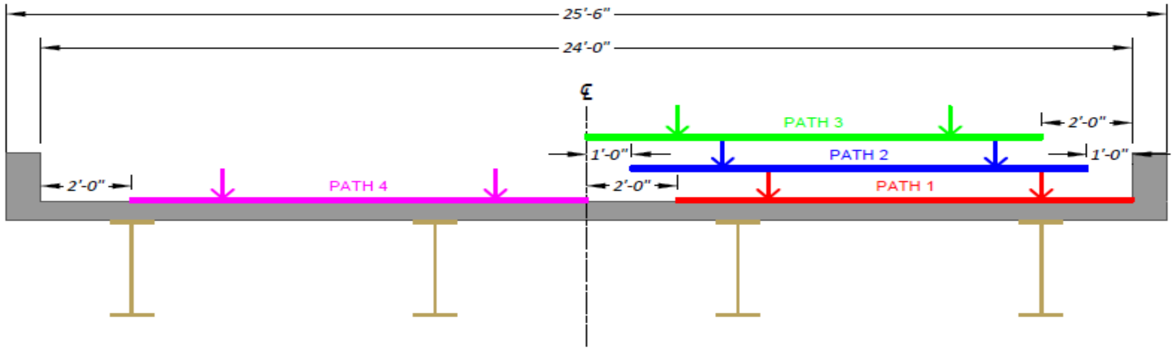

One-Lane HS20




Two-Lane HS20




One-Lane HL93

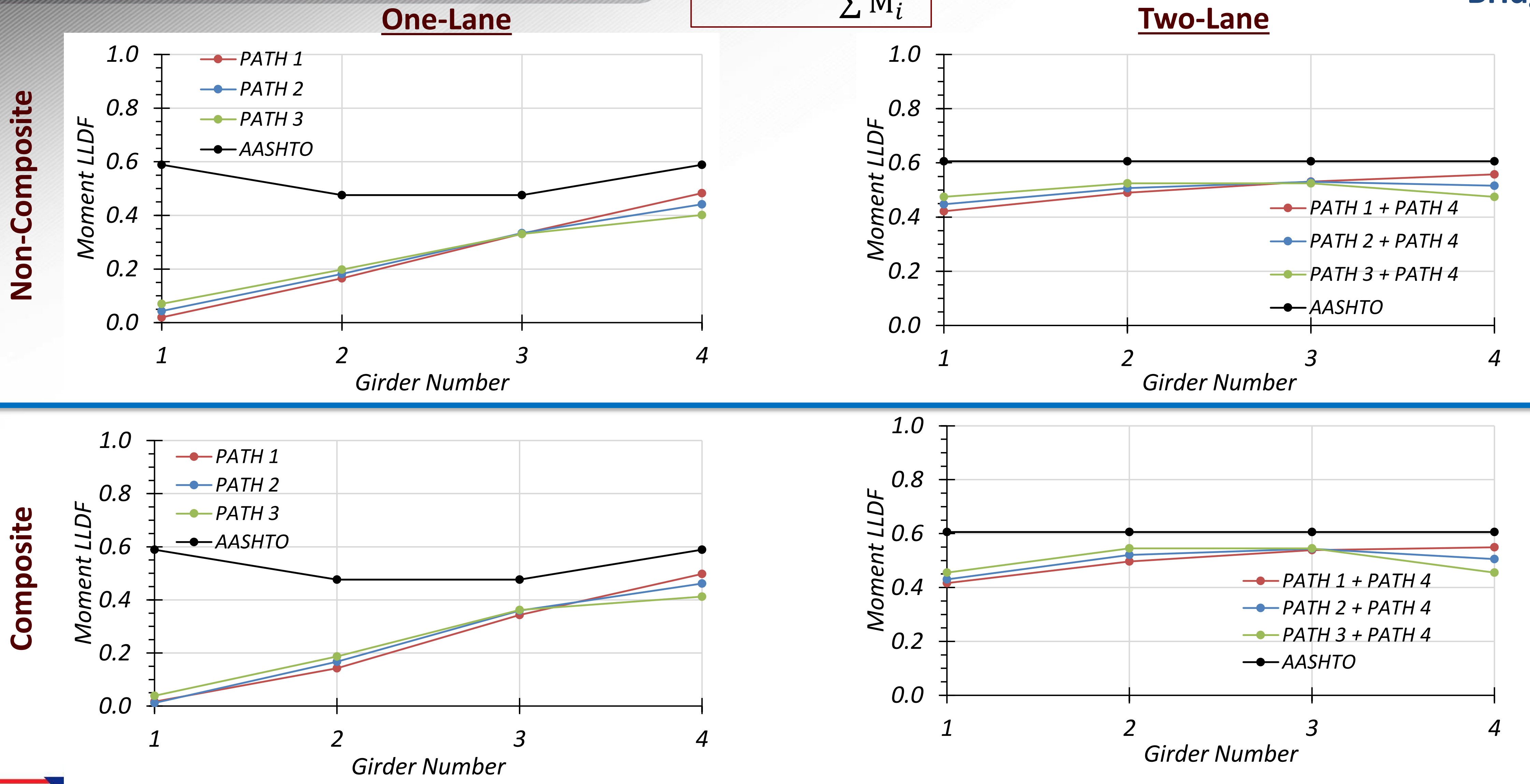



Two-Lane HL93

# HS20 Positive Moment LLDFs

## Bridge SC-12

$$LLDF = \frac{M_i}{\sum M_i}$$




AASHTO Standard Specifications provide slightly conservative LLDFs compared to the analysis.

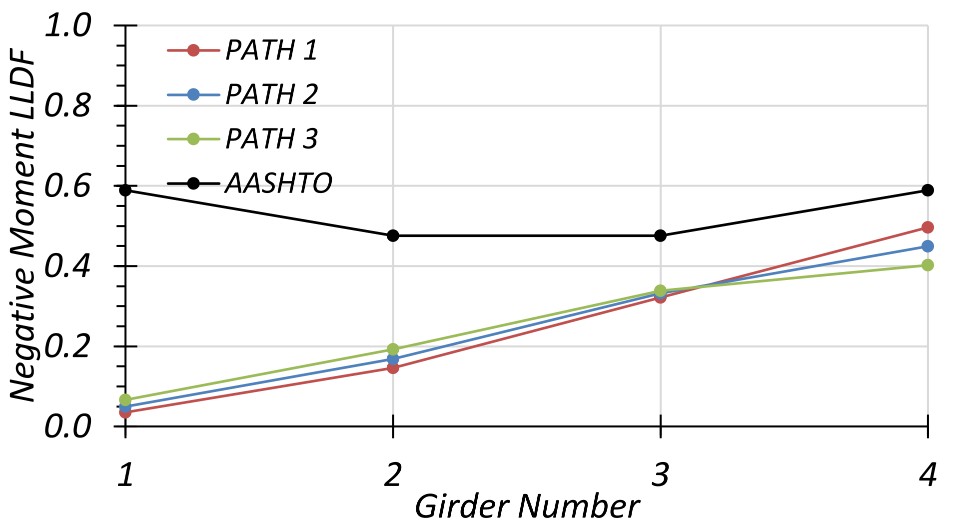
# HS20 Negative Moment LLDFs

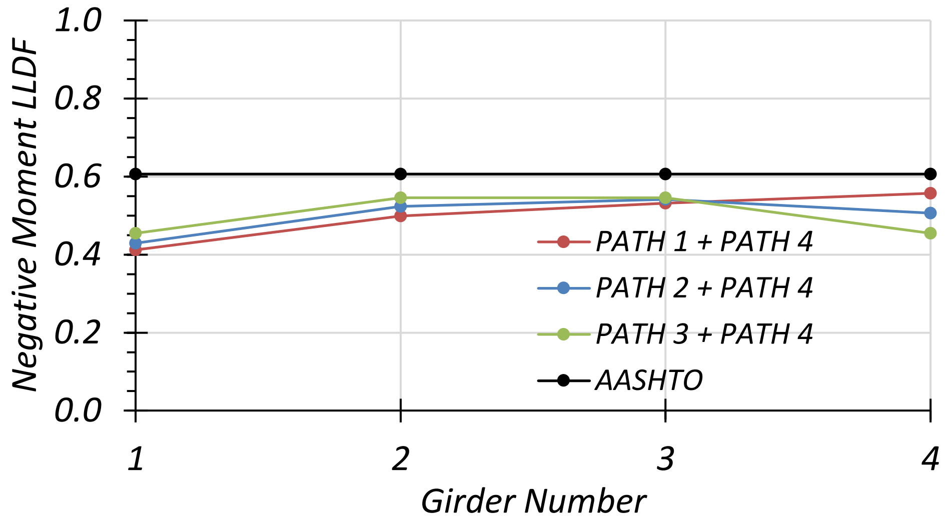
## Bridge SC-12

$$LLDF = \frac{M_i}{\sum M_i}$$

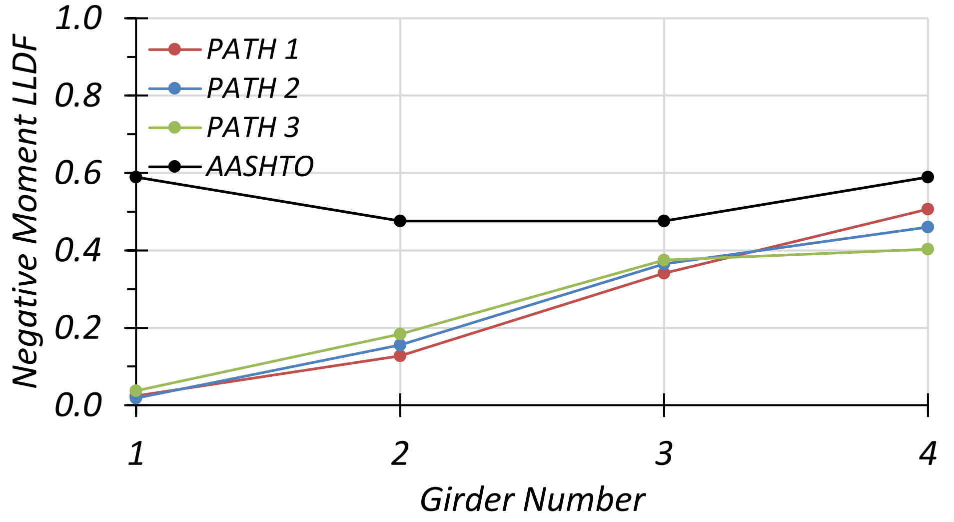
**One-Lane** | **Two-Lane**

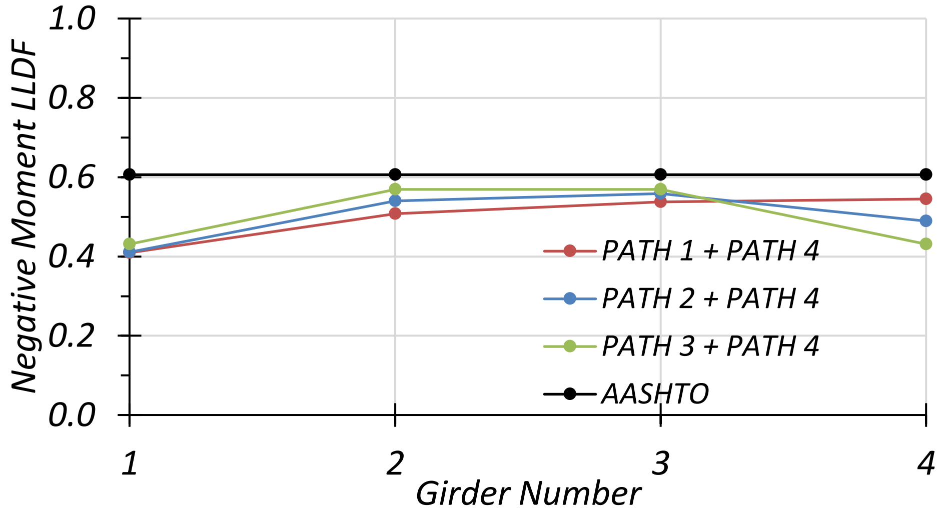
**Non-Composite**




**Composite**




AASHTO Standard Specifications provide slightly conservative LLDFs compared to the analysis.

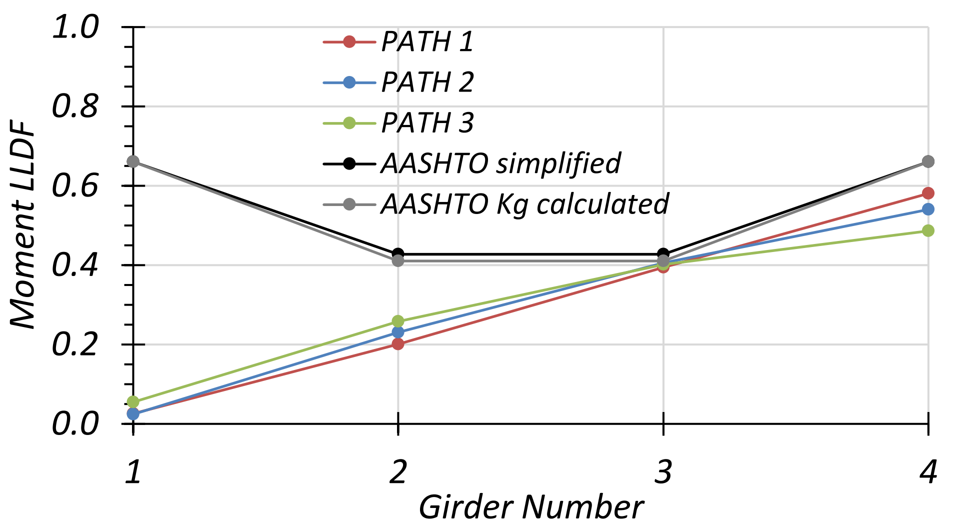
# HL93 Positive Moment LLDFs

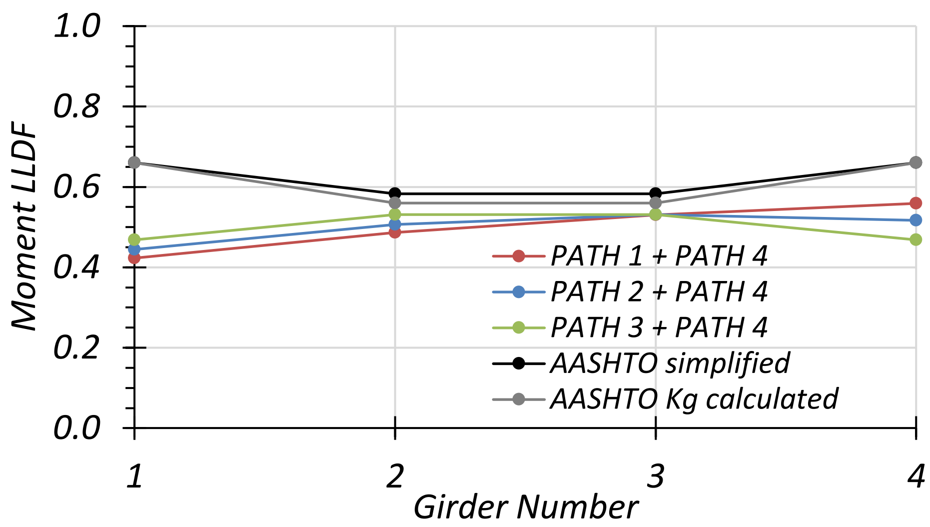
## Bridge SC-12

$$LLDF = \frac{M_i}{\sum M_i}$$

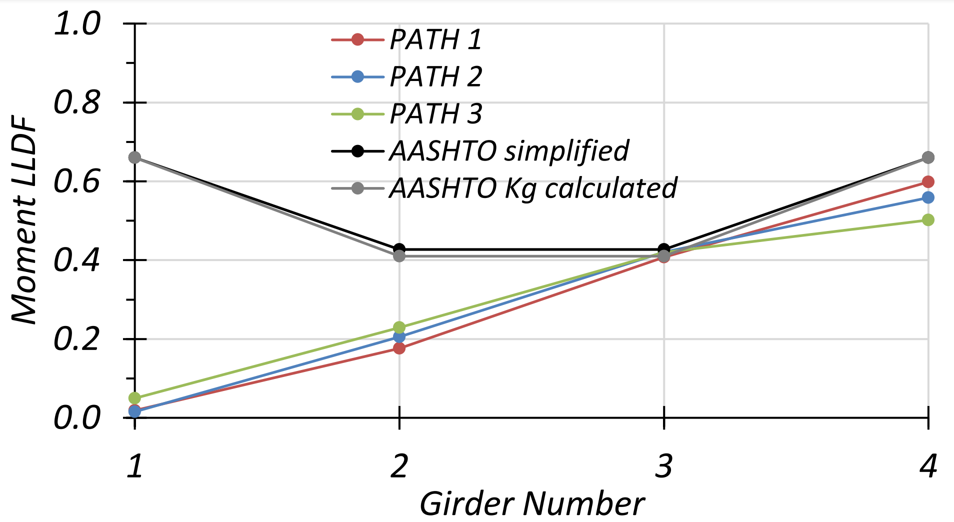
**One-Lane** / **Two-Lane**

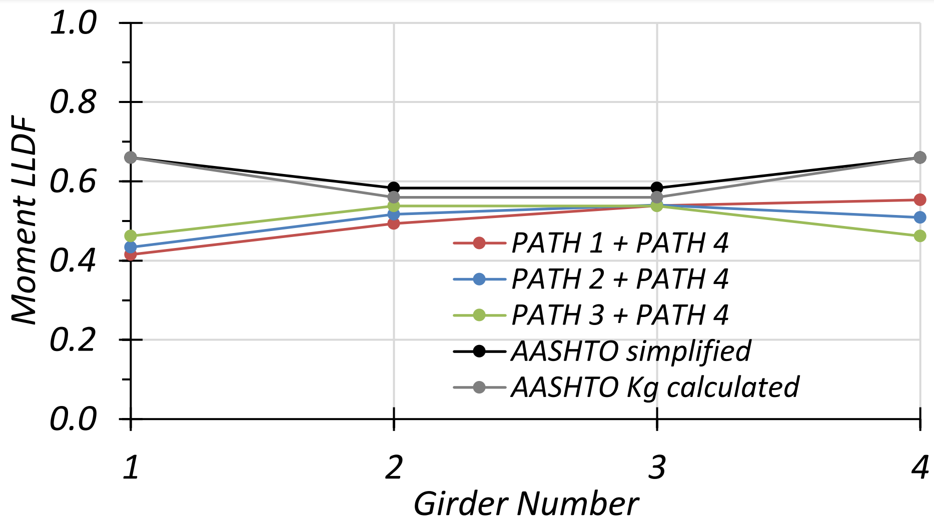
**Non-Composite**




**Composite**




AASHTO LRFD Specifications provide a good estimate of the maximum LLDFs from the analysis.

TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

# HL93 Negative Moment LLDFs

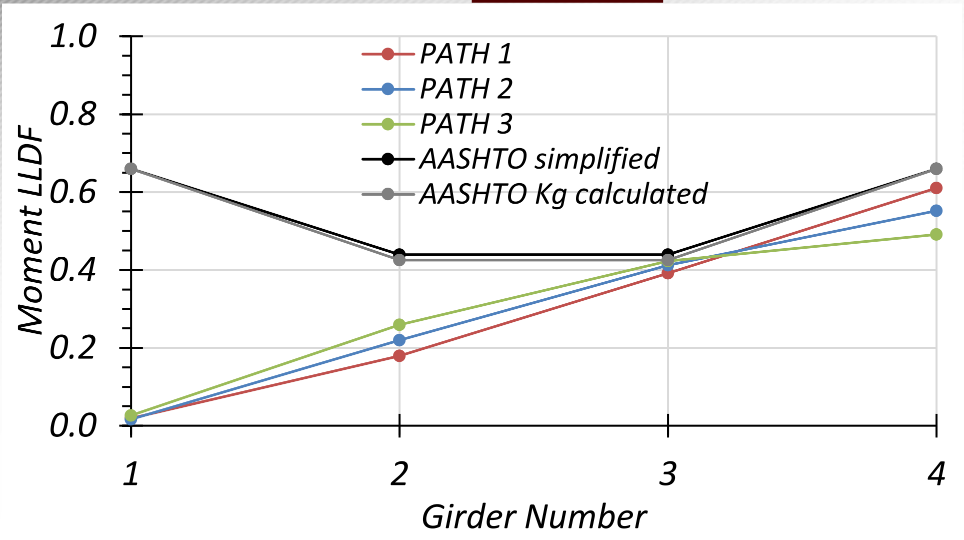
## Bridge SC-12

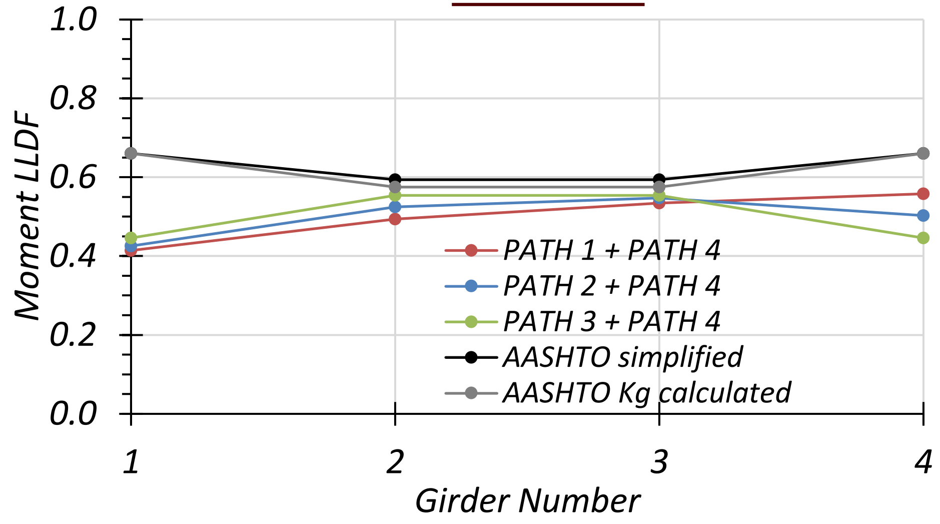
$$LLDF = \frac{M_i}{\sum M_i}$$

**One-Lane**

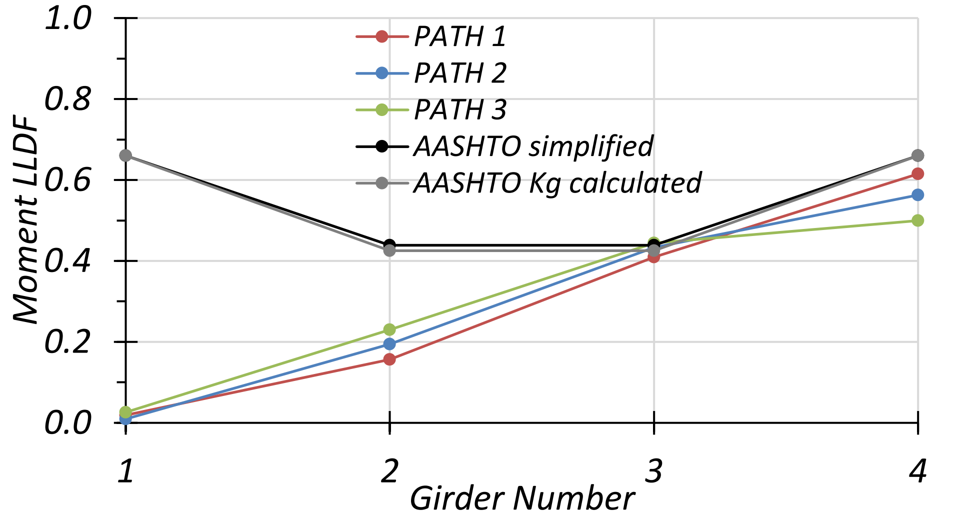
**Two-Lane**

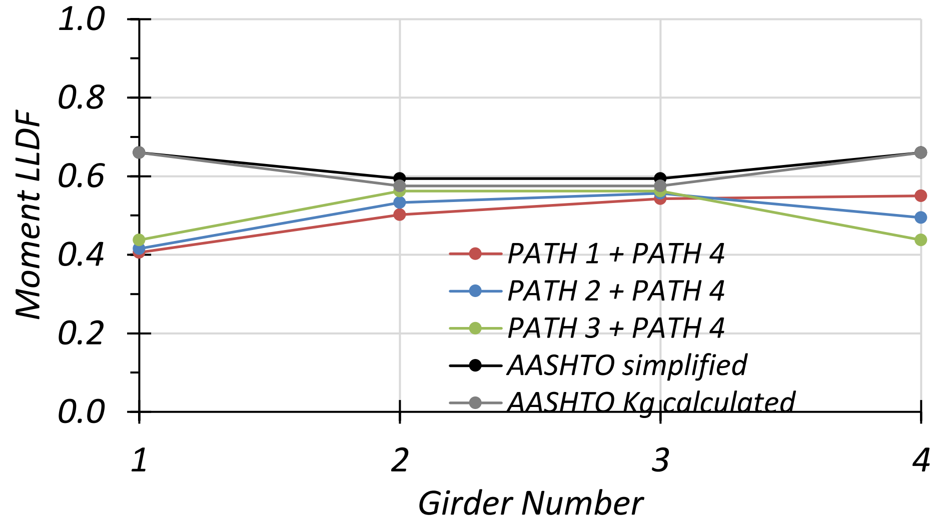
**Non-Composite**




**Composite**




AASHTO LRFD Specifications provide a good estimate of the maximum LLDFs from the analysis.

# Conclusions from FEM Analysis

## Bridge SM-5 and Bridge SC-12

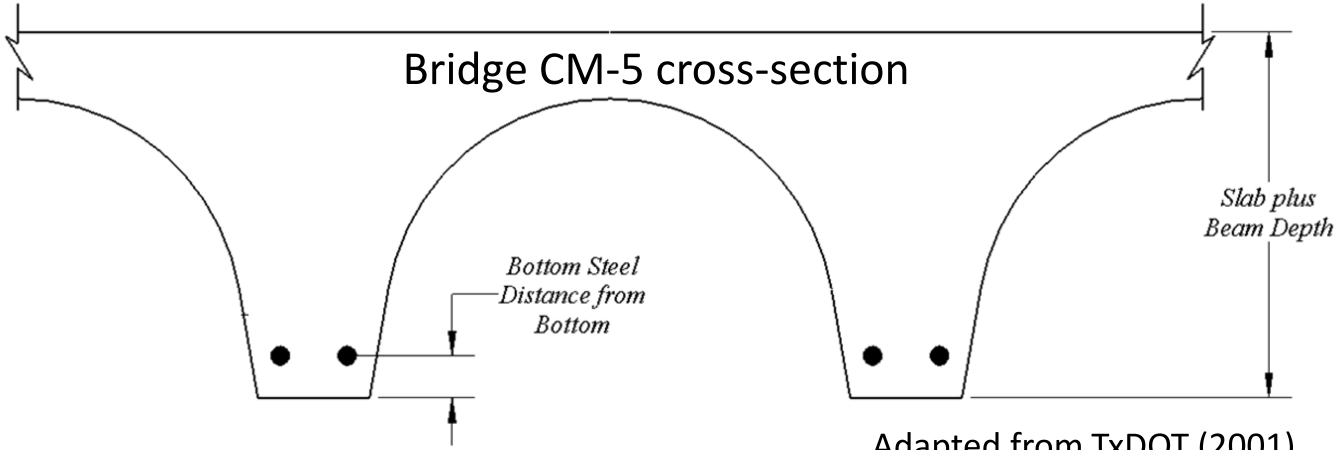
- TxDOT currently rates both steel bridges using the LFR method
  - AASHTO Standard Specification LLDFs
- Changes to LLDF calculations do not significantly affect the rating factors
- Composite action seems to slightly increase the controlling LLDFs, however, not significantly

→Bridges SM-5 and SC-12 were field tested to update and calibrate the FEM models

# Concrete Multi-girder Bridge

## Bridge CM-5

| ID | Dist. to CS (mi) | Route Prefix | Year Built | ADT | Max. Span Length (ft) | Deck Width (ft) | Condition Rating | | | Operating HS20 Rating Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Deck | Super-structure | Sub-structure | |
| Avg. | - | - | 1964 | - | 34 | 28 | 7 (Good) | 7 (Good) | 6 (Satisfactory) | 0.99 |
| CM-4 | 32 | 4 (Off-System) | 1950 | 250 | 29 | 22 | 7 (Good) | 7 (Good) | 5 (Fair) | 0.99 |

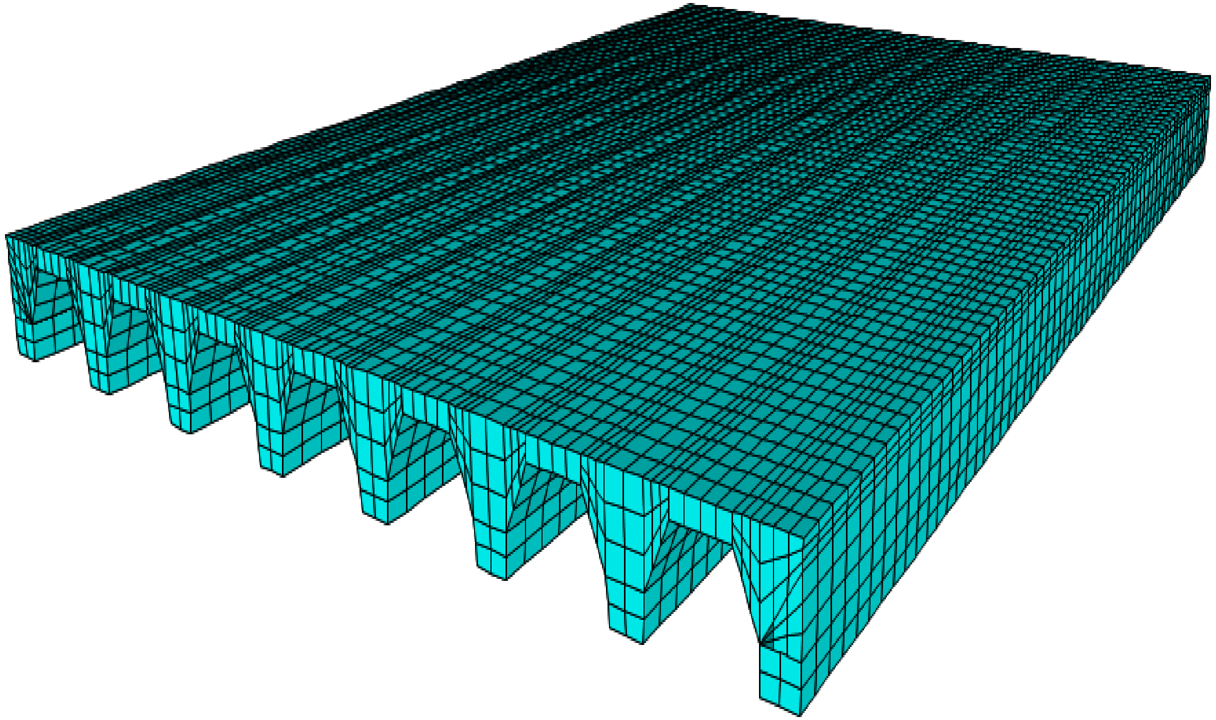



Adapted from TxDOT (2001)

# Model Development

## Bridge CM-5

- 3D FEM model developed in CSiBridge
  - Simply-supported ends
- Mesh sensitivity analysis using 4 in., 6 in, 12in., and 18 in. mesh sizes
  - 6 in. mesh size selected
- Initial model verification conducted by comparing midspan moments and end shears to expected values from structural analysis

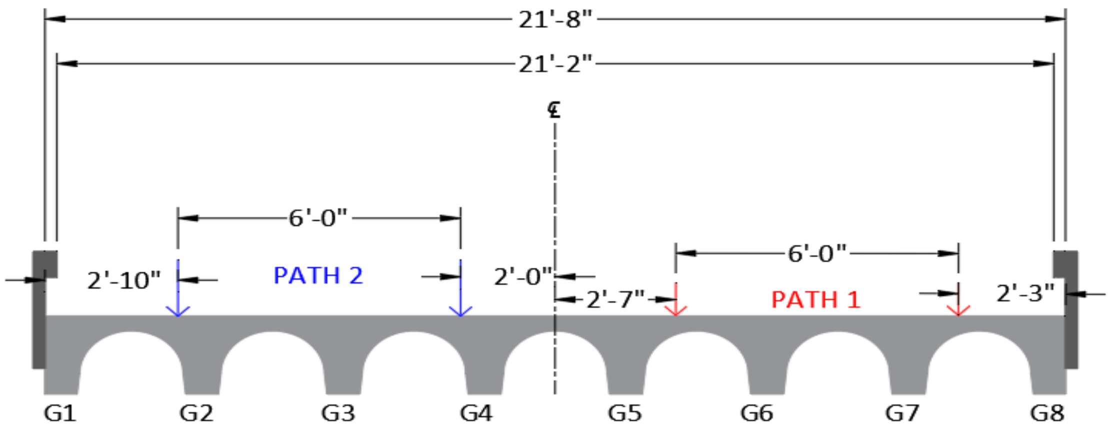


Bridge CM-5 FEM Model (6 in. mesh)

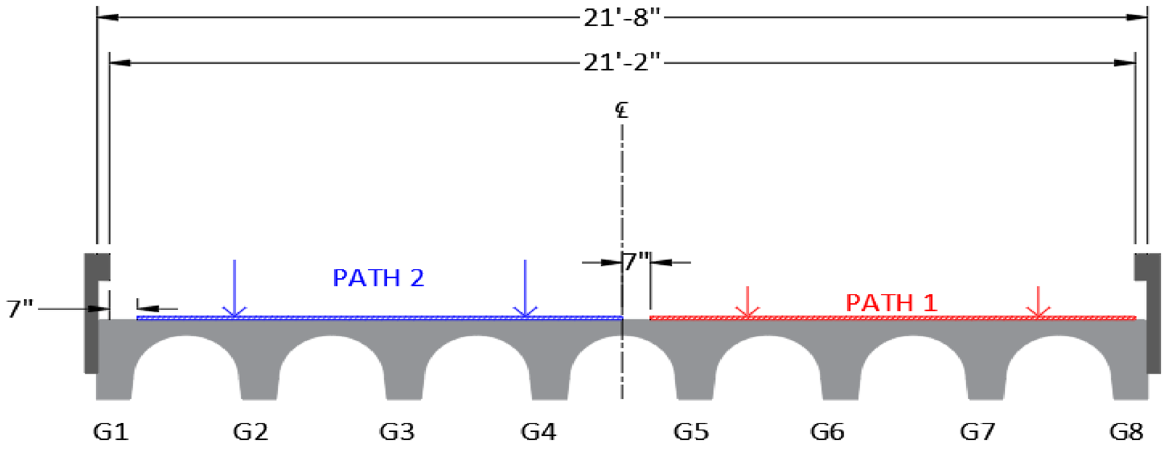
# Load Paths

## Bridge CM-5

- Defined based on AASHTO recommendations
- Path 1: 2 ft from edge of barrier
- Path 2: 2 ft from centerline of bridge
- HL93 design load → add lane load to the above truck configurations




HS-20 Truck




HL93 Design Load

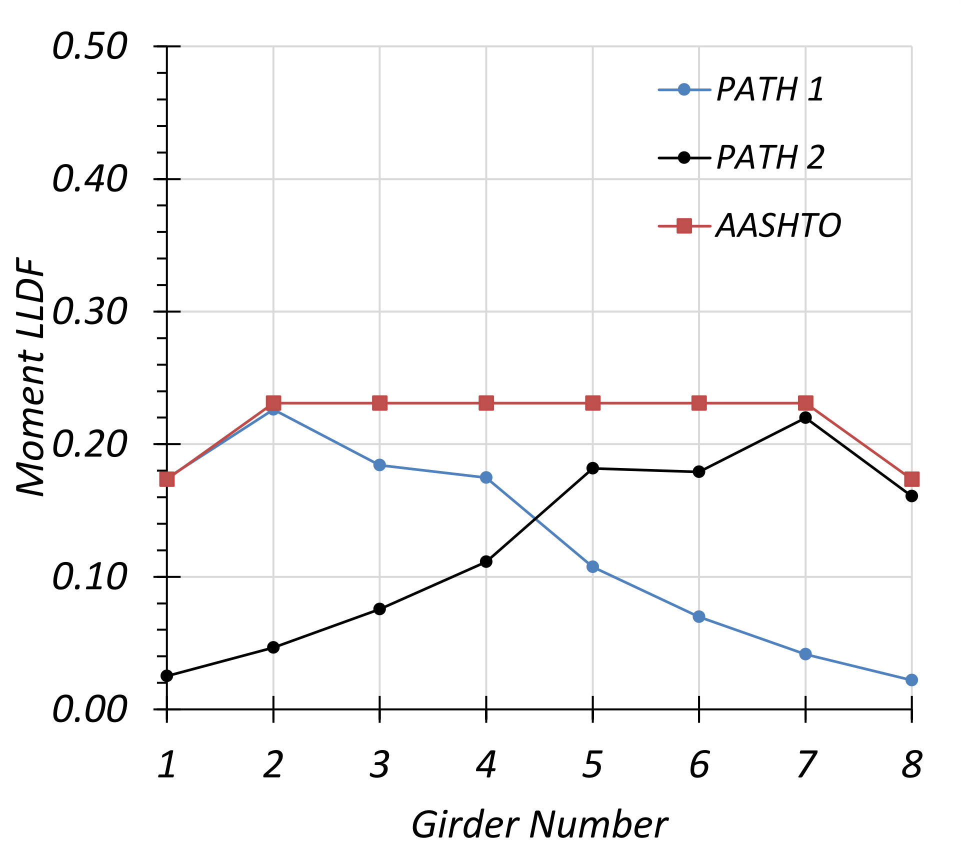
Updated – 08/04/2021

# HS-20 Moment LLDFs

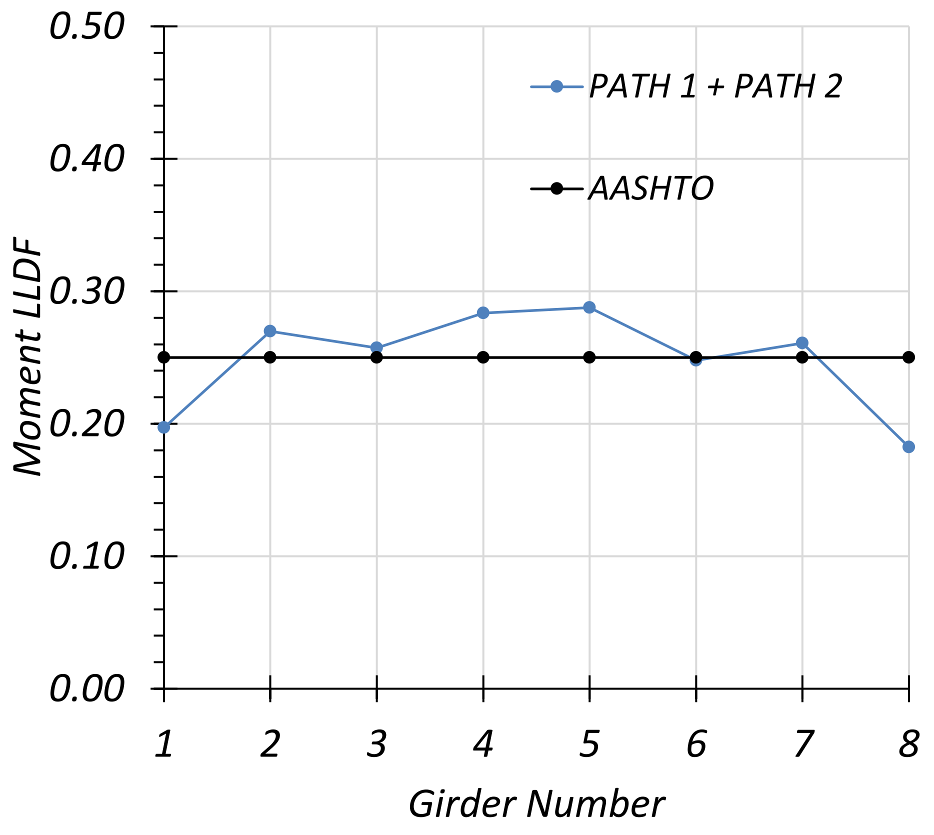
## Bridge CM-5

$$LLDF = \frac{M_i}{\sum M_i}$$

**One-lane**




**Two-lane**



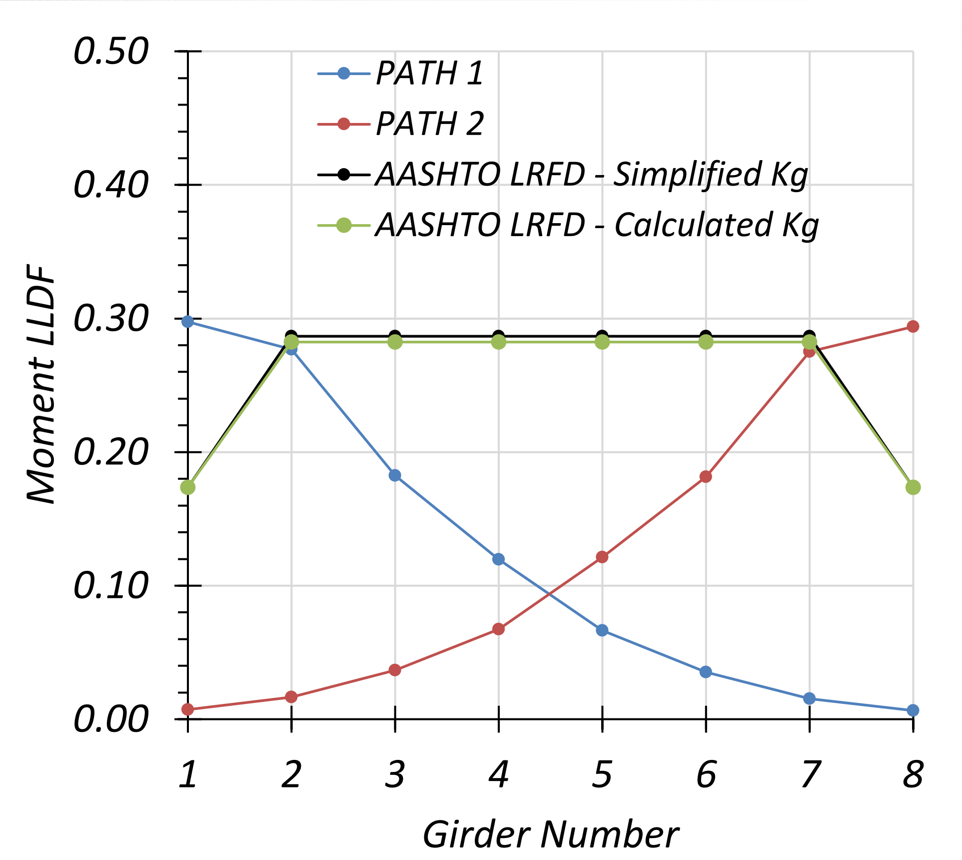

- AASHTO Standard accurately estimate the maximum LLDFs for one-lane loading
- AASHTO Standard slightly unconservative for two-lane LLDFs

Updated – 08/04/2021

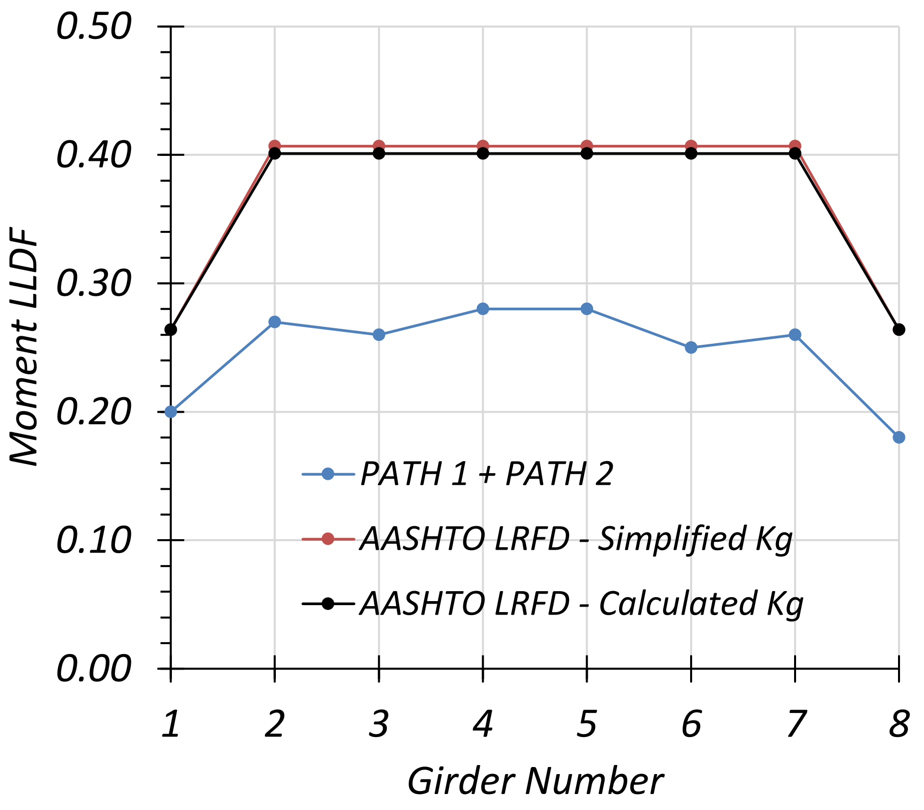
# HL-93 Moment LLDFs

## Bridge CM-5

### One-Lane




### Two-Lane




- AASHTO LRFD conservative for interior girder LLDFs for one-lane loading
- AASHTO LRFD unconservative for two-lane LLDFs

# Concrete Slab Bridge

## Bridge CS-9

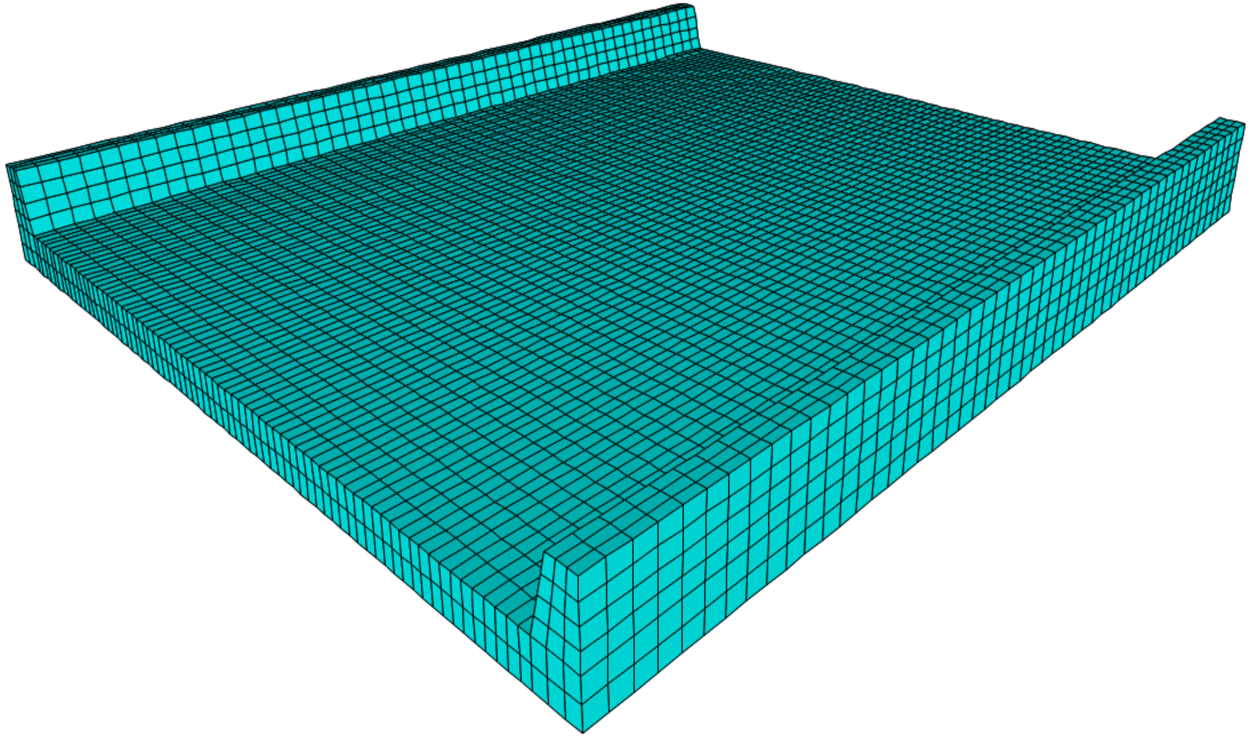
| ID | Dist. to CS (mi) | Route Prefix | Year Built | ADT | Max. Span Length (ft) | Deck Width (ft) | Condition Rating | | | Operating HS20 Rating Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Deck | Super-structure | Sub-structure | |
| Avrg. | - | - | 1949 | 795 | 22 | 28 | 6 (Satisfactory) | 6 (Satisfactory) | 6 (Satisfactory) | 0.98 |
| CS-9 | 157 | 3 (On-system) | 1948 | 30 | 25 | 21 | 6 (Satisfactory) | 6 (Satisfactory) | 7 (Good) | 0.94 |

Carries FM 216 and traverses the Flag Creek near Walnut Springs, approximately 7.0 miles north of FM 927

# Model Development

## Bridge CS-9

- 3D FEM model developed in CSiBridge
  - Simply-supported ends
- Mesh sensitivity analysis using 4 in., 6 in, 12in. and 18 in. mesh
  - 6 in. mesh size selected
- Initial model verification is done by comparing midspan moments and end shears to expected values from structural analysis

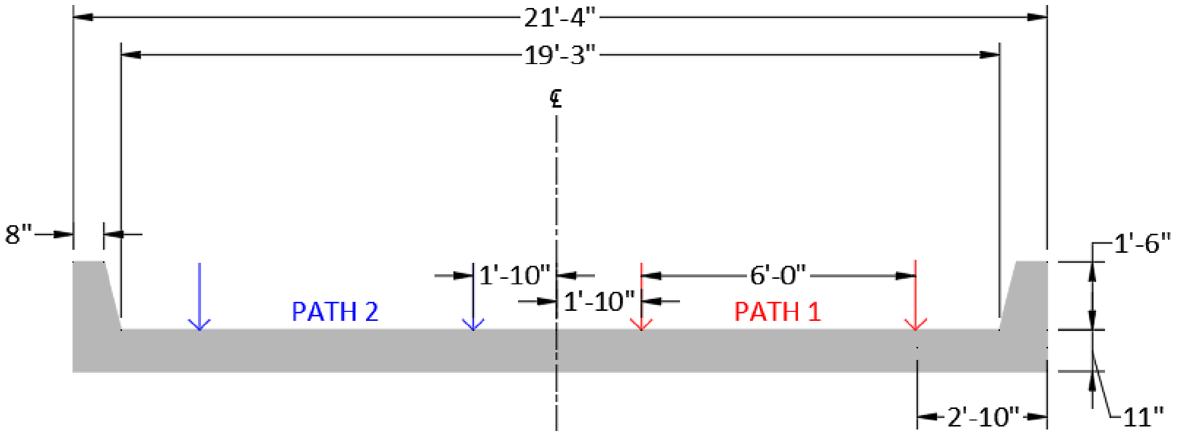


Bridge CS-9 FEM Model (6 in. mesh)

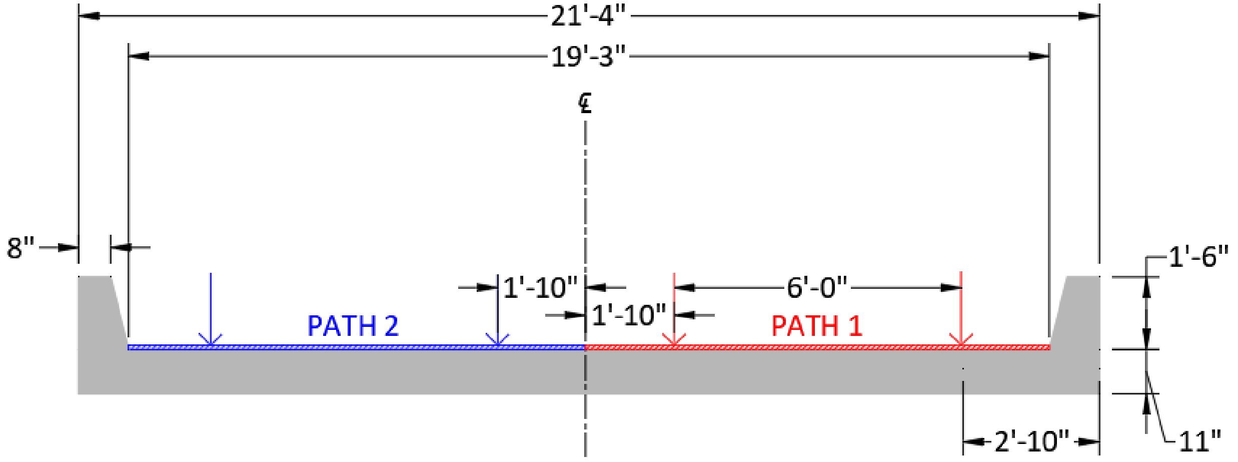
# Load Paths

## Bridge CS-9

- Defined based on AASHTO recommendations
- Narrow bridge width → identical load paths
- Path 1 and Path 2 are 1 ft 10 in. from centerline of bridge
- HL93 design load: add lane load to the above truck configurations




**HS-20 Truck**



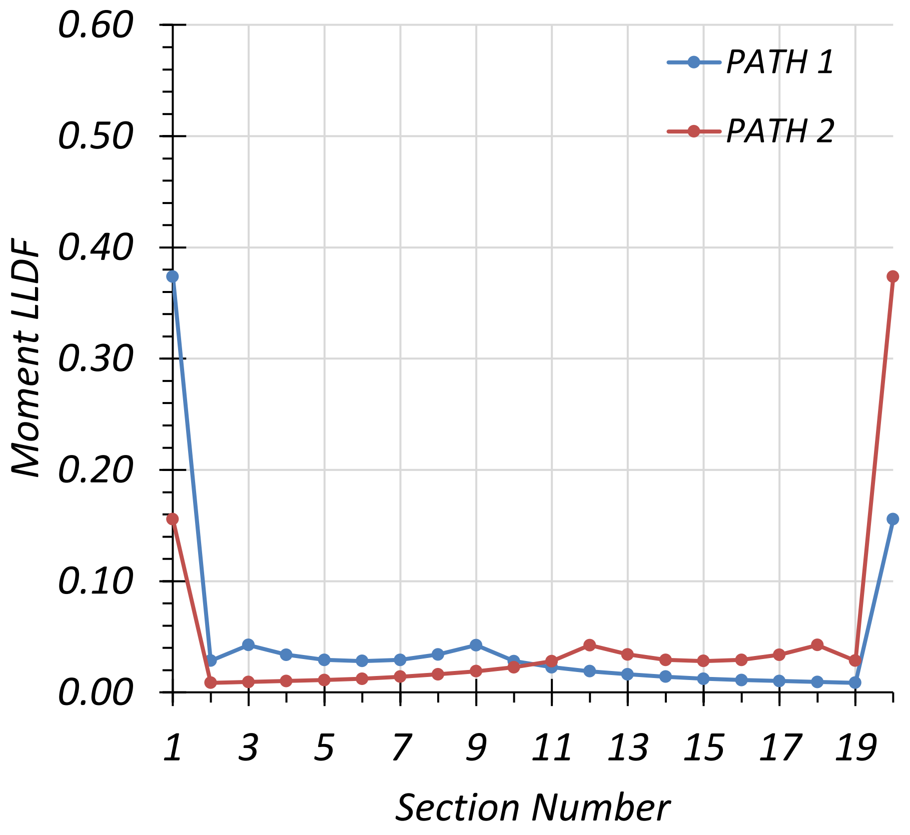

**HL93 Design Load**

# HS-20 Moment LLDFs

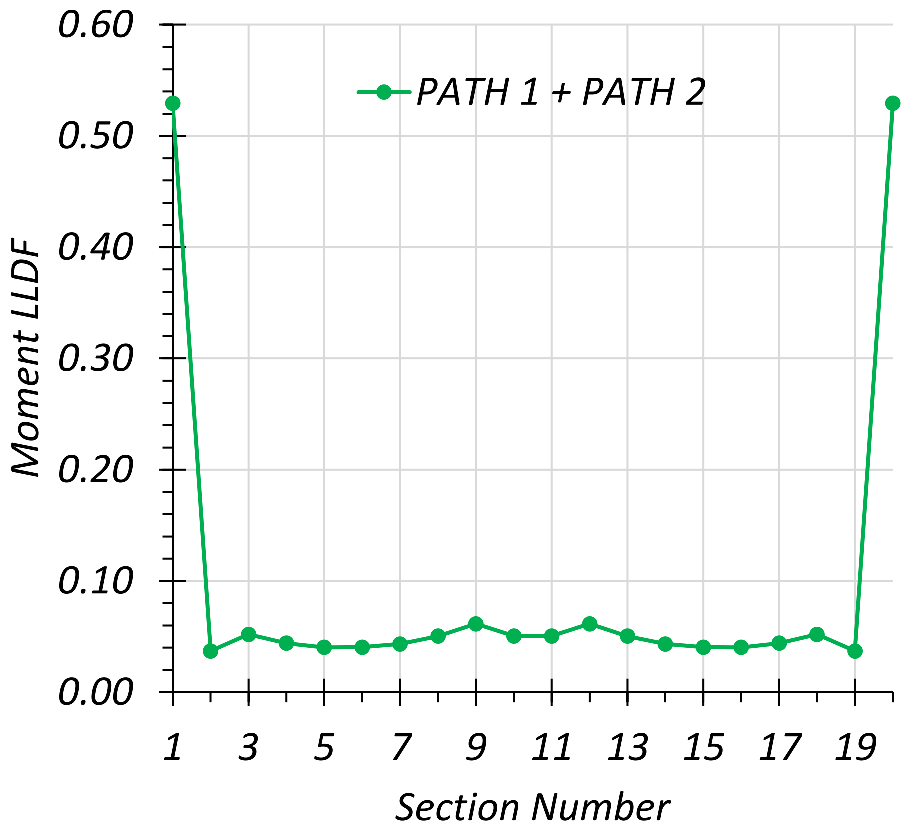
## Bridge CS-9

$$LLDF = \frac{M_i}{\sum M_i}$$

**One-Lane**




**Two-Lane**

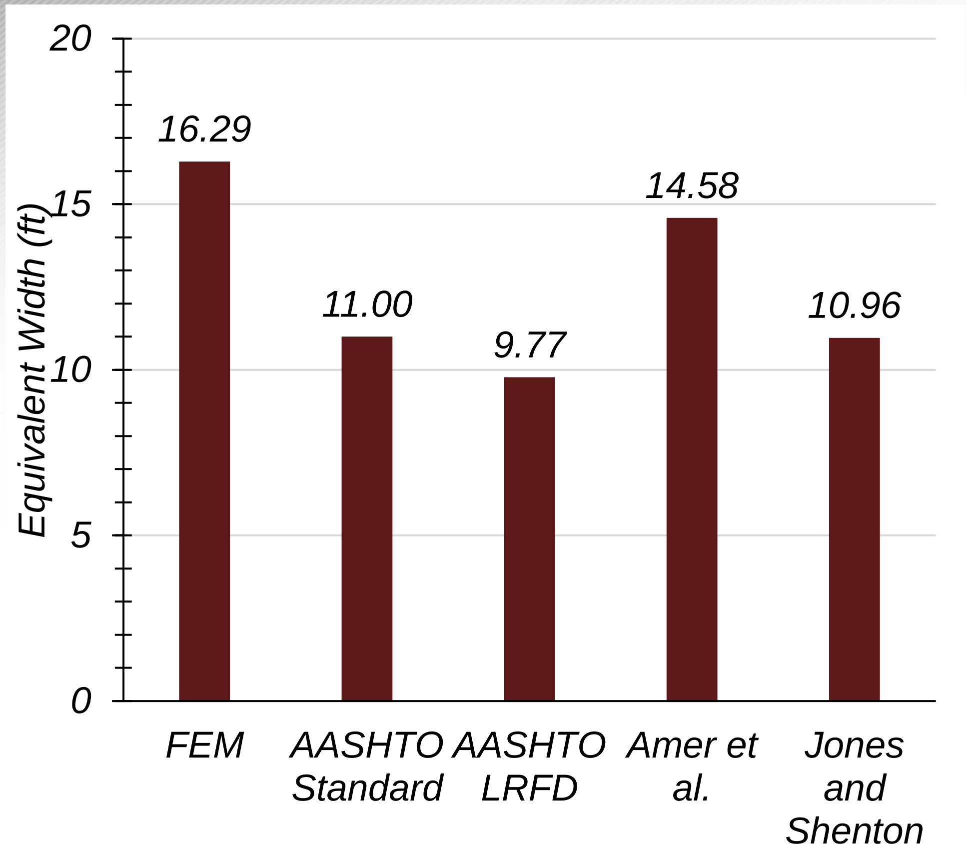



- Above results correspond to bridge width divided into 20 sections
- Stiffer curb sections attract significant portion of load

# HS-20 Equivalent Width

## Bridge CS-9

### Two-Lane Equivalent Width




### FEM vs IB346 Results

| Loading | Component | FEM Moment | IB346 Moment | IB346/ FEM |
|---|---|---|---|---|
| One-lane | Curb | 81.5 | 80.7 | 0.99 |
| | Slab | 8.9 | 2.4 | 0.27 |
| Two-lane | Curb | 115.4 | 80.7 | 0.7 |
| | Slab | 12.8 | 13.2 | 1.03 |

Note: Curb moment have kip-ft units and slab moment have kip-ft/ft units.

### Comparison with various studies

| Loading | FEM ($E^m_{FEM}$) | AASHTO Std. ($E^m_{AASHTO}$) | AASHTO LRFD ($E^m_{LRFD}$) | Amer et al. ($E^m_{Amer}$) | Jones and Shenton ($E^m_{Jones\,\&\,Shenton}$) |
|---|---|---|---|---|---|
| One-lane | 23.5 | 11.0 | 10.5 | 14.6 | 12.0 |
| Two-lane | 16.3 | 11.0 | 9.8 | 14.6 | 11.0 |

$$LLDF = \frac{M_i}{\sum M_i}$$

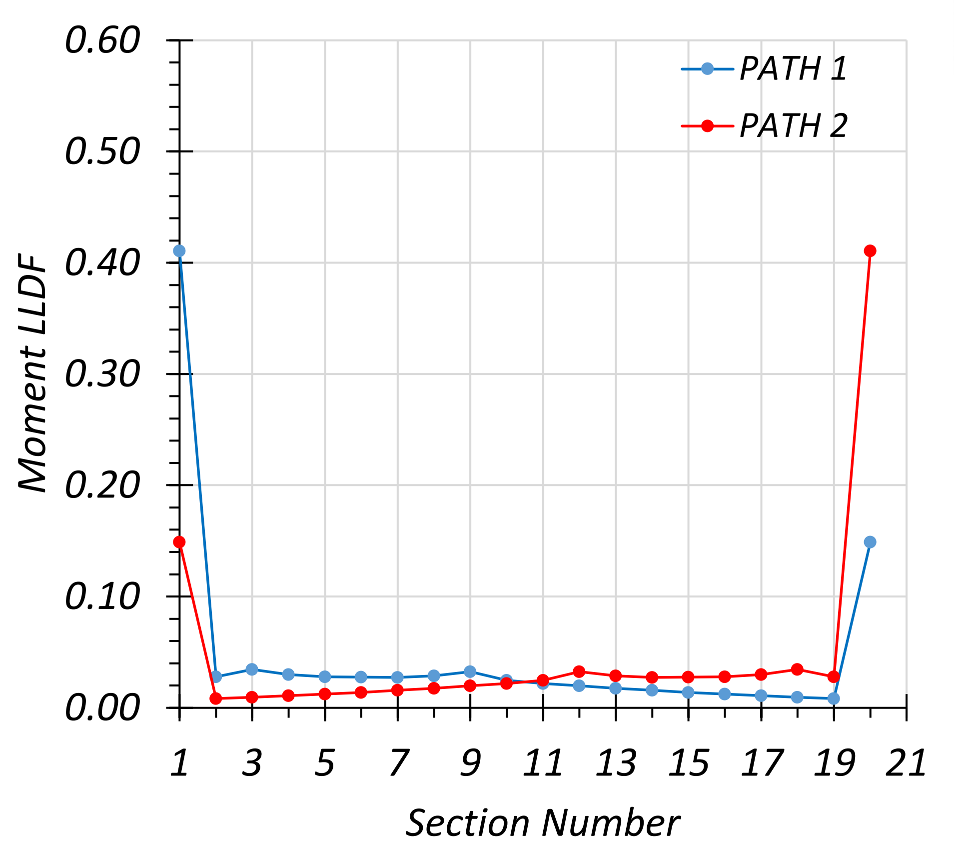
$$E = \frac{W_{Section}}{LLDF_{max}}$$

- IB346 estimate of slab moment is unconservative for one-lane loading while being slightly conservative for two-lane loading.
- AASHTO Standard Specifications provide conservative equivalent width.

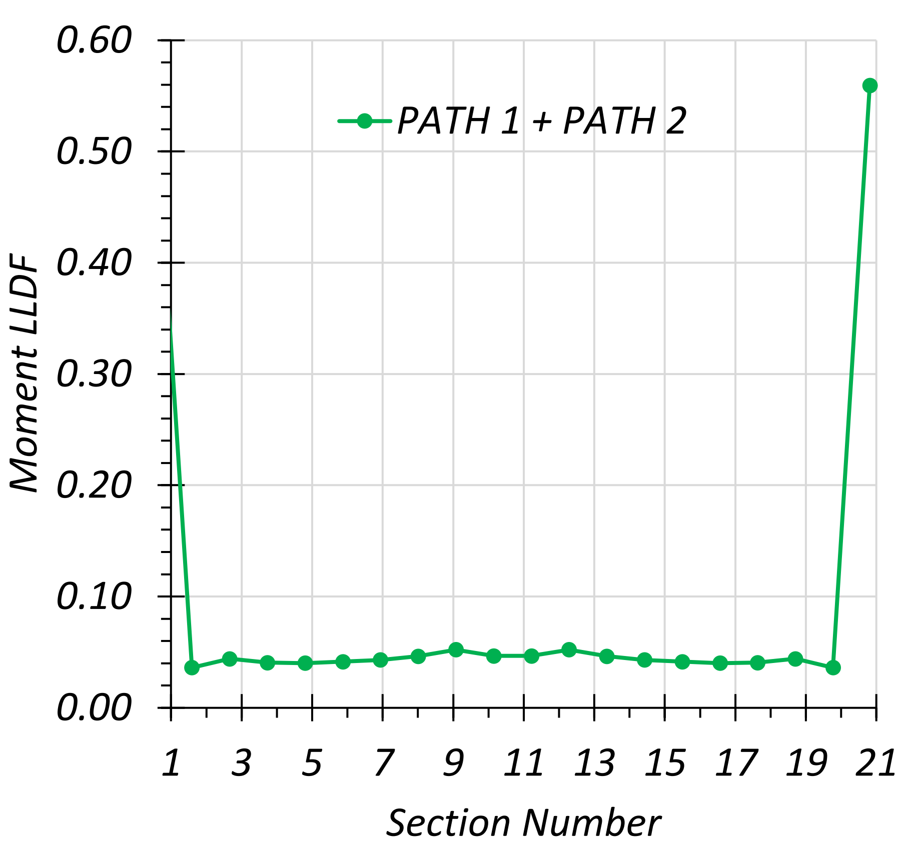
# HL93 Moment LLDFs

## Bridge CS-9

**One-lane**




**Two-lane**

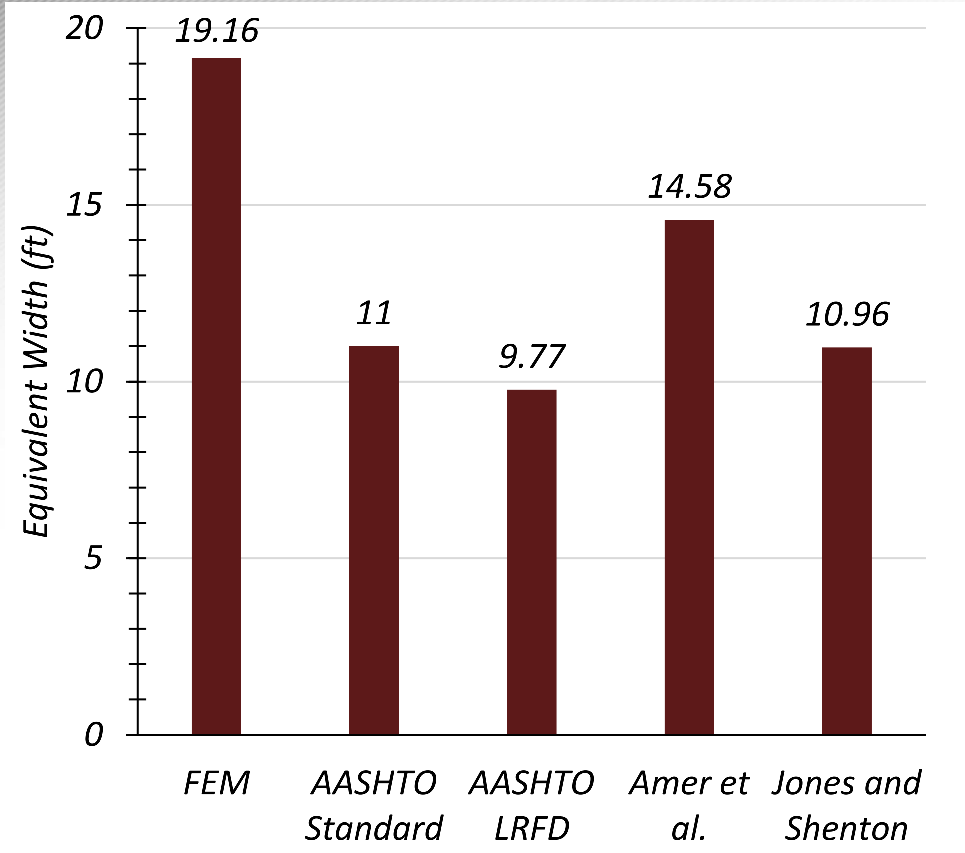



- Above results correspond to bridge width divided into 20 sections
- Stiffer curb sections attract greater load

# HL93 Equivalent Width

## Bridge CS-9

### Two-Lane Equivalent Width




### Comparison with various studies

| Loading | FEM $(E^m_{FEM})$ | AASHTO Std. $(E^m_{AASHTO})$ | AASHTO LRFD $(E^m_{LRFD})$ | Amer et al. $(E^m_{Amer})$ | Jones and Shenton $(E^m_{Jones\,\&\,Shenton})$ |
|---|---|---|---|---|---|
| One-lane | 29 | 11.0 | 10.5 | 14.6 | 12.0 |
| Two-lane | 19.2 | 11.0 | 9.8 | 14.6 | 11.0 |

- AASHTO Standard Specifications provide conservative equivalent width.

# Conclusions from FEM Analysis

## Bridge CM-5 and Bridge CS-9

### Concrete Multi-girder Bridge (CM-5)

- Current load rating using the LFR method
  - AASHTO Standard Specification LLDFs
- Changes to LLDF calculations likely will not be suggested.

→Bridge CM-5 was field tested to update and calibrate the FEM models.

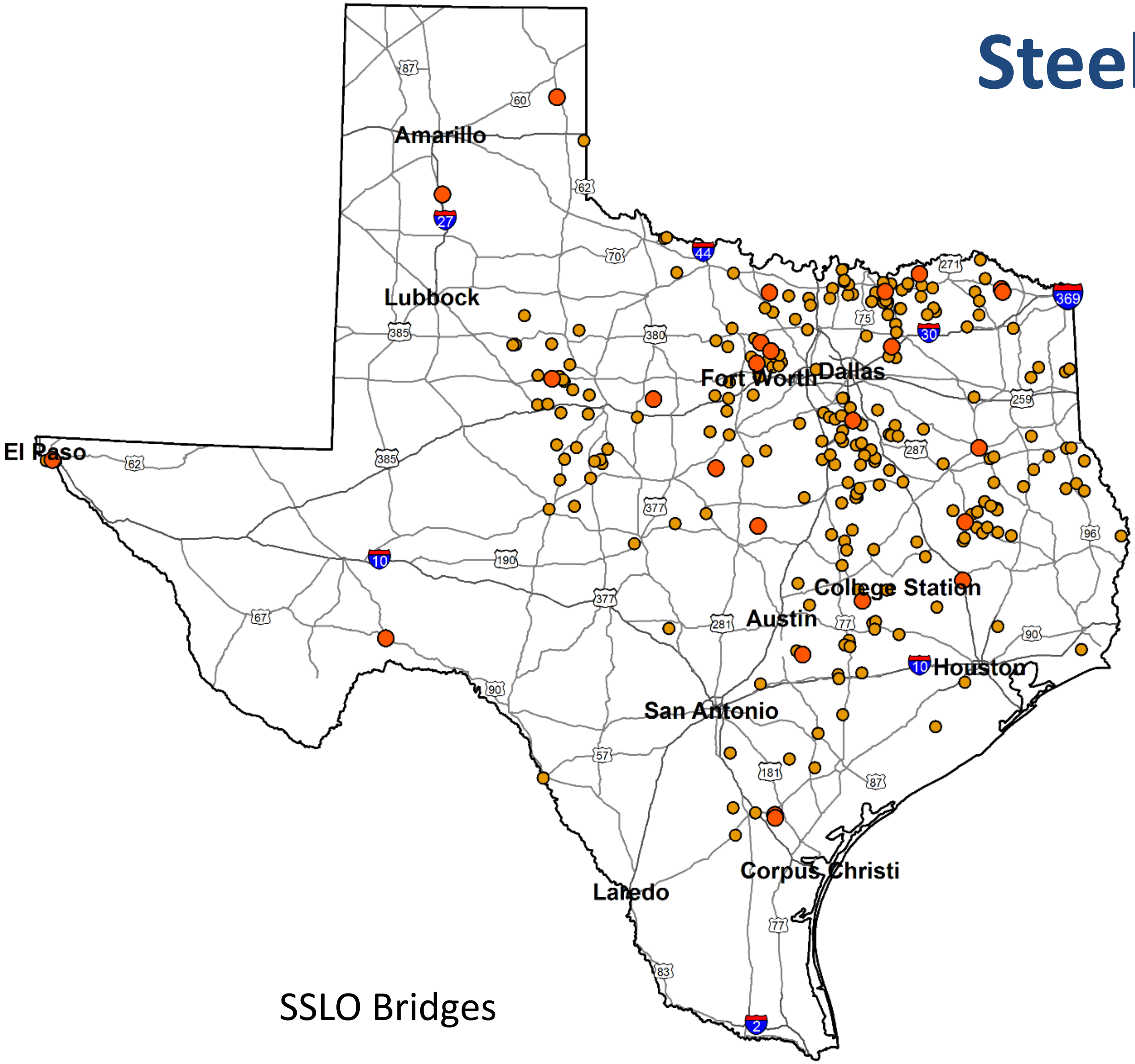
### Concrete Slab Bridge with Integral Curb (CS-9)

- Current load rating using the LFR method
  - IB346 to determine moment demands for Bridge CS-9
- Revisions may be necessary for live load distribution as the IB346 was found to be unconservative for one-lane loading and curbs.

→ Bridge CS-9 was field tested to update and calibrate the FEM models.

# Load Testing, Model Updating and Impact on Load Rating

# Steel Multi-Girder Bridge




SSLO Bridges

# Steel Multi-Girder Bridge

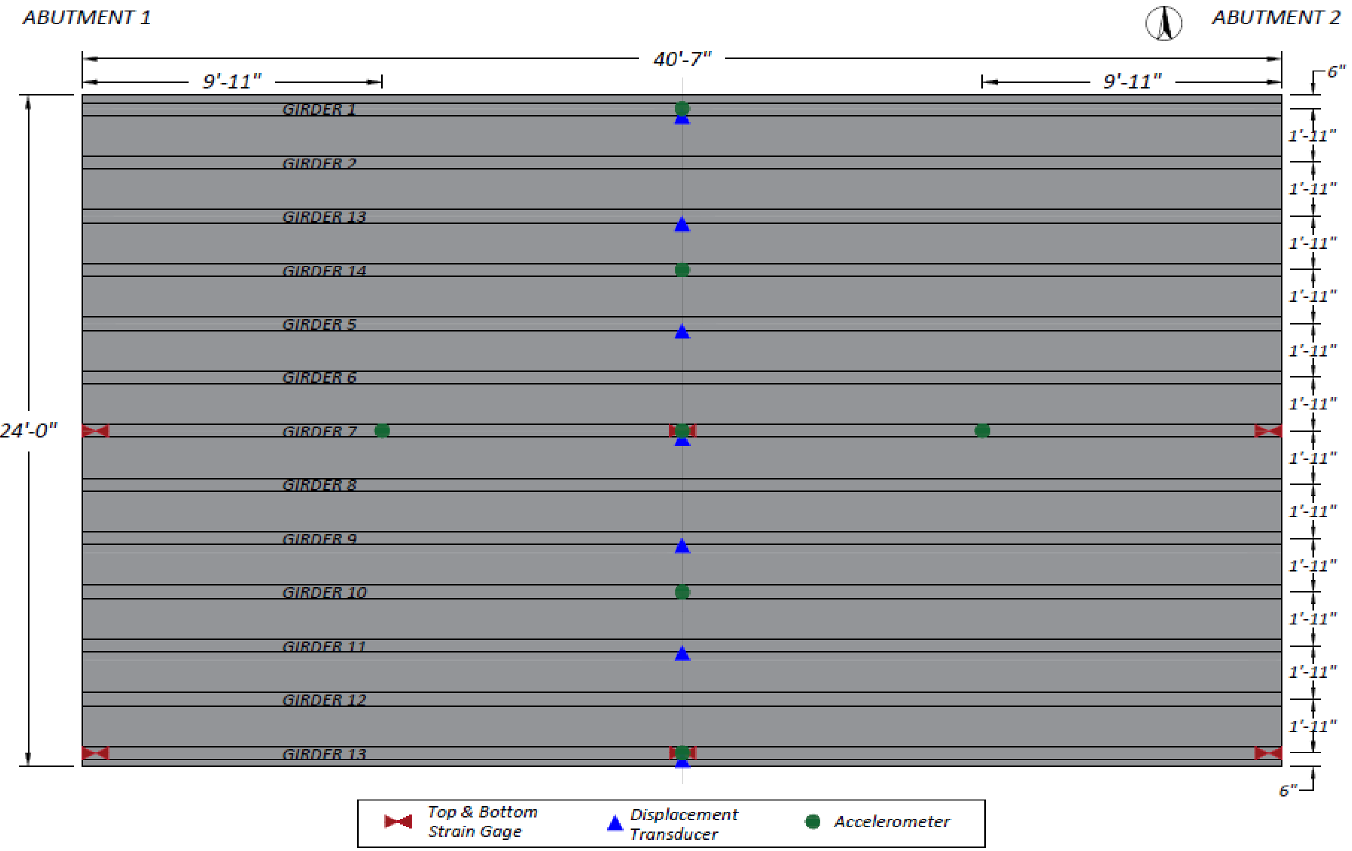
## Bridge SM-5

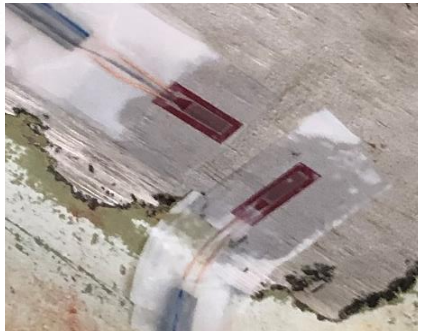
| ID | Route Prefix | Year Built | ADT | Max. Span Length (ft) | Deck Width (ft) | Girder Spacing (ft-in.) | Condition Rating | | | Operating HS20 Rating Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Deck | Superstructure | Substructure | |
| Avg. | - | 1974 | - | 36 | 20 | 4'-3" | 6 (satisfactory) | 6 (satisfactory) | 6 (satisfactory) | 0.83 |
| SM-5 | 3 (On-system) | 1938 | 300 | 41 | 24 | 1'-11" | 7 (good) | 6 (satisfactory) | 7 (good) | 0.79 |

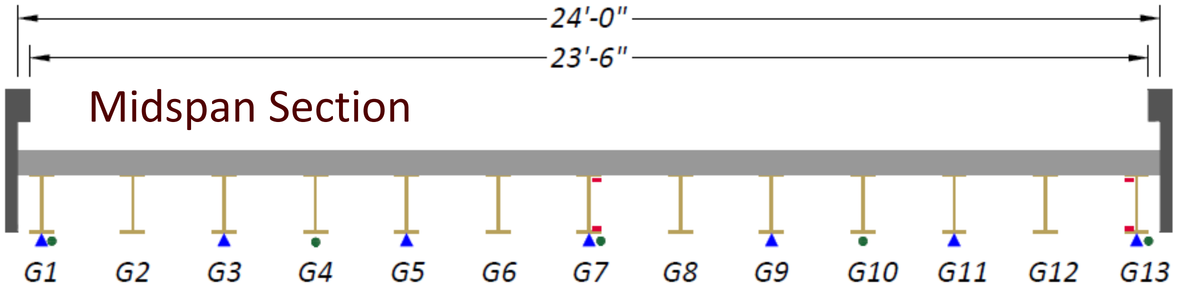
Carries PR 40 and traverses Big Chinquapin Creek near Huntsville, approximately 1.0 mi southwest of I-45

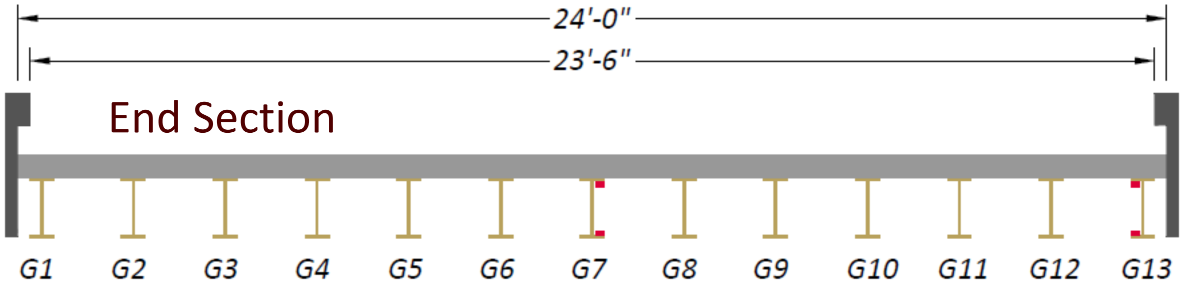
# Instrumentation

## Bridge SM-5



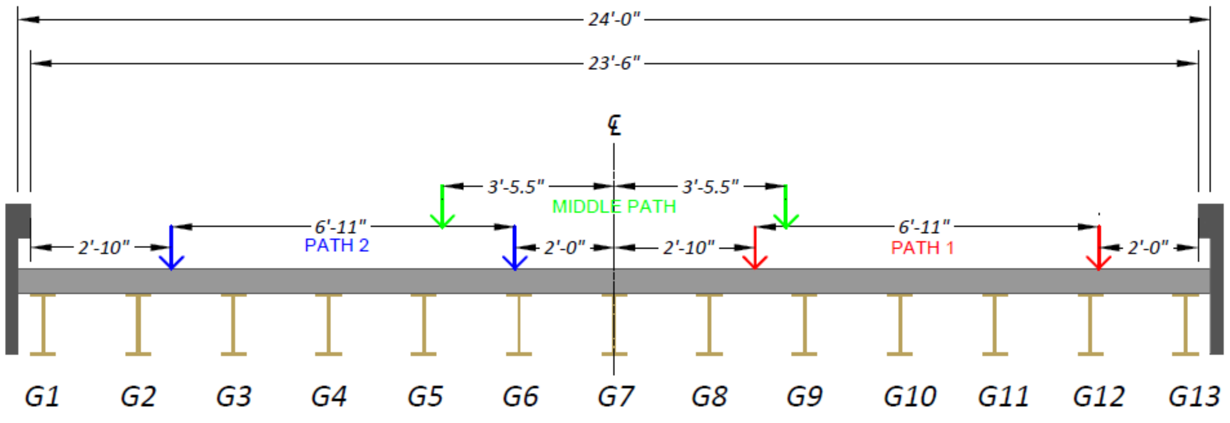





# Test Sequence

## Bridge SM-5




| Test Number | Test Location | Test Type |
|---|---|---|
| 1 | Path 1 | Static – Stop Location (Engine Running) |
| 2 | Path 2 | Static – Stop Location (Engine Running) |
| 3 | Path 1 | Static – Crawl Speed (5 mph) |
| 4 | Path 2 | Static – Crawl Speed (2 mph) |
| 5 | Path 1 | Dynamic (30 mph) |
| 6 | Path 2 | Dynamic (35 mph) |
| 7 | Path 1 | Dynamic (23 mph) |
| 8 | Path 2 | Dynamic (22 mph) |
| 9 | Path 1 | Static – Stop Location (Engine Stopped) |
| 10 | Path 2 | Static – Stop Location (Engine Stopped) |
| 11 | Path 1 | Static – Crawl Speed (2 mph) |
| 12 | Path 2 | Static – Crawl Speed (2 mph) |
| 13 | Middle Path | Static – Stop Location (Engine Stopped) |
| 14 | Middle Path | Static – Crawl Speed (2 mph) |
| 15 | Middle Path | Dynamic (34 mph) |
| 16 | North Edge | Impact |
| 17 | Centerline | Impact |
| 18 | South Edge | Impact |

Posting: 20,000 lb single axle
34,000 lb tandem axle
47,000 lb single vehicle
74,000 lb combination vehicle

TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

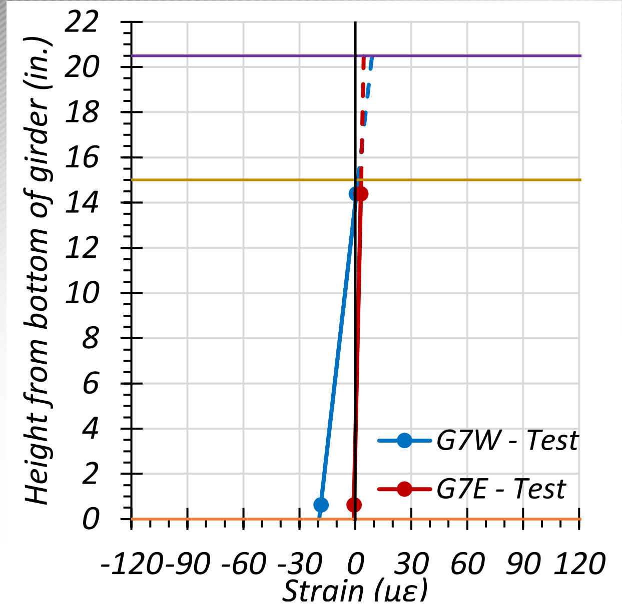
# Interior Girder G7 Strain Results
# Middle Path – Static Tests

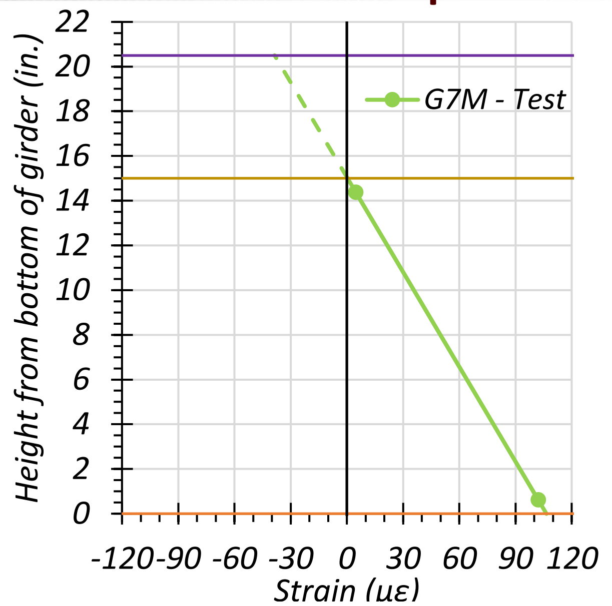
### Bridge SM-5

## Girder Ends

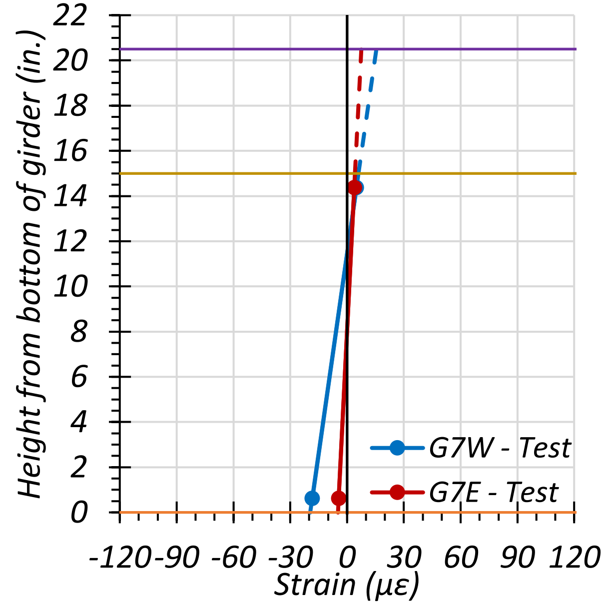
## Girder Midspan

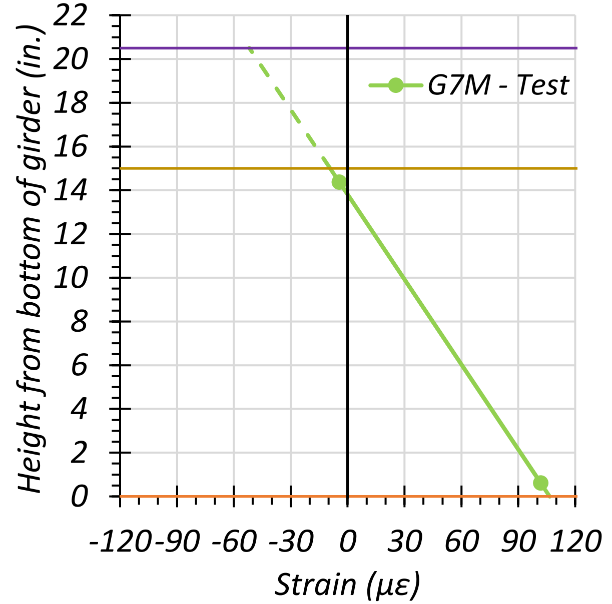
**Stop Location Test**

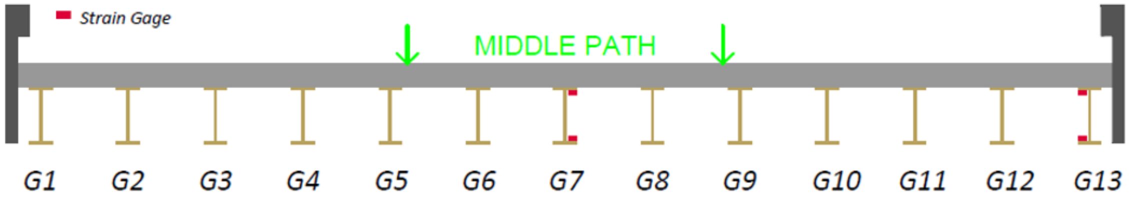



**Crawl Speed Test**




- Neutral Axis Locations
  - Stop Location: 15.05 in.
  - Crawl Speed: 13.80 in.
  - *Theoretical Non-Composite: 7.50 in.*
  - *Theoretical Composite: 14.28 in.*

Nearly full composite action

- Maximum Bottom Flange Strains/Stresses
  - Midspan: 102 με → 2.96 ksi
  - West end: -18.5 με → -0.54 ksi
  - East end: -4.4 με → -0.13 ksi

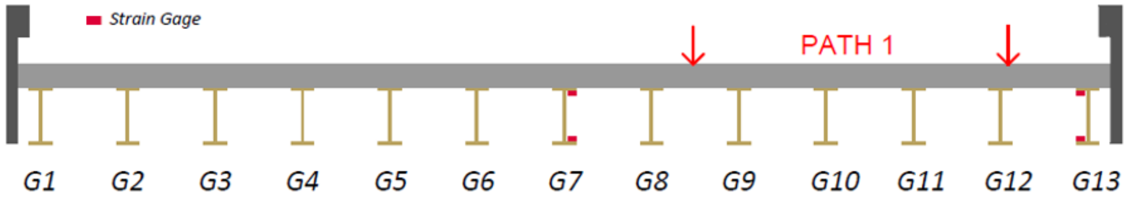
*Tension is positive*

Texas A&M Transportation Institute

TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

# Exterior Girder G13 Strain Results
# Path 1 – Static Tests

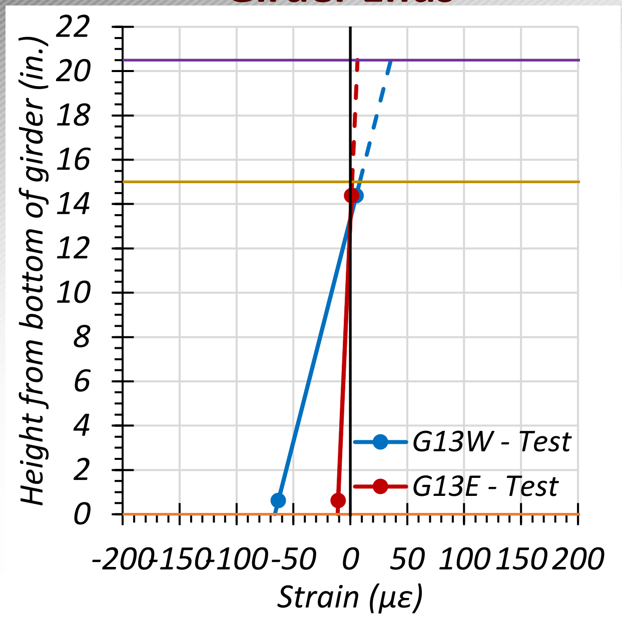
## Bridge SM-5

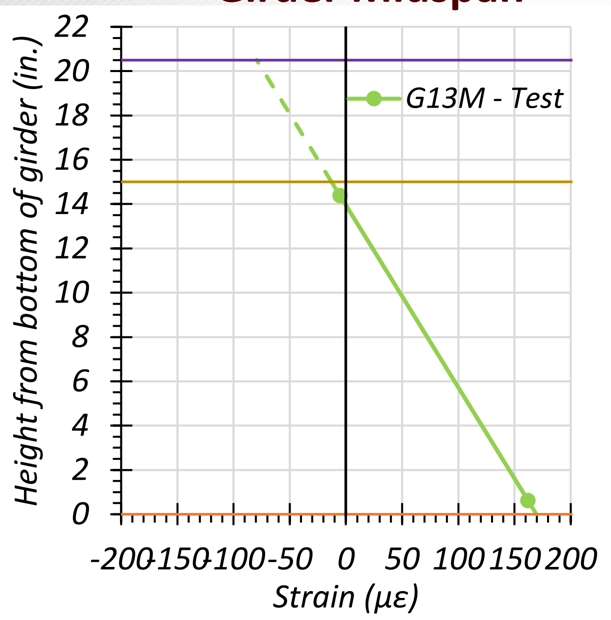



### Girder Ends

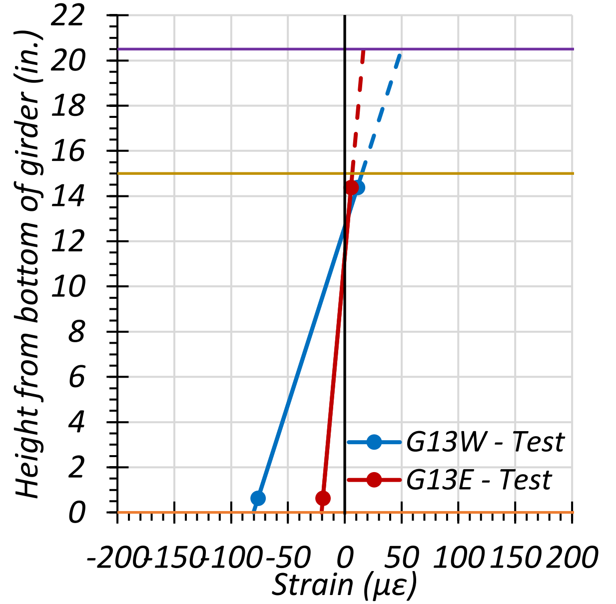
### Girder Midspan

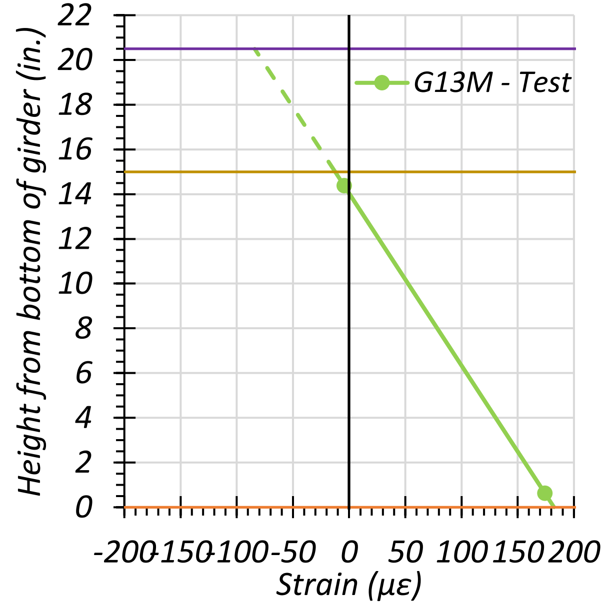
**Stop Location Test**




**Crawl Speed Test**




- Neutral Axis Locations
  - Stop Location: 13.96 in.
  - Crawl Speed: 14.04 in.
  - *Theoretical Non-Composite: 7.50 in.*
  - *Theoretical Composite: 13.60 in.*
- Maximum Bottom Flange Strains/Stresses
  - Midspan: 174.2 με → 5.05 ksi
  - West end: -75.3 με → -2.21 ksi
  - East end: -19.2 με → -0.56 ksi

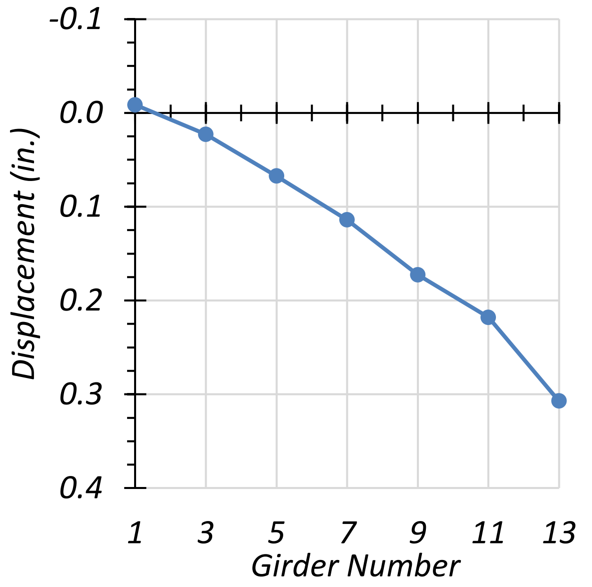
*Tension is positive*

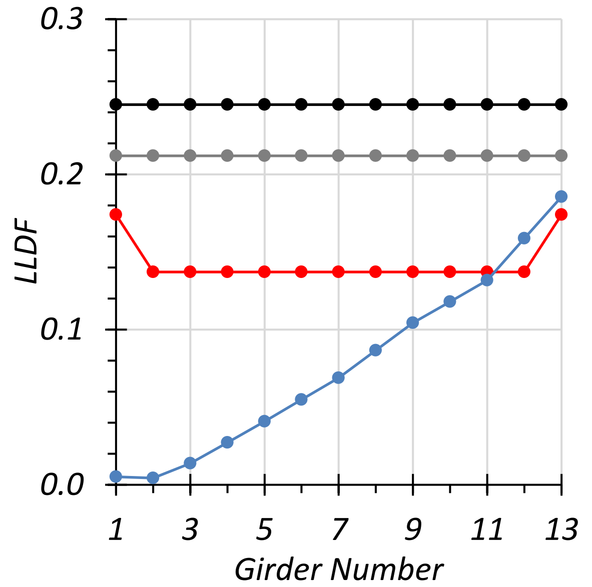
# Deflection Results
# Path 1 – Static Tests
## Bridge SM-5

$$LLDF = \frac{\Delta_i I_i}{\sum \Delta_i I_i}$$

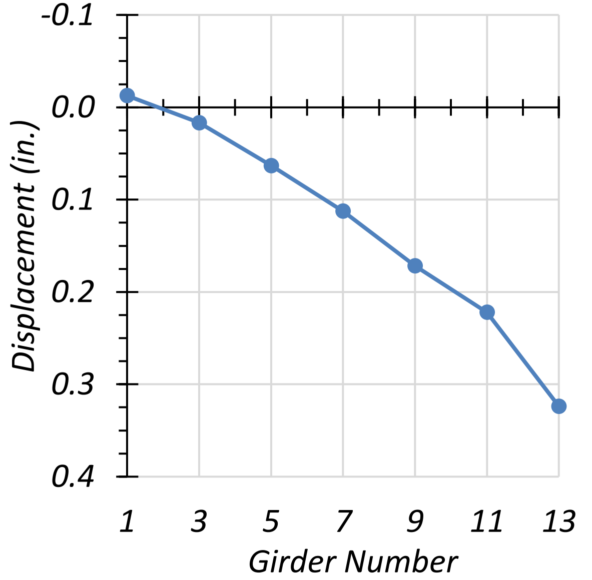
**Deflections** | **LLDFs**

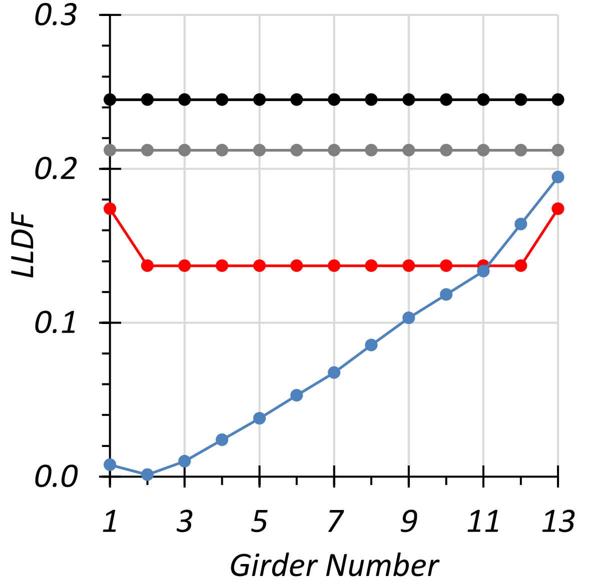
**Stop Location Test**

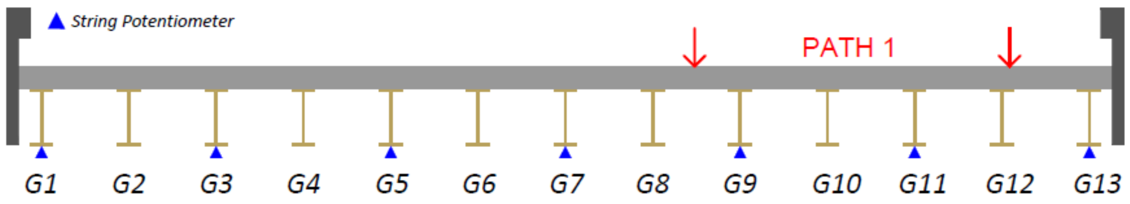



**Crawl Speed Test**




| Test and Girder Type | AASHTO Standard Specs ($g^m_{AASHTO\_Std}$) | AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$) | AASHTO LRFD $K_g$ Calculated ($g^m_{AASHTO\_K}$) | Test ($g^m_{test}$) | $g^m_{AASHTO\_Std}/g^m_{test}$ | $g^m_{AASHTO\_S}/g^m_{test}$ | $g^m_{AASHTO\_K}/g^m_{test}$ |
|---|---|---|---|---|---|---|---|
| Stop Location Interior | 0.137 | 0.245 | 0.212 | 0.159 | 0.86 | 1.54 | 1.33 |
| Stop Location Exterior | 0.174 | 0.245 | 0.212 | 0.186 | 0.94 | 1.32 | 1.14 |
| Crawl Speed Interior | 0.137 | 0.245 | 0.212 | 0.164 | 0.84 | 1.49 | 1.29 |
| Crawl Speed Exterior | 0.174 | 0.245 | 0.212 | 0.195 | 0.89 | 1.26 | 1.09 |

• Test • AASHTO Standard • AASHTO LRFD simplified
• AASHTO LRFD $K_g$ calculated

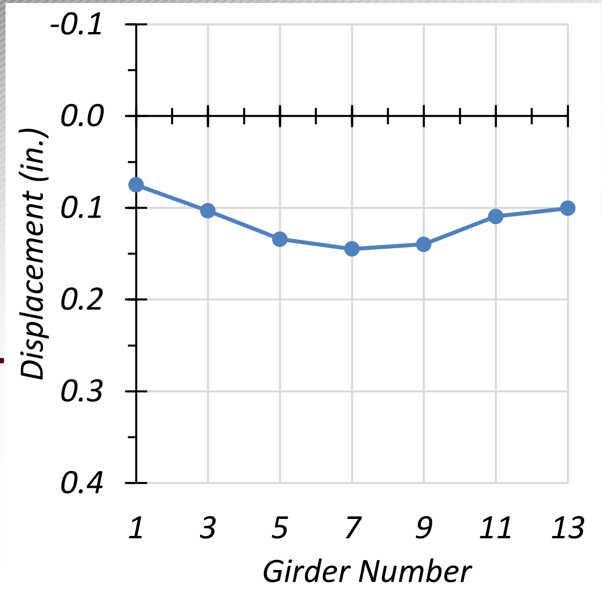
# Deflection Results
# Middle Path – Static Tests

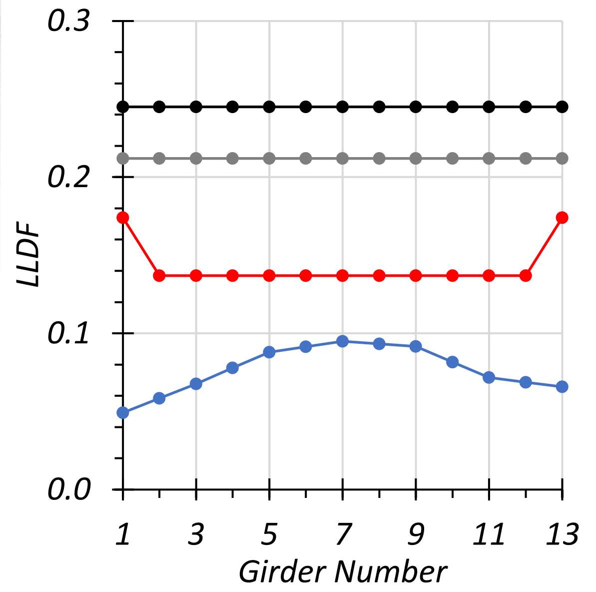
## Bridge SM-5

$$LLDF = \frac{\Delta_i I_i}{\sum \Delta_i I_i}$$

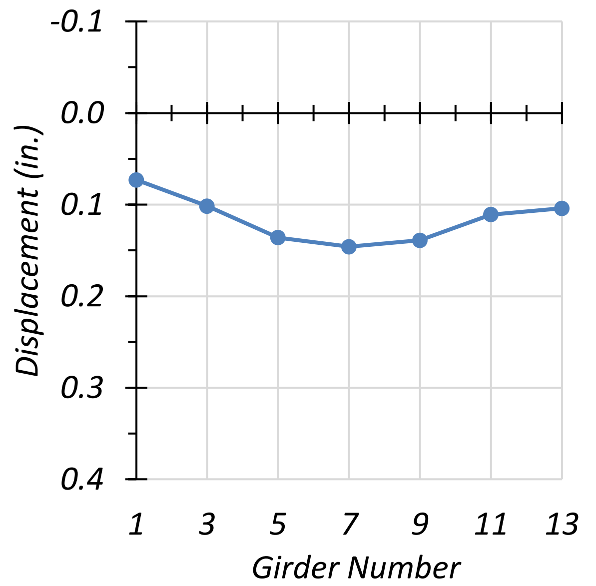
**Deflections** | **LLDFs**

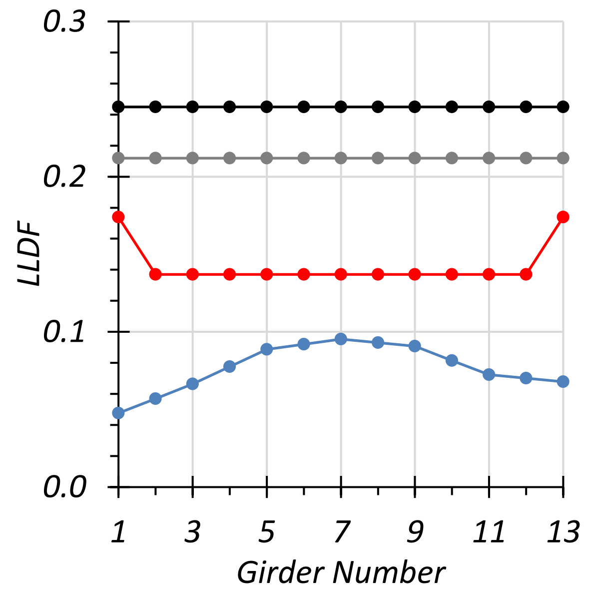
**Stop Location Test**

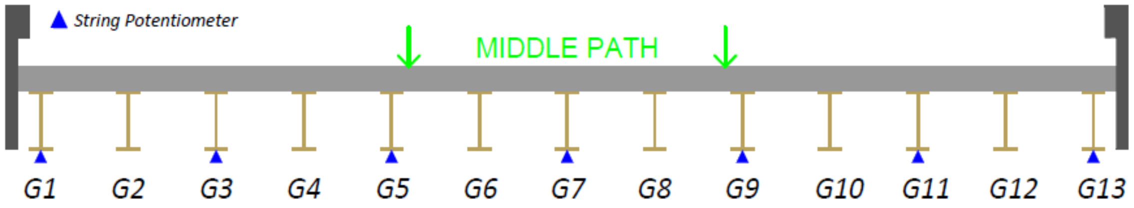



**Crawl Speed Test**



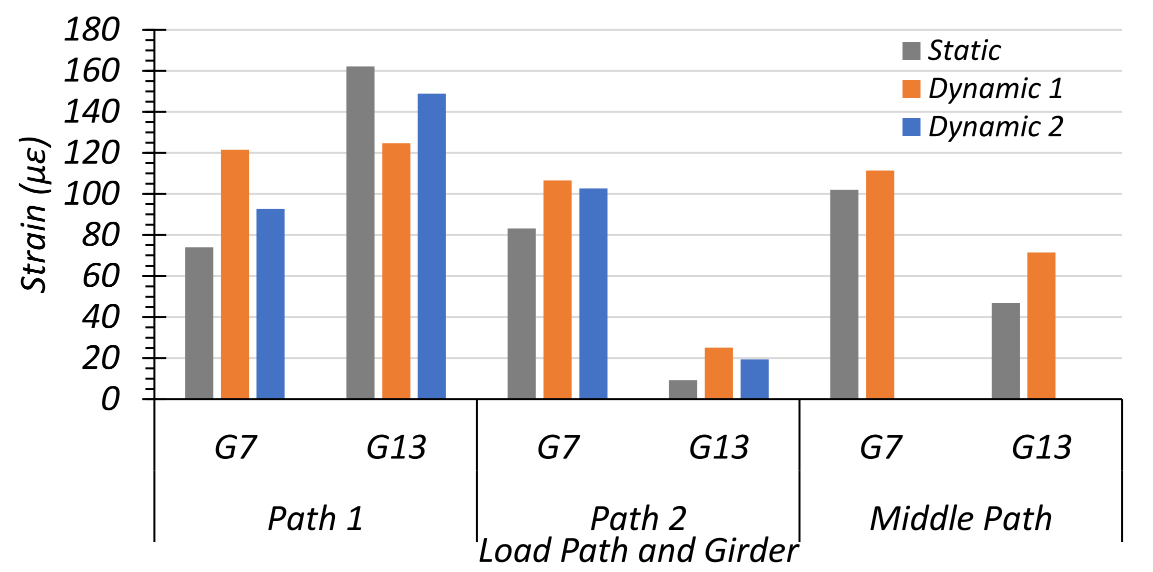




| Test and Girder Type | AASHTO Standard Specs ($g^m_{AASHTO\_Std}$) | AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$) | AASHTO LRFD $K_g$ Calculated ($g^m_{AASHTO\_K}$) | Test ($g^m_{test}$) | $g^m_{AASHTO\_Std}/g^m_{test}$ | $g^m_{AASHTO\_S}/g^m_{test}$ | $g^m_{AASHTO\_K}/g^m_{test}$ |
|---|---|---|---|---|---|---|---|
| Stop Location Interior | 0.137 | 0.245 | 0.212 | 0.095 | 1.44 | 2.58 | 2.23 |
| Stop Location Exterior | 0.174 | 0.245 | 0.212 | 0.066 | 2.64 | 3.71 | 3.21 |
| Crawl Speed Interior | 0.137 | 0.245 | 0.212 | 0.095 | 1.44 | 2.58 | 2.23 |
| Crawl Speed Exterior | 0.174 | 0.245 | 0.212 | 0.068 | 2.56 | 3.60 | 3.12 |

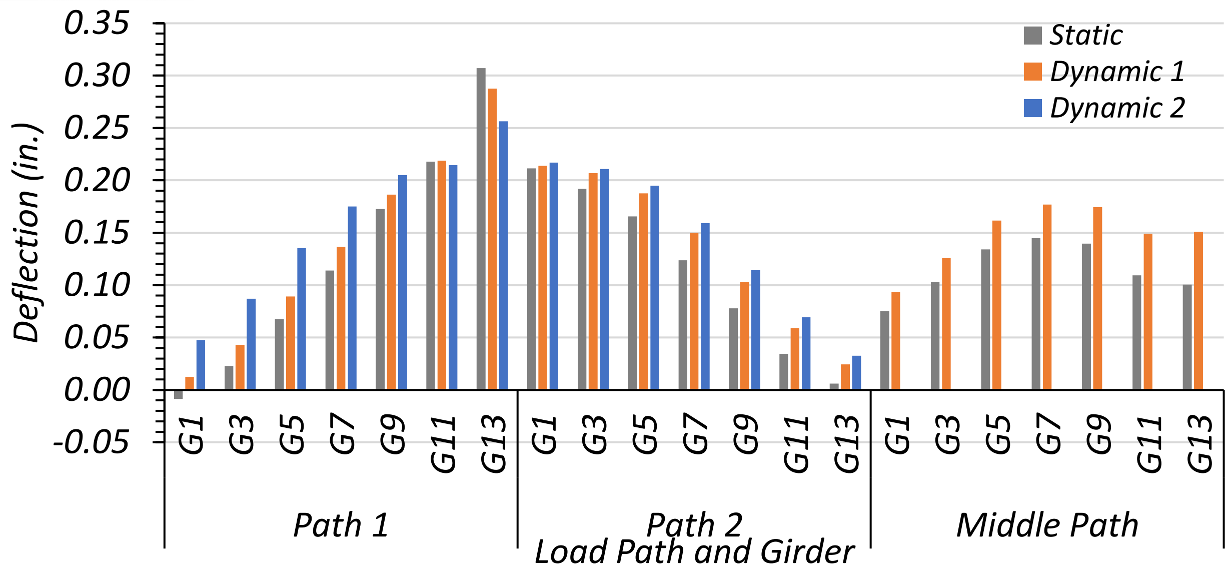
• Test • AASHTO Standard • AASHTO LRFD simplified
• AASHTO LRFD $K_g$ calculated

# Dynamic Test Results

## Bridge SM-5




Comparison of Maximum Strains for Static and Dynamic Tests




Comparison of Maximum Deflections for Static and Dynamic Tests

- Average G7 dynamic increase: 30.1%
- AASHTO Standard IM = 30%
- AASHTO LRFD IM: 33%

- Average dynamic increase for Middle Path: 28.7%
- AASHTO Standard IM = 30%
- AASHTO LRFD IM: 33%

*Note:*

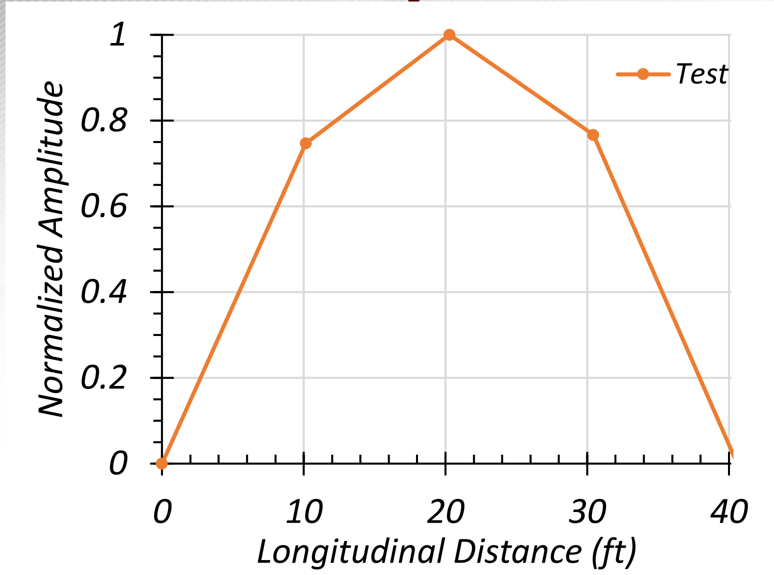
- *Path 1: Dynamic 1 = 23 mph, Dynamic 2 = 30 mph*
- *Path 2: Dynamic 1 = 22 mph, Dynamic 2 = 35 mph*
- *Middle Path: Dynamic 1 = 34 mph*

# Dynamic Bridge Characteristics

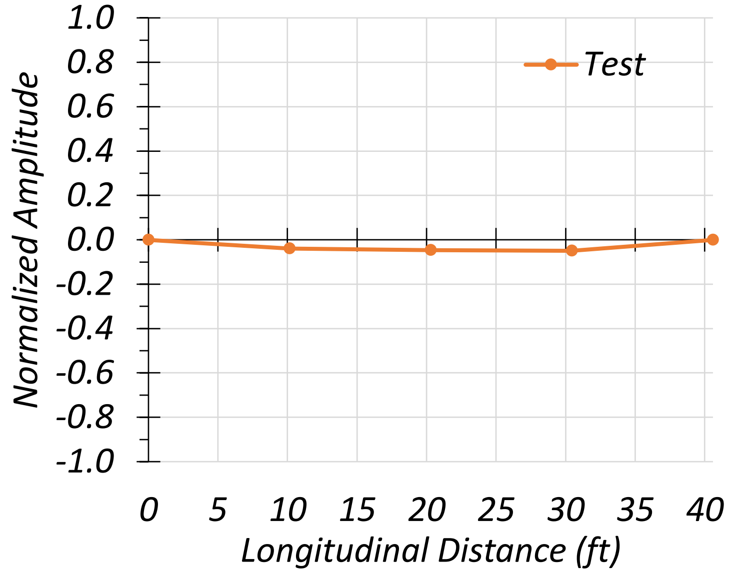
## Bridge SM-5

### Longitudinal Section

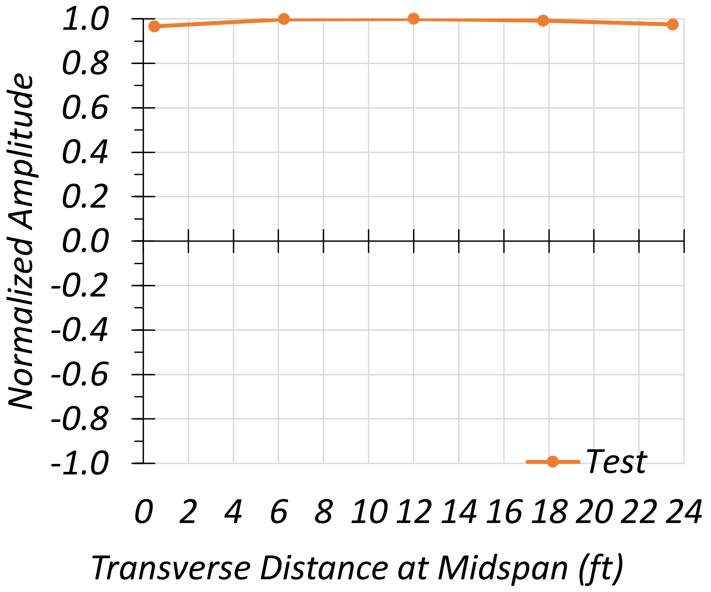
### Mode Shape 1 ($f_1$=7.57 Hz)

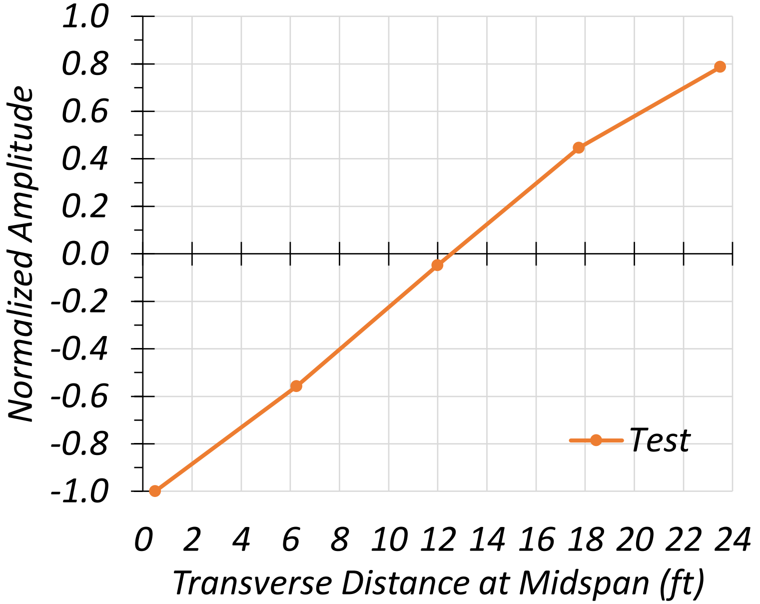



### Mode Shape 2 ($f_2$ = 9.03 Hz)




### Transverse Section

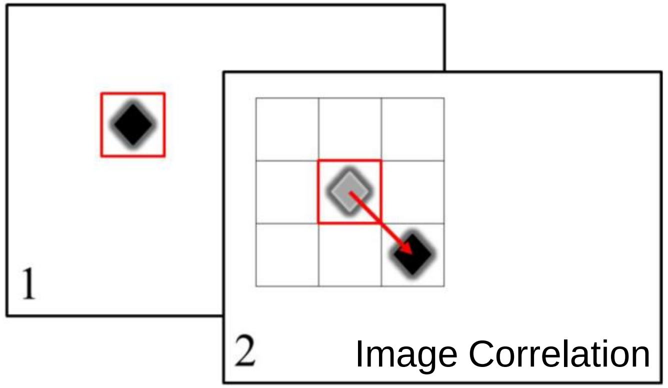


# Targetless Computer Vision

**Motivation:**

- Displacement measurements of structural response is often difficult or costly to employ because large arrays of instrumentation are required
- Computer vision techniques or digital image correlation (DIC) used in structural studies typically require pre-defined geometries or targets (such as TxDOT 0-6950)



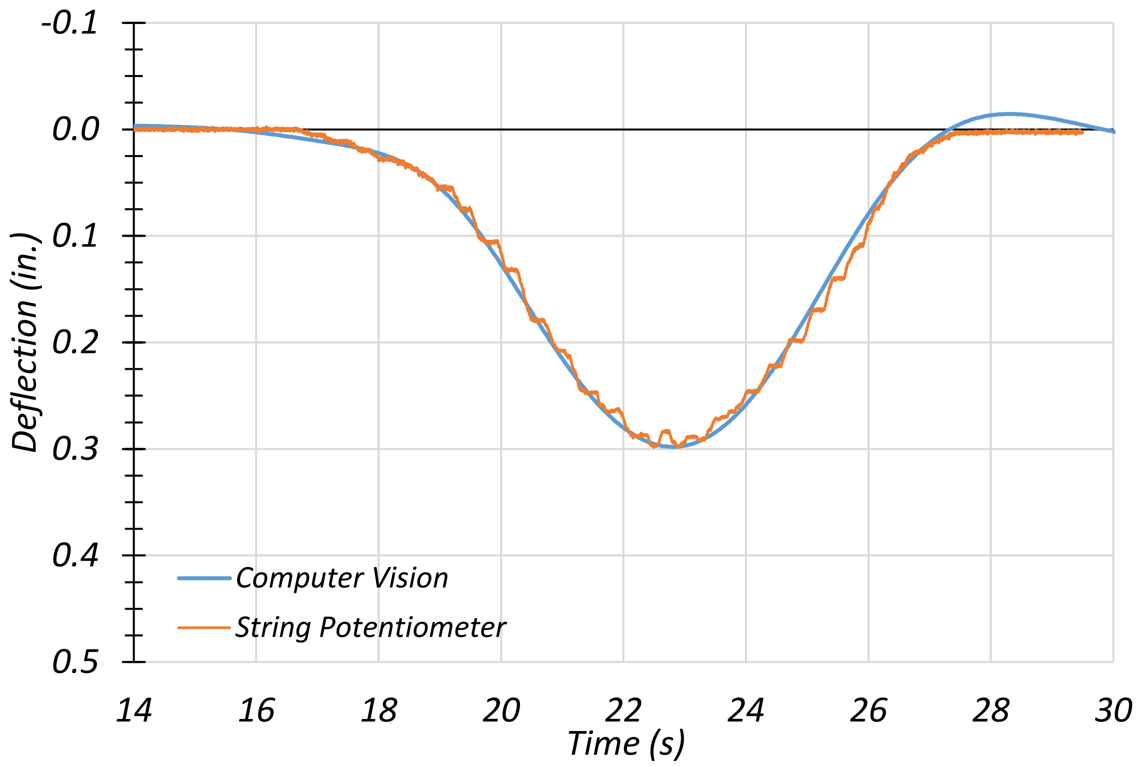

**Objectives:**

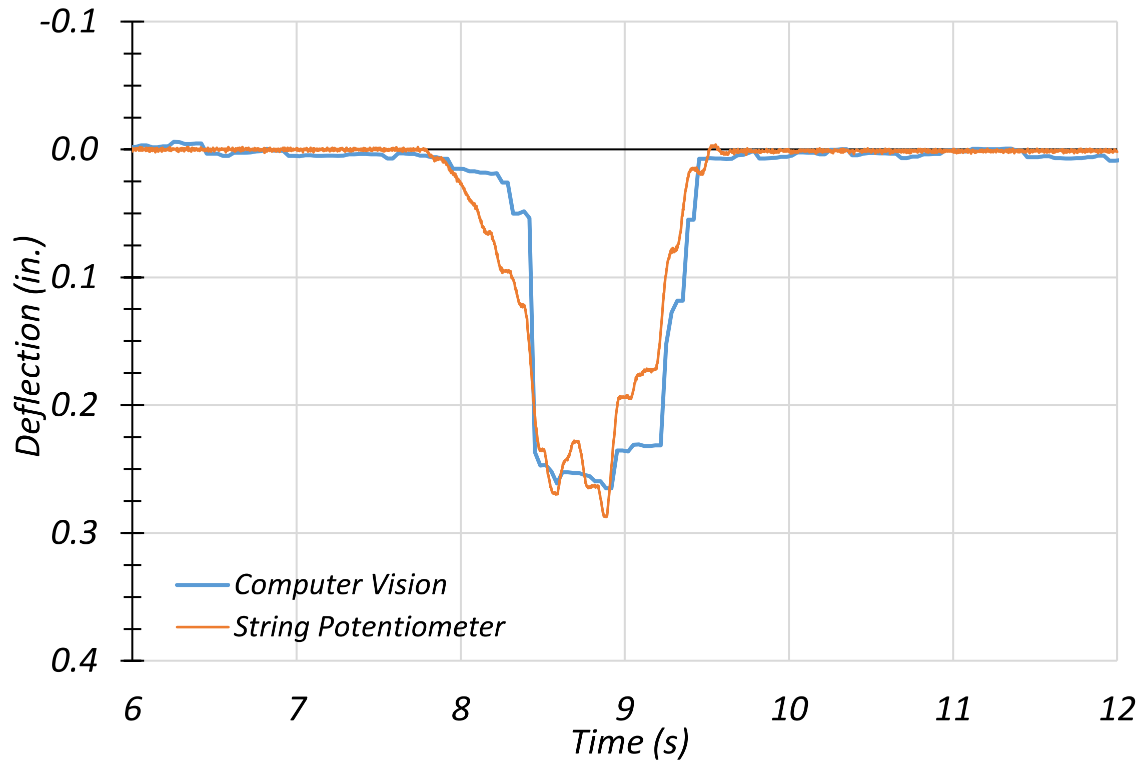
- Develop a *targetless method* to determine structural displacements using a consumer-grade camcorder or cell phone camera
- Conduct load testing of bridges using developed technique and compare against measurements with conventional instrumentation

# Targetless Computer Vision

# Targetless Computer Vision Results

## Bridge SM-5



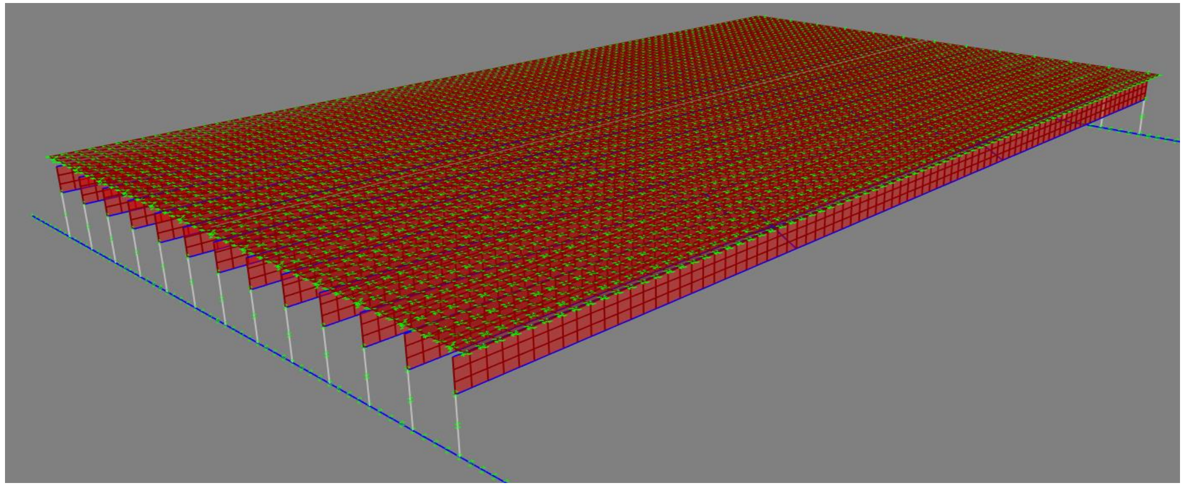

- Exterior Girder 13 – Path 1 – Crawl Speed Test
  - String Pot Deflection: 0.299 in.
  - Computer Vision Deflection: 0.298 in.
  - 0.3% Difference
  - Lowpass Butterworth filter with 600 Hz cutoff frequency

- Exterior Girder 13 – Path 1 – Dynamic Test at 23 mph
  - String Pot Deflection: 0.288 in.
  - Computer Vision Deflection: 0.265 in.
  - 8.3% Difference
  - Lowpass Butterworth filter with 300 Hz cutoff frequency

# Model Updating and Calibration

## Bridge SM-5

- Updated FEM models
  - NDE field measurements gave minimum deck $f_c'$ of 7.2 ksi (using corresponding MOE of 4836 ksi)
  - Simply supported boundary conditions
  - One model assumes fully composite action, and one assumes fully non-composite action
- Calibrated FEM model
  - Includes horizontal end springs at the bottom flange nodes and deck nodes to induce small end restraint
  - Includes springs between the deck and top flange nodes to induce partial composite action
  - Sensitivity analysis conducted to select and refine spring stiffness values

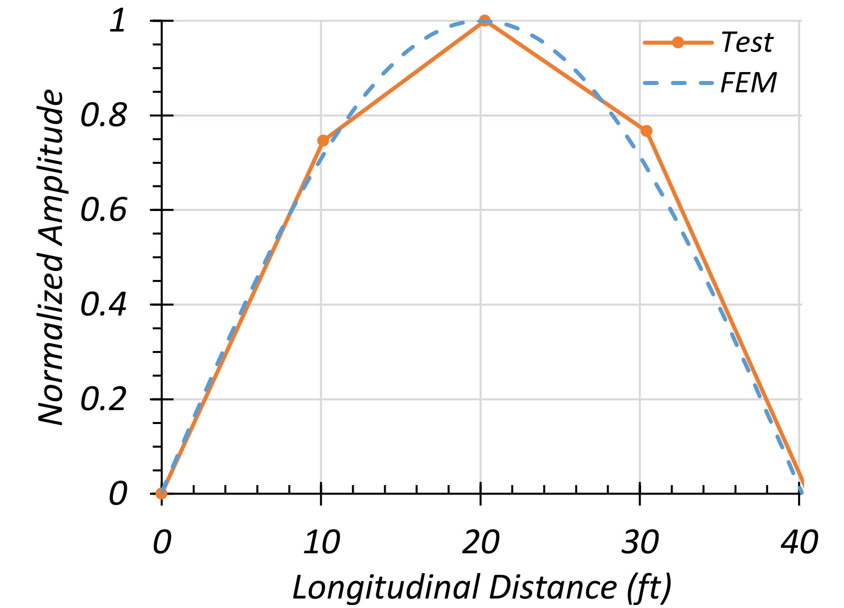


# Dynamic Characteristics Comparison

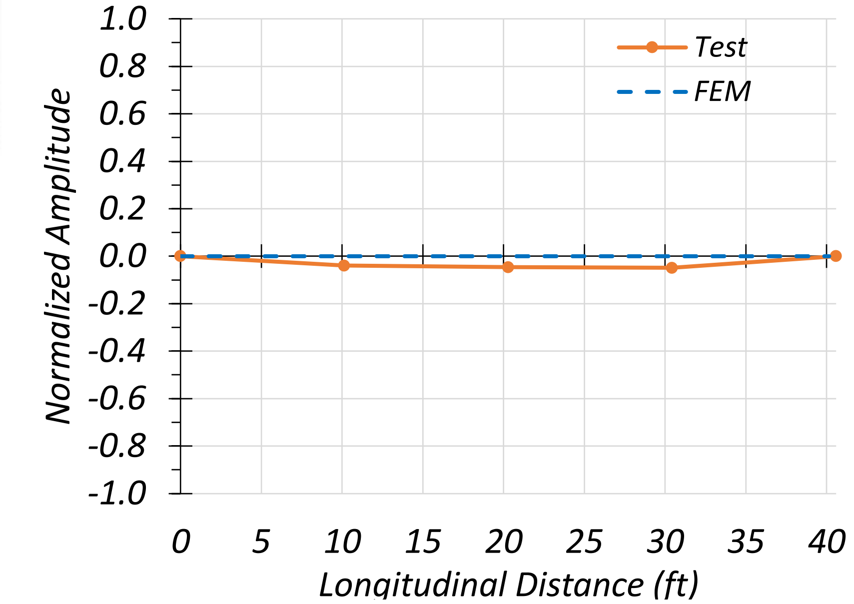
## Bridge SM-5

Longitudinal Section

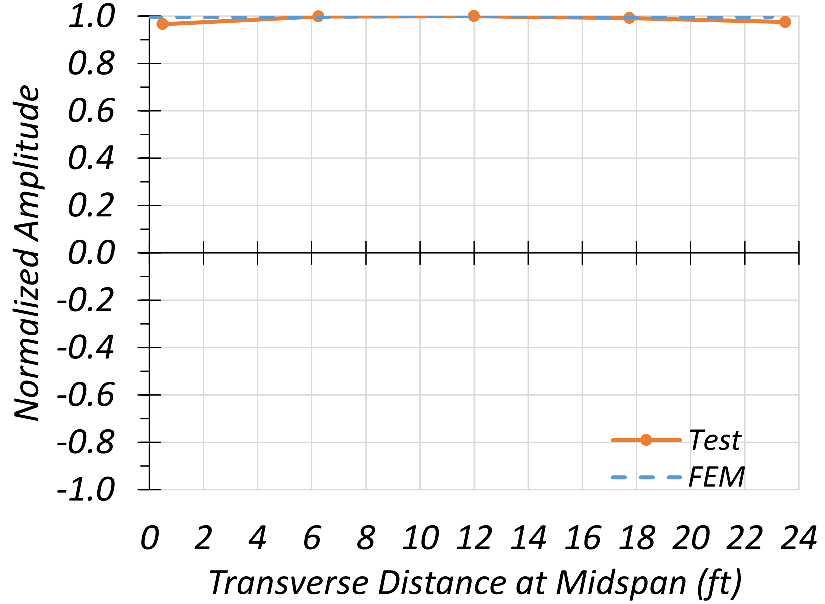
1st Mode (Test=7.57 Hz, FEM=6.54 Hz)

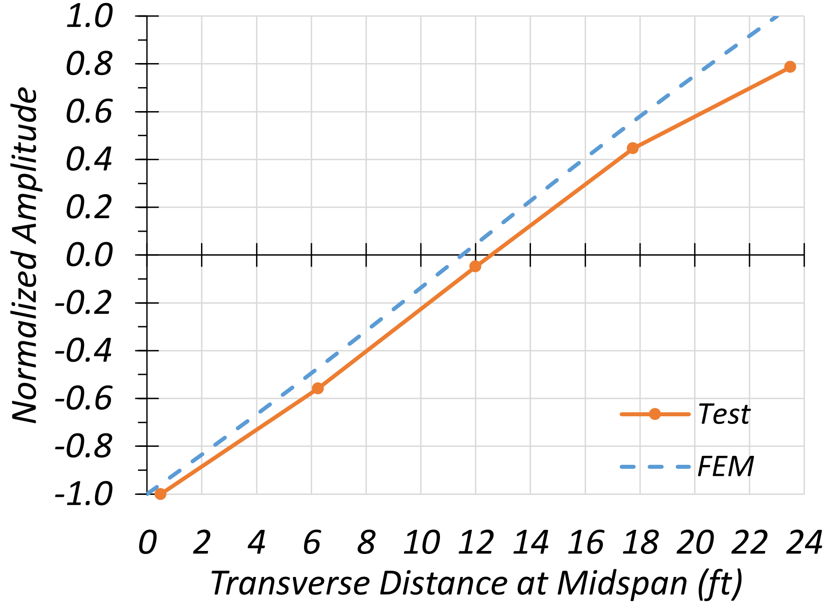



2nd Mode (Test=9.03 Hz, FEM=7.78 Hz)




Transverse Section

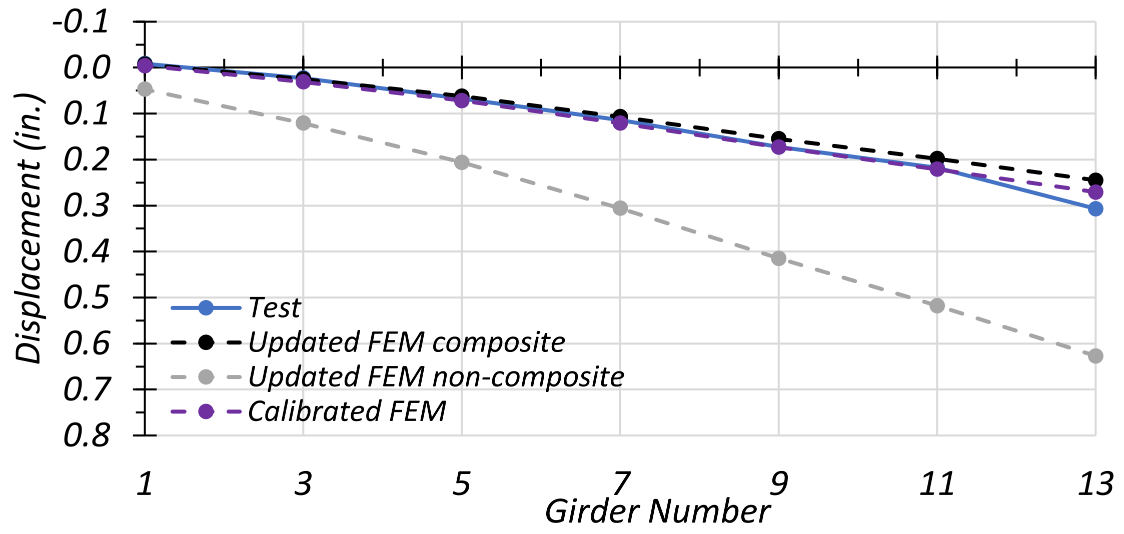


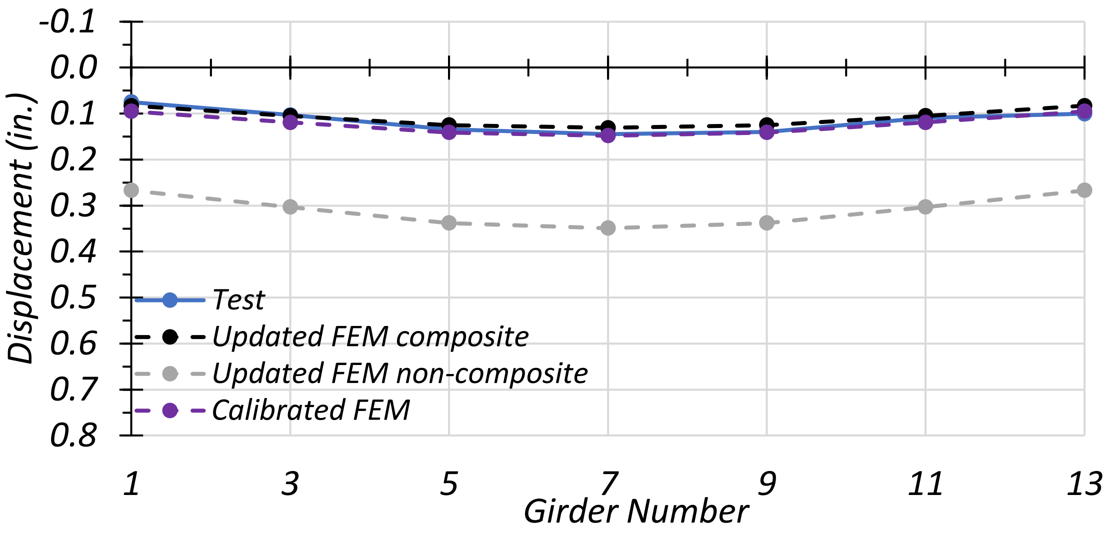
# Comparison of Model and Test Results

## Bridge SM-5

- Displacements - Crawl Speed Tests




**Path 1 Midspan Deflections**

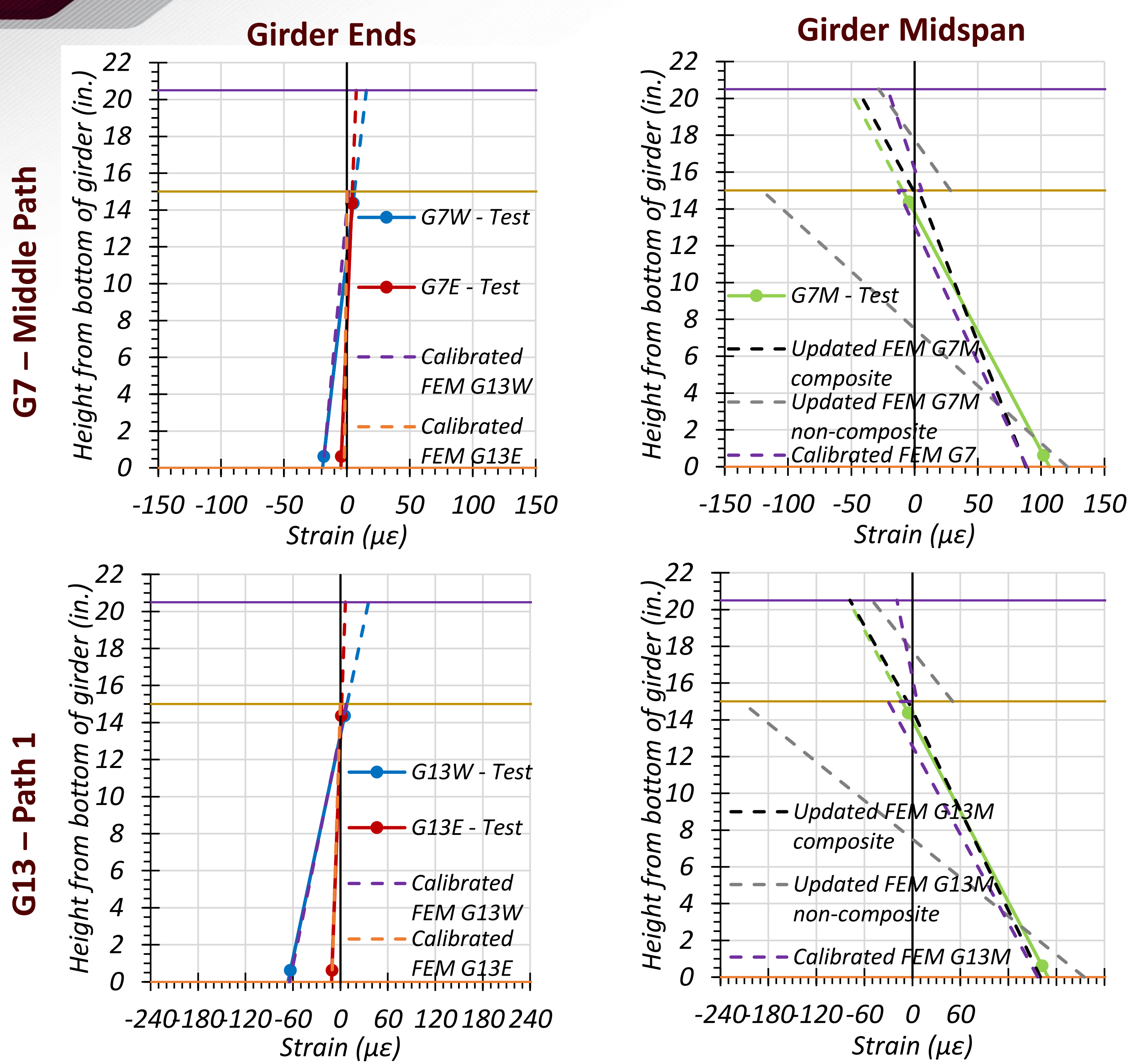



**Middle Path Midspan Deflections**

# Comparison of Model and Test Results

## Bridge SM-5

- Strains - Crawl Speed Tests



# Rating Factors for Bridge SM-5

### ASR RFs for One Test Vehicle

| Girder | Inventory RF | Operating RF |
|---|---|---|
| **G7** | 2.01 | 3.38 |
| **G13** | 1.30 | 2.26 |

### ASR RFs for Two-Lane HS20 from Calibrated FEM model

| Girder | Inventory RF | Operating RF |
|---|---|---|
| **G7** | 0.81 | 1.37 |
| **G13** | **0.74** | **1.29** |

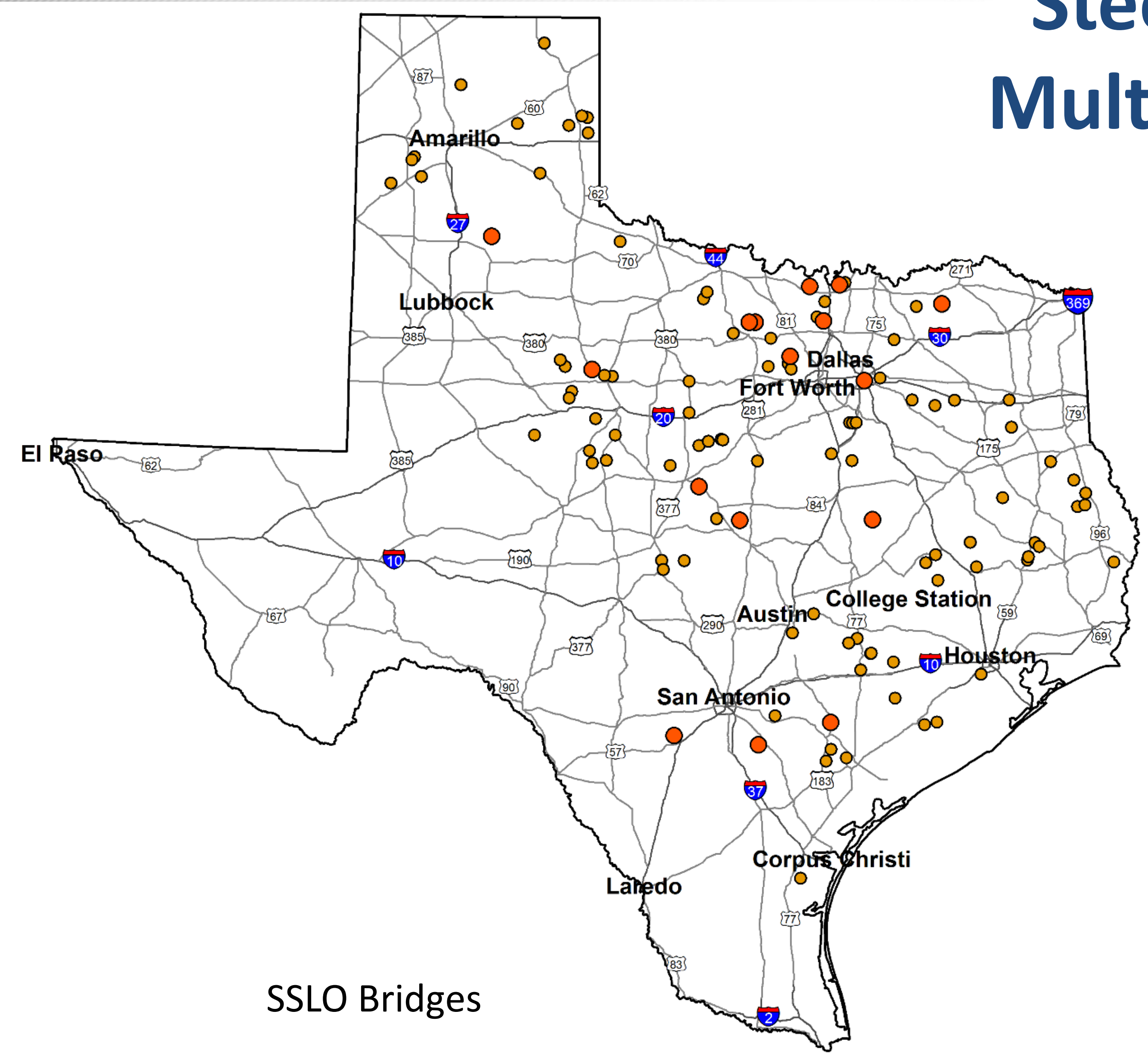
| Rating Factor | TxDOT | Updated | Updated/TxDOT |
|---|---|---|---|
| **Inventory** | 0.47 | **0.74** | 1.57 |
| **Operating** | 0.79 | **1.29** | 1.63 |

✓ *The updated RFs would allow for removal of the posting per TxDOT's load rating flowchart*

Changes due to:
- Nearly full composite action
- Partial end fixity

*Note: TxDOT uses LFR to rate this bridge. ASR allows the use of the FEM stresses to determine rating based on calibrated model.*

# Steel Continuous Multi-Girder Bridge




SSLO Bridges

# Steel Continuous Multi-Girder Bridge

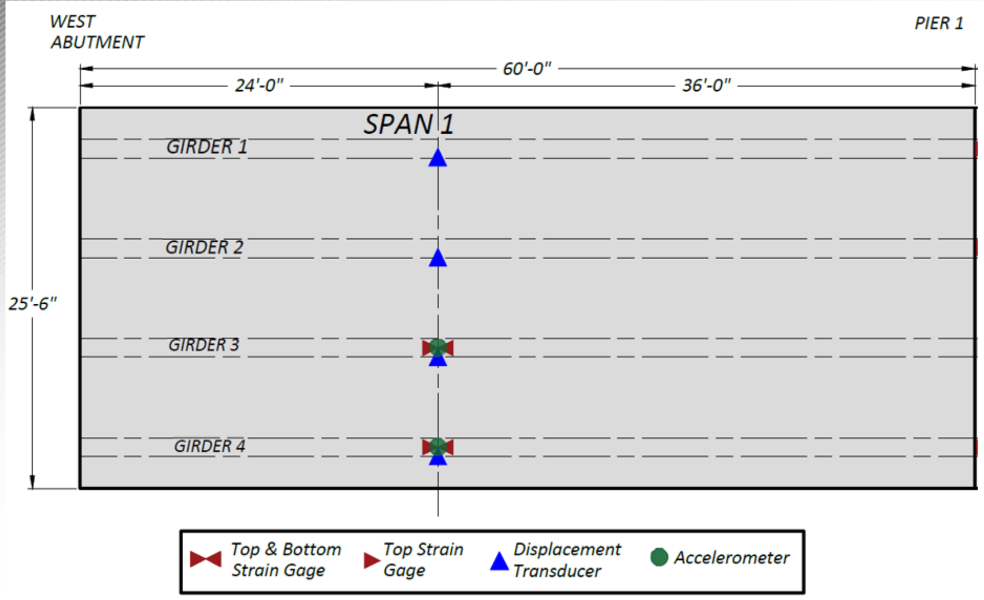
## Bridge SC-12

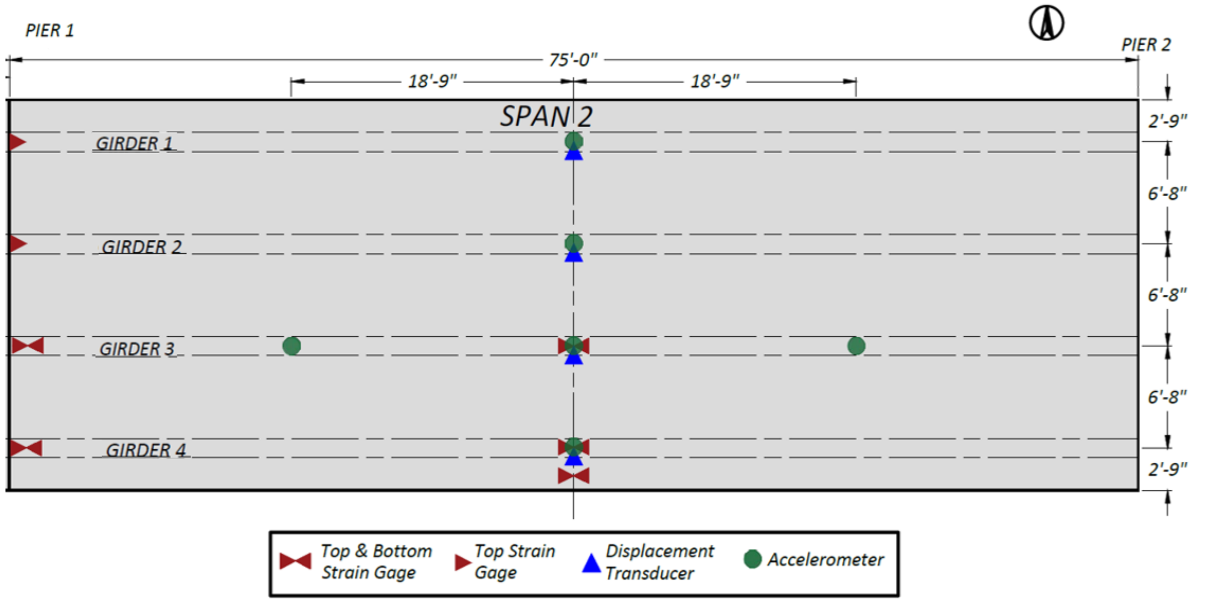
| ID | Route Prefix | Year Built | ADT | Max. Span Length (ft) | Deck Width (ft) | Girder Spacing (ft-in.) | Condition Rating | | | Operating HS20 Rating Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Deck | Super-structure | Sub-structure | |
| Avg. | - | 1962 | - | 25 | 20 | 3'-9" | 6 (Satisfactory) | 6 (Satisfactory) | 6 (Satisfactory) | 0.85 |
| SC-12 | 3 (On-System) | 1959 | 260 | 75 | 26 | 6'-8" | 6 (Satisfactory) | 7 (Good) | 7 (Good) | 0.93 |

Carries FM 1047 and traverses Simms Creek near Lometa, approximately 0.9 miles northwest of FM 581

# Instrumentation

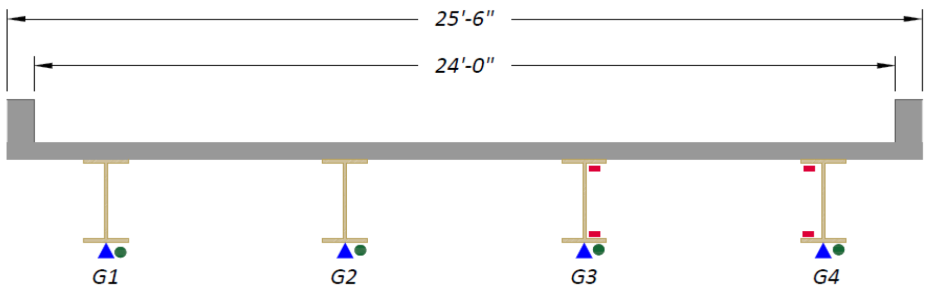
## Bridge SC-12



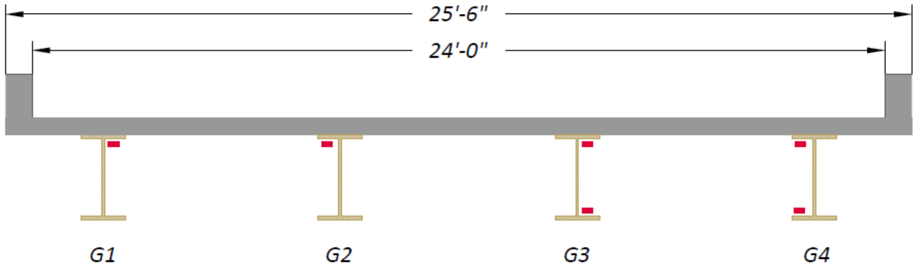




Span 3 not shown

**Midspan – Span 2**



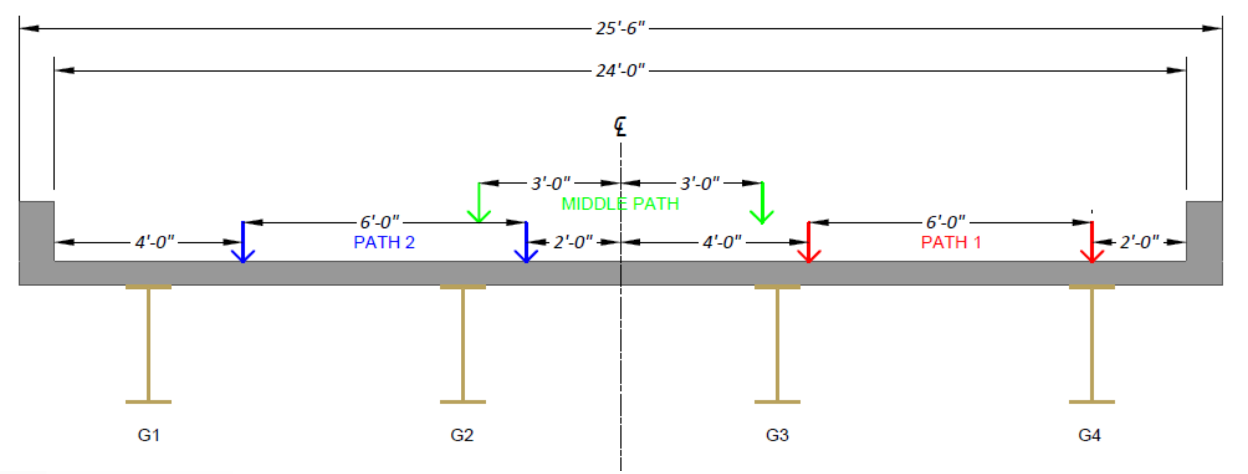

**Pier 1**




Texas Department of Transportation

# Test Sequence

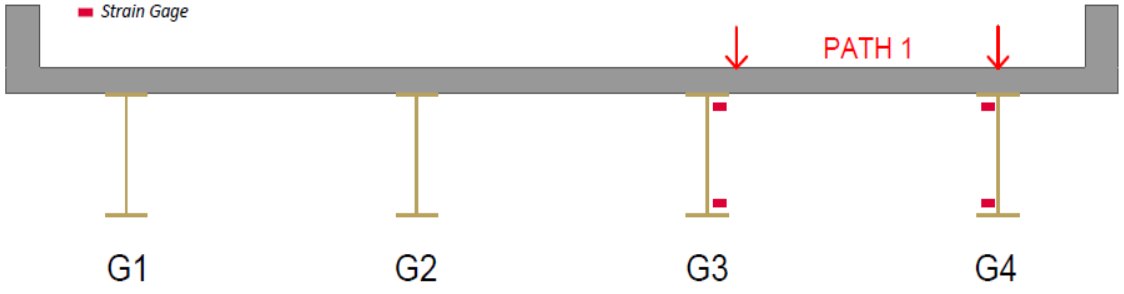
## Bridge SC-12




| Test Number | Test Location | Test Type |
|---|---|---|
| 1 | Path 1 – Span 1 | Static – Stop Location |
| 2 | Path 1 – Span 2 | Static – Stop Location |
| 3 | Path 1 | Static – Crawl (2 mph) |
| 4 | Path 1 | Dynamic (30 mph) |
| 5 | Path 1 | Dynamic (37 mph) |
| 6 | Path 2 – Span 1 | Static – Stop Location |
| 7 | Path 2 – Span 2 | Static – Stop Location |
| 8 | Path 2 | Static – Crawl (2 mph) |
| 9 | Path 2 | Dynamic (29 mph) |
| 10 | Path 2 | Dynamic (44 mph) |
| 11 | Middle Path – Span 1 | Static – Stop Location |
| 12 | Middle Path – Span 2 | Static – Stop Location |
| 13 | Middle Path | Static – Crawl (2 mph) |
| 14 | Middle Path | Dynamic (30 mph) |
| 15 | Middle Path | Dynamic (44 mph) |
| 16 | Middle Path | Dynamic (57 mph) |
| 17 | Span 1 – North Edge | Impact |
| 18 | Span 1 – Centerline | Impact |
| 19 | Span 1 – South Edge | Impact |
| 20 | Span 2 – Midspan – North Edge | Impact |
| 21 | Span 2 – Midspan – Centerline | Impact |
| 22 | Span 2 – Midspan – South Edge | Impact |
| 23 | Span 2 – Quarter span – North Edge | Impact |
| 24 | Span 2 – Quarter span – Centerline | Impact |
| 25 | Span 2 – Quarter span – South Edge | Impact |

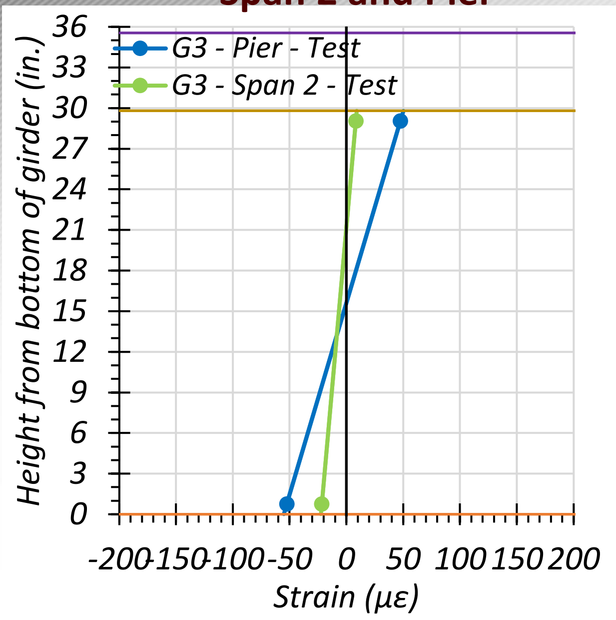
# Interior Girder G3 Strain Results
# Span 1, Path 1 – Static Tests

## Bridge SC-12

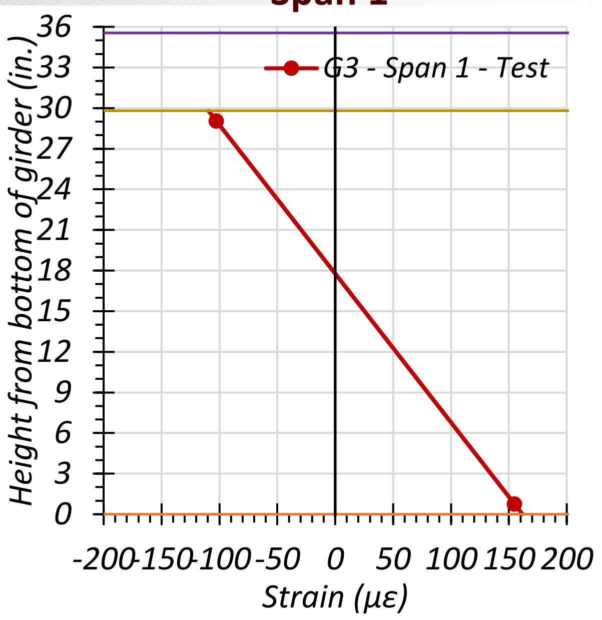



**Stop Location Test**

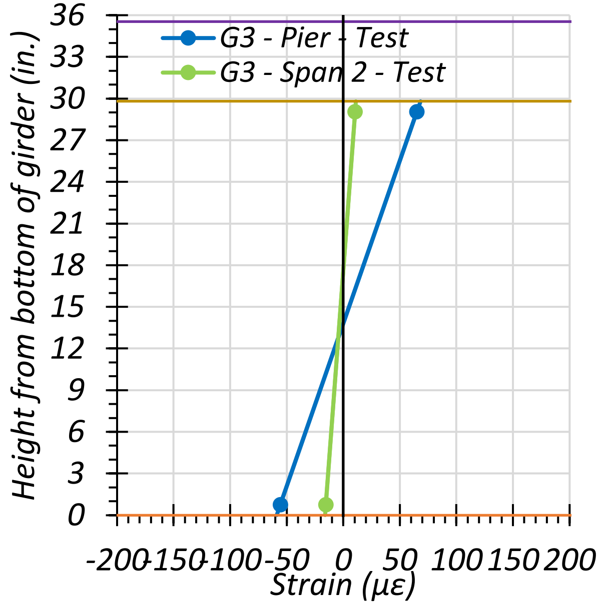
Span 2 and Pier

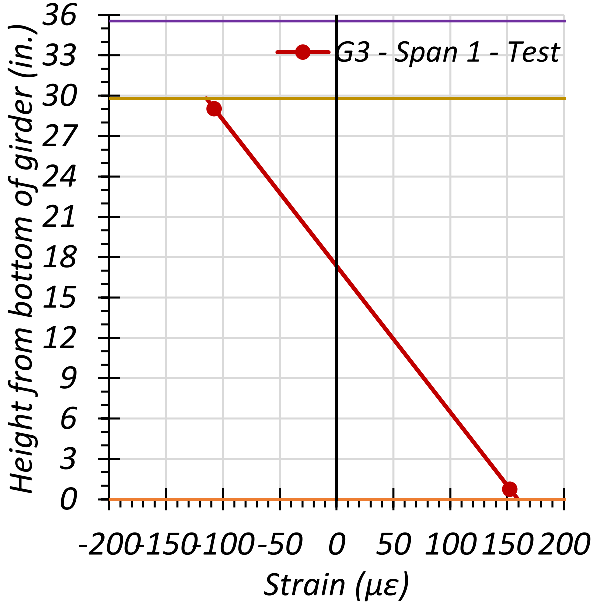



Span 1




**Crawl Speed Test**




- Positive Bending Neutral Axis Locations
  - Stop Location: 17.77 in.
  - Crawl Speed: 17.34 in.
  - *Theoretical Non-Composite: 14.90 in.*
  - *Theoretical Composite: 26.11 in.*
- Maximum Bottom Flange Strains/Stresses
  - Span 1: 154.9 με → 4.49 ksi
  - Pier 1: -55.6 με → -1.61 ksi
  - Span 2: -21.6 με → -0.63 ksi

*Tension is positive*

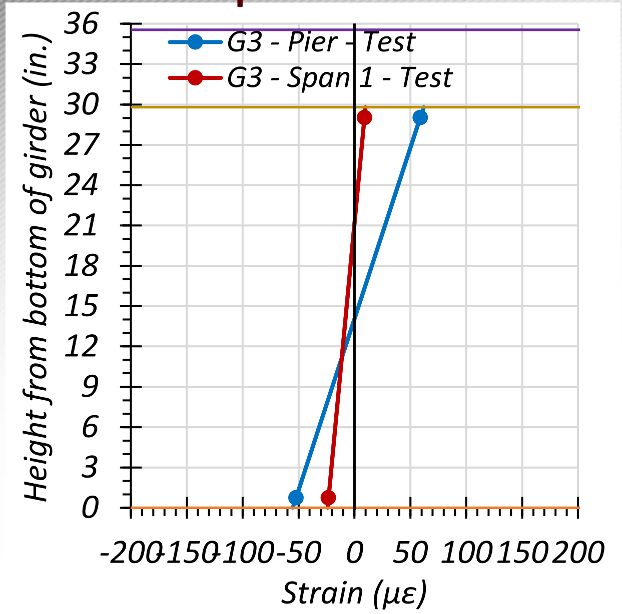
# Interior Girder G3 Strain Results
# Span 2, Path 1 – Static Tests

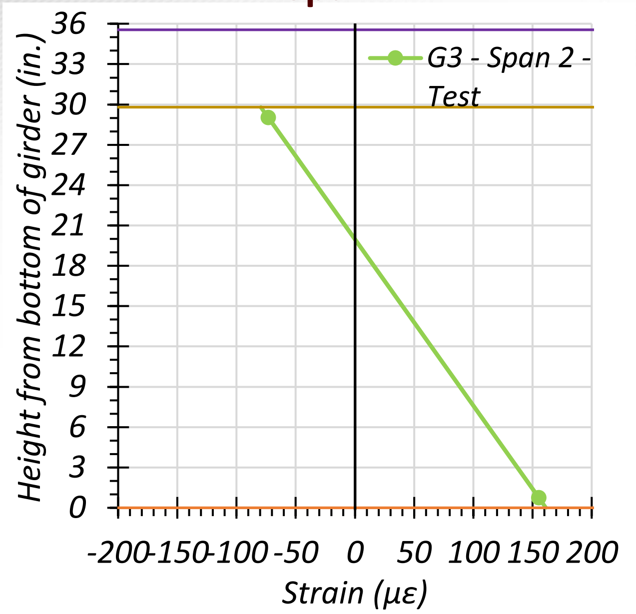
### Bridge SC-12

Span 1 and Pier

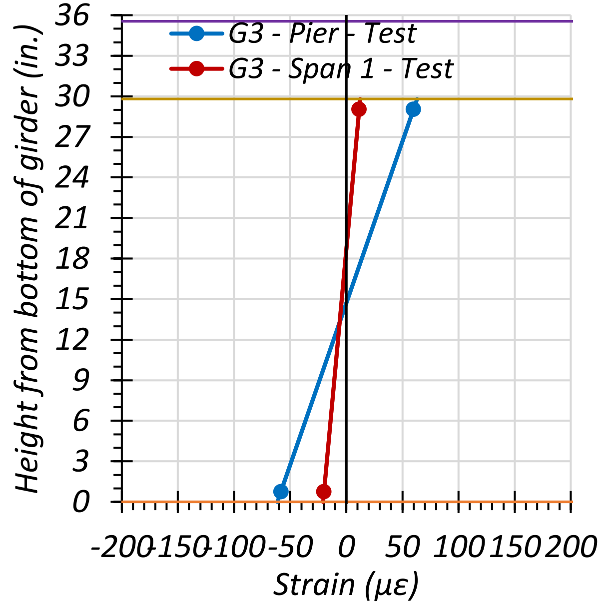
Span 2

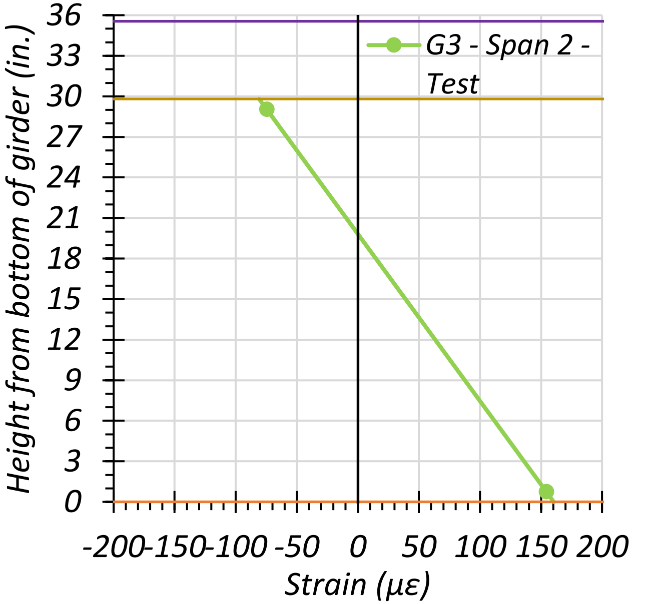
Stop Location Test

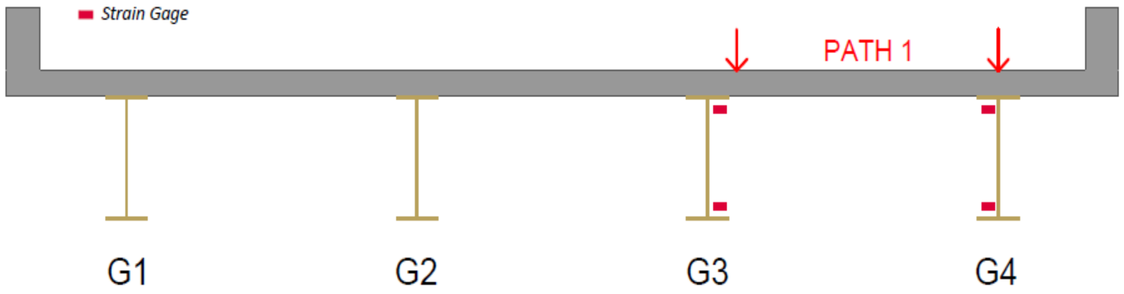



Crawl Speed Test




- Positive Bending Neutral Axis Locations
  - Stop Location: 19.97 in.
  - Crawl Speed: 19.56 in.
  - *Theoretical Non-Composite: 14.90 in.*
  - *Theoretical Composite: 26.11 in.*

Partial composite action

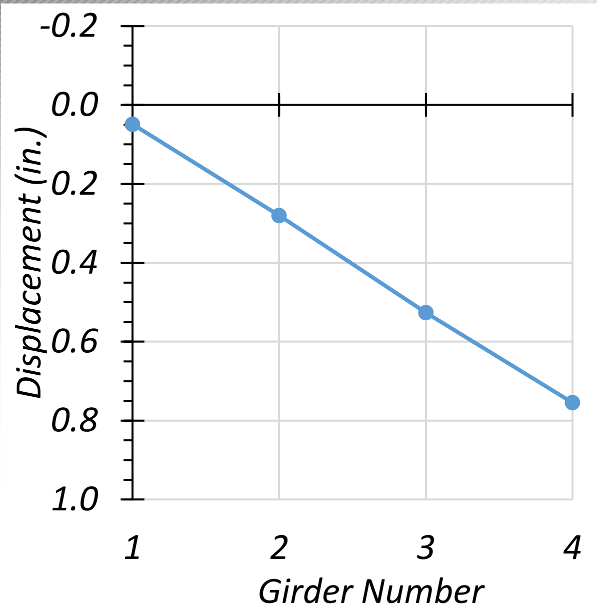
- Maximum Bottom Flange Strains/Stresses
  - Span 2: 155.1 με → 4.50 ksi
  - Pier 1: -58.2 με → -1.69 ksi
  - Span 1: -23.1 με → -0.67 ksi

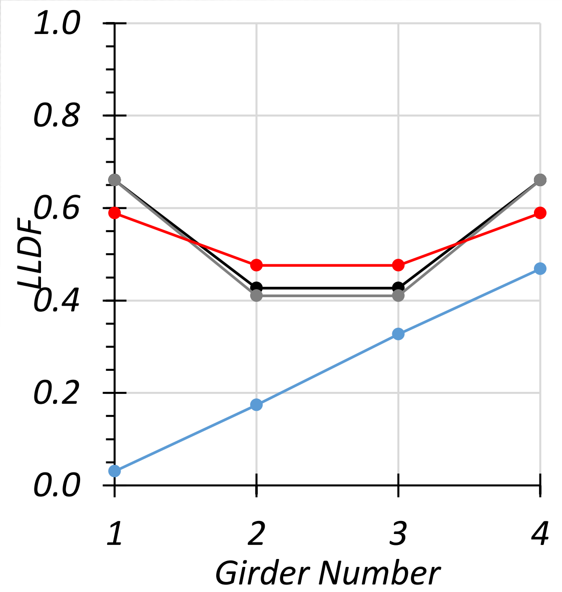
*Tension is positive*

# Deflection Results
# Span 2, Path 1 – Static Tests
## Bridge SC-12

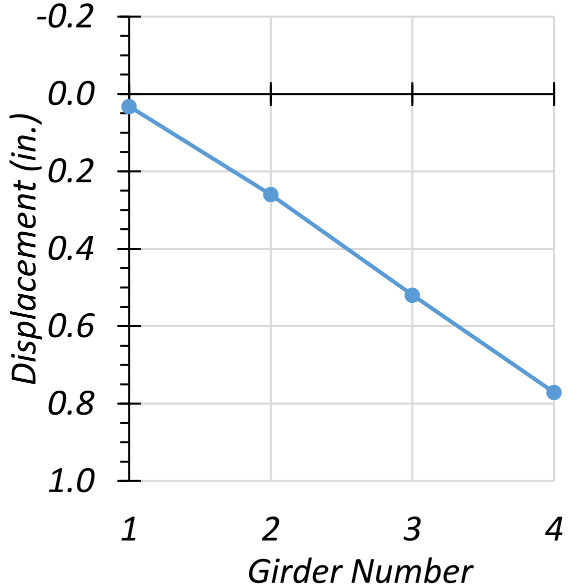
**Deflections** **LLDFs**

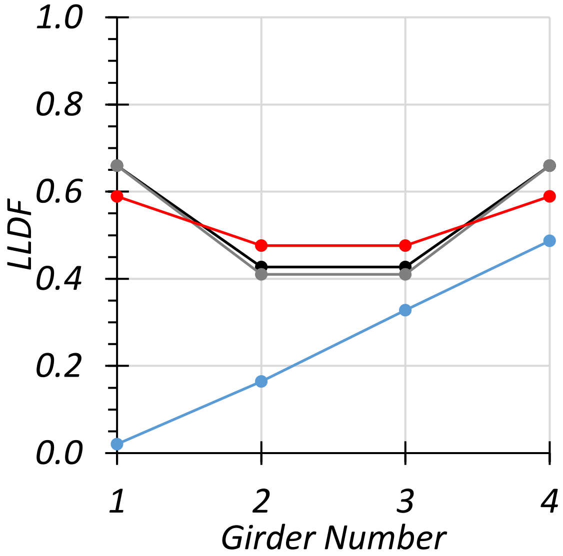
**Stop Location Test**

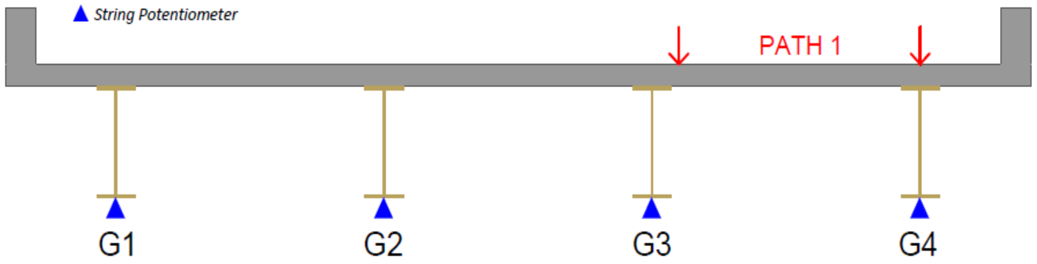



**Crawl Speed Test**



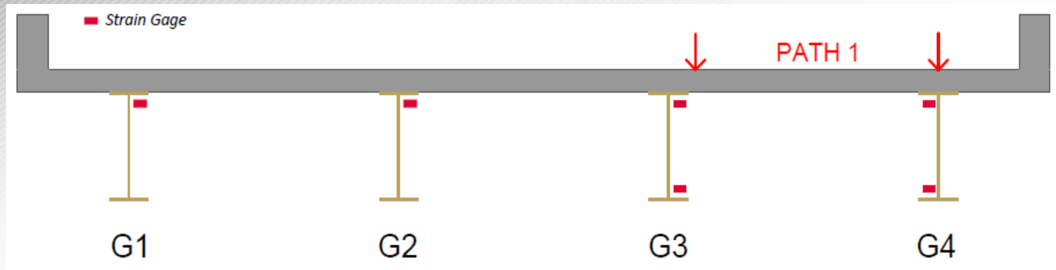



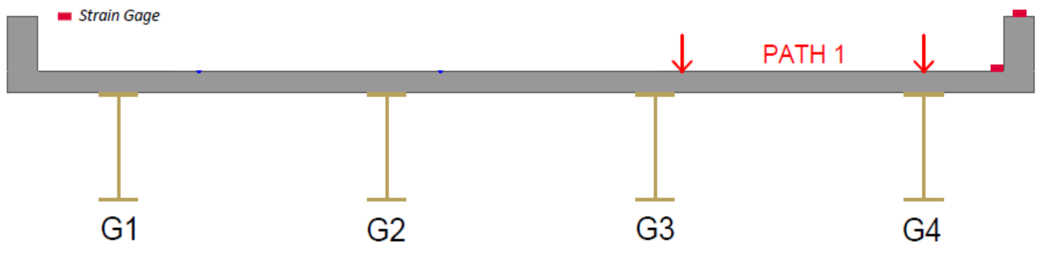

| Test and Girder Type | AASHTO Standard Specs ($g^m_{AASHTO\_Std}$) | AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$) | AASHTO LRFD $K_g$ Calculated ($g^m_{AASHTO\_K}$) | Test ($g^m_{test}$) | $g^m_{AASHTO\_Std}/g^m_{test}$ | $g^m_{AASHTO\_S}/g^m_{test}$ | $g^m_{AASHTO\_K}/g^m_{test}$ |
|---|---|---|---|---|---|---|---|
| Stop Location Interior | 0.476 | 0.427 | 0.410 | 0.327 | 1.46 | 1.31 | 1.25 |
| Stop Location Exterior | 0.589 | 0.660 | 0.660 | 0.469 | 1.26 | 1.41 | 1.41 |
| Crawl Speed Interior | 0.476 | 0.427 | 0.410 | 0.328 | 1.45 | 1.30 | 1.25 |
| Crawl Speed Exterior | 0.589 | 0.660 | 0.660 | 0.487 | 1.21 | 1.36 | 1.36 |

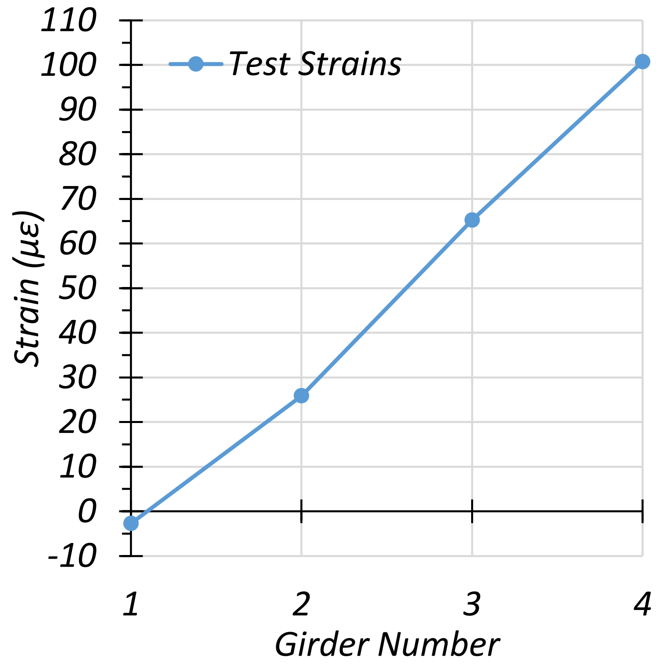
Test AASHTO Standard AASHTO LRFD simplified
AASHTO LRFD $K_g$ calculated

# Pier Location and Curb Strain Results, Path 1 – Crawl Speed Test

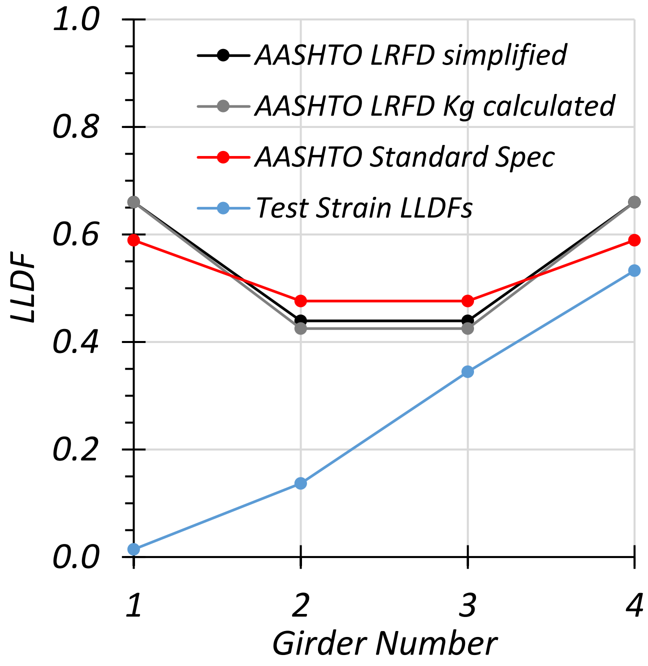
## Bridge SC-12



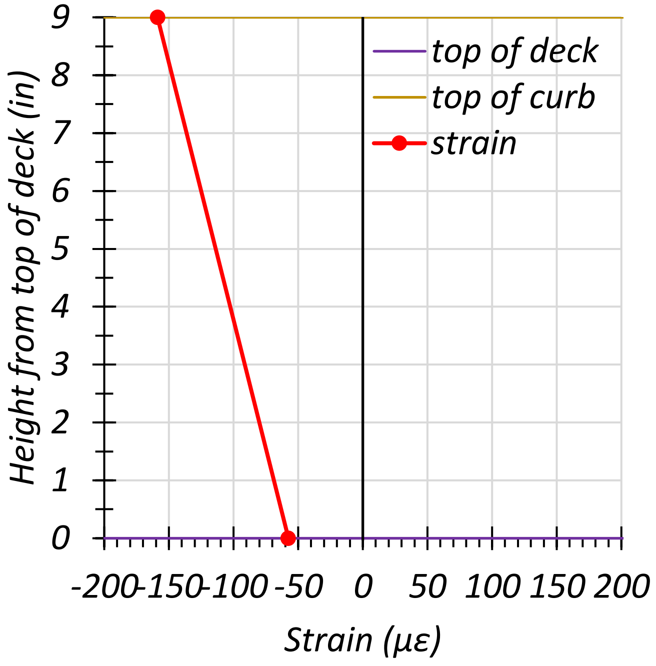




Top Flange Strains



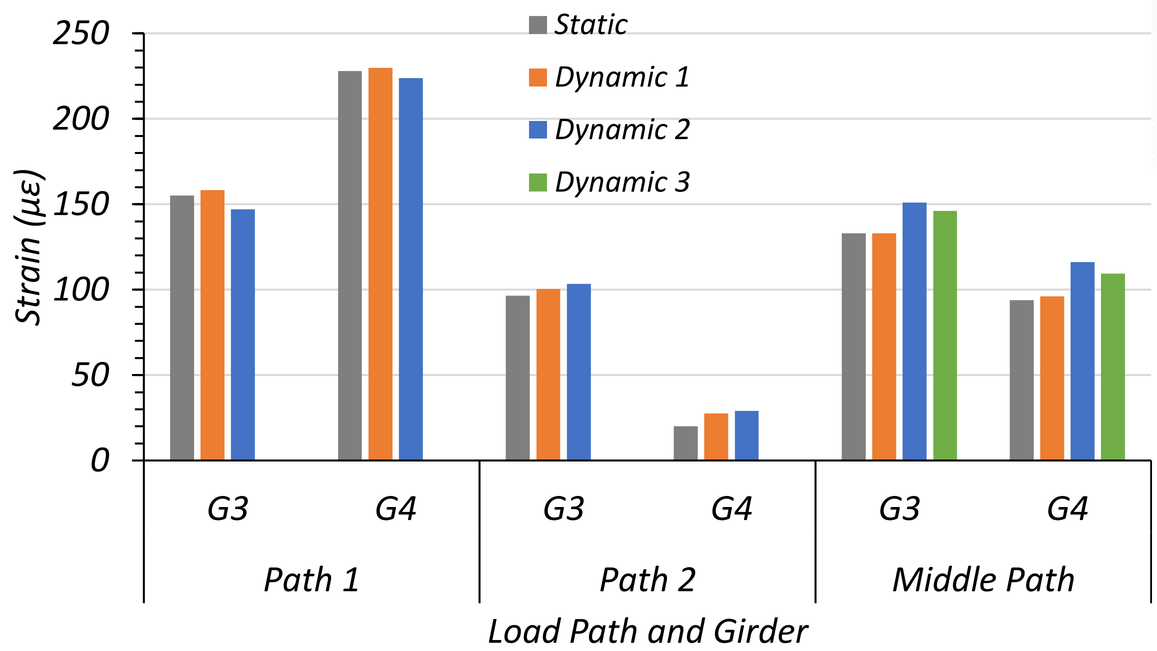

Negative Moment LLDFs

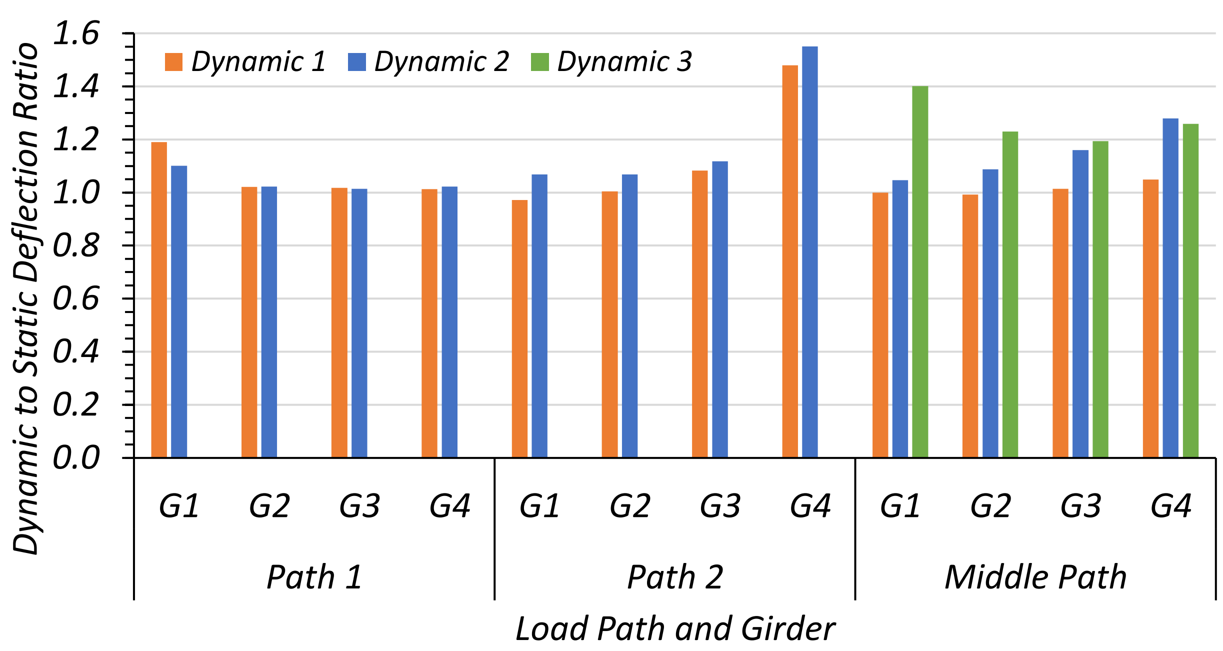



Curb Strain Results

# Dynamic Test Results – Span 2

## Bridge SC-12



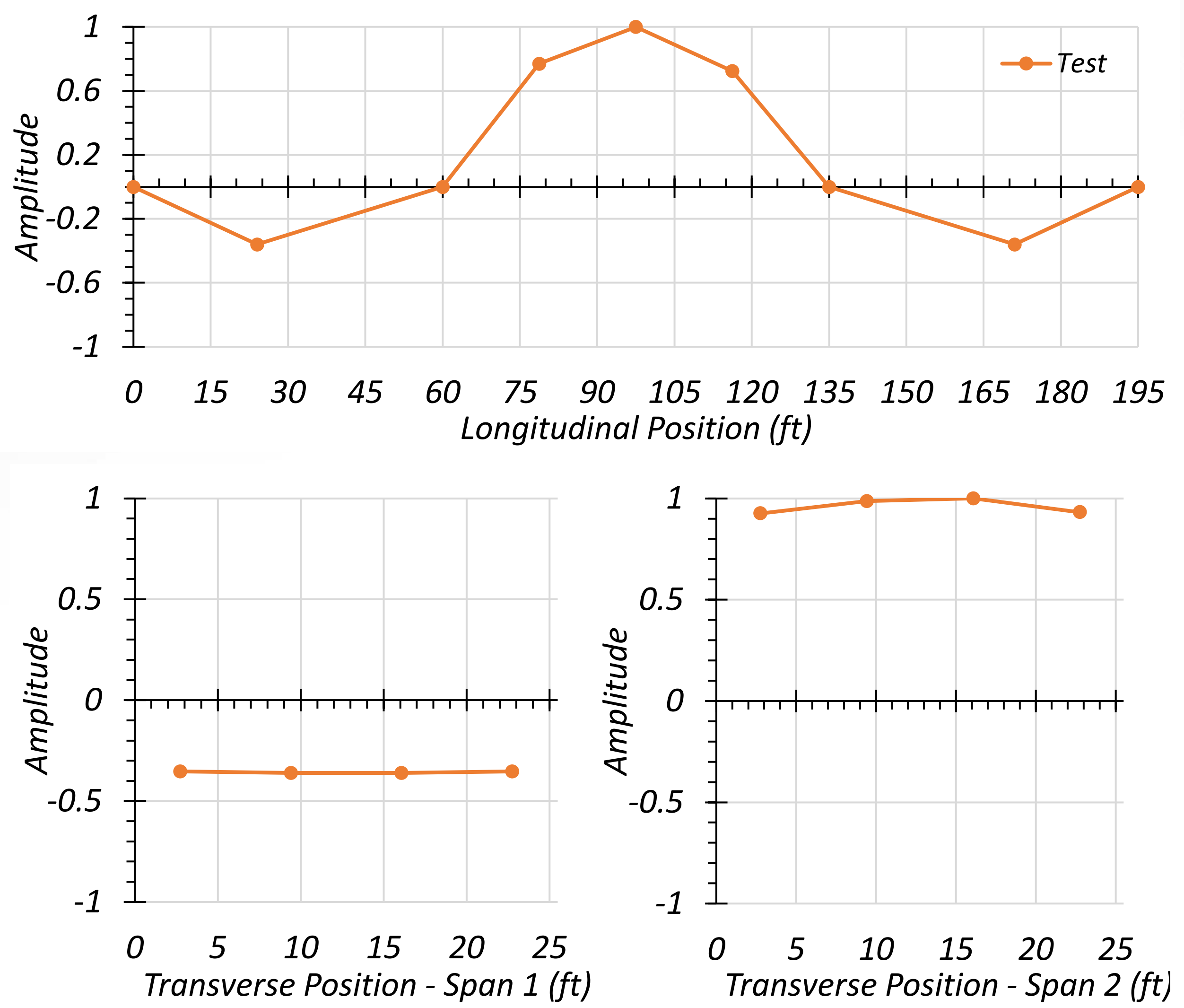

- Average dynamic increase for both girders: 11%
- AASHTO Standard Specifications IM:25%
- AASHTO LRFD Specifications IM: 33%

- Average dynamic increase for both girders: 12%
- AASHTO Standard Specifications IM:25%
- AASHTO LRFD Specifications IM: 33%

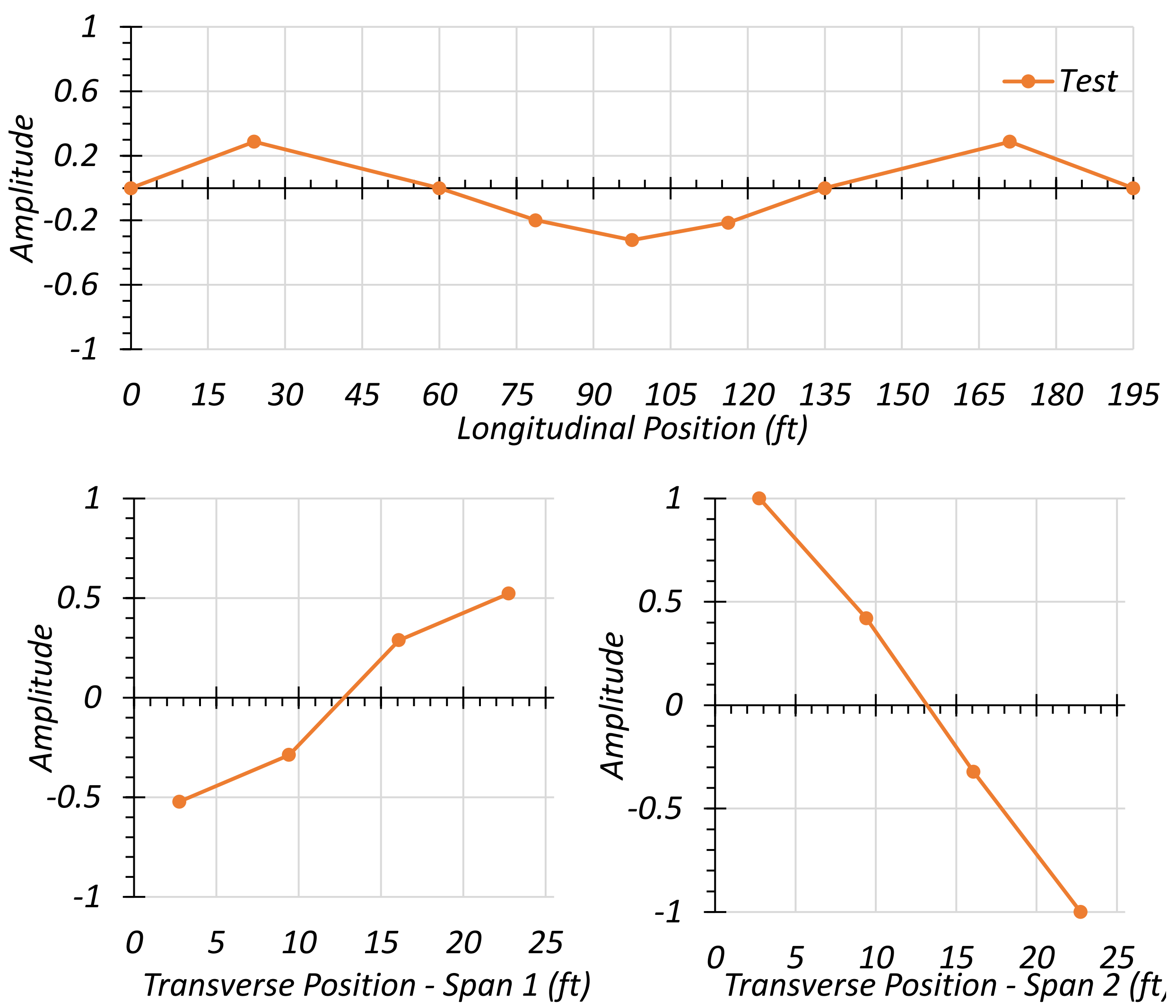
*Note:*
- *Path 1: Dynamic 1 = 30 mph, Dynamic 2 = 37 mph*
- *Path 2: Dynamic 1 = 29 mph, Dynamic 2 = 44 mph*
- *Middle Path: Dynamic 1 = 30 mph, Dynamic 2 = 44 mph, Dynamic 3 = 57 mph*

# Dynamic Bride Characteristics

## Bridge SC-12



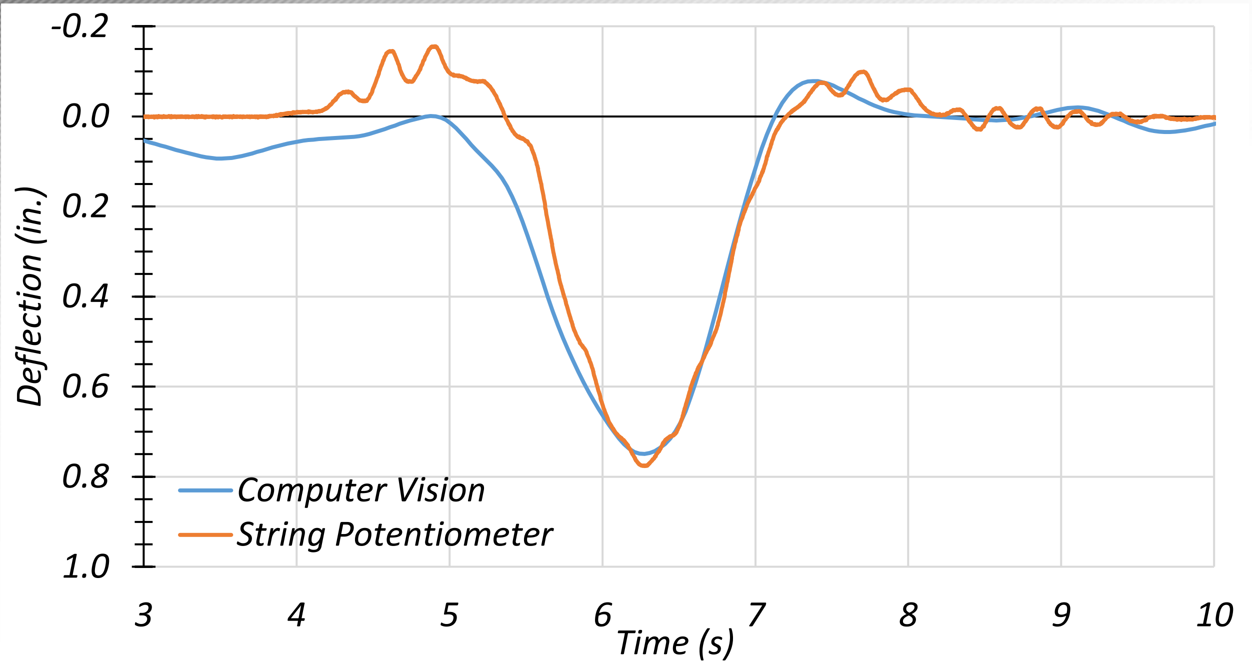

**Mode Shape 1 (3.78 Hz)**

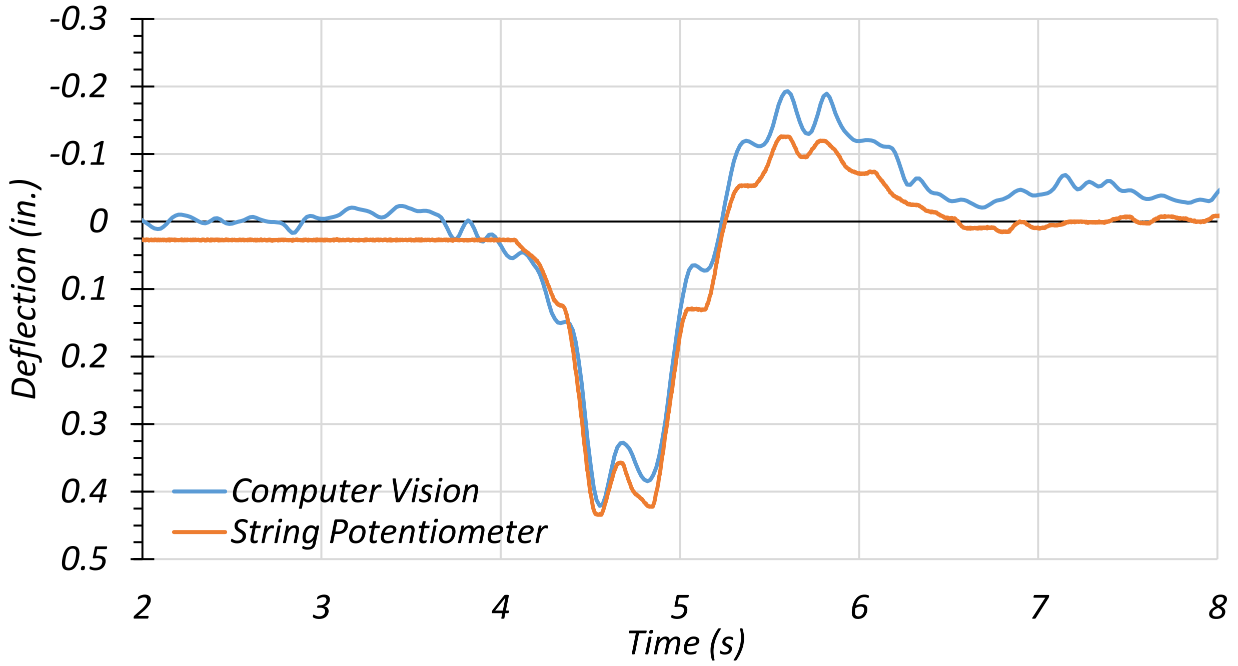



**Mode Shape 2 (6.71 Hz)**

# Computer Vision Results

## Bridge SC-12



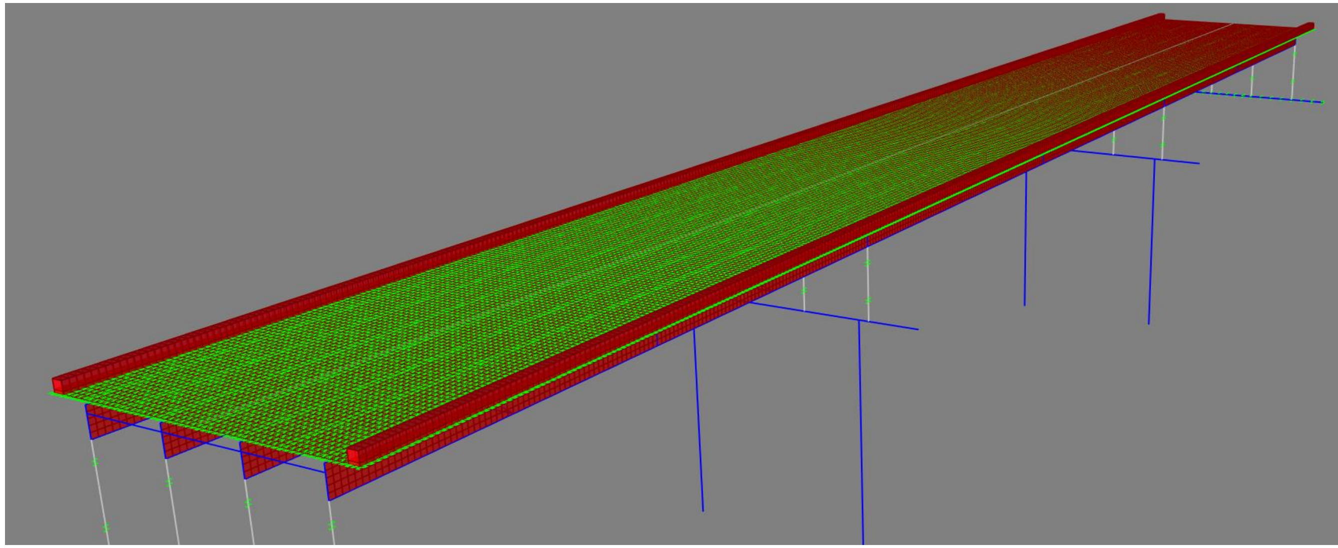

- Girder 4 – Path 1 – Span 2 – Dynamic Test at 30 mph
  - String Pot Deflection: 0.776 in.
  - Computer Visions Deflection: 0.750 in.
  - 3.4% Difference
  - Lowpass Butterworth filter with 300 Hz cutoff frequency

- Girder 1 – Path 2 – Span 1 – Dynamic Test at 29 mph
  - String Pot Deflection: 0.434 in.
  - Computer Visions Deflection: 0.421 in.
  - 3.0% Difference
  - Lowpass Butterworth filter with 300 Hz cutoff frequency

# Model Updating and Calibration

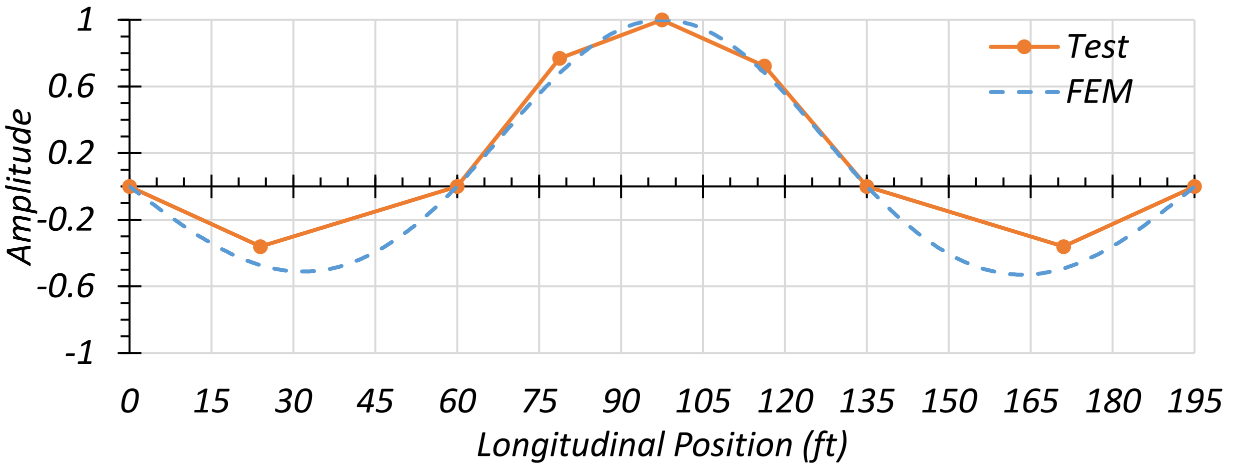
## Bridge SC-12

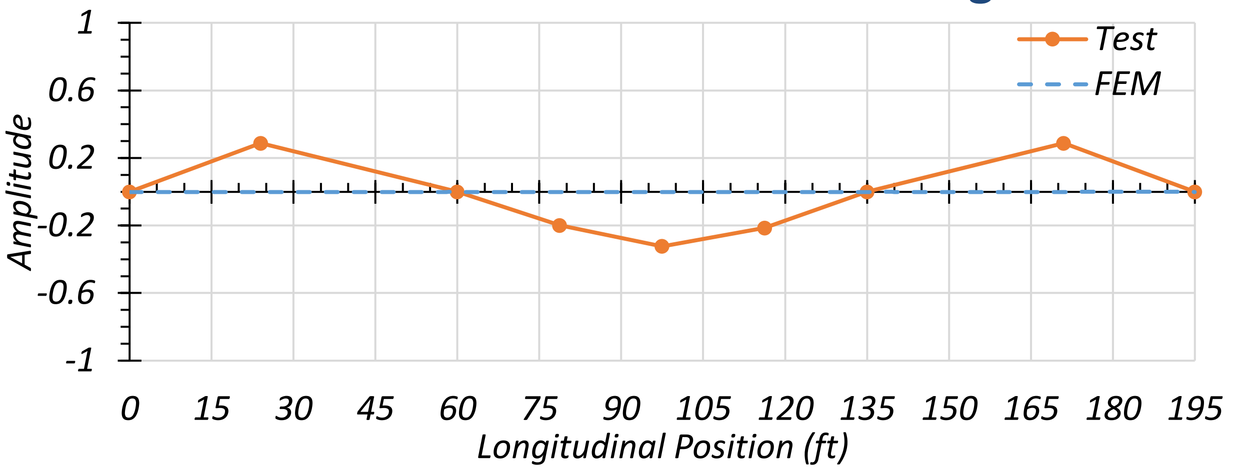
- Updated FEM models
  - NDE field measured minimum $f_c'$ of 6.25 ksi (corresponding MOE = 4506 ksi)
  - One model assumes fully composite action, one model assumes fully non-composite action
- Calibrated FEM model
  - Includes springs between the deck and top flange nodes to induce partial composite action
  - A sensitivity analysis was conducted for the deck-girder springs to select stiffness
  - Spring stiffness values were selected and refined based on the sensitivity analysis
  - Includes reduced stiffness in the deck near the interior piers to account for concrete deck cracking in tension due to negative moment

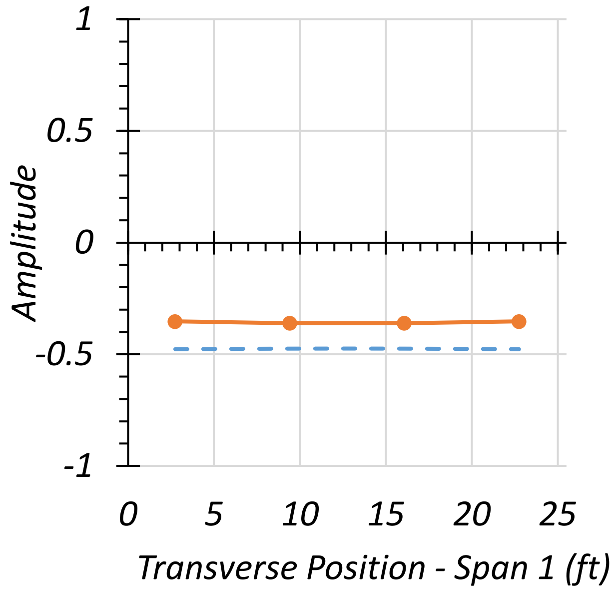


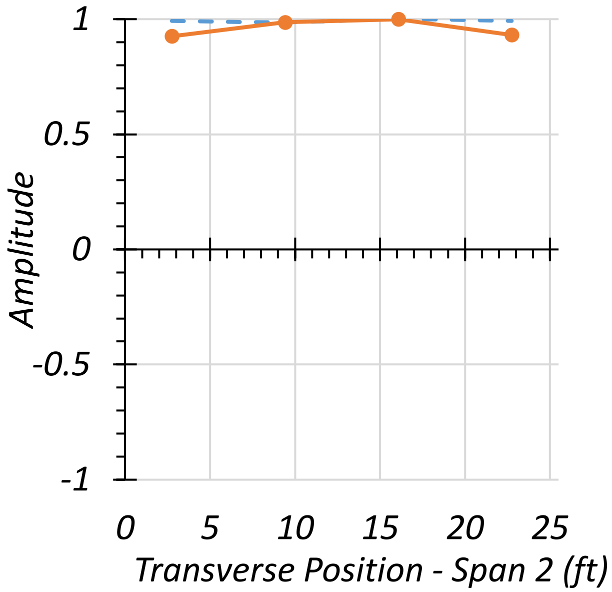
# Dynamic Characteristics Comparison

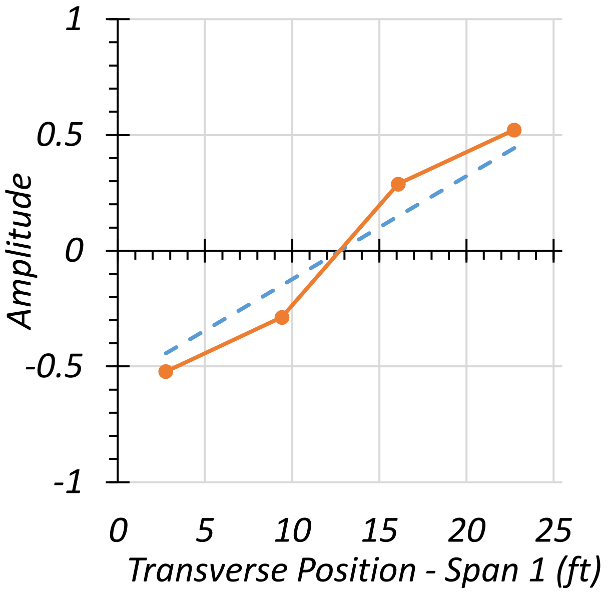
## Bridge SC-12

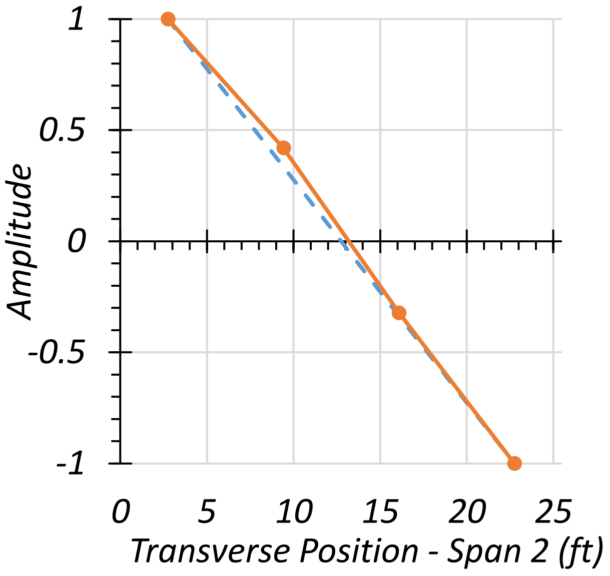



**1st Mode (Test = 3.78 Hz, FEM = 3.32 Hz)**

**2nd Mode (Test = 6.71 Hz, FEM = 5.95 Hz)**

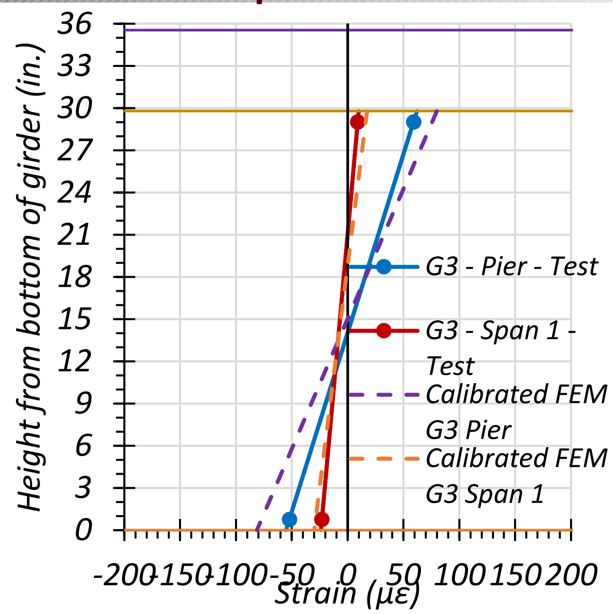
TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

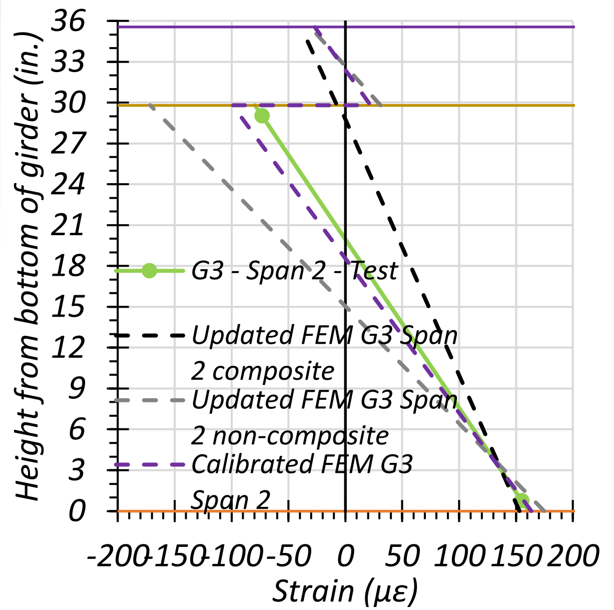
# Comparison of Model and Test Results – Span 2

### Span 1 and Pier

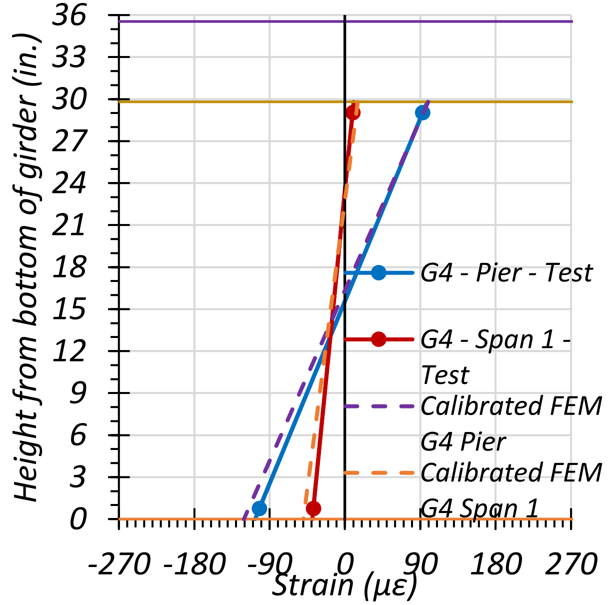
### Span 2

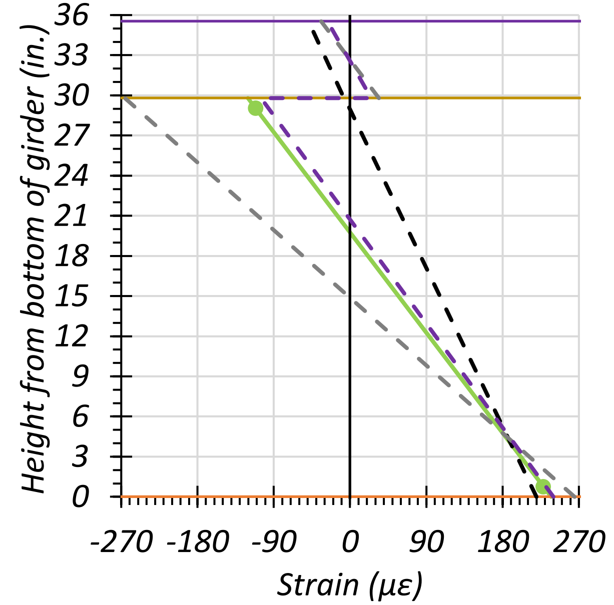
G3 – Path 1

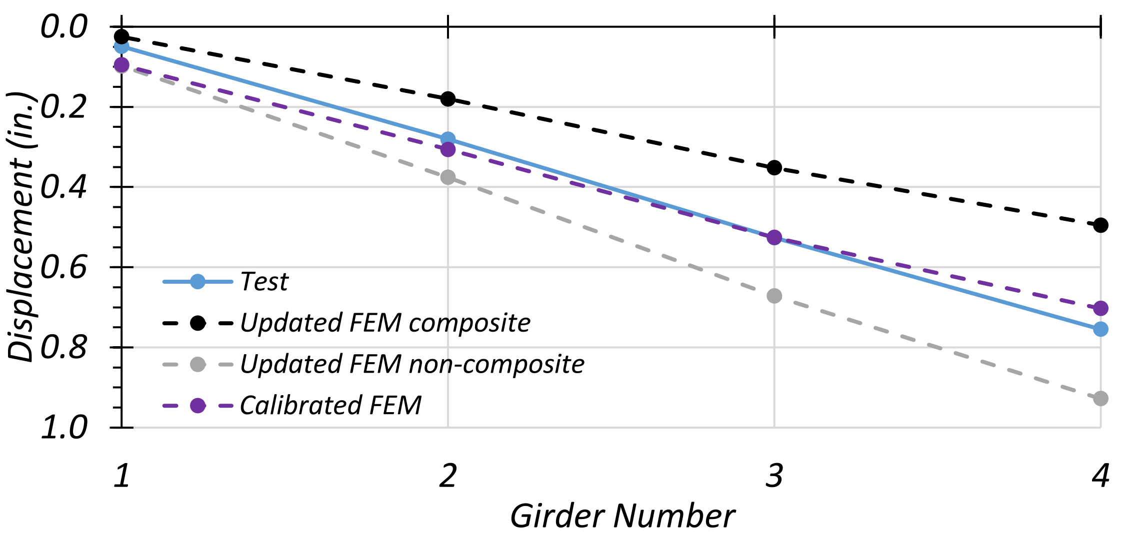


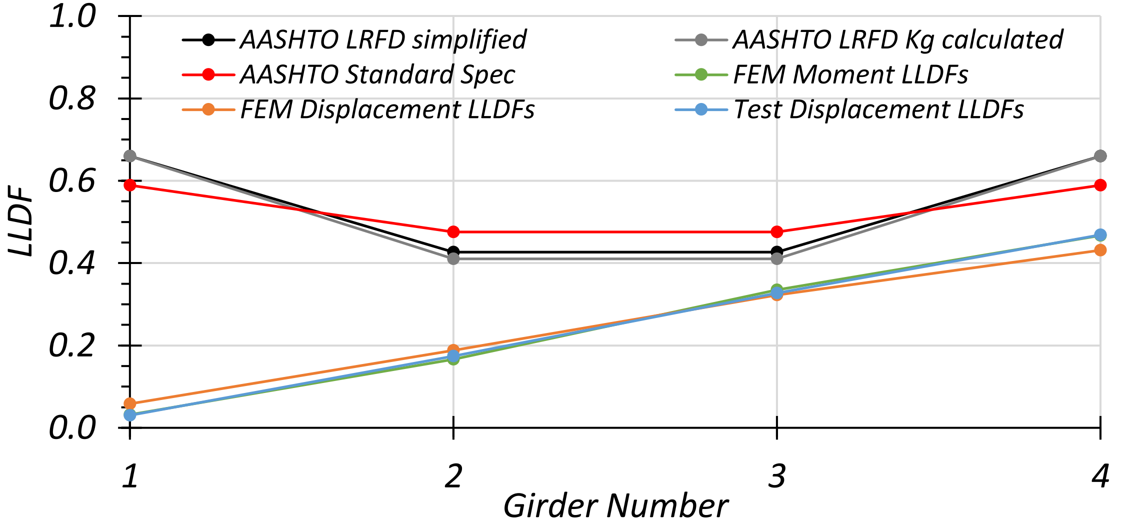

G4 – Path 1




Path 1 Midspan Deflections




Path 1 LLDFs

# Rating Factors for Bridge SC-12

## ASR RFs for one Test Vehicle

| Girder | Positive Moment Region | | Negative Moment Region | |
|---|---|---|---|---|
| | Inventory RF | Operating RF | Inventory RF | Operating RF |
| G3 | 2.03 | 3.16 | 3.41 | 5.97 |
| G4 | 1.24 | 1.98 | 1.84 | 3.38 |

## ASR RFs for two-lane HS20 from Calibrated FEM model

| Girder | Positive Moment Region | | Negative Moment Region | |
|---|---|---|---|---|
| | Inventory RF | Operating RF | Inventory RF | Operating RF |
| G3 | 0.92 | 1.44 | 0.92 | 1.61 |
| G4 | 0.80 | 1.29 | $\boxed{0.73}$ | $\boxed{1.34}$ |

| Rating Factor | TxDOT | Updated | Updated/TxDOT |
|---|---|---|---|
| Inventory | 0.55 | 0.73 | 1.33 |
| Operating | 0.93 | 1.34 | 1.44 |

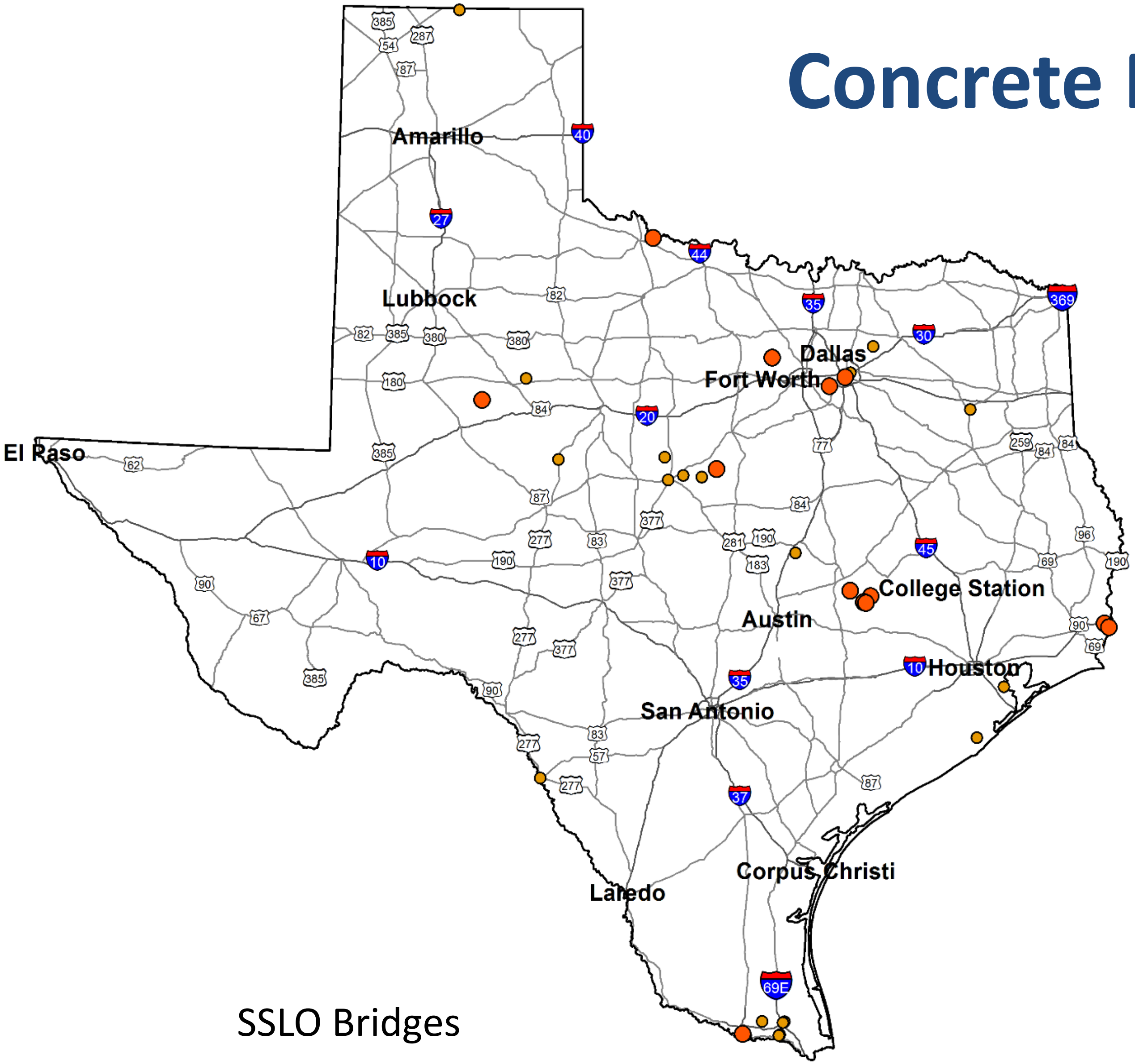
✓ The proposed RFs would allow for removal of the posting per TxDOT's load rating flowchart

Changes due to:

- Partial composite action
- LLDFs used by FEM model

*Note: TxDOT uses LFR to rate this bridge. ASR allows the use of the FEM stresses to determine rating based on calibrated model.*

# Concrete Multi-Girder Bridge

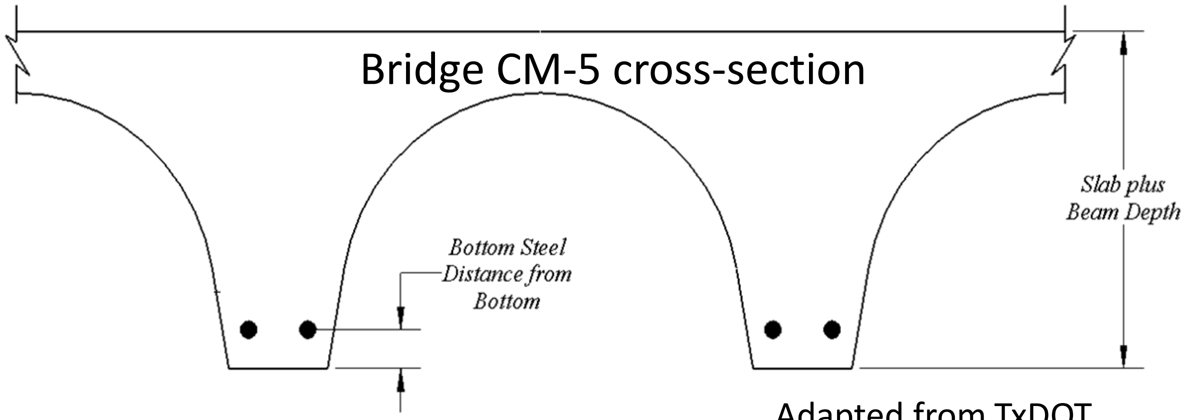



SSLO Bridges

# Concrete Multi-girder Bridge

## Bridge CM-5

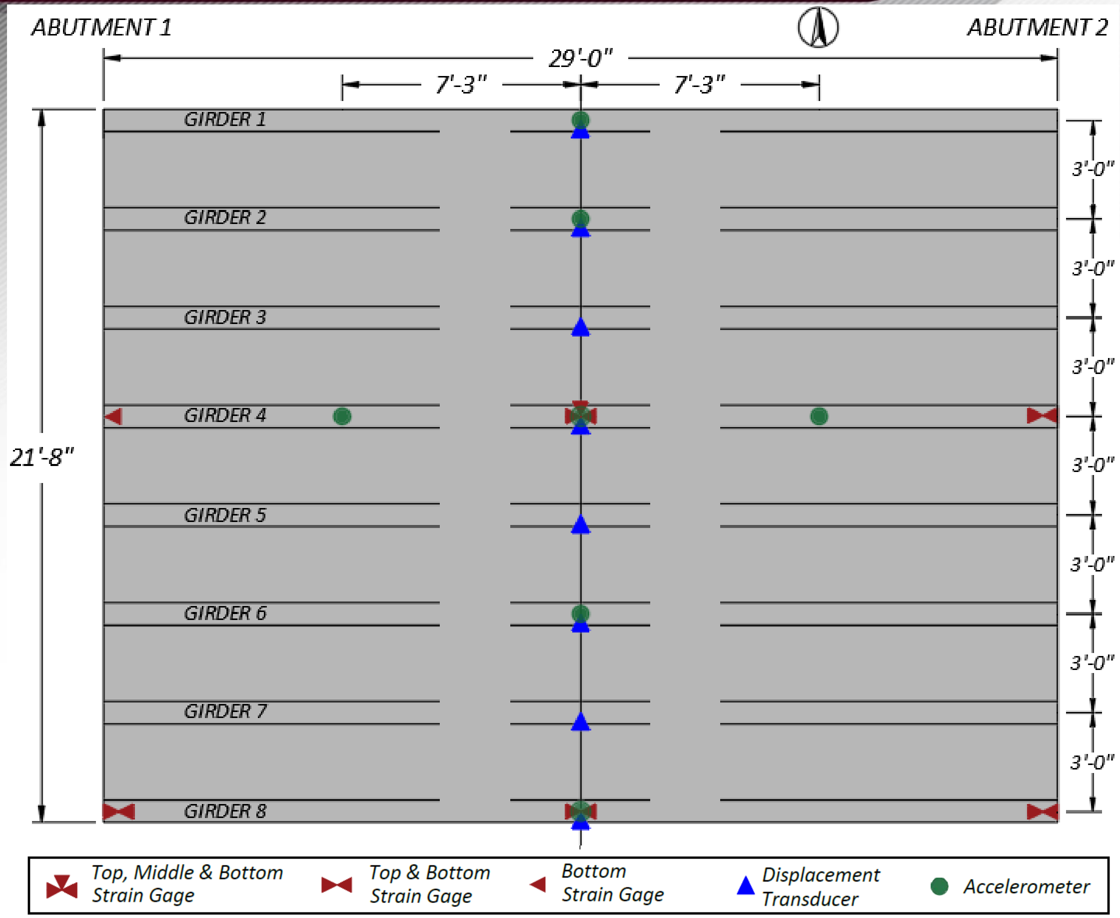
| ID | Dist. to CS (mi) | Route Prefix | Year Built | ADT | Max. Span Length (ft) | Deck Width (ft) | Condition Rating | | | Operating HS20 Rating Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Deck | Super-structure | Sub-structure | |
| Avg. | - | - | 1964 | - | 34 | 28 | 7 (Good) | 7 (Good) | 6 (Satisfactory) | 0.99 |
| CM-4 | 32 | 4 (Off-System) | 1950 | 250 | 29 | 22 | 7 (Good) | 7 (Good) | 5 (Fair) | 0.99 |




Adapted from TxDOT (2001)

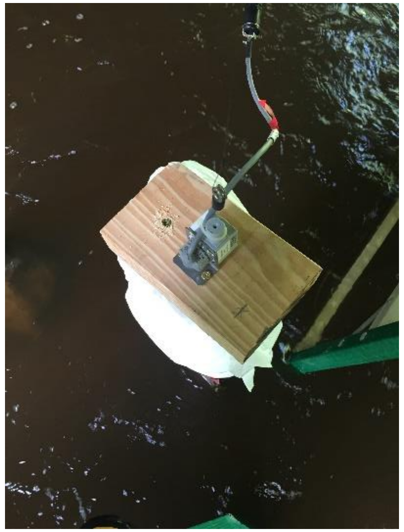
# Instrumentation

## Bridge CM-5

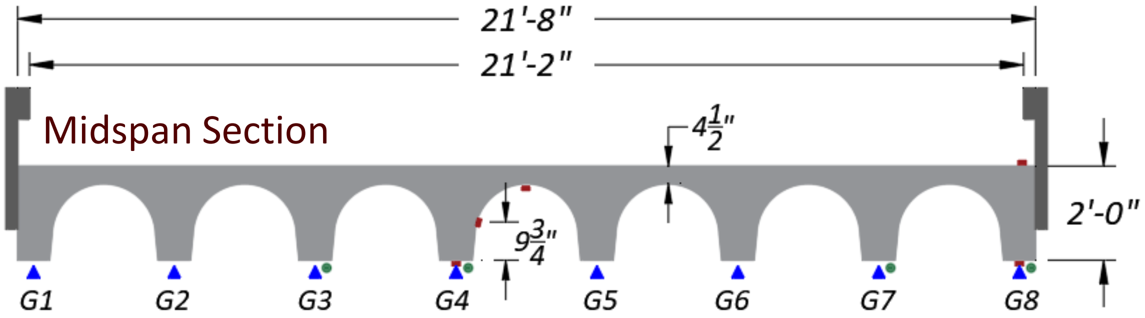


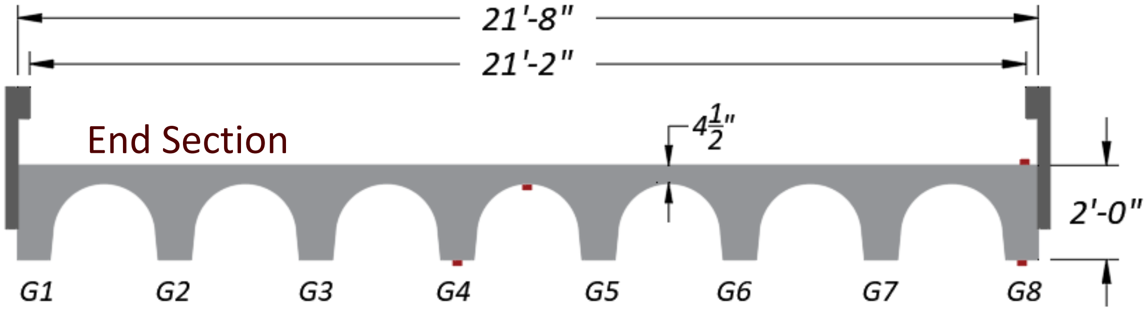

Strain Gauge

Accelerometer

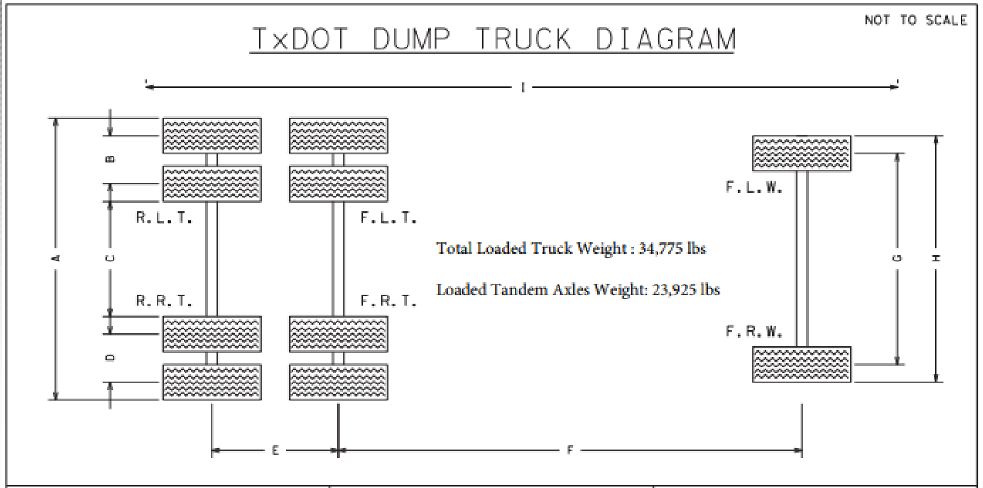


String Potentiometer



# Testing
## Bridge CM-5




**TRUCK INFORMATION**

Truck Make: Sterling
Truck Model: LT 9500
Truck Year: 2005

**VEHICLE STICKER INFORMATION**

Front Axle: 9,300 LBS
Front Tandem Axle: 6,850 LBS
Rear Tandem Axle: 6,850 LBS
Gross Vehicle Weight (Empty): 23,000 LBS

**TRUCK MEASUREMENTS**

| REFERENCE | DISTANCE |
|---|---|
| A | 7'-11" |
| B | 1'-1" |
| C | 4'-4" |
| D | 1'-1" |
| E | 4'-5" |
| F | 14'-1" |
| G | 6'-11" |
| H | 8'-0" |
| I | 23'-11" |

**LOADED WEIGHTS**

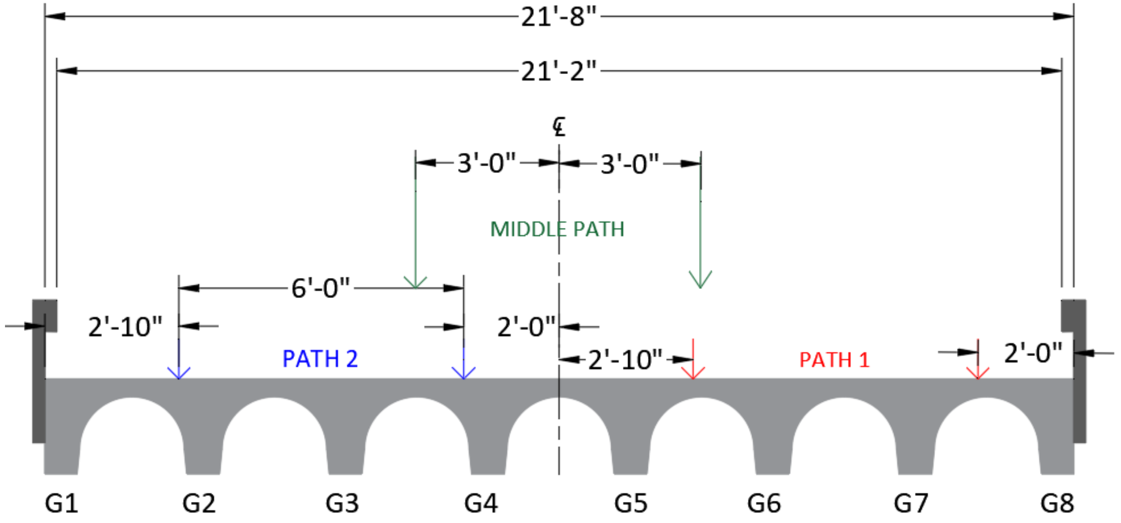
| LOCATION | WEIGHT |
|---|---|
| Front R Wheel | 5,450 |
| Front L Wheel | 5,400 |
| Front R Tandem | 5,925 |
| Front L Tandem | 6,300 |
| Rear R Tandem | 5,550 |
| Rear L Tandem | 6,150 |

Material Type: Flexbase


Load Posting

TxDOT Dump Truck

| Test Protocol | |
|---|---|
| Static Tests | Dynamic Tests |
| • Stop Location | • 31 & 41 mph |
| • Crawl Speed | • Impact Tests |




Test Load Paths

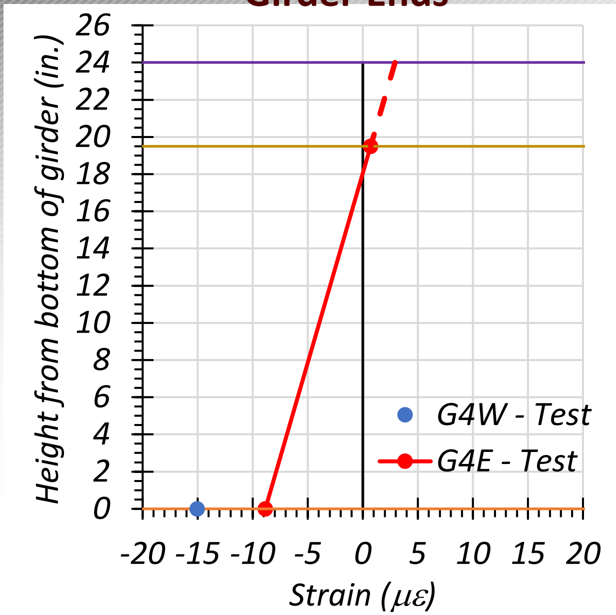
# Interior Girder G4 Strain Results, Middle Path – Static Tests

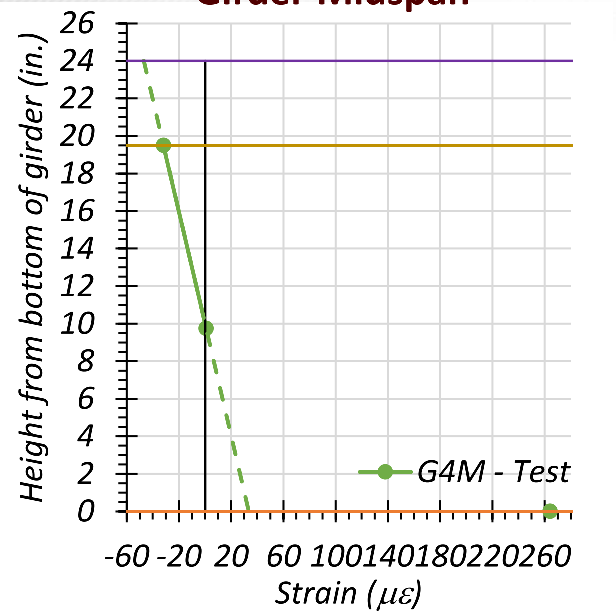
## Bridge CM-5

Girder Ends

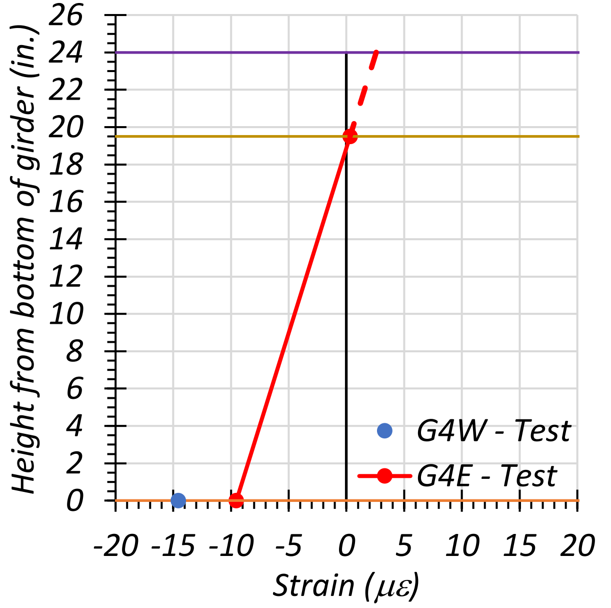
Girder Midspan

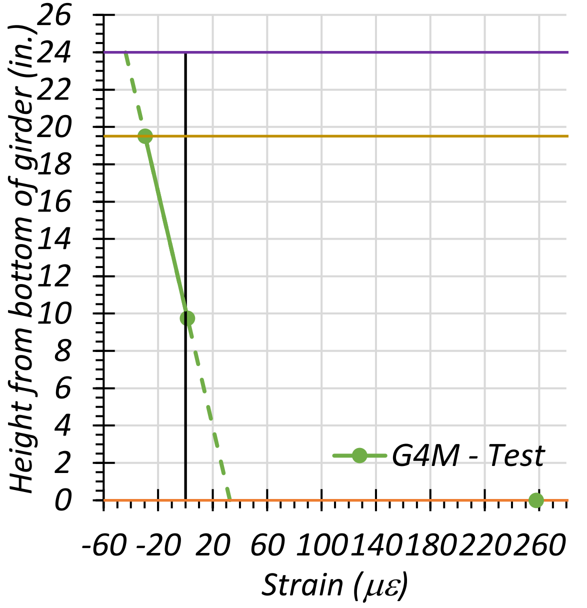
Stop Location Test

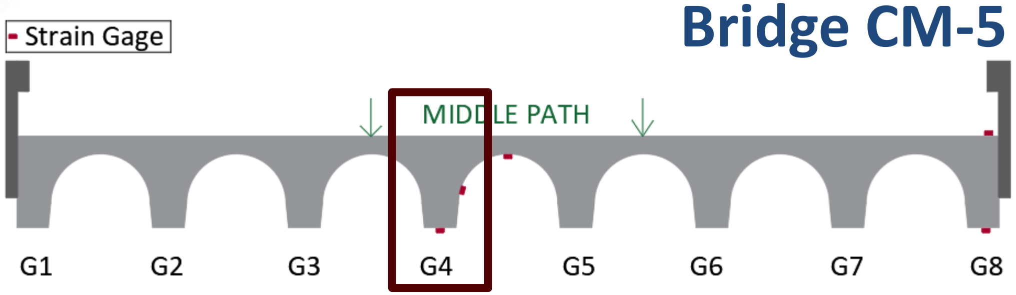



Crawl Speed Test




- Neutral Axis Location - Midspan
  - Stop location N.A. = 10.40 in.
  - Crawl speed N.A. = 10.65 in.
  - *Theoretical cracked N.A. = 19.91 in.*
  - *Theoretical uncracked N.A. = 14.05 in.*
  - *Issue with bottom strain gauge at midspan.*
- End Restraint?
  - Compressive strains at bottom of girder ends→ partial end restraint

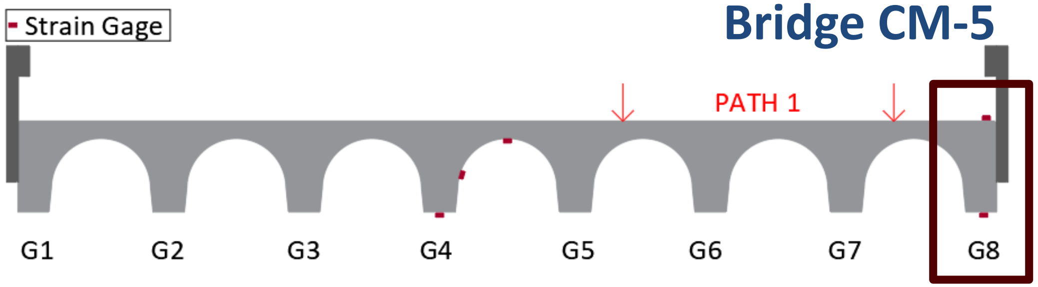
top of slab   bottom of slab   bottom of girder

*Tension is positive*

TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

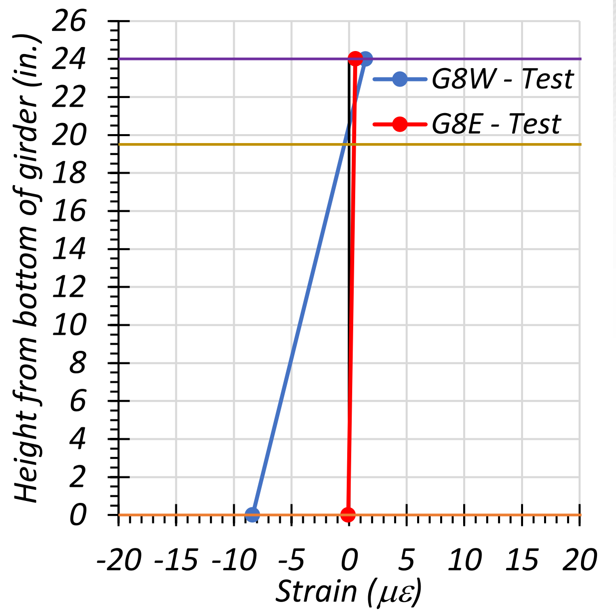
# Exterior Girder G8 Strain Results
# Path 1 – Static Tests

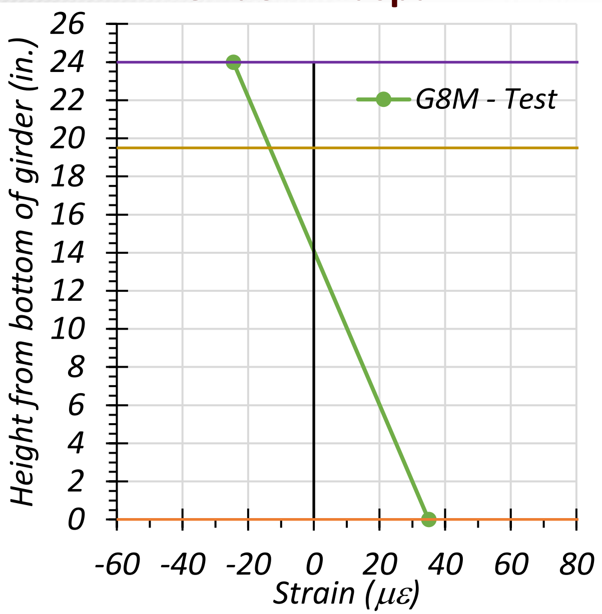
### Bridge CM-5



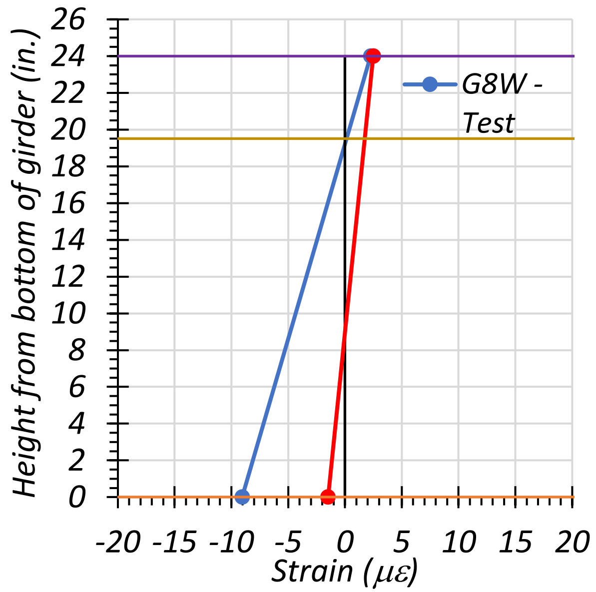

**Girder Ends** | **Girder Midspan**

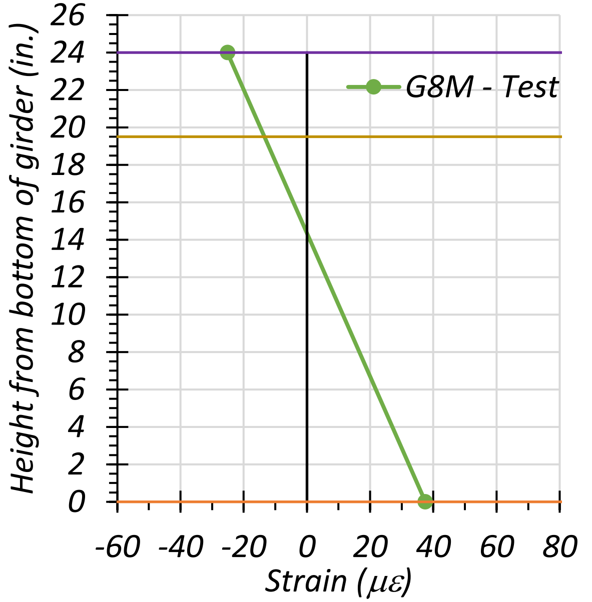
**Stop Location Test**




**Crawl Speed Test**




- Neutral Axis Location – Midspan
  - Theoretical cracked N.A. = 18.87 in.
  - Theoretical uncracked N.A. = 15.21 in.
  - Stop location N.A. = 15.02 in.
  - Crawl speed N.A. = 14.37 in.
- End Restraint?
  - Compressive strains at bottom of girder ends → partial end restraint

top of slab | bottom of slab | bottom of girder

*Tension is positive*

Texas A&M Transportation Institute

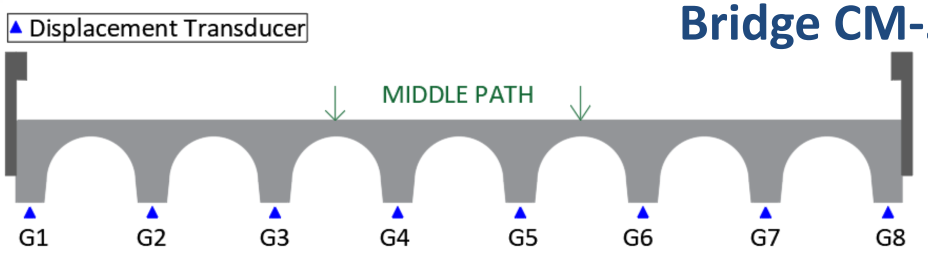
TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

**Updated – 08/04/2021**

# Deflection Results
# Middle Path – Static Tests

$$LLDF = \frac{\Delta_i I_i}{\sum \Delta_i I_i}$$

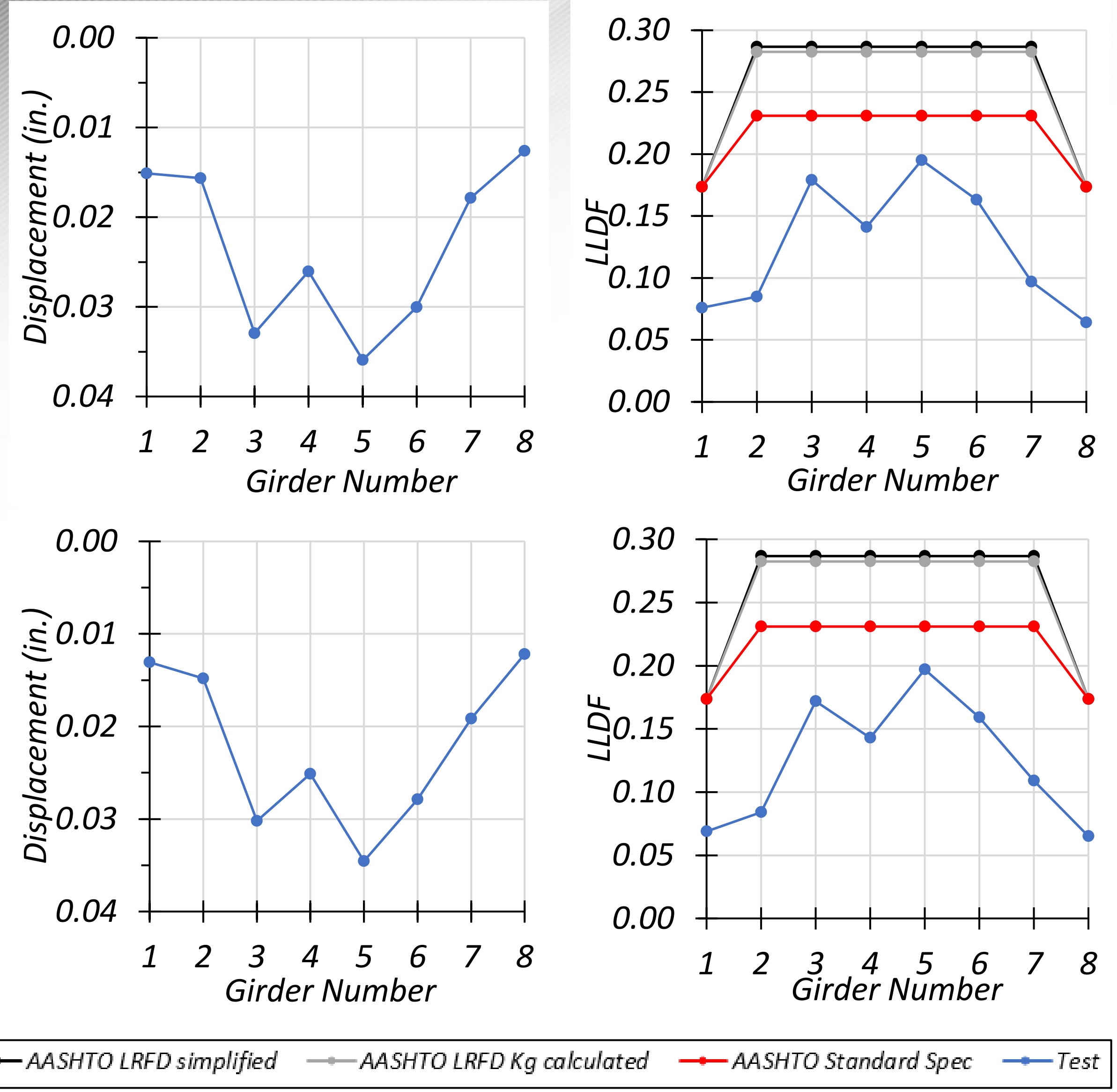
## Bridge CM-5




**Deflections** **LLDFs**

**Stop Location Test**

**Crawl Speed Test**




| Test and Girder Type | AASHTO Standard Specs ($g^m_{AASHTO\_Std}$) | AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$) | AASHTO LRFD $K_g$ Calculated ($g^m_{AASHTO\_K}$) | Test ($g^m_{test}$) | $g^m_{AASHTO\_Std}/g^m_{test}$ | $g^m_{AASHTO\_S}/g^m_{test}$ | $g^m_{AASHTO\_K}/g^m_{test}$ |
|---|---|---|---|---|---|---|---|
| Stop Location Interior | 0.231 | 0.287 | 0.283 | 0.195 | 1.18 | 1.47 | 1.45 |
| Stop Location Exterior | 0.174 | 0.174 | 0.174 | 0.076 | 2.29 | 2.29 | 2.29 |
| Crawl Speed Interior | 0.231 | 0.287 | 0.283 | 0.197 | 1.17 | 1.46 | 1.44 |
| Crawl Speed Exterior | 0.174 | 0.174 | 0.174 | 0.069 | 2.52 | 2.52 | 2.52 |

- AASHTO Standard Specifications provide conservative LLDFs
- AASHTO LRFD Specifications provide highly conservative LLDFs

TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

Updated – 08/04/2021

# Deflection Results
# Path 1 – Static Tests

$$LLDF = \frac{\Delta_i I_i}{\sum \Delta_i I_i}$$

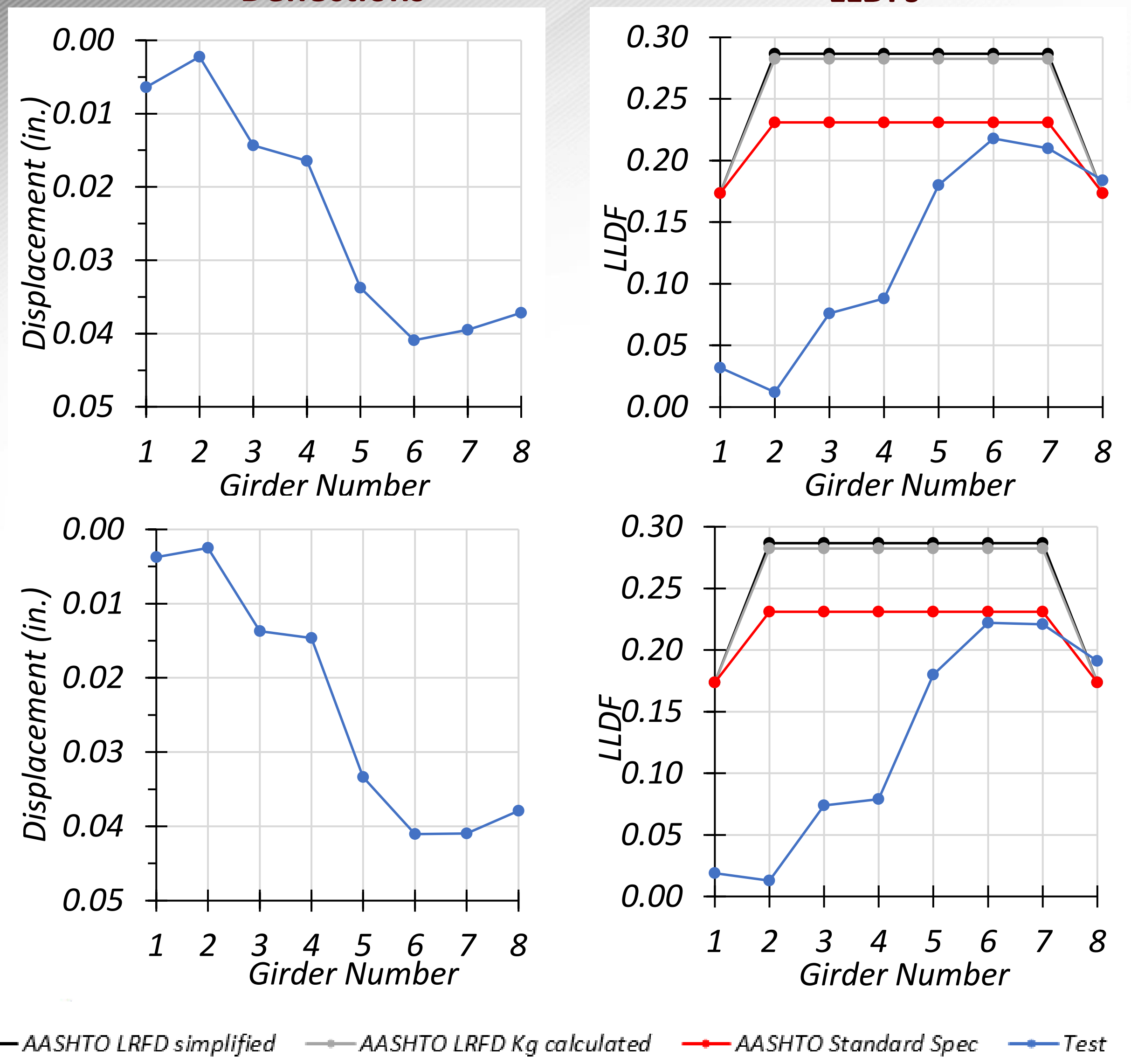
## Bridge CM-5

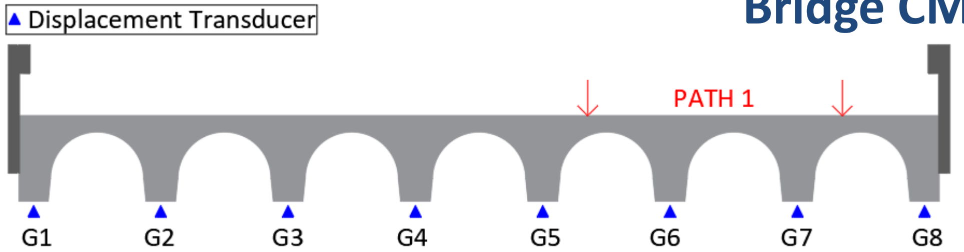
Deflections

LLDFs

Stop Location Test

Crawl Speed Test



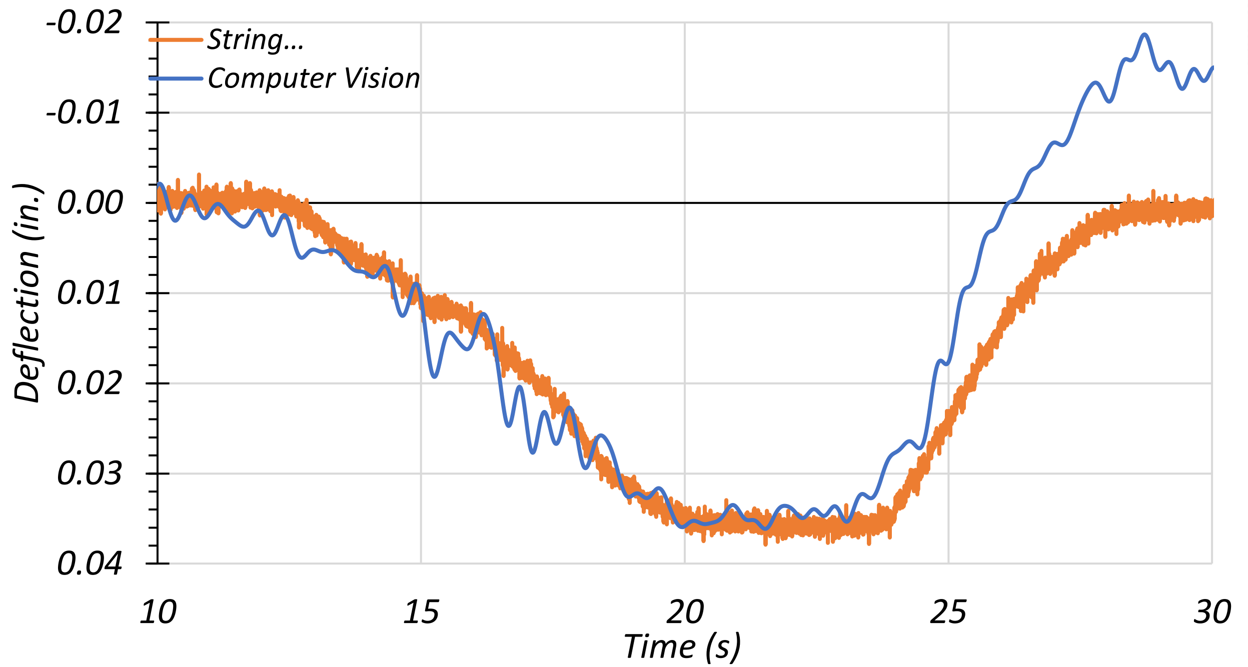

| Test and Girder Type | AASHTO Standard Specs ($g^m_{AASHTO\_Std}$) | AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$) | AASHTO LRFD $K_g$ Calculated ($g^m_{AASHTO\_K}$) | Test ($g^m_{test}$) | $g^m_{AASHTO\_Std}/g^m_{test}$ | $g^m_{AASHTO\_S}/g^m_{test}$ | $g^m_{AASHTO\_K}/g^m_{test}$ |
|---|---|---|---|---|---|---|---|
| Stop Location Interior | 0.231 | 0.287 | 0.283 | 0.218 | 1.06 | 1.32 | 1.30 |
| Stop Location Exterior | 0.174 | 0.174 | 0.174 | 0.184 | 0.95 | 0.95 | 0.95 |
| Crawl Speed Interior | 0.231 | 0.287 | 0.283 | 0.222 | 1.04 | 1.29 | 1.27 |
| Crawl Speed Exterior | 0.174 | 0.174 | 0.174 | 0.191 | 0.91 | 0.91 | 0.91 |

- AASHTO Standard Specifications accurately estimate maximum LLDFs
- AASHTO LRFD Specifications provide highly conservative LLDFs

# Computer Vision Results

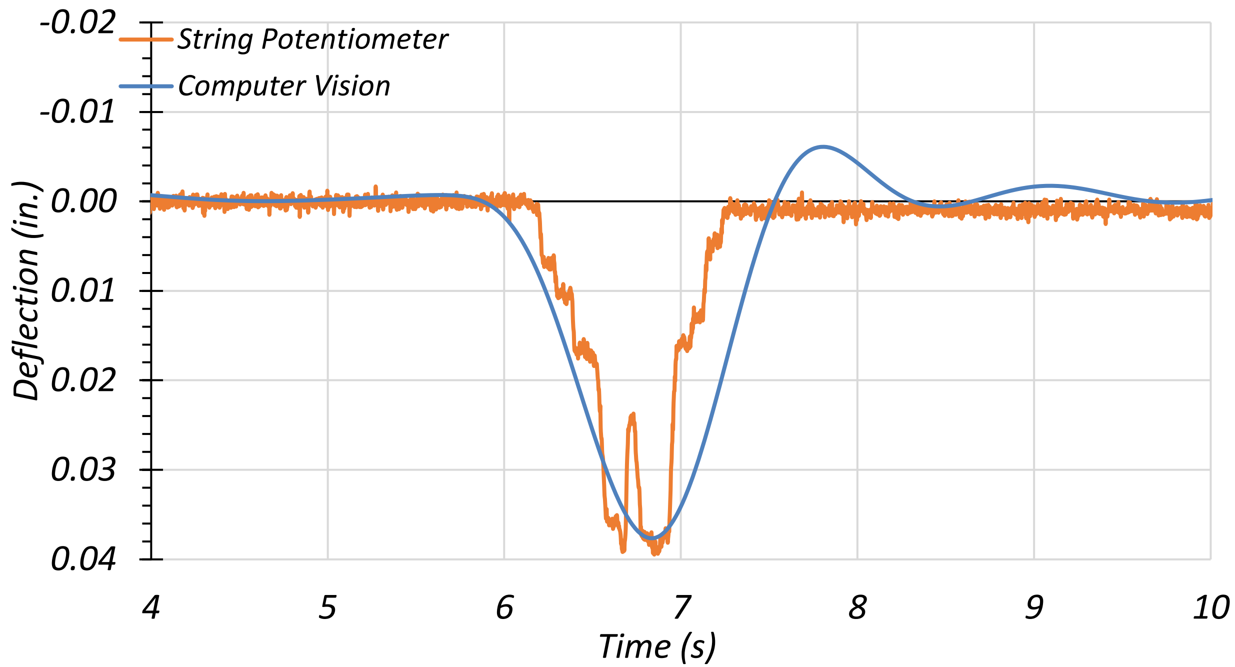
## Bridge CM-5

### G8 – Path 1 – Crawl test




- Girder G8 – Path 1 – Crawl test
- String potentiometer deflection = 0.036 in.
- Computer vision deflection = 0.037 in.
- Difference = 5%
- Bandpass filter, Cut-off frequency = 0.001 Hz to 3 Hz

### G1 – Path 2 – Dynamic test

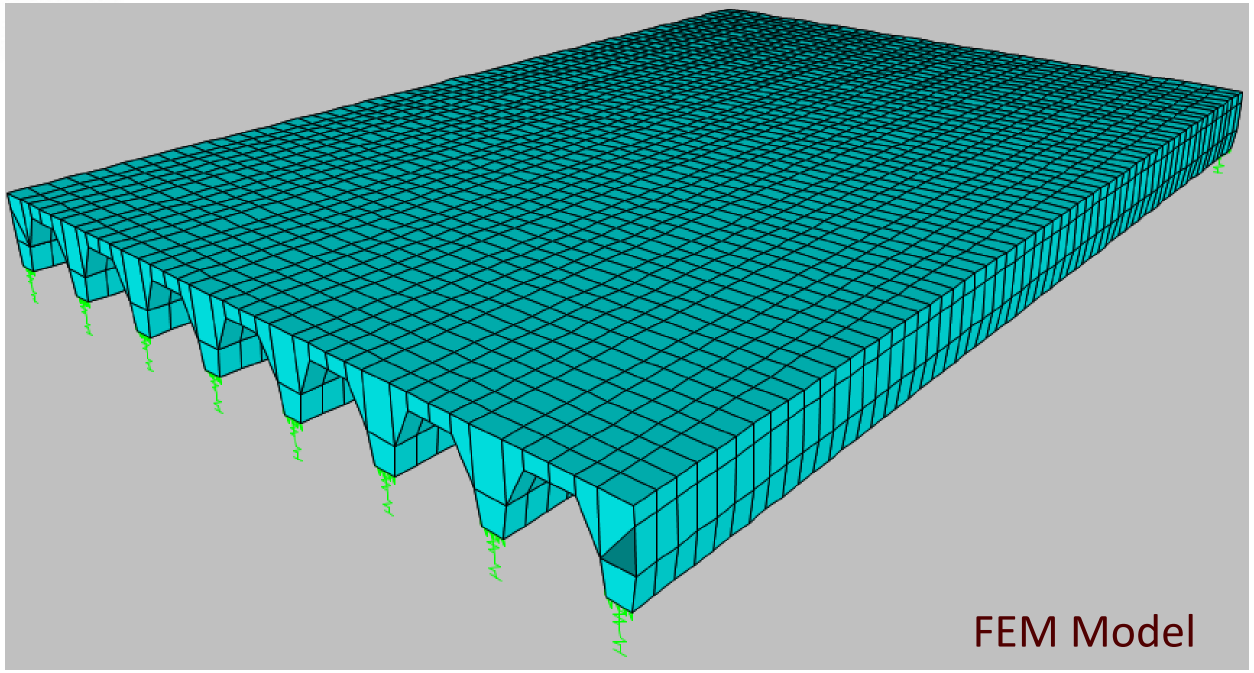



- Girder G8 – Path 1 – Crawl test
- String potentiometer deflection = 0.040 in.
- Computer vision deflection = 0.038 in.
- Difference = 5%
- Bandpass filter, Cut-off frequency = 0.001 Hz to 3 Hz

# Model Update & Calibration

## Bridge CM-5

- FEM Model Update
  - $f_c{}' = 7\ ksi$ from NDE test
  - Corresponding $E_c = 5579$ ksi
  - Simply-supported ends
- FEM Model Calibration
  - Material calibration to incorporate cracked concrete behavior
  - Mander model adopted with $f_t = 0.01 f_c{}'$
  - End restraint calibration through spring stiffness sensitivity analysis (bottom longitudinal springs)


FEM Model

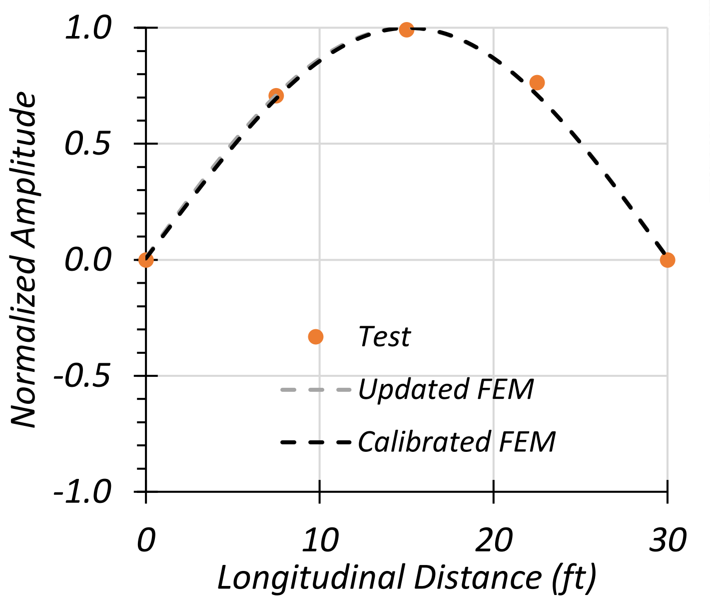
# Dynamic Characteristics Comparison

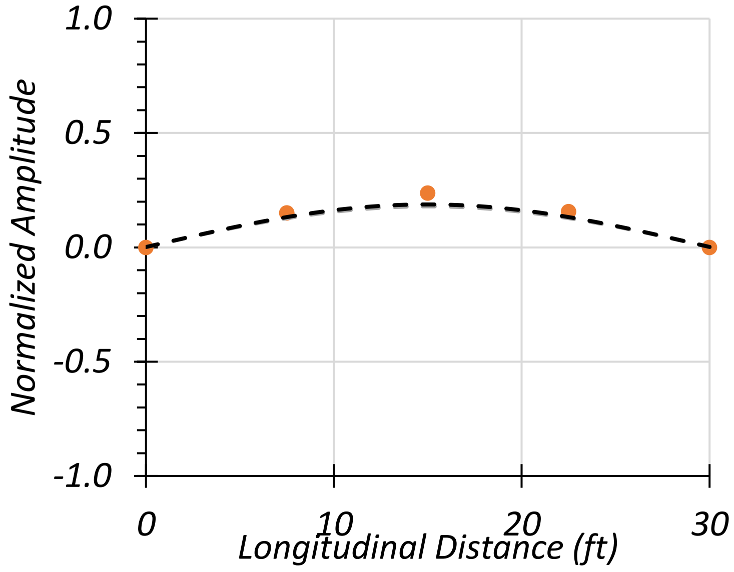
## Bridge CM-5

**1st Mode (Test=11.8 Hz, FEM=13.7 Hz)**

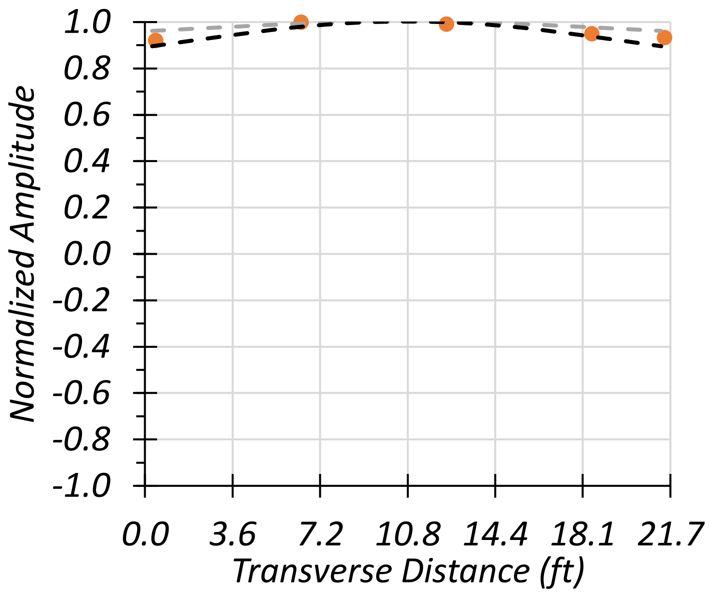
**2nd Mode (Test=16.6 Hz, FEM=16.9 Hz)**

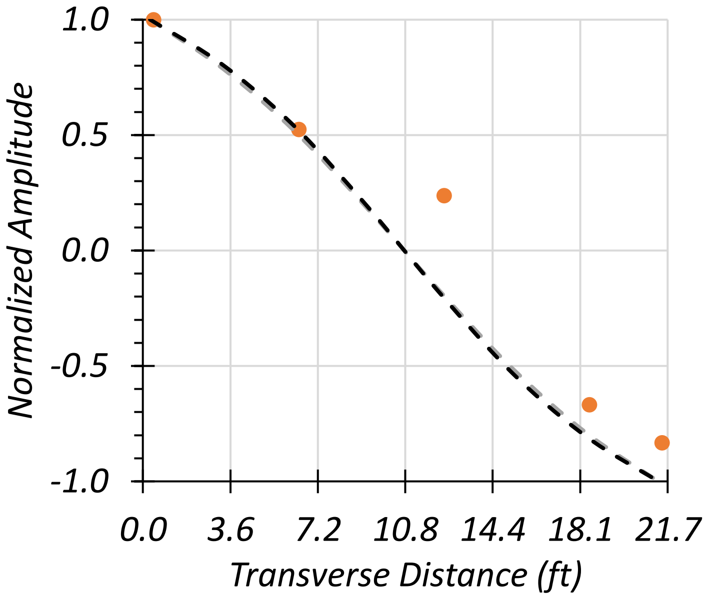
**Longitudinal Section**




**Transverse Section**



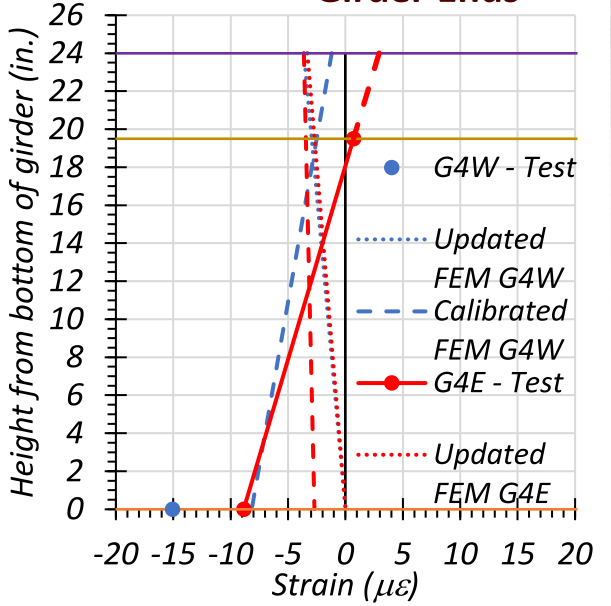
TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

# Comparison Model and Test Results

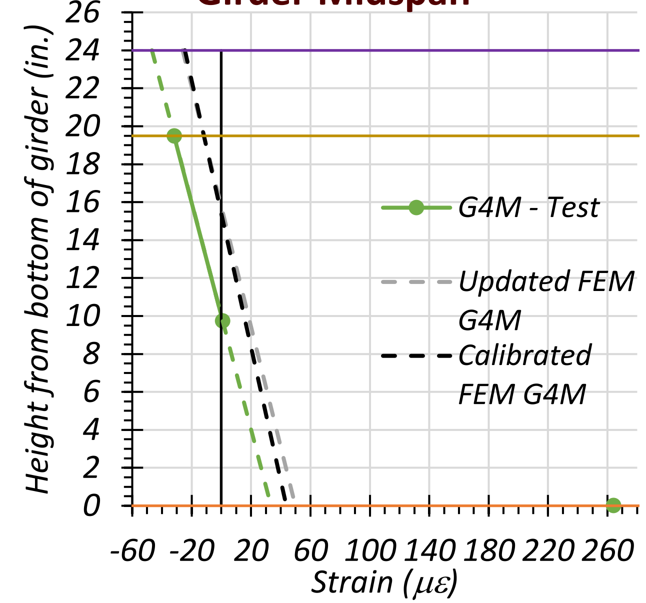
## Bridge CM-5

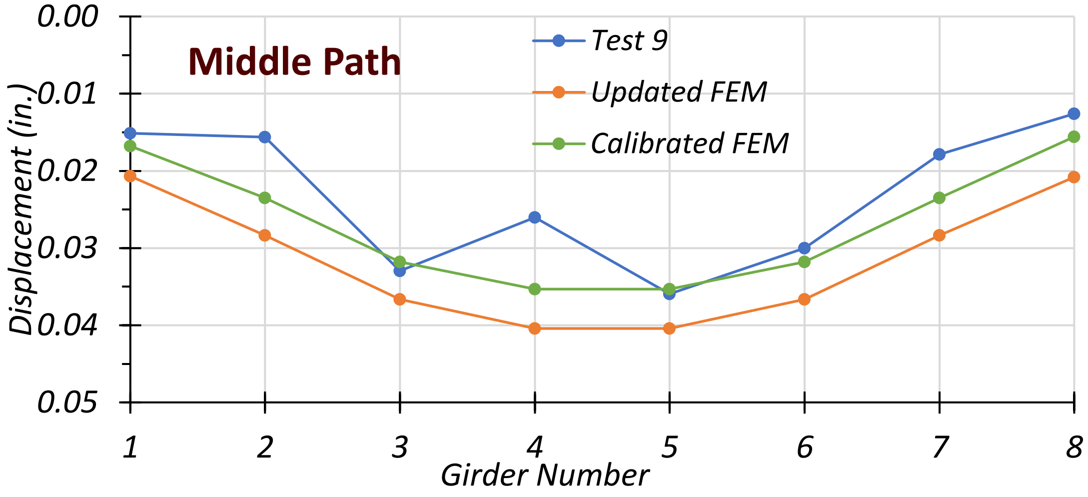
G4 – Middle Path

### Girder Ends

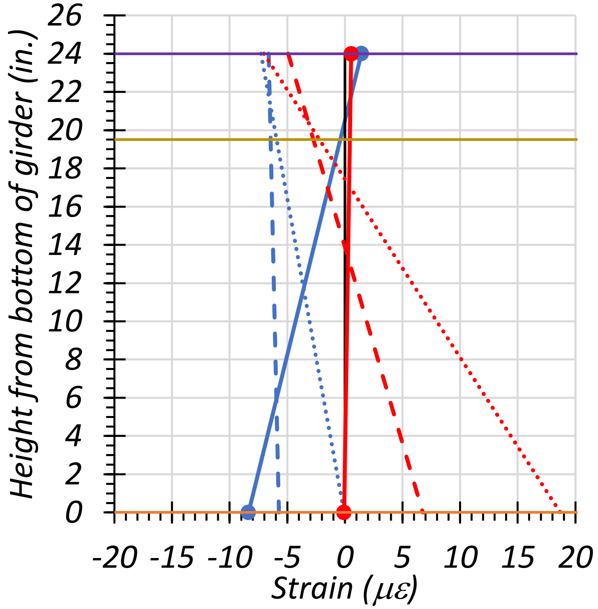


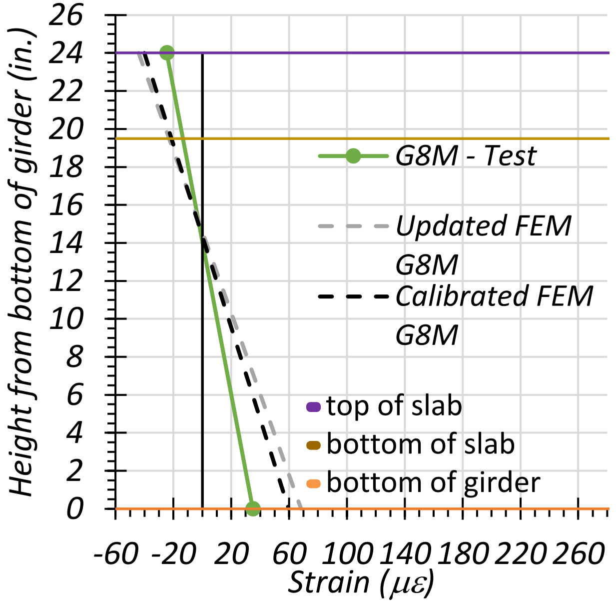

### Girder Midspan

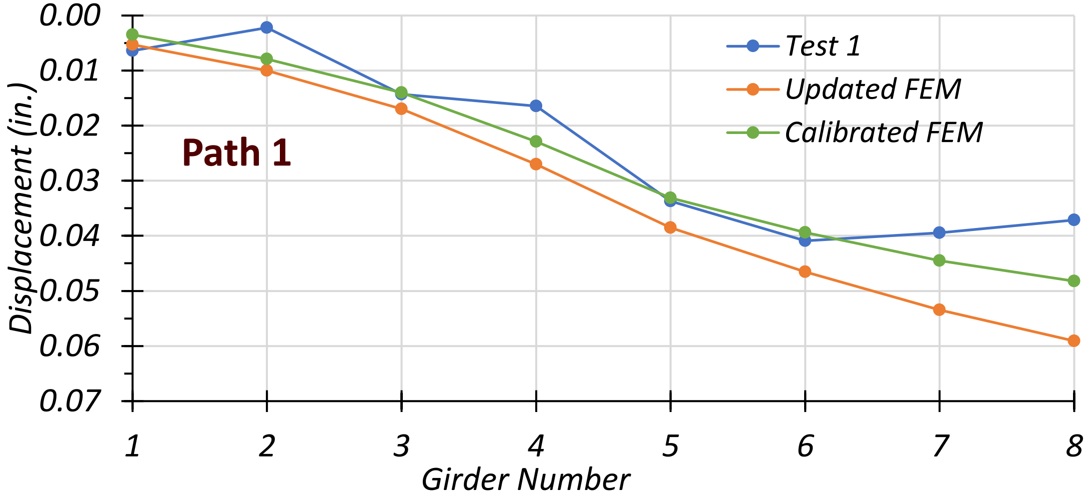



G8 – Path 1




Texas A&M Transportation Institute

# Rating Factors for Bridge CM-5

*RFs calculated using LFR method*

## Reduction in Number of Lanes

| Rating Factor | Basic Load Rating | Load Rating with Lane Reduction | Lane Reduction/ Basic Load Rating |
|---|---|---|---|
| Inventory | 1.17 | 1.27 | 1.09 |
| Operating | 1.96 | 2.12 | 1.08 |

## Updated Material Properties

| Rating Factor | Basic Load Rating | Load Rating with Measured Material Properties | Measured Material Properties/ Basic Load Rating |
|---|---|---|---|
| Inventory | 1.17 | 1.20 | 1.03 |
| Operating | 1.96 | 2.01 | 1.03 |

## End Fixity

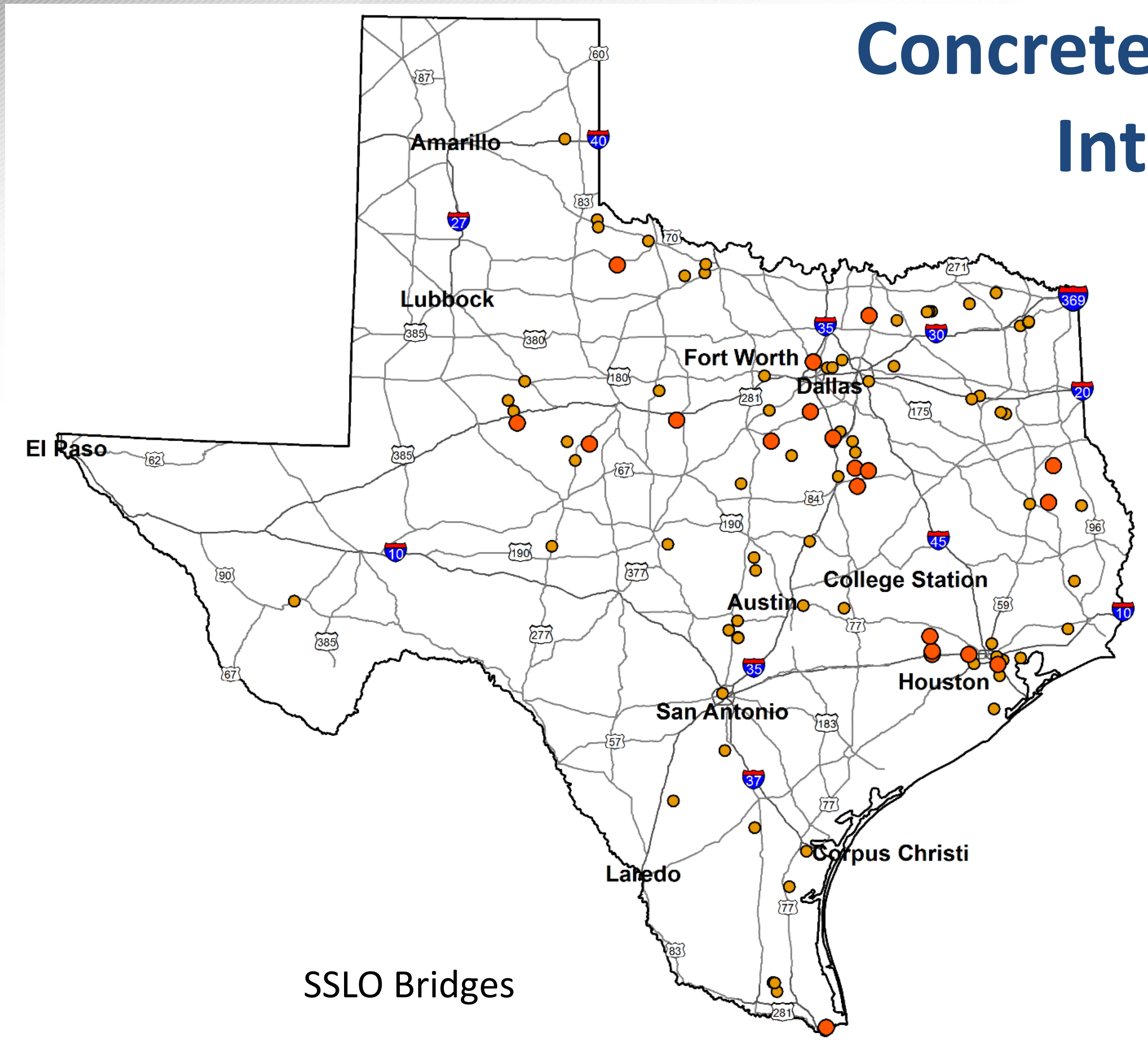
| Rating Factor | Basic Load Rating | Load Rating with End Fixity | End Fixity/ Basic Load Rating |
|---|---|---|---|
| Inventory | 1.17 | 1.19 | 1.02 |
| Operating | 1.96 | 1.99 | 1.01 |

✓ *The updated RFs would allow for removal of the posting per TxDOT's load rating flowchart*

Changes due to:

- Lane reduction
- Material strength update
- Partial end fixity

# Concrete Slab Bridge with Integral Curbs




SSLO Bridges

# Concrete Slab Bridge

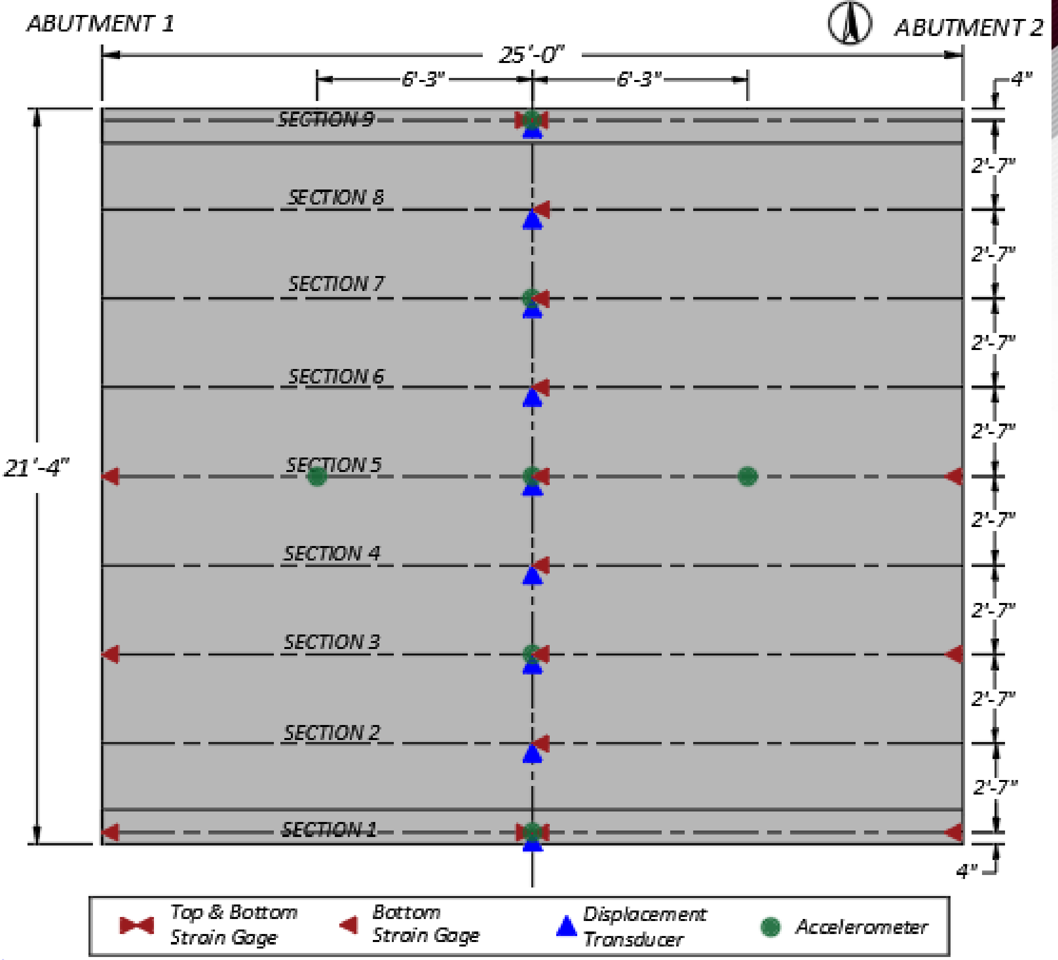
## Bridge CS-9

| ID | Dist. to CS (mi) | Route Prefix | Year Built | ADT | Max. Span Length (ft) | Deck Width (ft) | Condition Rating | | | Operating HS20 Rating Factor |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Deck | Super-structure | Sub-structure | |
| Avrg. | - | - | 1949 | 795 | 22 | 28 | 6 (Satisfactory) | 6 (Satisfactory) | 6 (Satisfactory) | 0.98 |
| CS-9 | 157 | 3 (On-system) | 1948 | 30 | 25 | 21 | 6 (Satisfactory) | 6 (Satisfactory) | 7 (Good) | 0.94 |

Carries FM 216 and traverses the Flag Creek near Walnut Springs, approximately 7.0 miles north of FM 927

# Instrumentation

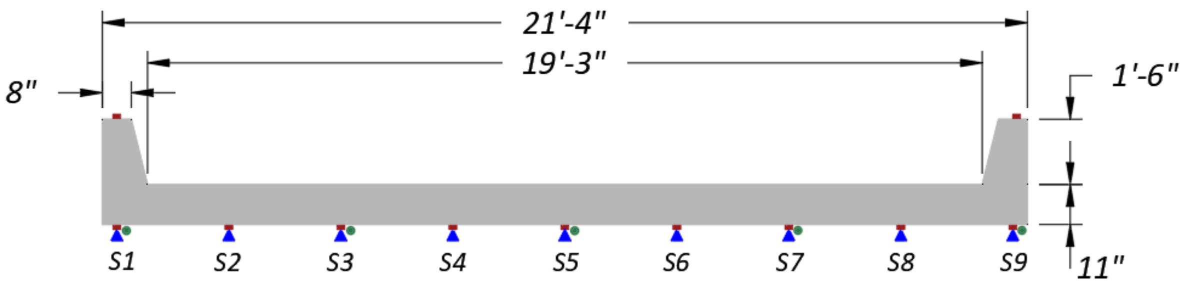
## Bridge CS-9



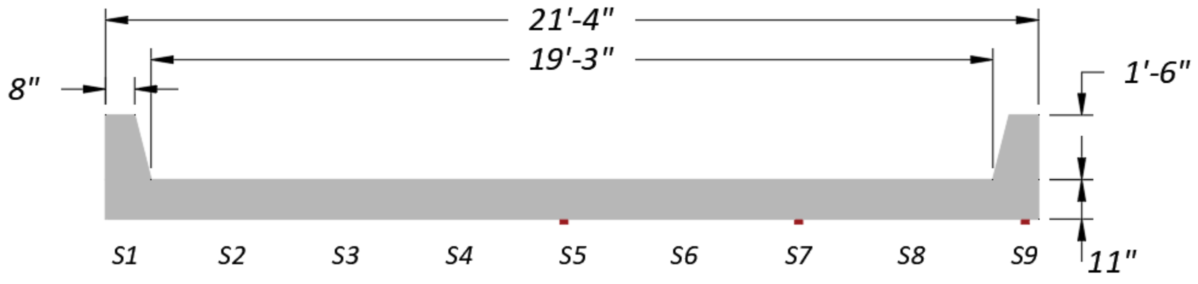

Strain Gauge

Accelerometer

String Potentiometers



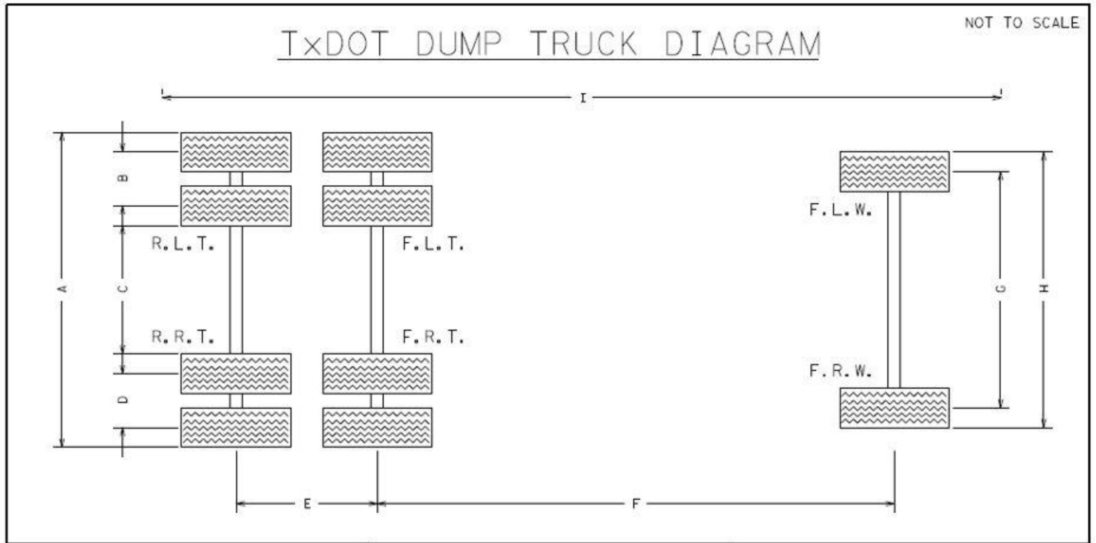

**Midspan Section**




**End Section**

# Testing

## Bridge CS-9




**TRUCK INFORMATION**

Truck Make: Sterling
Truck Model:
Truck Year: 2006

**VEHICLE STICKER INFORMATION**

Front Axle: ______ LBS
Front Tandem Axle: 7050 LBS
Rear Tandem Axle: 6750 LBS
Gross Vehicle Weight (Empty): ______ LBS

**TRUCK MEASUREMENTS**

| REFERENCE | DISTANCE |
|---|---|
| A | 8'-1" |
| B | 1'-2" |
| C | 4'-0.5" |
| D | 1'-2" |
| E | 4'-5" |
| F | 13'-10.5" |
| G | 6'-11" |
| H | 7'-9.5" |
| I | 24'-0" |

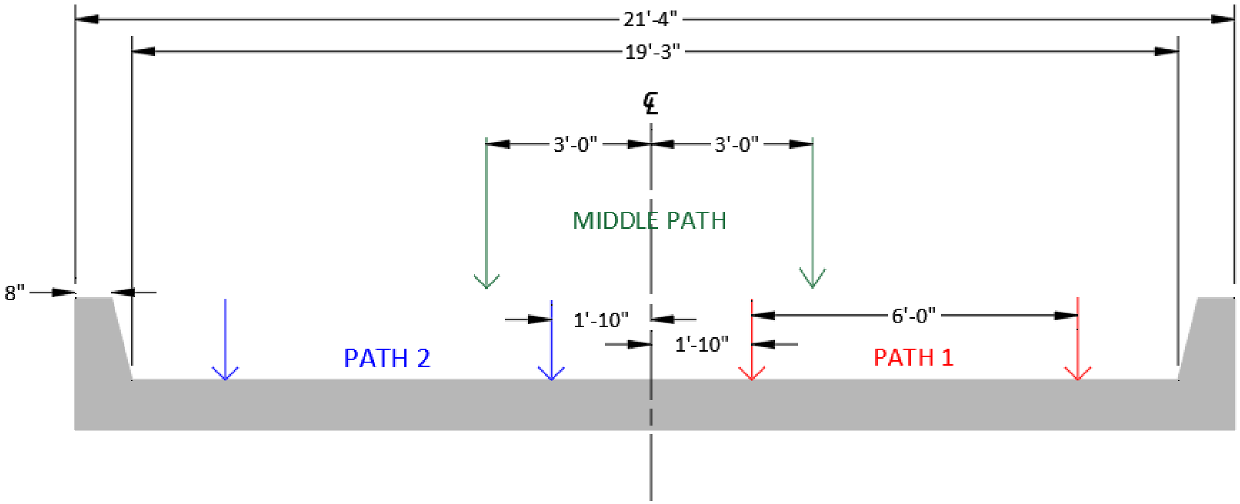
**LOADED WEIGHTS**

| LOCATION | WEIGHT |
|---|---|
| Front R Wheel | 5200 |
| Front L Wheel | 5250 |
| Front R Tandem | 7100 |
| Front L Tandem | 7100 |
| Rear R Tandem | 6900 |
| Rear L Tandem | 6600 |

Material Type:

| Test Protocol | |
|---|---|
| Static Tests<br>• Stop Location<br>• Crawl Speed | Dynamic Tests<br>• 30 & 40 mph<br>• Impact Tests |





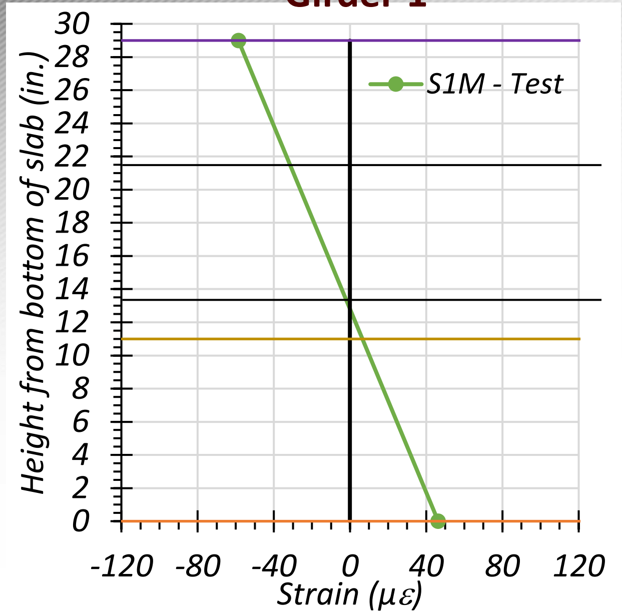
TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

# Exterior Sec. S1 and S9 Strain Results Paths 1 and 2 – Static Tests

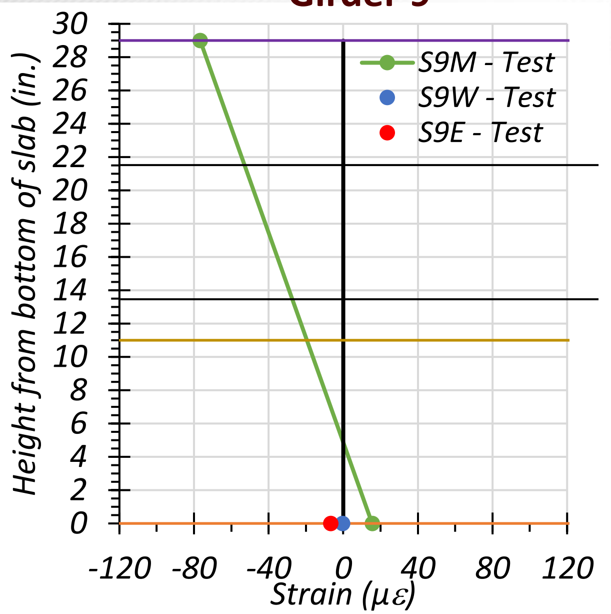
## Bridge CS-9

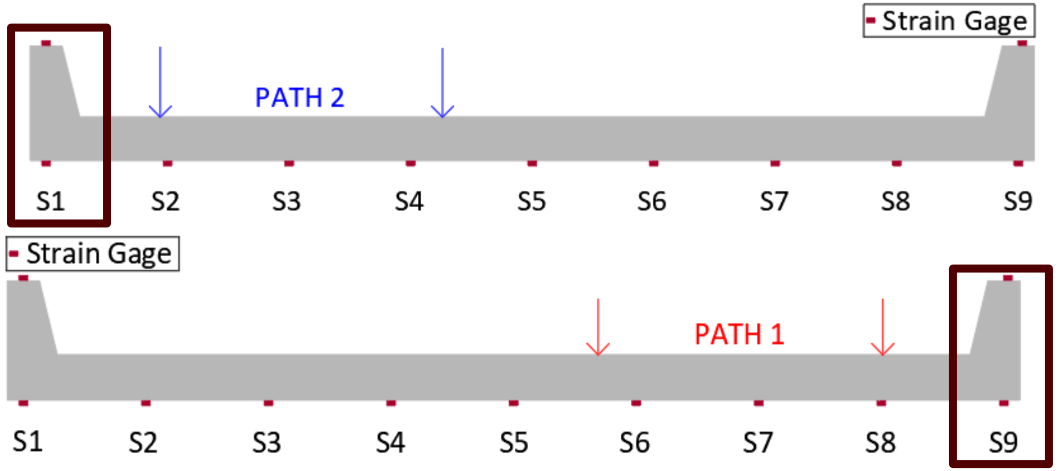
Stop Location Test

Girder 1

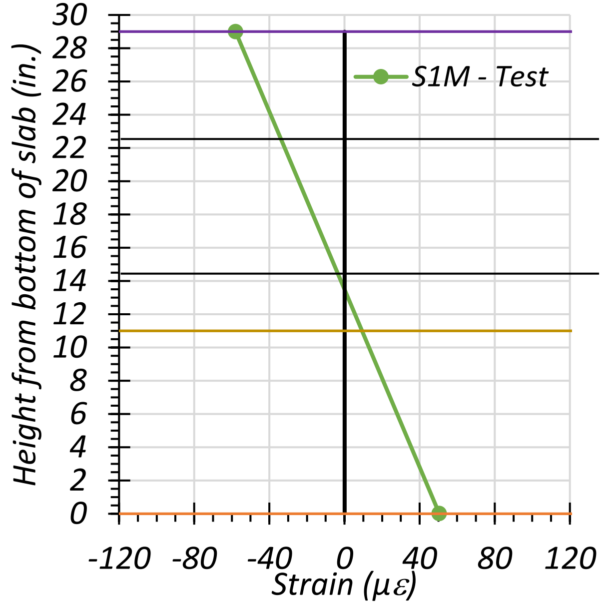


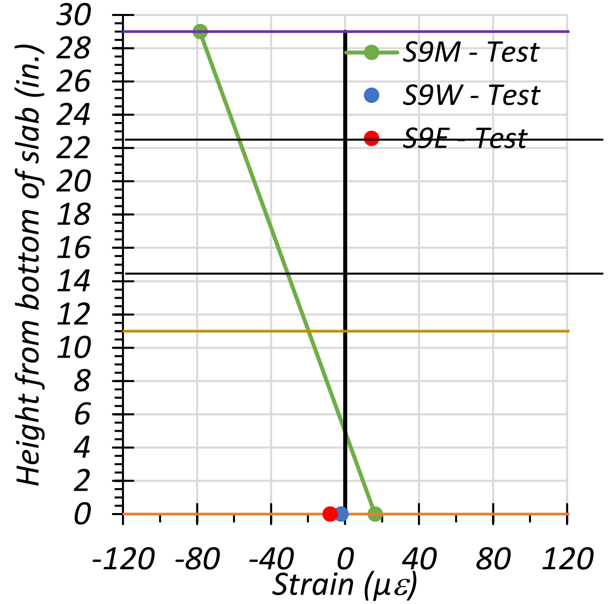

Girder 9




Crawl Speed Test




- Neutral Axis Location – Midspan
  - S1 Stop location N.A. = 15.8 in.
  - S1 Crawl speed N.A. = 14.56 in.
  - S9 Stop location N.A. = 5.79 in.
  - S9 Crawl speed N.A. = 4.96 in.
  - *Theoretical cracked N.A. = 21.43 in.*
  - *Theoretical uncracked N.A. = 13.33 in.*

Different strain profiles at curb sections

top of slab | bottom of slab | bottom of girder

*Tension is positive*

Texas A&M Transportation Institute

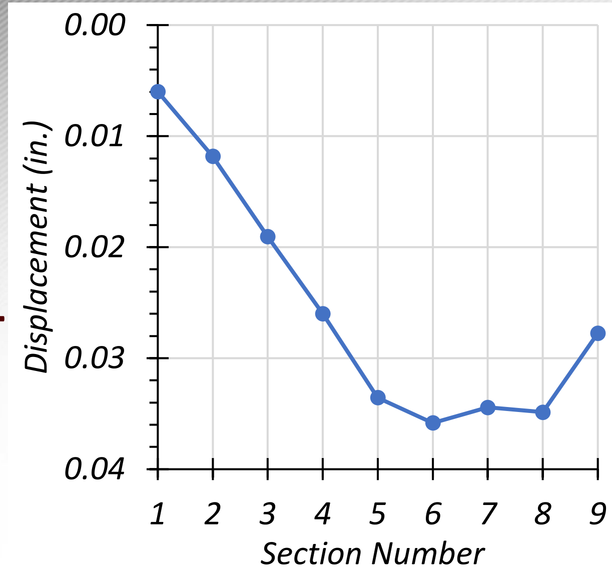
TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

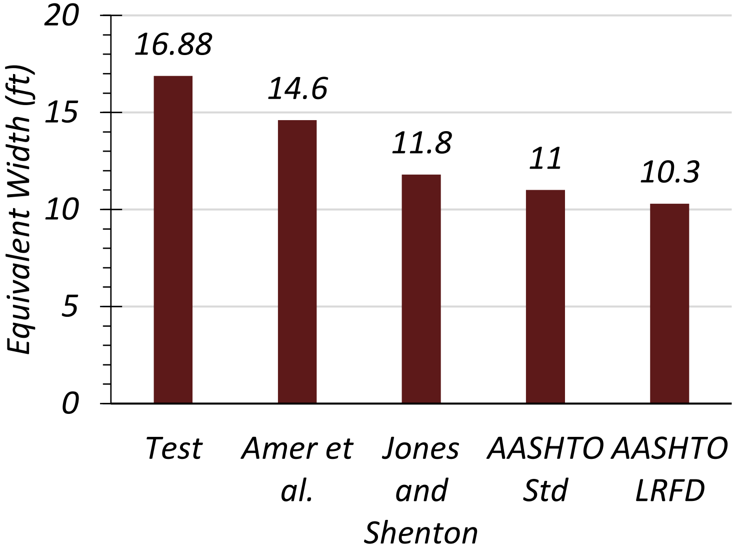
# Deflection Results
# Path 1 –Static Tests

## Bridge CS-9

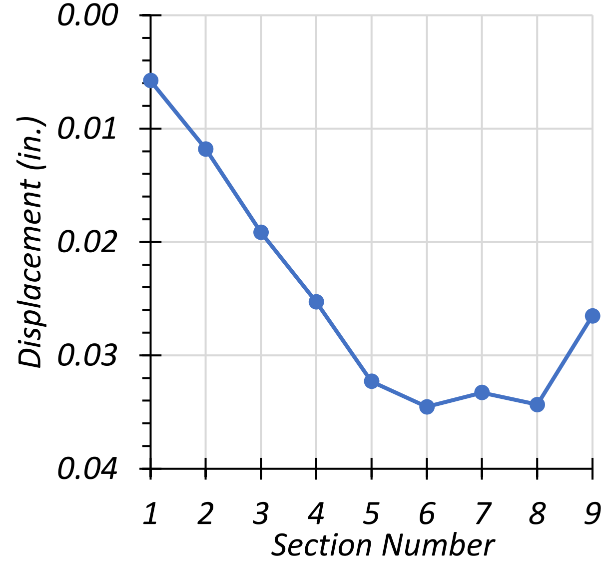
**Deflections** | **Equivalent Width**

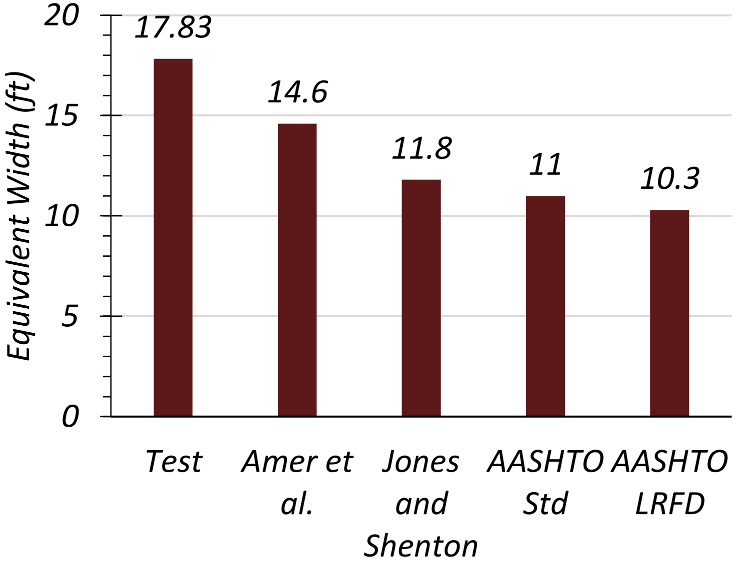
**Stop Location Test**

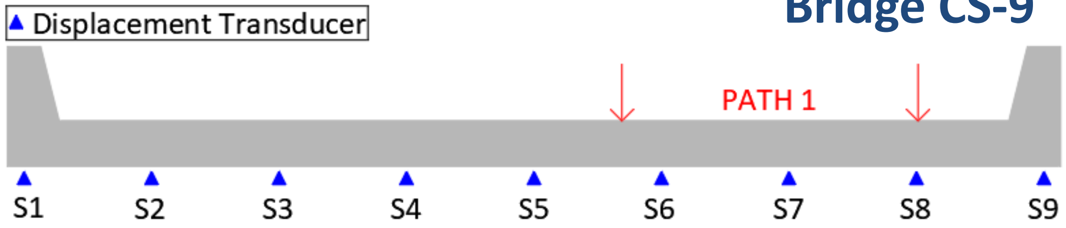



**Crawl Speed Test**




| Test | Test ($E^m_{Test}$) | Amer et al. ($E^m_{Amer}$) | Jones and Shenton* ($E^m_{Jones\ \&\ Shenton}$) | AASHTO* ($E^m_{AASHTO}$) | AASHTO LRFD* ($E^m_{LRFD}$) |
|---|---|---|---|---|---|
| Stop Location | **16.9** | 14.6 | 11.8 | 11.0 | 10.3 |
| Crawl Speed | **17.8** | 14.6 | 11.8 | 11.0 | 10.3 |

Note: * Approaches do not consider the effect of integral curbs.

$$LLDF = \frac{\Delta_i I_i}{\sum \Delta_i I_i}$$

$$E = \frac{W_{Section}}{LLDF_{max}}$$

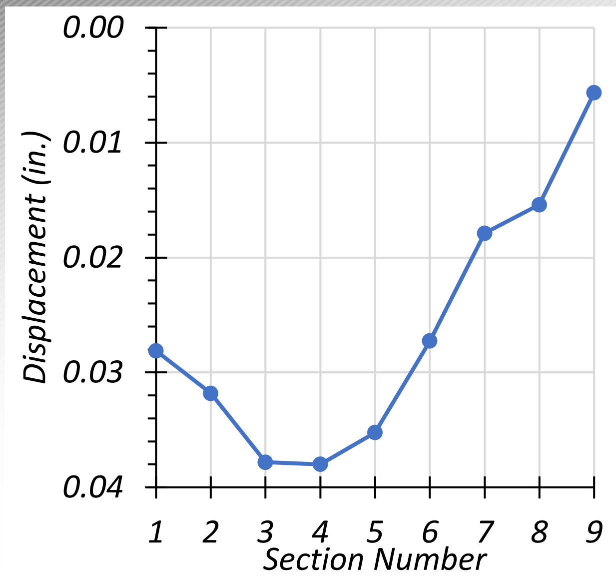
- AASHTO Standard Specifications provide *conservative* equivalent widths
- AASHTO LRFD Specifications provide *highly conservative* equivalent widths

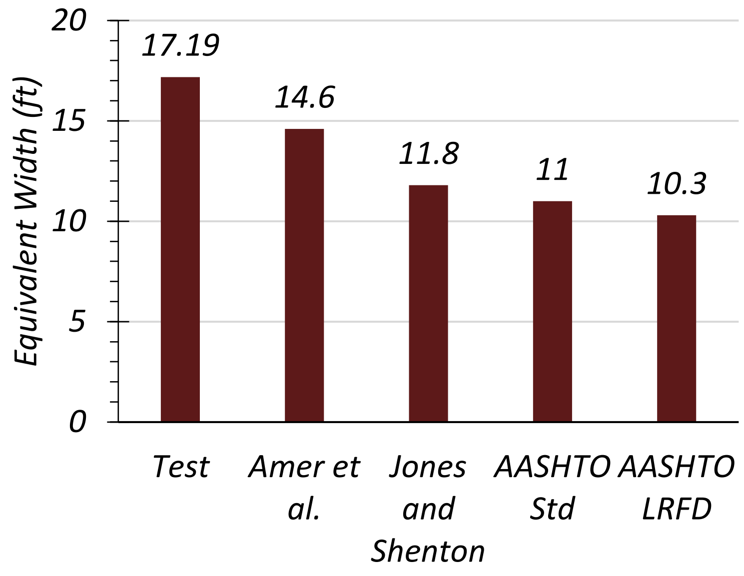
# Deflection Results
# Path 2 – Static Tests
## Bridge CS-9

### Deflections

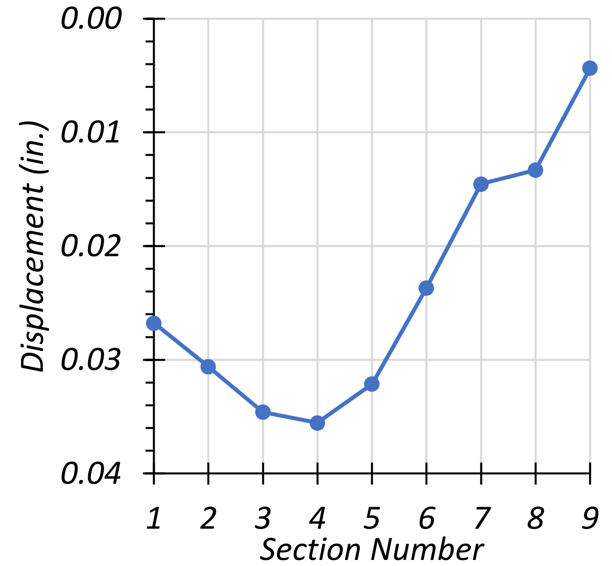
### Equivalent Width

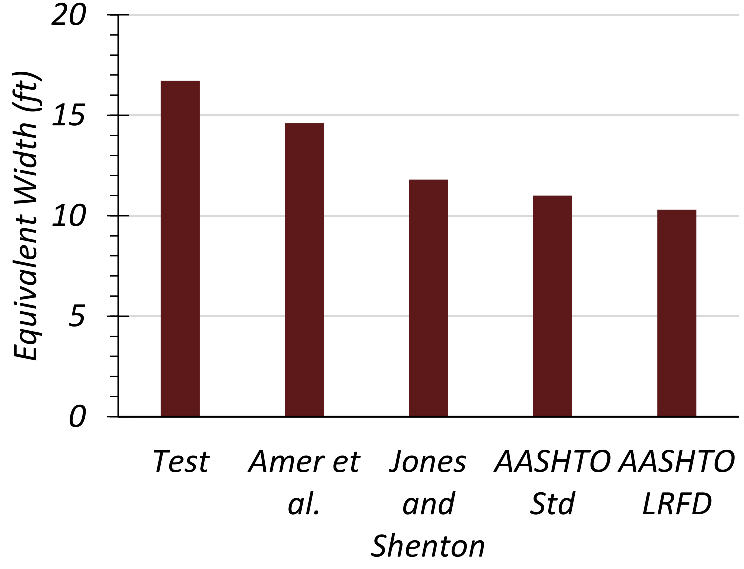
**Stop Location Test**

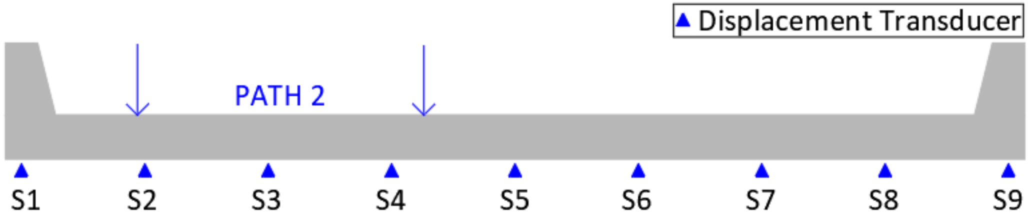



**Crawl Speed Test**



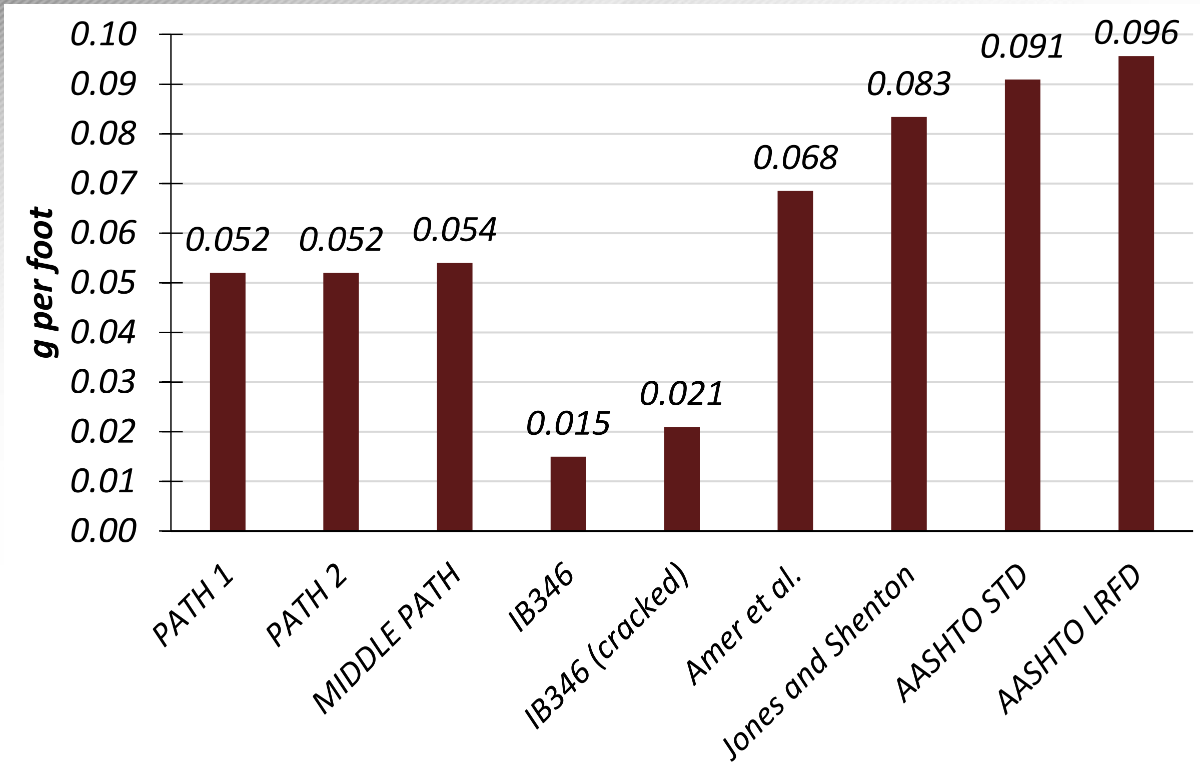

| Test | Test ($E^m_{Test}$) | Amer et al. ($E^m_{Amer}$) | Jones and Shenton* ($E^m_{Jones\ \&\ Shenton}$) | AASHTO* ($E^m_{AASHTO}$) | AASHTO LRFD* ($E^m_{LRFD}$) |
|---|---|---|---|---|---|
| Stop Location | **17.2** | 14.6 | 11.8 | 11.0 | 10.3 |
| Crawl Speed | **16.7** | 14.6 | 11.8 | 11.0 | 10.3 |

Note: * Approaches do not consider the effect of integral curbs.

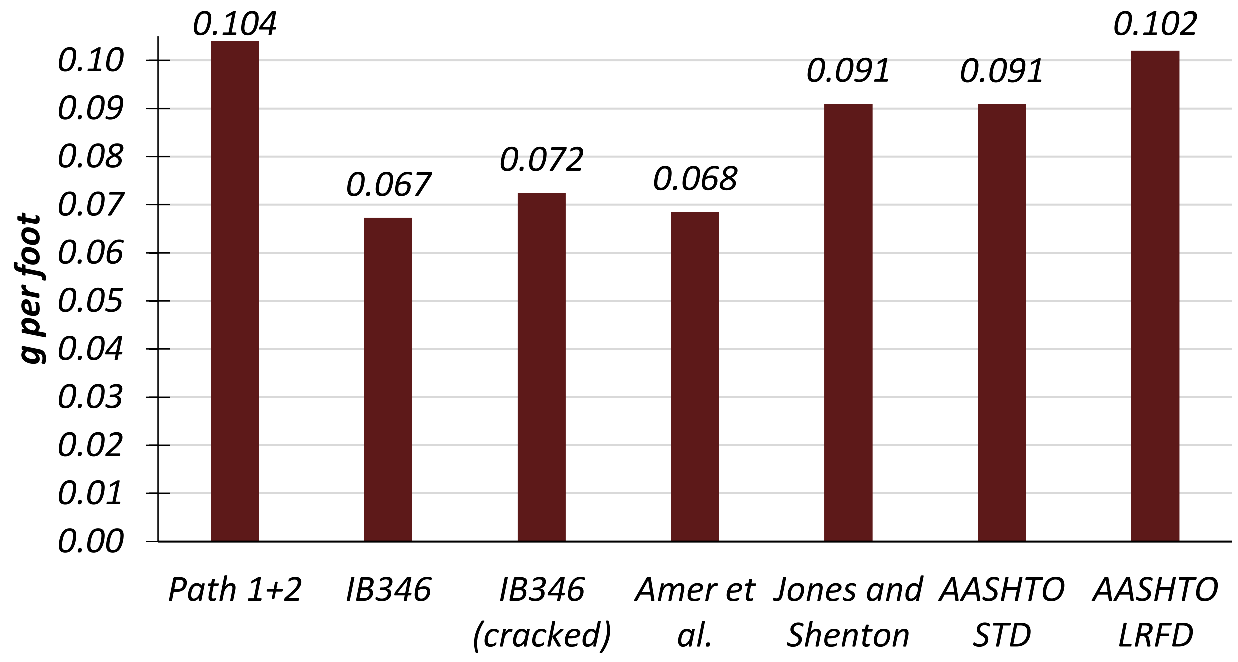
- AASHTO Standard Specifications provide *conservative* equivalent widths
- AASHTO LRFD Specifications provide *highly conservative* equivalent widths

# HS-20 $g_{per\ foot}$
## Bridge CS-9

One-Lane Loading




Two-Lane Loading




$$g = LLDF = \frac{\Delta_i I_i}{\sum \Delta_i I_i} \qquad g_{per\ foot} = \frac{g_{Test}}{W_{mid-slab}} \qquad g_{per\ foot} = \frac{1}{E}$$

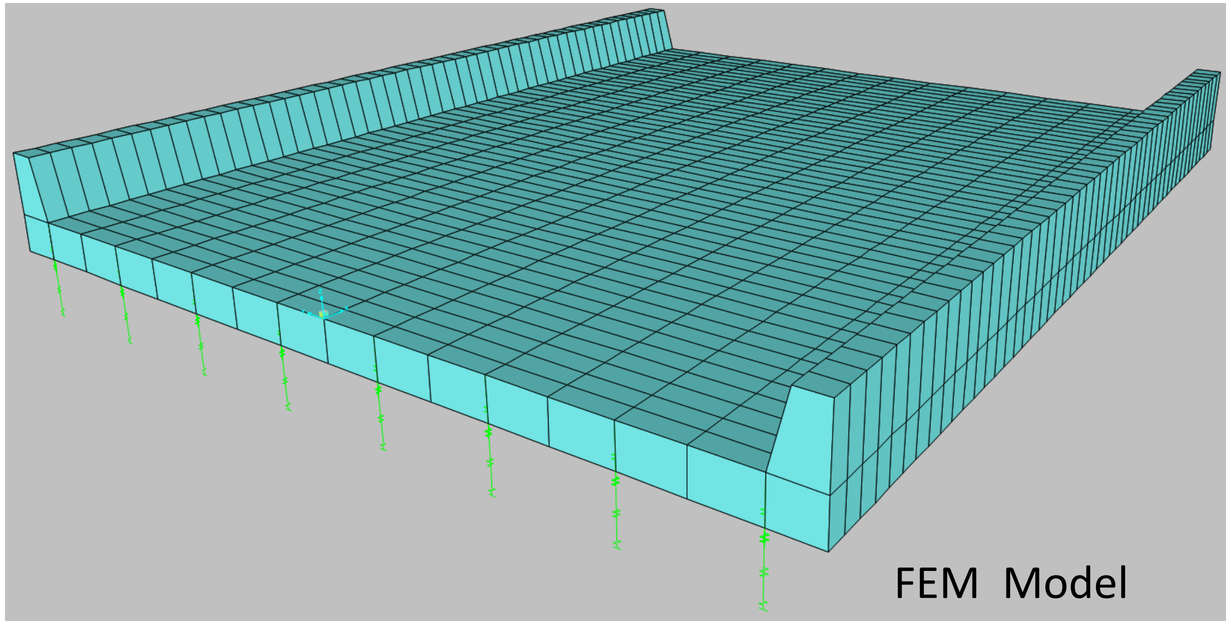
- Amer et al. (1999) provide reasonably good estimate for *g per foot* for one-lane case
- AASHTO LRFD provides better estimate for two-lane loading

# Model Update & Calibration

## Bridge CS-9

- FEM Model Update
  - $f_c{}' = 5.2\ \text{ksi}$ from NDE test
  - Corresponding $E_c = 4809$ ksi
  - Simply-supported ends

- FEM Model calibration
  - Incorporated cracked concrete behavior
  - Mander model adopted with $f_t = 0.01 f_c{}'$
  - End restraint calibration through spring stiffness sensitivity analysis (bottom longitudinal springs applied)



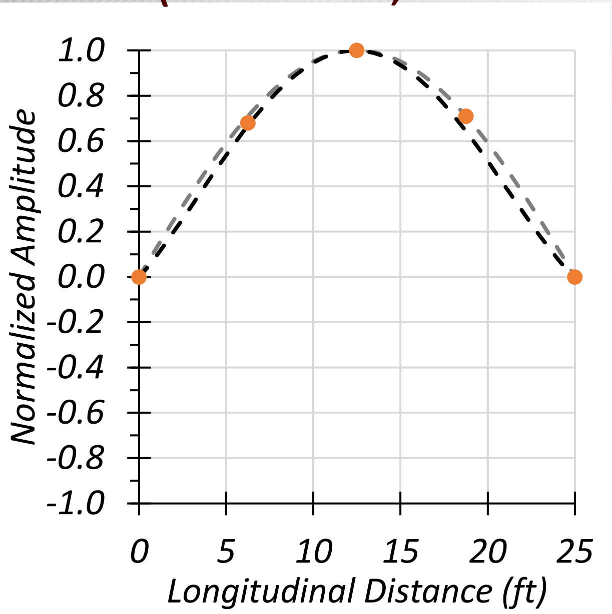
# Dynamic Characteristics Comparison

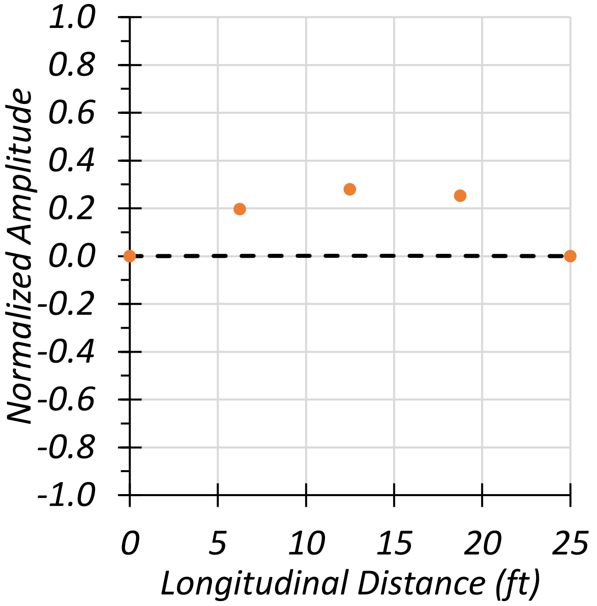
## Bridge CS-9

**1st Mode (Test=14.7 Hz, FEM=16.7 Hz)**

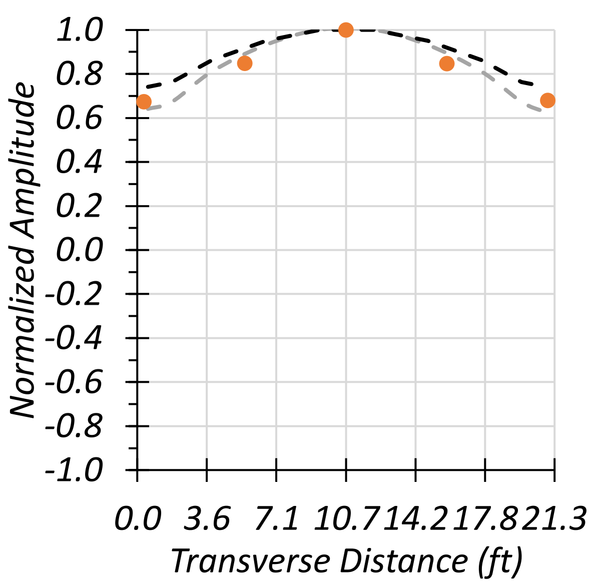
**2nd Mode (Test=22.5 Hz, FEM=23.1 Hz)**

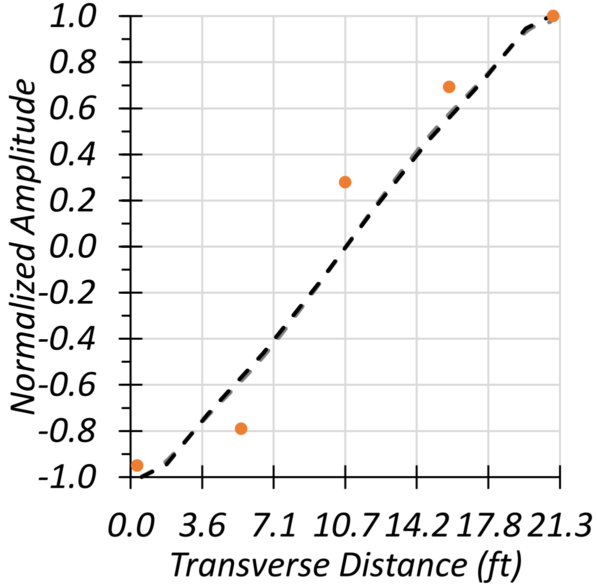
**Longitudinal Section**




**Transverse Section**



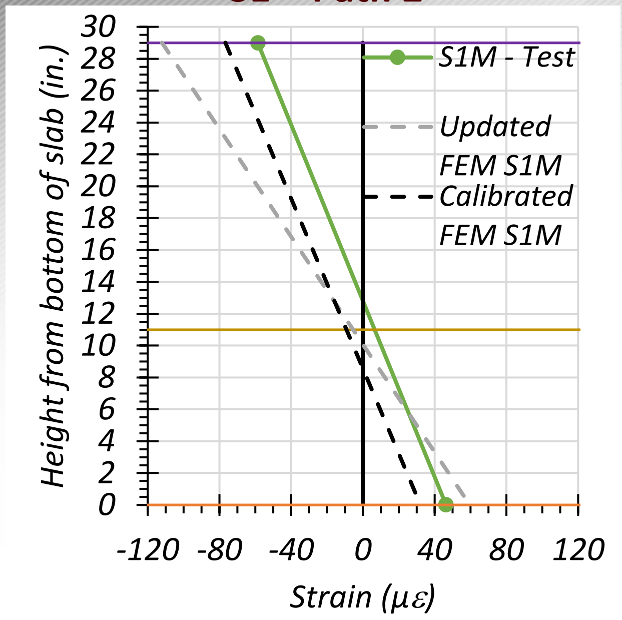



# Comparison of Updated and Calibrated Models with Test Results

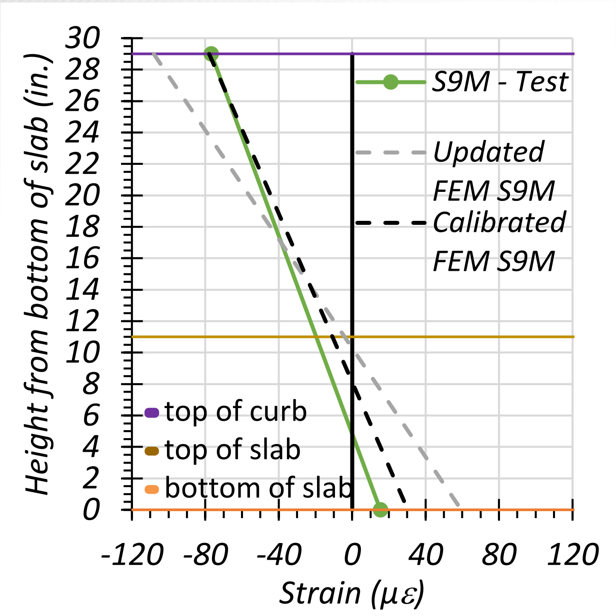
## Bridge CS-9

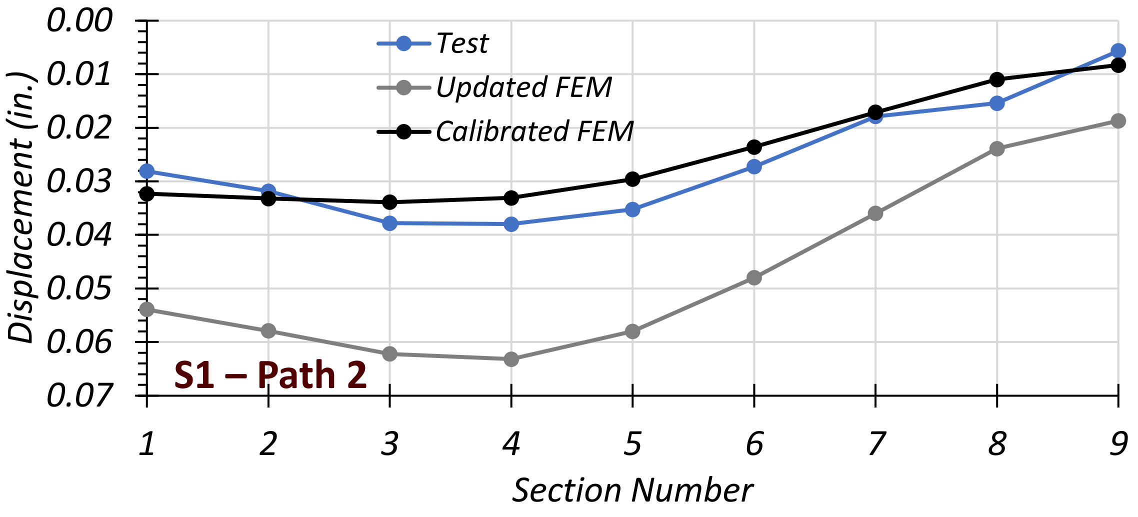
### Stop Location Test

**S1 – Path 2**

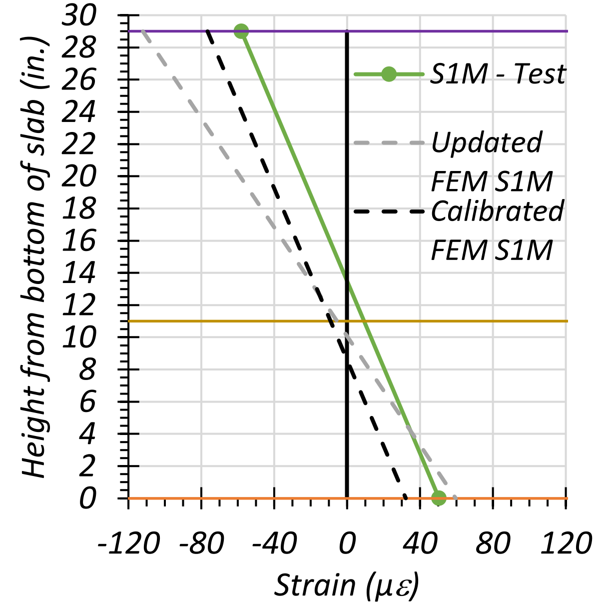


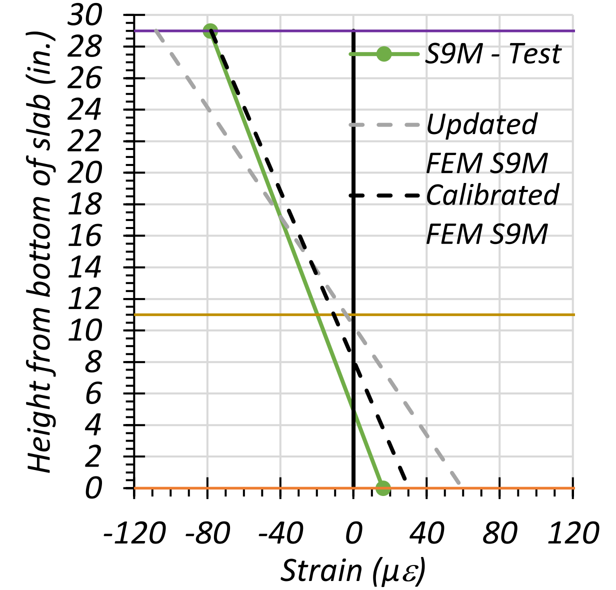

**S9 – Path 1**

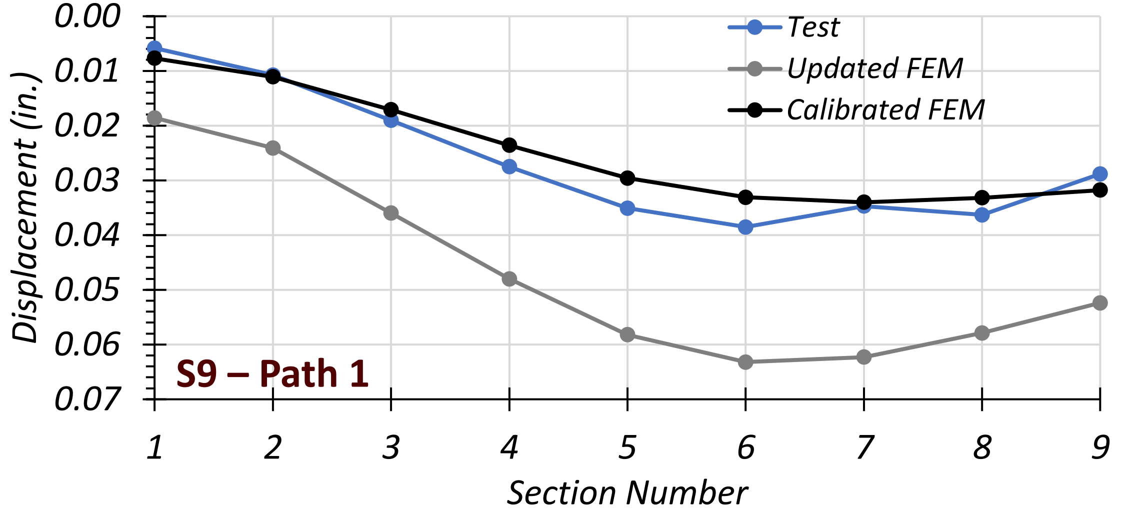



### Crawl Speed Test



# New Rating Factors

## Bridge CS-9

*RFs calculated using LFR method*

### Updated Material Properties

| Rating Factor | Basic Load Rating | Load Rating with Measured Material Properties | Measured Material Properties/Basic Load Rating |
|---|---|---|---|
| **Inventory** | 0.42 | 0.45 | 1.07 |
| **Operating** | 0.98 | 1.05 | 1.07 |

### End Fixity

| Rating Factor | Basic Load Rating | Load Rating with End Fixity | End Fixity/Basic Load Rating |
|---|---|---|---|
| **Inventory** | 0.42 | 0.42 | 1.01 |
| **Operating** | 0.98 | 0.98 | 1.01 |

✓ *The updated RFs would allow for removal of the posting per TxDOT's load rating flowchart*

Changes due to:
- Material strength update
- Partial end fixity

# Refined Load Rating Guidelines

# Recommendations

- Volume 3 of the project report provides
  - Recommendations based on results of this study
    - Steel multi-girder bridges
    - Concrete multi-girder bridges
    - Concrete slab bridges with integral curbs
  - Commentary
  - Example applications
  - Each of the four bridge types reviewed in detail are included



| RECOMMENDATION | COMMENTARY |
|---|---|
| **2.1 INSPECTION** | |
| The following should be performed during routine inspection of the bridge. Observations made will be relevant to the methods used to determine refined load ratings. | |
| **2.1.1 Geometry and Traffic** | **C2.1.1 Geometry and Traffic** |
| Examine and note the bridge geometry with respect to the roadway width, lane widths, and number of lanes. | Refer to the NBI records for ADT and ADTT information. |
| **2.1.2 Girder Flange Embedment** | **C2.1.2 Girder Flange Embedment** |
| Examine if the top flanges of the girders are embedded in the concrete deck and estimate the depth of embedment. Confirm the depth of embedment relative to that shown in the structural drawings. If the flanges are embedded, examine the condition of the underside of the deck near the girder flanges. | Cracking of the deck near the top flanges of a bridge with embedded flanges could indicate that slippage is occurring between the deck and girders. If no cracks are present, this suggests that composite action between the girder and deck is occurring. |
| **2.1.3 End Conditions** | **C2.1.3 End Conditions** |
| Examine the conditions at the ends of the bridge for signs of potential end fixity. Look for rust or deterioration causing locking between the girders and the bearing. If the top surface of the concrete deck is exposed, look for the presence of transverse tension cracks in the deck near the abutments. | Cracking of the top surface of the deck near bridge ends could indicate the presence of end restraint leading to some negative moment at the girder ends. If significant, this can reduce the positive moment demand at midspan. |

# Items During Inspection

- Geometry and Traffic
  - Examine and note the bridge width, roadway width, and number of lanes
  - Obtain the ADT and ADTT from NBI records
- Girder Flange Embedment (for steel bridges)
  - Examine if the top flanges of the girders are embedded in the concrete deck
  - If so, examine the condition of the underside of the deck near the girder flanges (concrete cracking)
- End Conditions
  - Examine the conditions at the ends of the bridge for signs of potential end restraint
    - Rust or deterioration causing locking between girders and bearing
    - Transverse tensions cracks in the deck near the abutments (if not hidden by asphalt)
- Material Properties
  - Gather mill test certificates or as-built information to use higher strength than default values in MBE
  - Consider concrete strength testing where it can benefit load rating factors (core tests or NDE tests)

# Number of Lanes

- Consider ADTT and types of trucks that could be passing on the bridge
- Consider analyzing bridges with low ADTT and a roadway width under 24'-0" as one-lane bridges
  - Very low likelihood of two design trucks passing each other side-by-side on a narrow bridge in a rural setting.
- Bridges could be restriped as a one-lane bridge where this does not impede functionality or safety
- Analysis should present realistic scenarios
- This approach was observed in some bridge inspection records

## Bridge Inventory Record

Bridge Length: 31 ft. Deck Width: 22.0 ft. Lanes On: 2 Lanes Under: 0
Skew Angle: 0 Deg. ☐ Lf. Fwd. ☐ Rt. Fwd. Bridge Rail: None
Clear Width Between: 20.4 ft. ☒ Curbs, ☐ Rails, ☐ Pvmt Edges Approach Rdway Wid: 18 ft.

## TxDOT Load Rating Calcs

```
Single span steel stringer bridge                        * 1-Lane Bridge
Span  1                                          Span Length =  30.0 FT
6.0 IN Reinforced Concrete             No Separately Applied Surfacing
FY = 33.0 KSI
Corrosion Loss =  3 %                            Fully Braced Stringer
```

# Partial Composite Action
# Office Analysis (Level I Analysis)

- Analyze controlling steel bridge girder as both non-composite and composite
  - This provides an upper and lower bound RF
- Check if the RF is close to 1.0 when analyzed as non-composite and much higher than 1.0 when analyzed as composite
  - In this scenario, assigning an amount of partial composite action would still likely be conservative
- Assign an amount of partial composite action to the bridge that is more realistic than non-composite analysis, but still ensures safety
  - If the girder top flanges are embedded and the deck underside is in good condition, almost fully composite action has been observed. This approach is more appropriate for this condition.
- Use a ratio to reduce the controlling concrete or steel interface shear force in a composite section analysis
- Load rate the bridge using this partial composite behavior

# Partial Composite Action – Load Test (Level II Analysis)

- For bridges exhibiting no signs of end fixity
- Determine theoretical composite and non-composite moments of inertia and deflections of the desired girder (using a known truck)
- Conduct a short load test with the same known truck to determine a test deflection of the girder
- Prorate the measured test deflection between the composite and non-composite deflections
- Use the prorated amount to determine the acting partially composite moment of inertia

*For example:*

| | |
|---|---|
| Theoretical Composite Deflection (in.) | 0.236 |
| Theoretical Non-Composite Deflection (in.) | 0.438 |
| Test Deflection (in.) | 0.351 |
| Prorated Amount $\left(\frac{\Delta_{nc}-\Delta_{test}}{\Delta_{nc}-\Delta_{c}}\right)$ | 0.43 |

| | |
|---|---|
| Composite Inertia (in$^4$) | 11,300 |
| Non-Composite Inertia (in$^4$) | 4470 |
| Test Inertia (in$^4$) $\left(I_{nc} + \Delta_{proprated}(I_c - I_{nc})\right)$ | 7407 |

# Partial Composite Action – Load Test (Level II Analysis), Cont.

- Use Equation C-I3-4 in the 14th edition AISC Steel Construction Manual to determine the $\frac{\sum Q_n}{C_f}$ ratio

$$I_{equiv} = I_{nc} + \sqrt{\frac{\sum Q_n}{C_f}}(I_c - I_{nc})$$

  - $\frac{\sum Q_n}{C_f}$ is the ratio of the true interface shear resistance over the interface shear resistance necessary for fully composite action
  - From the previous example:

$$7407 = 4470 + \sqrt{\frac{\sum Q_n}{C_f}}(11{,}300 - 4470)$$

$$\frac{\sum Q_n}{C_f} = 0.66$$

- Multiply this ratio by the controlling concrete or steel shear transfer force in a composite section capacity analysis
- Update nominal moment strength and rating factor including partial composite action

# Partial Composite Action – Load Test (Level III Analysis)

- For bridges exhibiting signs of end fixity
- Conduct a field load test using a known truck to determine the fixing moment at the ends of a girder
  - Deflection must also be measured, as in the Level II Analysis
- Calculate the deflection due to end fixity using the following equation:

$$\Delta = \frac{ML^2}{8EI}$$

- Add the magnitude of this deflection to the magnitude of the measured test deflection to obtain a larger magnitude deflection
- Use this deflection to perform the same procedure as in a Level II Analysis
- Obtain a new partial composite moment capacity

# Live Load Distribution Factors

- For multi-girder bridges considered in this study, it is suggested to continue using the AASHTO Standard Specification LLDFs when load rating
- To explore refined LLDFs for a specific bridge, two levels of analysis / testing are possible:
  - **Level I Analysis:**
    - Develop an FEM model of the bridge to more accurately determine the live load distribution to the girders.
  - **Level II Analysis:**
    - Conduct a load test on the bridge to more accurately determine the live load distribution to the girders.
    - The results can be analyzed to evaluate the actual LLDFs and to update an FEM model to further assess live load distribution.

# Continuous Steel Bridge Considerations

- Use fewer simplifying assumptions that may be conservative
  - Some load rating calculations simplify using 0.8*L* or 0.75*L* and treat span as simply supported

- For dead load moment demand:
  - Use continuous beam coefficients to determine moments if spans are approximately equal
  - Use a thorough multi-span structural analysis method to determine moments if spans are not equal

- For live load moment demand:
  - Use a thorough multi-span structural analysis method to determine moments if spans are not equal

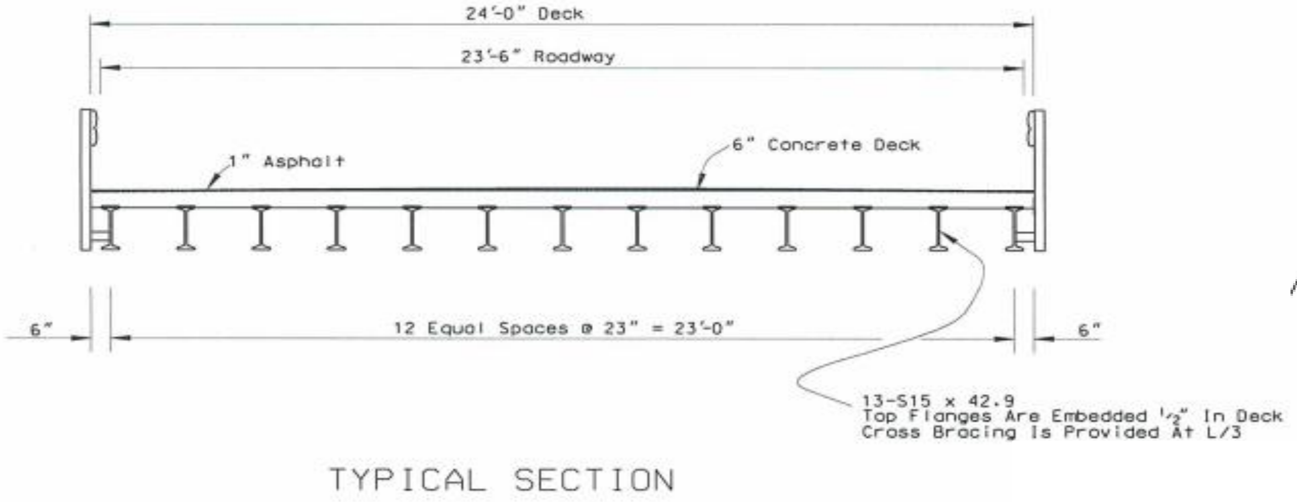
# Concrete Slab with Integral Curbs (FS) Bridge Considerations

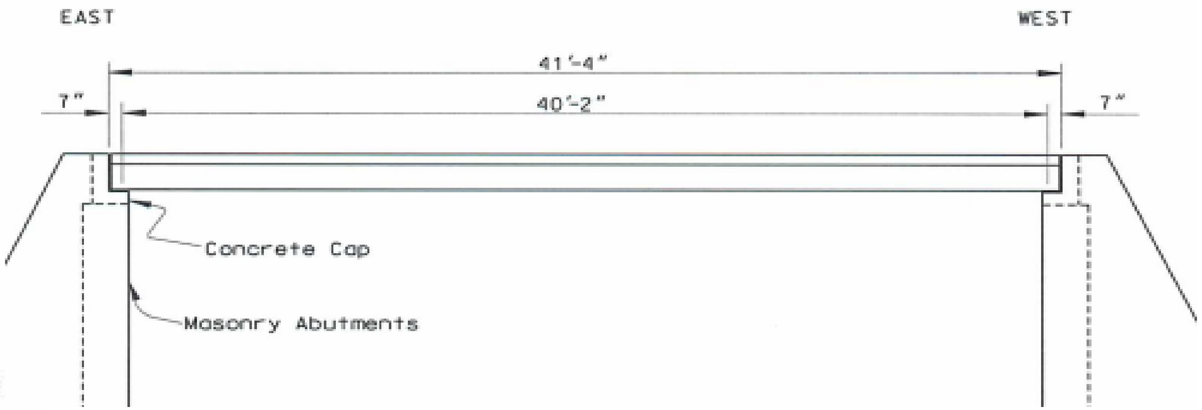
- Continue using Illinois Bulletin 346 to determine curb moments
- Amer et al. (1999) equivalent width to determine interior slab moment demands for one-lane loaded case
- AASHTO LRFD equivalent width to determine interior slab moment demands for two-lane loaded case
- Illinois Bulletin 346 with adjusted L-curb definition may be possible

# Load Rating Examples

# Steel Multi-Girder Bridge SM-5

- Span length = 40'-2"
- Roadway width = 23'-6"
- 13 - S15x42.9 girders
- Girder top flanges embedded into 6 in. concrete deck
- 23 in. girder spacing



# Number of Lanes

- Bridge SM-5
- Striped as two-lane, roadway width of 23'-6"
- Road leads into Huntsville State Park, design vehicles unlikely
- Likelihood of two design trucks crossing at same time is very minimal

→ Analyzed using one-lane LLDFs from the AASHTO Standard Specifications

| Rating Level | Basic Load Rating* | Load Rating with Lane Reduction | Lane Reduction/Basic Load Rating |
|---|---|---|---|
| **Inventory** | 0.49 | **0.62** | 1.27 |
| **Operating** | 0.81 | **1.03** | 1.27 |

*Basic load rating considers two-lane loaded case

# Partial Composite Action – Level II

- Bridge SM-5
- Girder top flanges embedded into deck
- Exhibited almost fully composite behavior during load testing
- As an example, analyzed as partially composite
- Deflection prorated amount equals 0.94 (see detailed example calcs.)
- $\frac{\sum Q_n}{C_f}$ ratio equals 0.88

| Rating Factor | Basic Load Rating* | Level II Partial Composite Load Rating | Level II Partial Composite/Basic Load Rating |
|---|---|---|---|
| **Inventory** | 0.49 | **0.99** | 2.02 |
| **Operating** | 0.81 | **1.65** | 2.04 |

*Basic load rating considers non-composite section

# Partial Composite Action – Level III

- Bridge SM-5
- Consideration is given to measured end restraint (which is small).
- Upward deflection due to measured end compressive strain converted to fixing moment is equal to 0.026 in.
- New deflection prorated amount equals 0.82
- New $\frac{\sum Q_n}{C_f}$ ratio equals 0.82
- Applied live load moment on an interior girder reduces to 99.6 kip-ft from 102.4 kip-ft

| Rating Factor | Basic Load Rating* | Level III Load Rating | Level III/Basic Load Rating |
|---|---|---|---|
| **Inventory** | 0.49 | **1.01** | 2.06 |
| **Operating** | 0.81 | **1.69** | 2.09 |

*Basic load rating considers non-composite section

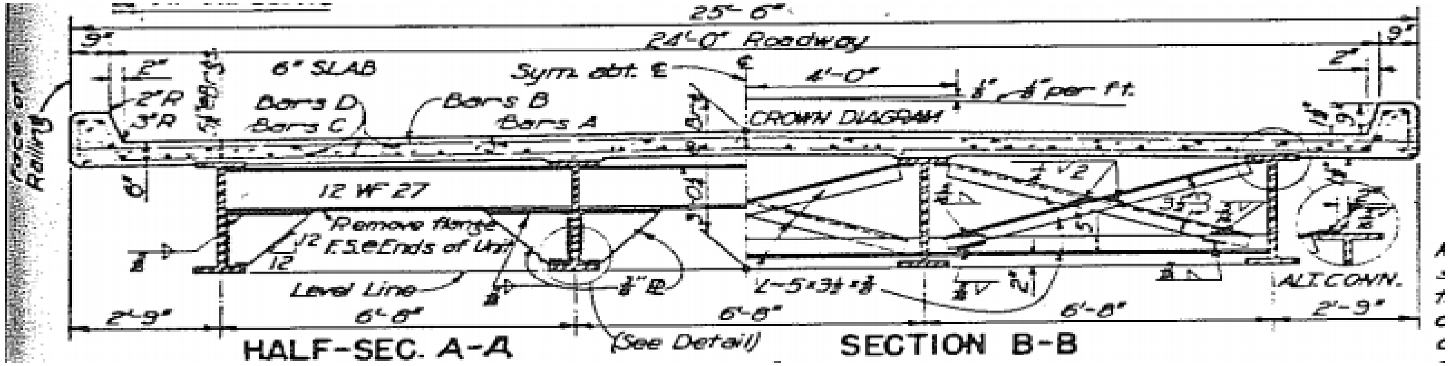
# Bridge SM-5 Summary

- Reduction in number of lanes increases the RF by 27 percent
- Largest RF increase comes from considering partial composite action
  - Both a Level II Analysis and a Level III Analysis more than double the RF
- Note:  considering end restraint alone increases the RF by only 2 percent

✓ Considering partial composite action or reducing the number of lanes allows the posting to be removed per the on-system load posting flowchart

# Continuous Steel Multi-Girder Bridge SC-12

- Span lengths of 60'- 75'-60'
- Roadway width of 24'-0"
- 4 - W30x108 girders
- Girder top flanges not embedded
- 6'-8" girder spacing
- 9 x 3/8 in. cover plate in negative moment region



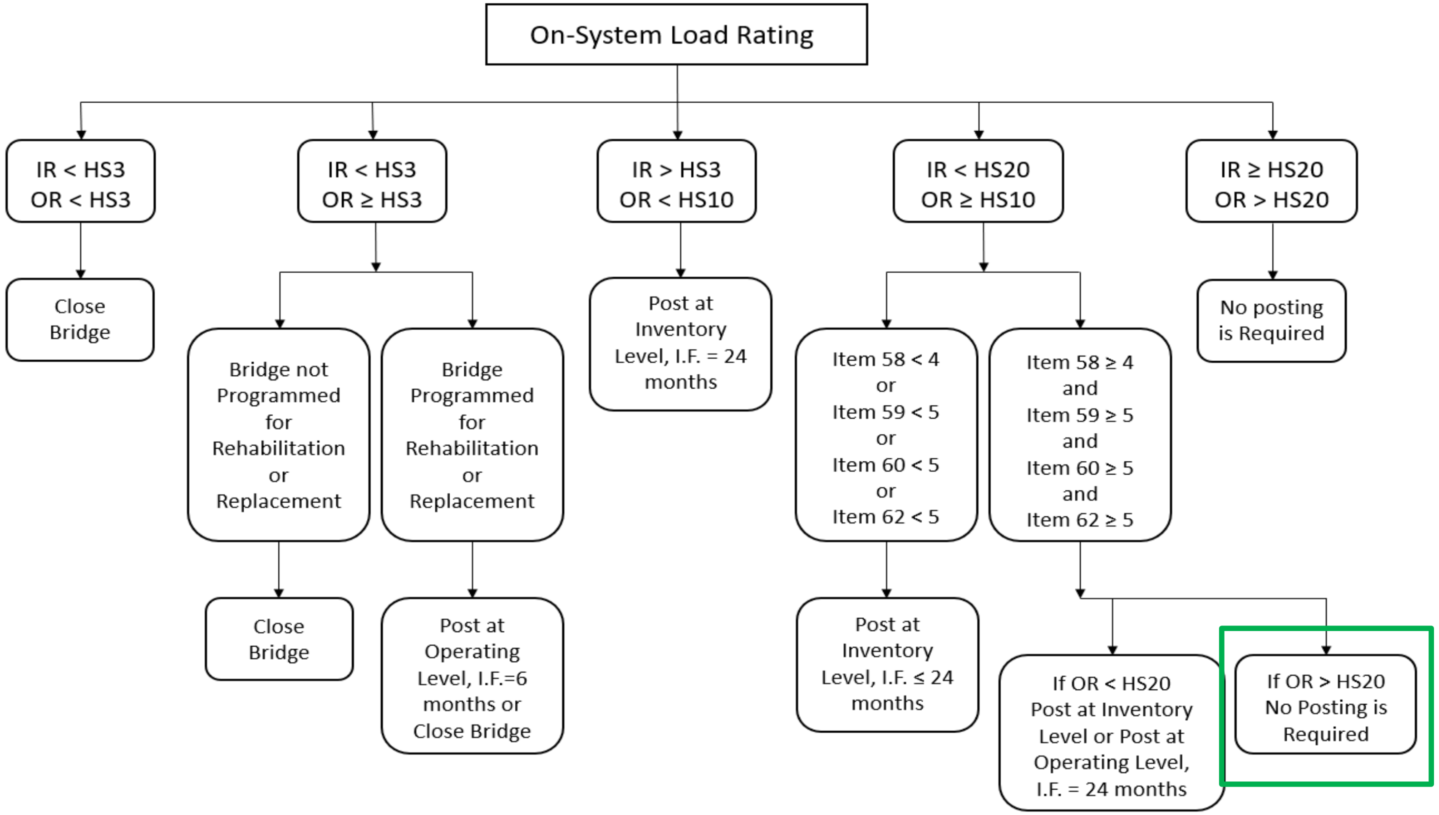
# Partial Composite Action – Level II

- Bridge SC-12
- Girder top flanges not embedded into deck
- Exhibited partial composite behavior during load testing
- Deflection prorated amount equals 0.43
- $\frac{\sum Q_n}{C_f}$ ratio equals 0.66
- Strength RFs: Inventory = 0.88, Operating = 1.47
- Service RFs: Inventory = **0.60**, Operating = **1.01**

| Rating Factor | Basic Load Rating | Level II Partial Composite Load Rating | Level II Partial Composite/Basic Load Rating |
|---|---|---|---|
| **Inventory** | 0.54 | 0.60 | 1.11 |
| **Operating** | 0.91 | 1.01 | 1.11 |

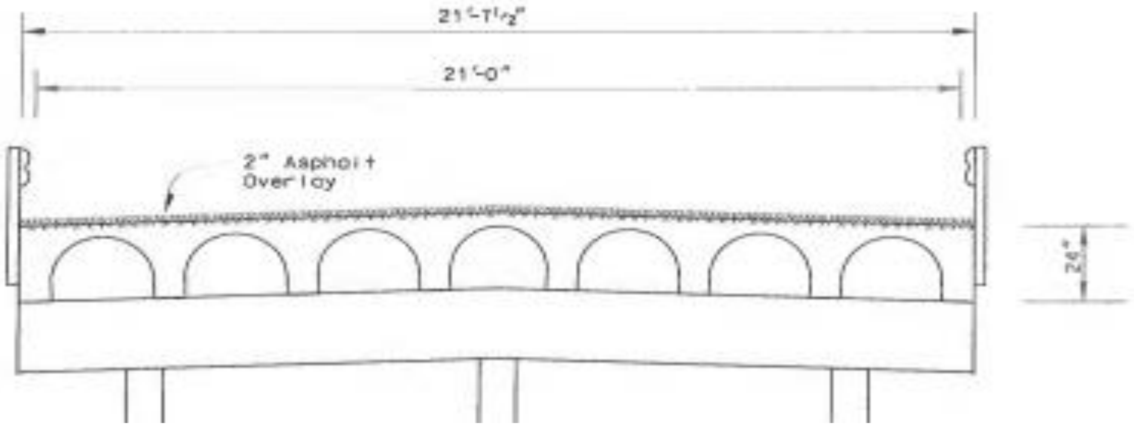
# Bridge SC-12 Summary

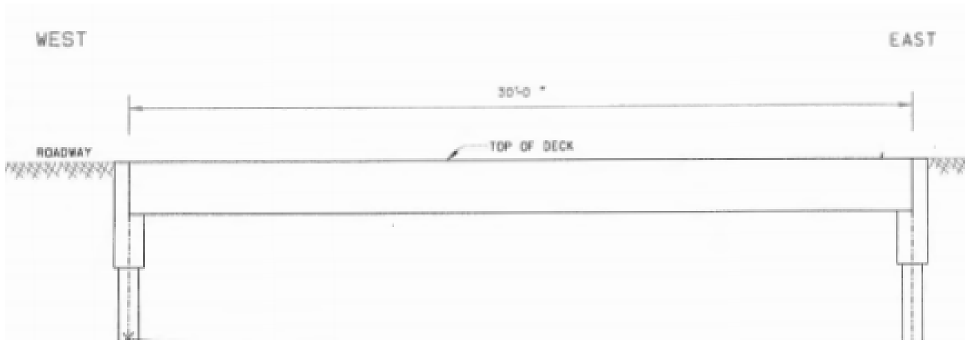
- Considering partial composite action allows for increases in the RFs
  - Approximately 62 percent increase in the Strength RFs
  - Approximately 11 percent increase when considering the Service RFs
- Allows the posting to be removed per the on-system load posting flowchart



# Concrete Multi-girder Bridge CM-5

- Span length of 29’-0"
- Roadway width of 21’-2"
- Eight 24 in. deep cast-in-place concrete pan girders
- 36 in. c/c girder spacing
- In the absence of structural drawings for Bridge CM-5, the information provided in the standard drawing provided on the TxDOT website ‘CG 30'-4" Spans’ were used.



# Number of Lanes

- Bridge CM-5
- Striped as two-lane, roadway width of 21’-2“
- ADT = 150
- Bridge was assumed to be load posted due to the condition rating of substructure being less than 6.
- Likelihood of two design trucks crossing at same time is very minimal
- Analyzed using one-lane LLDFs from the AASHTO Standard Specifications

| Rating Level | Basic Load Rating* | Refined Load Rating with Lane Reduction | Refined Load Rating/ Basic Load Rating |
|---|---|---|---|
| **Inventory** | 1.17 | **1.27** | 1.09 |
| **Operating** | 1.96 | **2.12** | 1.08 |

*Basic load rating considers two-lane loaded case

# Measured Material Properties

- Bridge CM-5
- In the absence of structural drawings for Bridge CM-5, the concrete compressive strength was taken to be 4 ksi according to the standard drawing provided on the TxDOT website ‘CG 30'-4" Spans’
- The compressive strength for concrete was measured on site to be 7 ksi

| Rating Factor | Basic Load Rating | Refined Load Rating Using Updated Concrete Strength | Refined Load Rating/ Basic Load Rating |
|---|---|---|---|
| **Inventory** | 1.17 | 1.20 | 1.03 |
| **Operating** | 1.96 | 2.01 | 1.03 |

Note: Basic load rating considers $f_c' = 4.0$ ksi

# End Fixity – Level II

- Bridge CM-5
- Exhibited partial end restraint during load testing
- Compressive strains at the bottom of girder ends obtained from FEM model were converted to end fixing moments
- Applied live load moment on an interior girder reduces to 85.5 kip-ft from 86.8 kip-ft

| Rating Factor | Basic Load Rating | Load Rating with End Fixity | End Fixity/Basic Load Rating |
|---|---|---|---|
| **Inventory** | 1.17 | 1.19 | 1.02 |
| **Operating** | 1.96 | 1.99 | 1.01 |

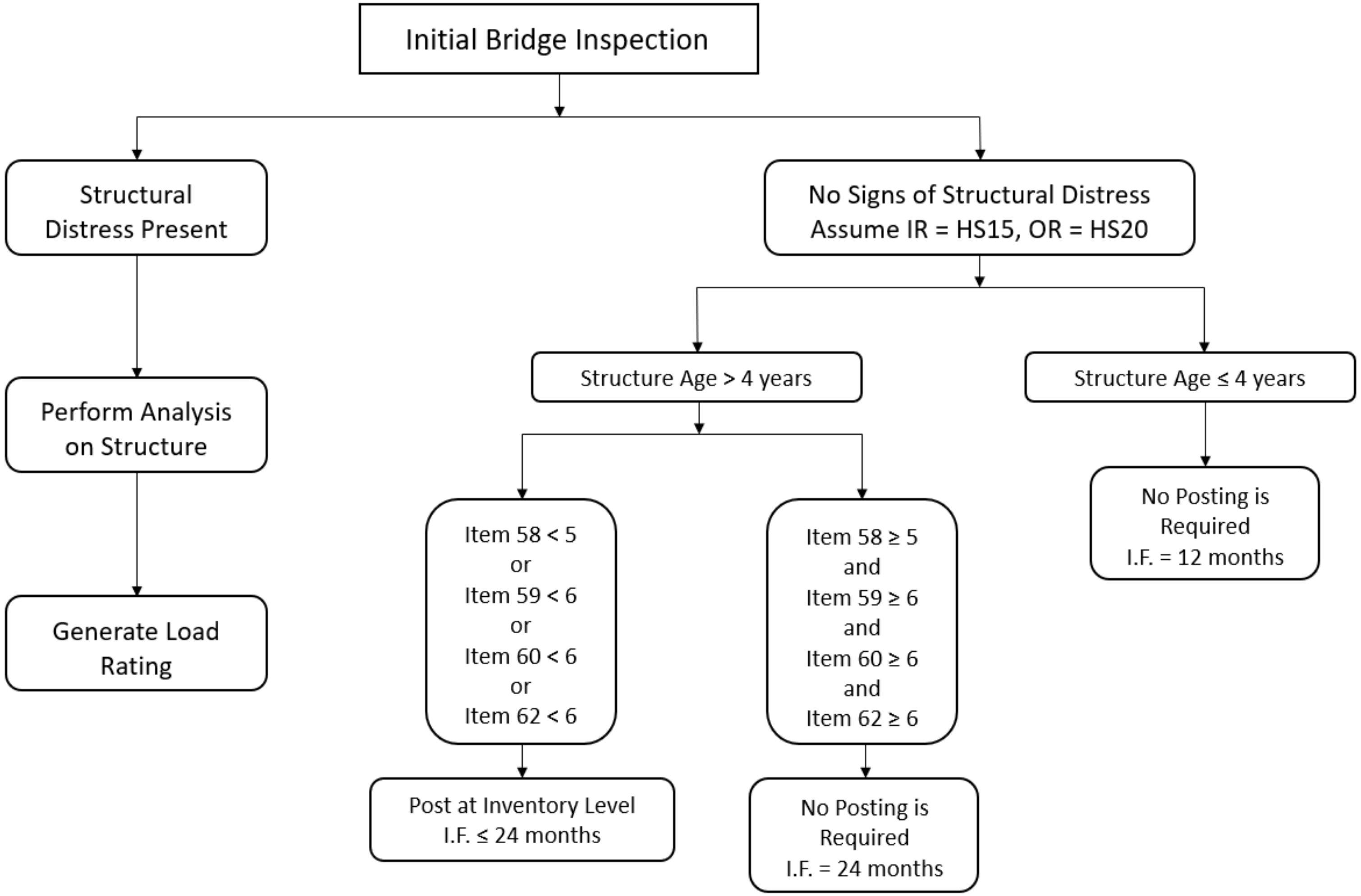
Note: Basic load rating considers simply supported boundary conditions

# Bridge CM-5 Summary

- In the absence of structural drawings for Bridge CM-5, the RFs were calculated based on the information provided in the standard drawing provided on the TxDOT website ‘CG 30'-4" Spans’
- Considering measured concrete strength increases the RF by 1 percent
- Reduction in number of lanes increases the RF by 8 percent
- Considering only end fixity increases the RF by 1 percent
- Reducing the number of lanes to one allows the posting to be removed per the load posting flowchart for concrete bridges with no plans
- However, this bridge has a substructure condition rating less than 6 and needs to be posted at inventory level with inspection frequency of at most 24 months

# TxDOT Load Posting Flowchart

## Concrete Bridges with No Plans



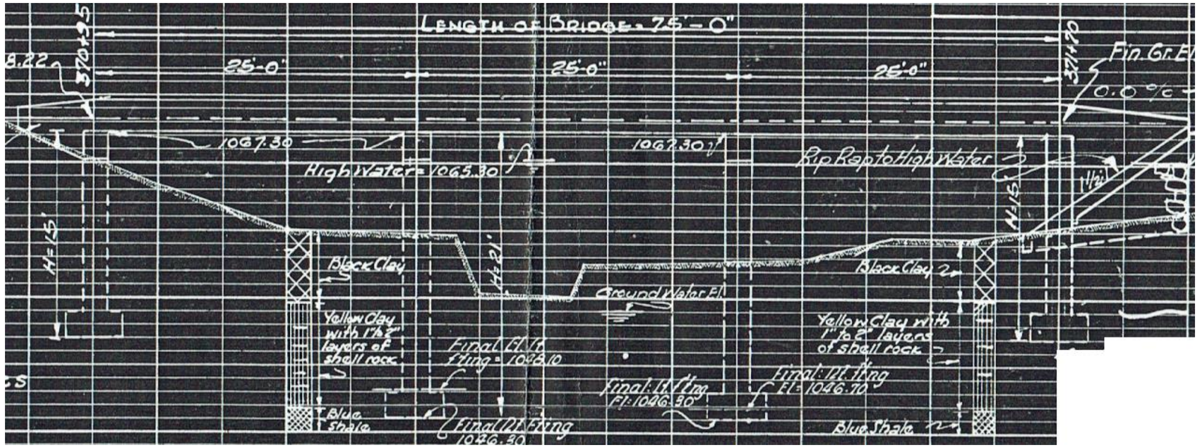

9: Excellent Condition
8: Very Good Condition
7: Good Condition
6: Satisfactory Condition
5: Fair Condition
4: Poor Condition
3: Serious Condition
2: Critical Condition
1: "Imminent" Failure Condition
0: Failed Condition

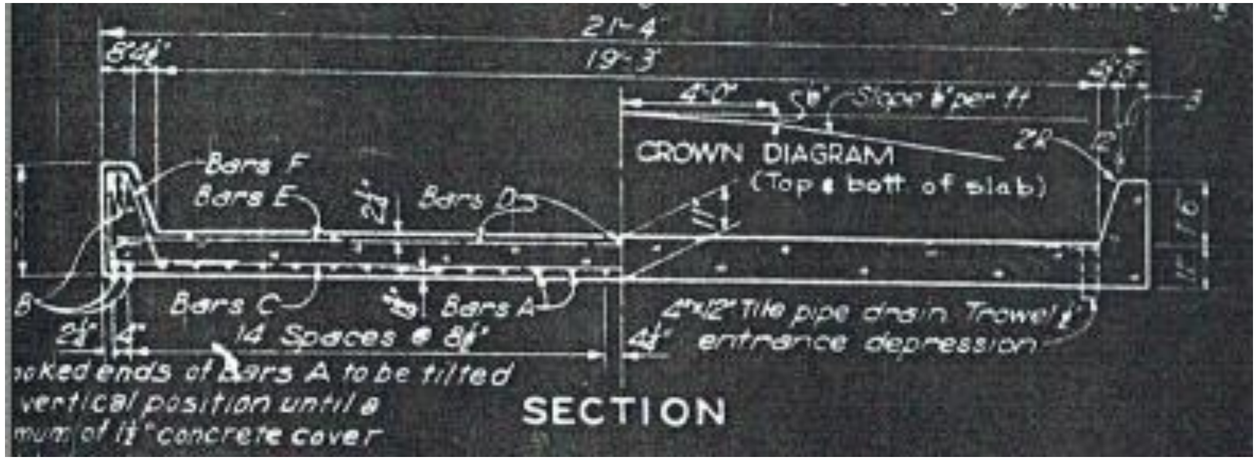
Item 58: Deck condition rating
Item 59: Superstructure condition rating
Item 60: Substructure condition rating
Item 62: Culvert condition rating

*Adapted from TxDOT Bridge Inspection Manual, 2018*

# Bridge CS-9

- Three simply supported spans
- Span lengths of 25'-25'-25'
- Roadway width of 20'-0“
- 11 in. thick slab
- Curb dimensions of 8 in. wide at top, 12.5 in. wide at bottom and 18 in. above top of slab



# Measured Material Properties

- Bridge CS-9
- The structural drawings for Bridge CS-9 specify a concrete compressive strength of 2.5 ksi
- The compressive strength for concrete was measured on site to be 5.2 ksi using NDE testing

| Rating Factor | Basic Load Rating | Refined Load Rating Using Updated Concrete Strength | Refined Load Rating/ Basic Load Rating |
|---|---|---|---|
| **Inventory** | 0.42 | 0.45 | 1.07 |
| **Operating** | 0.98 | 1.05 | 1.07 |

Note: Basic load rating considers $f_c' = 2.5$ ksi

# End Fixity – Level II

- Bridge CS-9
- Exhibited some end restraint during load testing
- Compressive strains at the bottom of the slab ends obtained from FEM model were converted to end fixing moments
- Applied live load moment on an interior girder reduces to 156.2 kip-ft from 155.9 kip-ft

| Rating Factor | Basic Load Rating | Refined Load Rating with End Fixity | Refined Load Rating/ Basic Load Rating |
|---|---|---|---|
| **Inventory** | 0.42 | 0.42 | 1.01 |
| **Operating** | 0.98 | 0.98 | 1.01 |

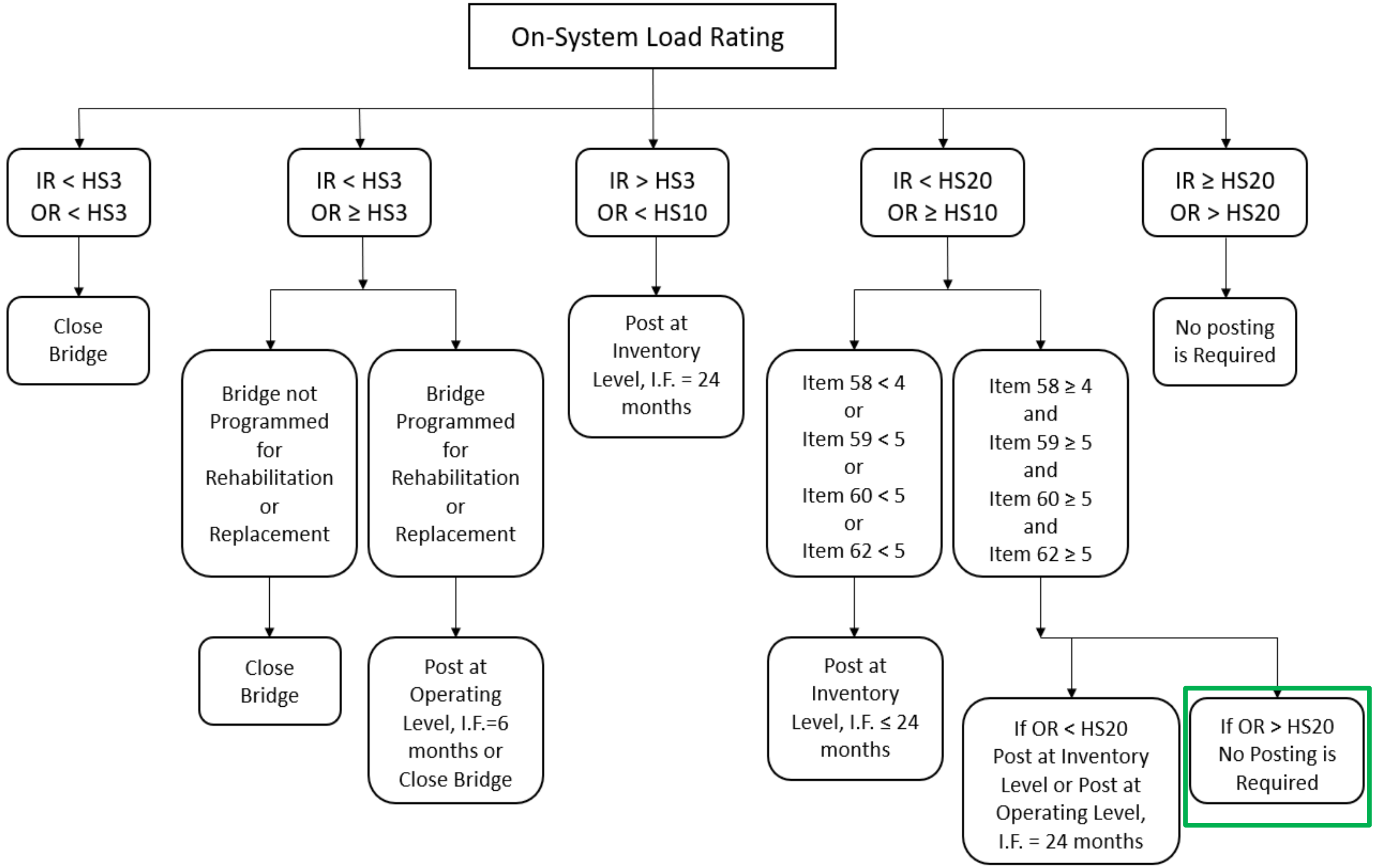
Note: Basic load rating considers simply supported boundary conditions

# Bridge CS-9 Summary

- Considering only end fixity increases the RF by 1 percent
- Considering measured concrete strength increases the inventory RF by 7 percent and operating RF by 14 percent
- Considering measured material properties allows the posting to be removed per the on-system load posting flowchart

# TxDOT Load Posting Flowchart

## Concrete Bridges with No Plans




9: Excellent Condition
8: Very Good Condition
7: Good Condition
6: Satisfactory Condition
5: Fair Condition
4: Poor Condition
3: Serious Condition
2: Critical Condition
1: "Imminent" Failure Condition
0: Failed Condition

Item 58: Deck condition rating
Item 59: Superstructure condition rating
Item 60: Substructure condition rating
Item 62: Culvert condition rating

*Adapted from TxDOT Bridge Inspection Manual, 2018*

# Summary, Conclusions, and Recommendations

# Number of Lanes

- Bridge SM-5
  - Located at the entrance to a state park
  - Narrow roadway width of 23'-6" with no shoulders
- The likelihood of two design vehicles passing on the bridge at the same time is very small
- Narrow bridges in rural locations could be analyzed as one-lane bridges
- TxDOT already practices this occasionally in their load rating calculations

# Composite Action

- Bridge SM-5 showed clear signs of acting as nearly fully composite
- Bridge SC-12 exhibited signs of partial composite behavior
- For simply supported steel multi-girder bridges with the top flange embedded in the deck, similar to Bridge SM-5:
  - The overall condition of the bridge should be checked
  - It should be confirmed that there is no cracking on the underside of the deck near the girder flanges
  - A short load test can be done to compare the deflection with theoretical composite or non-composite deflections
  - Determine the proper amount of composite action to use during rating, informed by field measurements and observations and supporting calculations
- For other steel multi-girder bridges:
  - A short load test could be done to compare the deflection with theoretical composite or non-composite deflections
  - Determine the proper amount of partial composite action to use during rating, informed by field measurements and observations and supporting calculations

# End Fixity

- Bridge SM-5, Bridge CM-5 and Bridge CS-9 exhibited partial end restraint during loading
  - Confirmation of partial end restraint could be obtained through
    - Strain gauge readings on the bottom flanges on the girder at one or both ends of the bridge
    - Visual observations such as deterioration causing locking between the girders and the bearing seat or tensions cracks in the deck near the abutment
  - Determining amount of partial end fixity to consider during load rating is most reliably informed by a short field test. However, the potential benefit in increasing the load rating is typically limited.

# Live Load Distribution

- In general, the AASHTO Standard Specifications did a good job of estimating the LLDFs of considered bridges without being overly conservative
- The AASHTO LRFD Specifications can be highly conservative in some cases
- It is recommended that TxDOT continue using the AASHTO Standard Specification LLDFs in their load rating process
- Bridge CS-9 (Concrete Slab Bridge with integral Curbs)
  - Continue using Illinois Bulletin 346 to determine curb moments
  - Illinois Bulletin 346 provides unconservative moment estimate for interior slab region for both one-lane and two-lane loading cases
    - Use Amer et al. (1999) equivalent width to determine interior slab moment demands for one-lane loaded case
    - Use AASHTO LRFD equivalent width to determine interior slab moment demands for two-lane loaded case

# Refined Analysis

- FEM modeling programs are becoming more efficient to use and refined analysis models can provide a more accurate picture of the bridge behavior
- Updated material properties can also help improve ratings
  - Increased steel yield strength can greatly increase capacity
  - Increased concrete strength may be able to help composite or partially composite steel girder bridge structures
  - Increased concrete strength slightly increases the moment capacity for concrete bridges
- If there is a bridge that TxDOT desires to remove the postings more so than a typical structure, FEM modeling and analysis could be helpful

# Computer Vision

- The targetless computer vision method worked well for dynamic load cases
- This technology can provide a quick and effective way to obtain girder deflections during loading
- Deflection measurements from computer vision could help determine the amount of partial composite action occurring or the live load distribution to girders

# Summary and Recommendations

- Existing bridges come on all shapes and sizes and have their own unique characteristics and challenges. This is no exception for load rating.
- Steel bridges are the largest group of SSLO bridges in Texas and exhibited the greatest potential for increased load posting.

| Material/Design | Bridge Type | No. of SSLO Bridges | | |
|---|---|---|---|---|
| | | On System | Off System | Total |
| Steel | Stringer/Multi-beam or Girder | 14 | 243 | 257 |
| Concrete | Slab | 42 | 59 | 101 |
| Concrete | Stringer/Multi-beam or Girder | 2 | 35 | 37 |
| Steel Continuous | Stringer/Multi-beam or Girder | 6 | 103 | 109 |
| Prestressed | Other | 0 | 68 | 68 |
| Concrete Continuous | Slab | 4 | 38 | 42 |

# Summary and Recommendations

- Several approaches have been outlined for reviewing load postings for steel and concrete bridges using refined methods.
- Field Testing and Refined Analysis
  - Can lead to increase load ratings
  - Particularly for steel girder bridges not originally designed to act compositely
- In-situ Material Properties
  - Mill test certificates for rebar strengths
  - Laboratory testing of extracted specimens (concrete cores)
  - NDE tests – Schmidt hammer tests, Ultrasonic Pulse Velocity (UPV) tests
  - NDE to locate reinforcement when drawings are not available

# Summary and Recommendations

- Verification of Number of Lanes
  - Bridges striped to be two-lane may not be wide enough
  - Install one-lane traffic sign near approach ends, remove two-lane stripes
- Computer Vision
  - Non-contact targetless approach to determine bridge deflections during load testing
- End Fixity
  - Limited potential to increase load posting
  - Determine through visual inspection (tensile cracks at top of deck)
  - Compressive strains recorded via strain gauges at bridge ends

## Thank you for your attention!

## Questions and Discussion