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

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

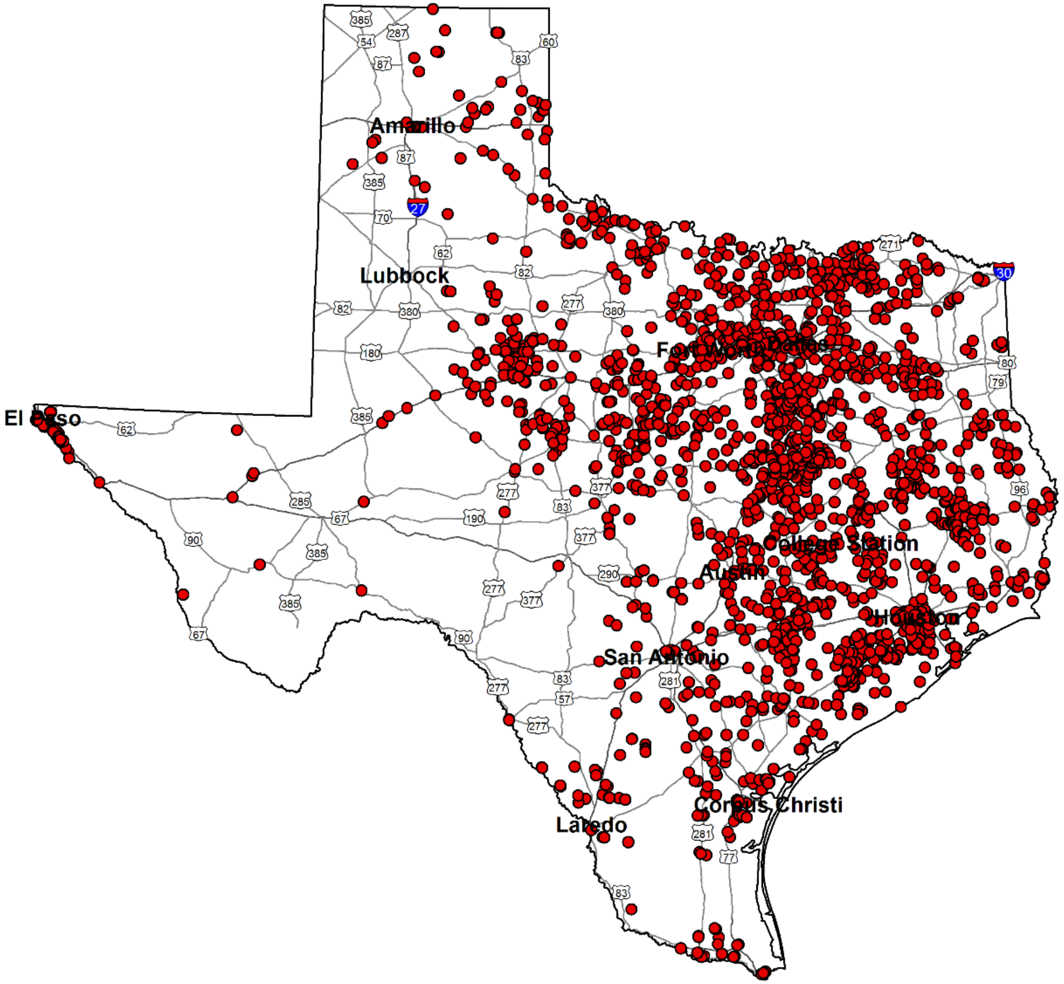
Workshop Overview

- 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)


Amarillo
Lubbock
El Paso
Fort Worth
Dallas
College Station
Austin
Houston
San Antonio
Corpus Christi
Laredo

Load posted bridges in Texas (2111)

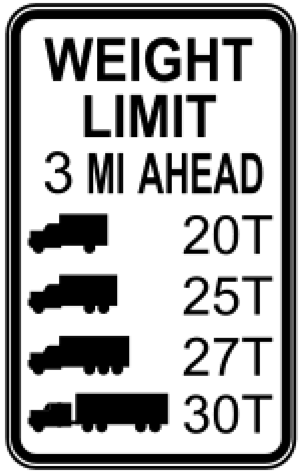
Motivation

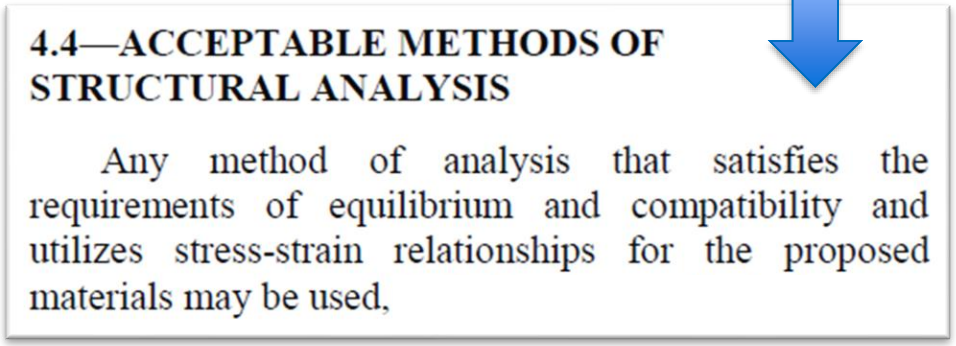
Impact on freight movement and economic vitality

  - 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.

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

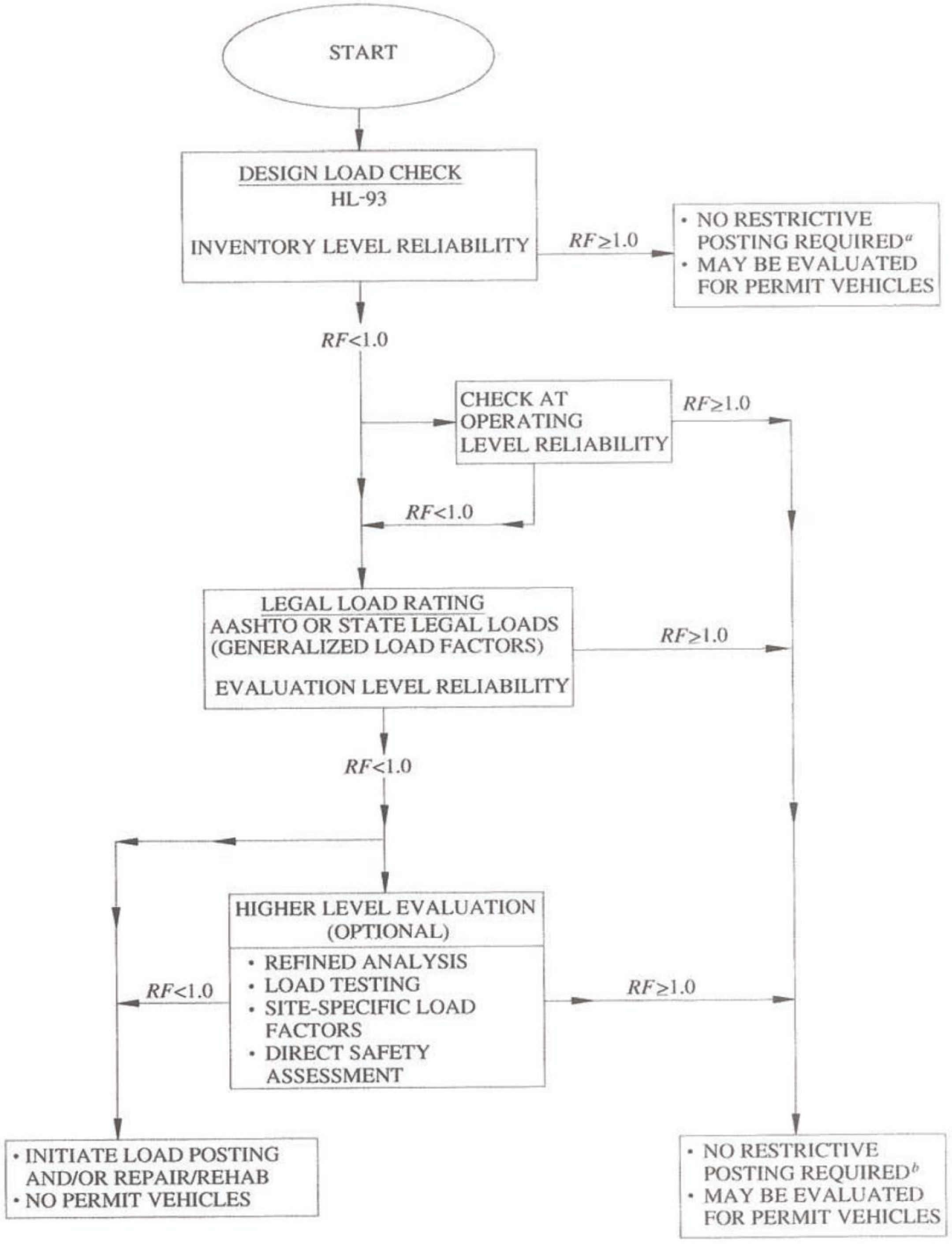
Allowable Stress Rating (ASR) and Load Factor Rating (LFR)

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

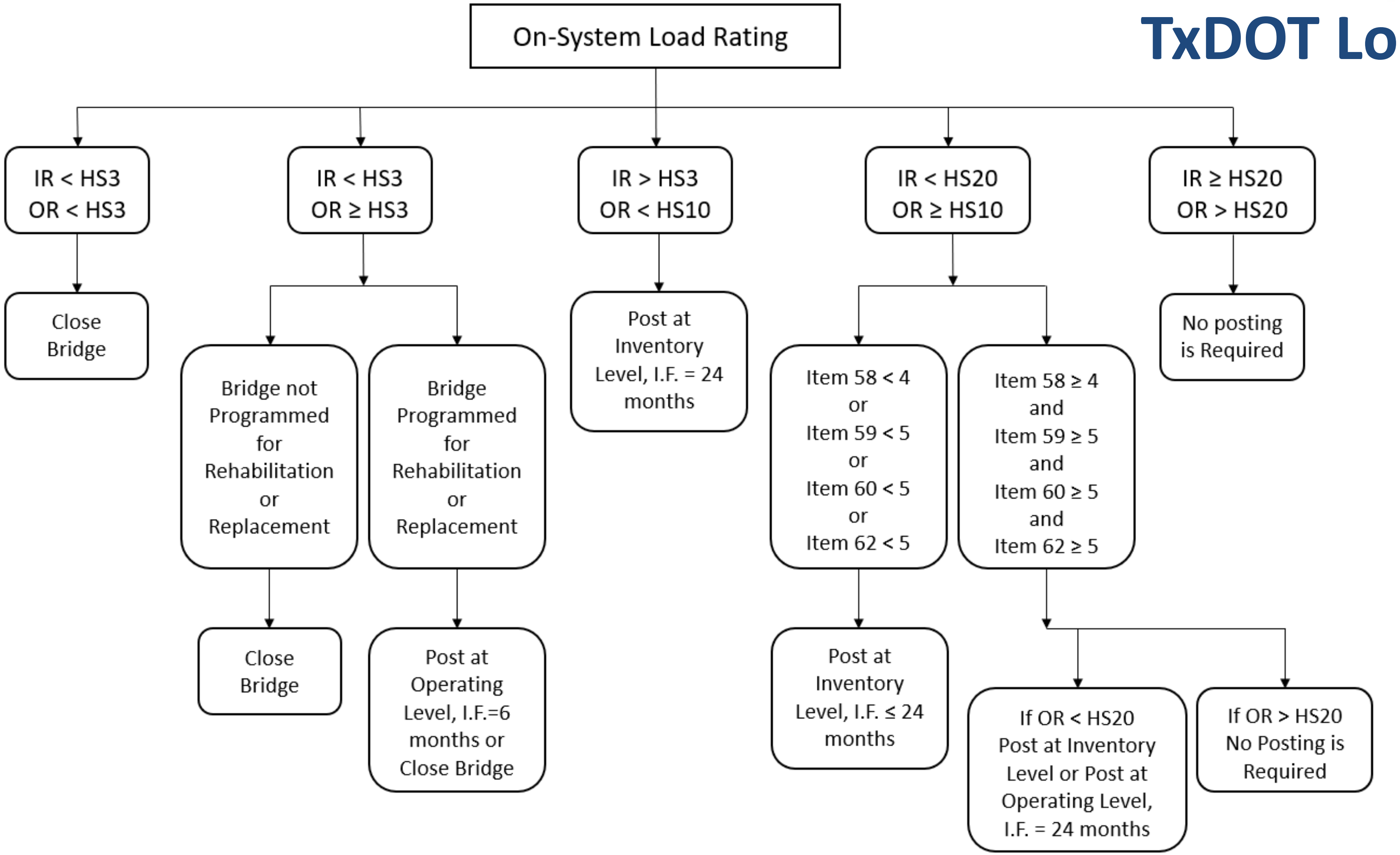

START
DESIGN LOAD CHECK
HL-93
INVENTORY LEVEL RELIABILITY
RF≥1.0
• NO RESTRICTIVE POSTING REQUIRED^a
• MAY BE EVALUATED FOR PERMIT VEHICLES
RF<1.0
CHECK AT OPERATING LEVEL RELIABILITY
RF≥1.0
RF<1.0
LEGAL LOAD RATING
AASHTO OR STATE LEGAL LOADS
(GENERALIZED LOAD FACTORS)
EVALUATION LEVEL RELIABILITY
RF≥1.0
RF<1.0
HIGHER LEVEL EVALUATION (OPTIONAL)
• REFINED ANALYSIS
• LOAD TESTING
• SITE-SPECIFIC LOAD FACTORS
• DIRECT SAFETY ASSESSMENT
RF<1.0
RF≥1.0
• INITIATE LOAD POSTING AND/OR REPAIR/REHAB
• NO PERMIT VEHICLES
• NO RESTRICTIVE POSTING REQUIRED^b
• MAY BE EVALUATED FOR PERMIT VEHICLES

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

TxDOT Load Rating Specifics

On-System Bridges



On-System Load Rating

IR < HS3
OR < HS3

Close Bridge

IR < HS3
OR ≥ HS3

Bridge not Programmed for Rehabilitation or Replacement

Close Bridge

Bridge Programmed for Rehabilitation or Replacement

Post at Operating Level, I.F.=6 months or Close Bridge

IR > HS3
OR < HS10

Post at Inventory Level, I.F. = 24 months

IR < HS20
OR ≥ HS10

Item 58 < 4 or Item 59 < 5 or Item 60 < 5 or Item 62 < 5

Post at Inventory Level, I.F. ≤ 24 months

Item 58 ≥ 4 and Item 59 ≥ 5 and Item 60 ≥ 5 and Item 62 ≥ 5

If OR < HS20 Post at Inventory Level or Post at Operating Level, I.F. = 24 months

If OR > HS20 No Posting is Required

IR ≥ HS20
OR > HS20

No posting is Required

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

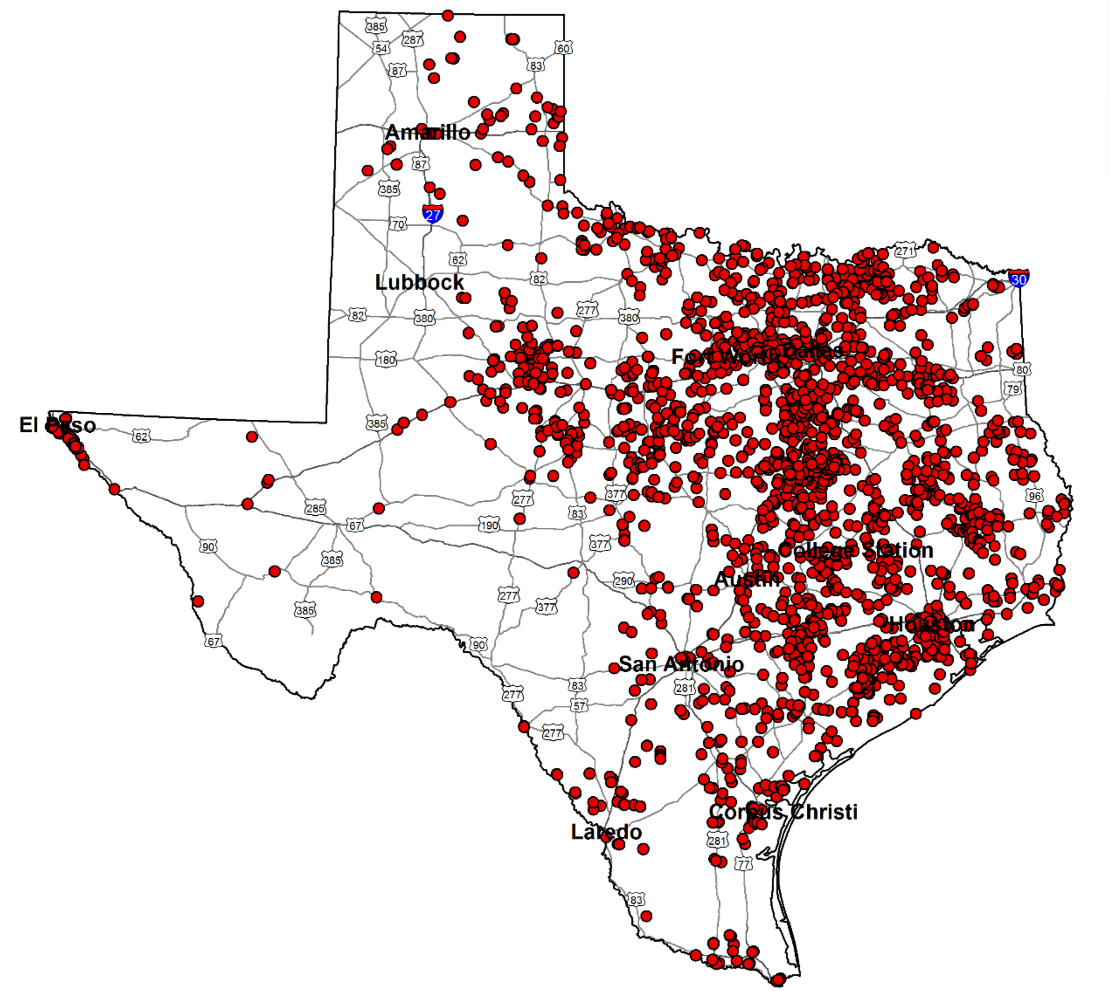
Introduction

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

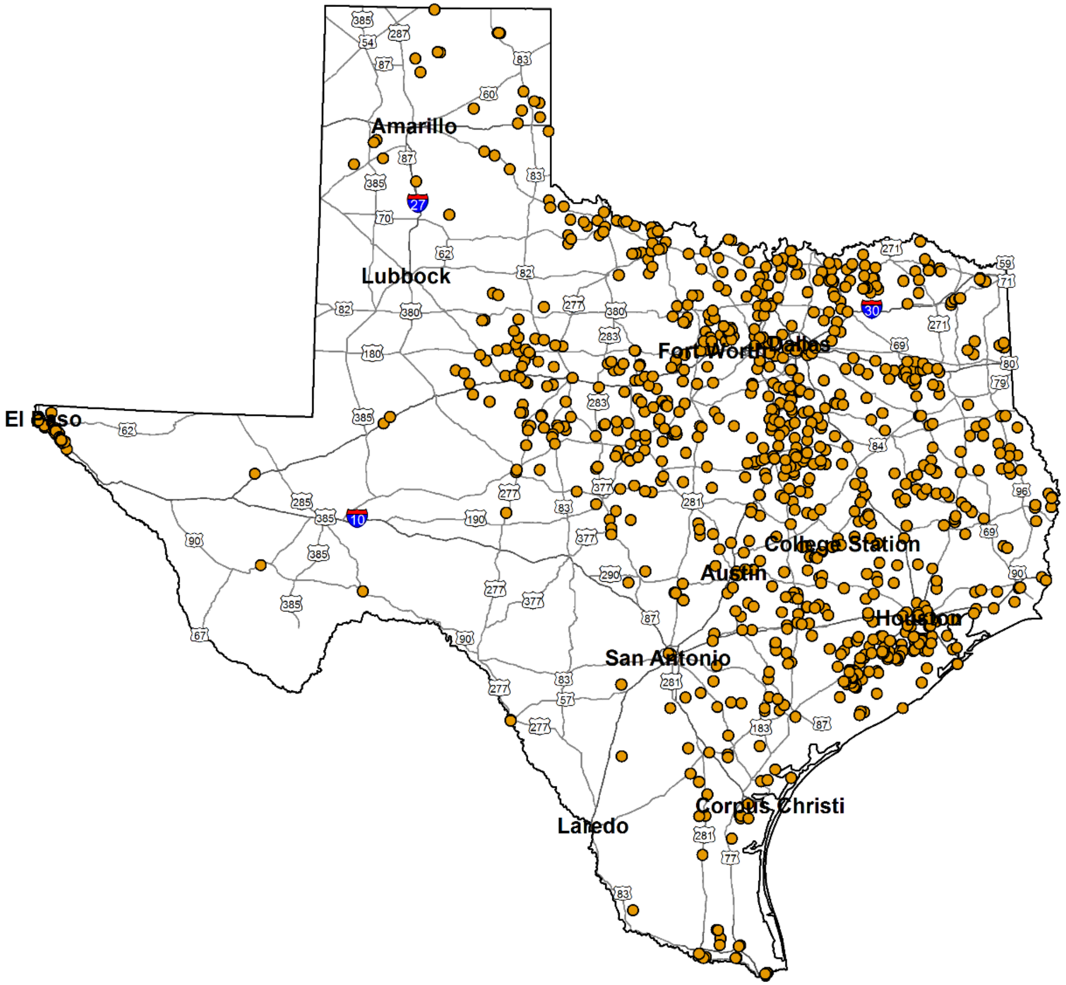
Condition Classification	**On-System**	**Off-System**	**Total**
Structurally Deficient (SD)	39	473	512
Functionally Obsolete (FO)	58	572	630
Sub-standard for Load Only (SSLO)	78	891	969
Total	175	1936	2111

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

Geographic Locations


Amarillo
Lubbock
El Paso
Fort Worth
Dallas
College Station
Austin
Houston
San Antonio
Corpus Christi
Laredo

All LP bridges in Texas (2111 bridges)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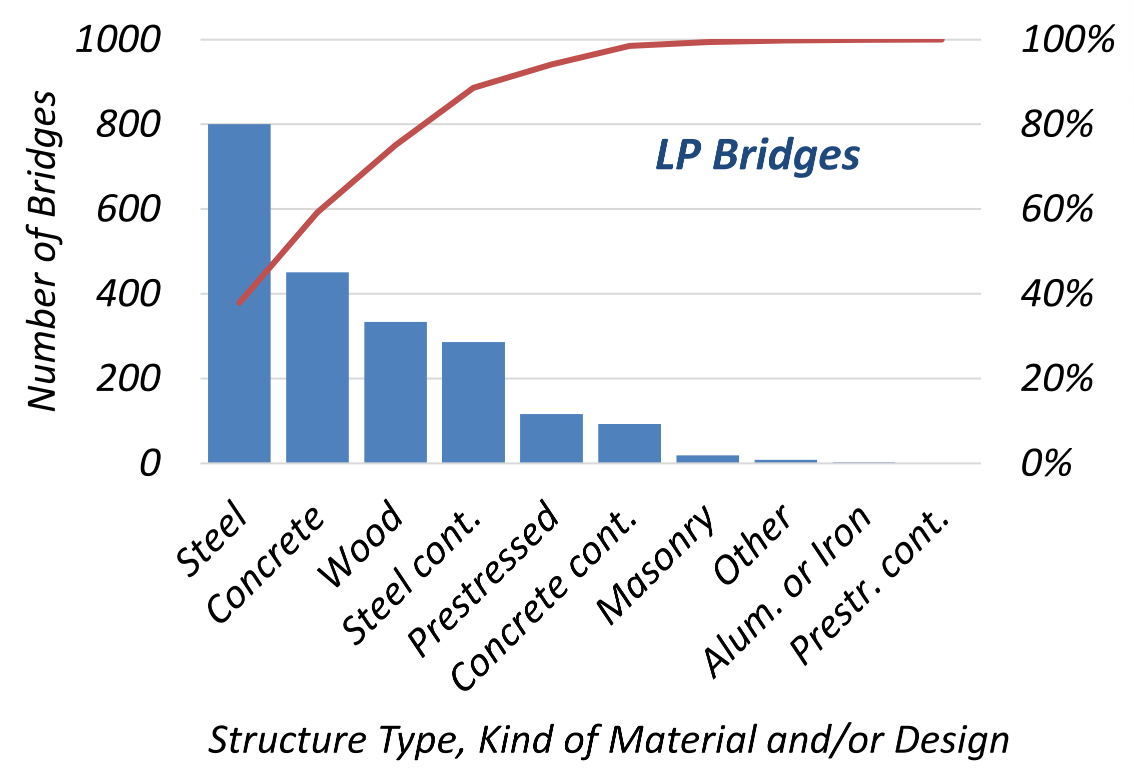
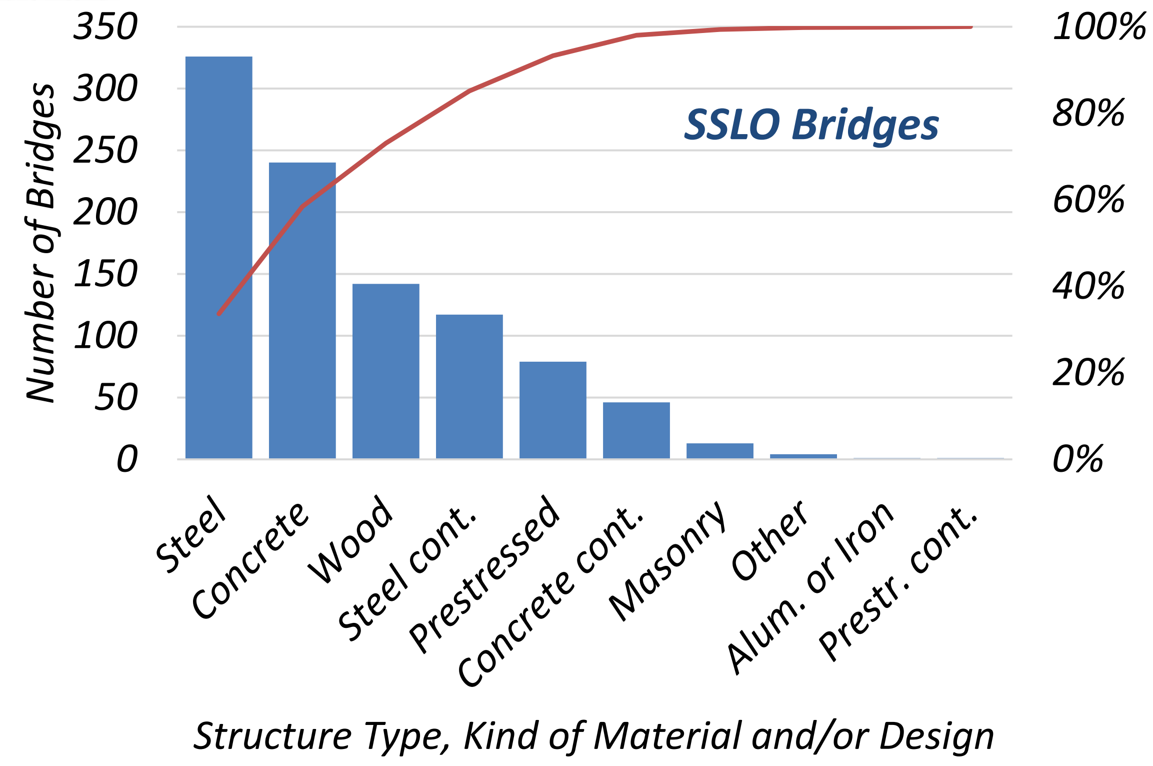
All SSLO bridges in Texas (969 bridges)

Distribution of Load Posted Bridges



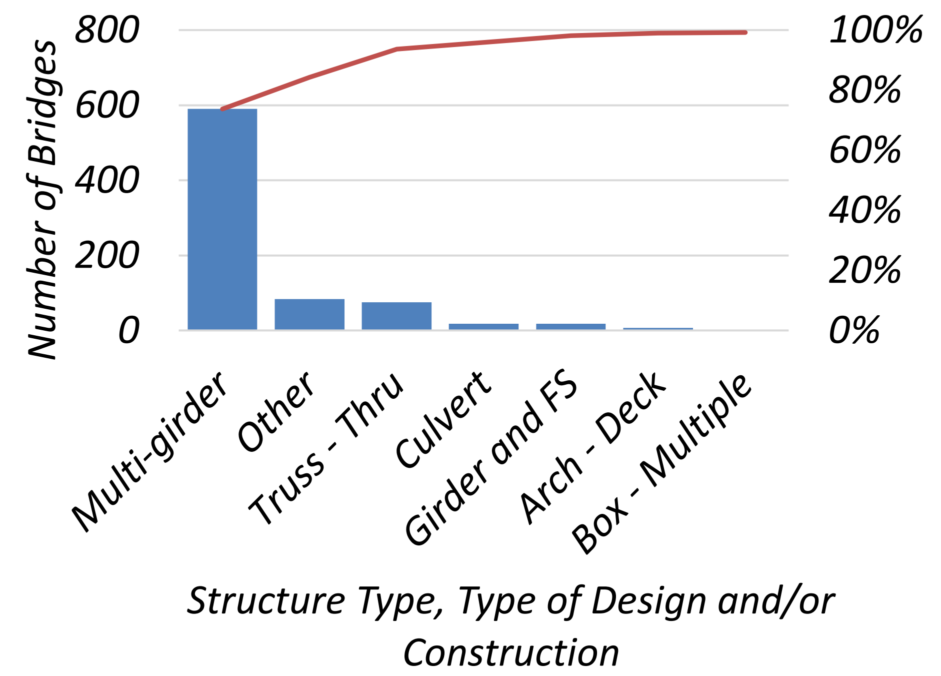


Kind of Material/Design	No. of Bridges	Percentage
Steel	800	38%
Concrete	451	21%
Wood	334	16%
Steel cont.	286	14%
Prestressed	116	5%

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

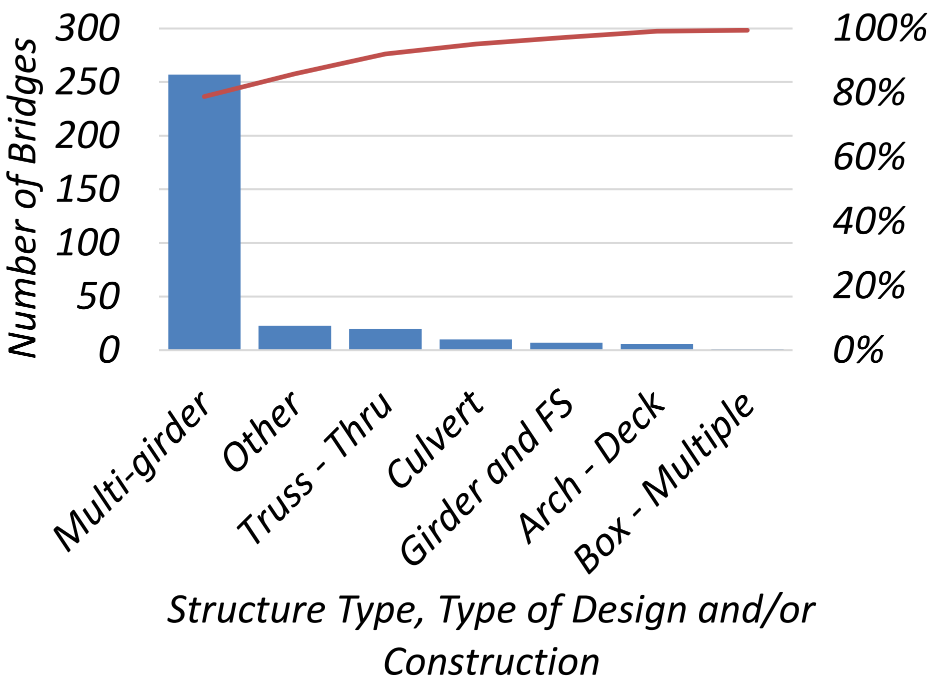
Distribution of Steel Bridges

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%

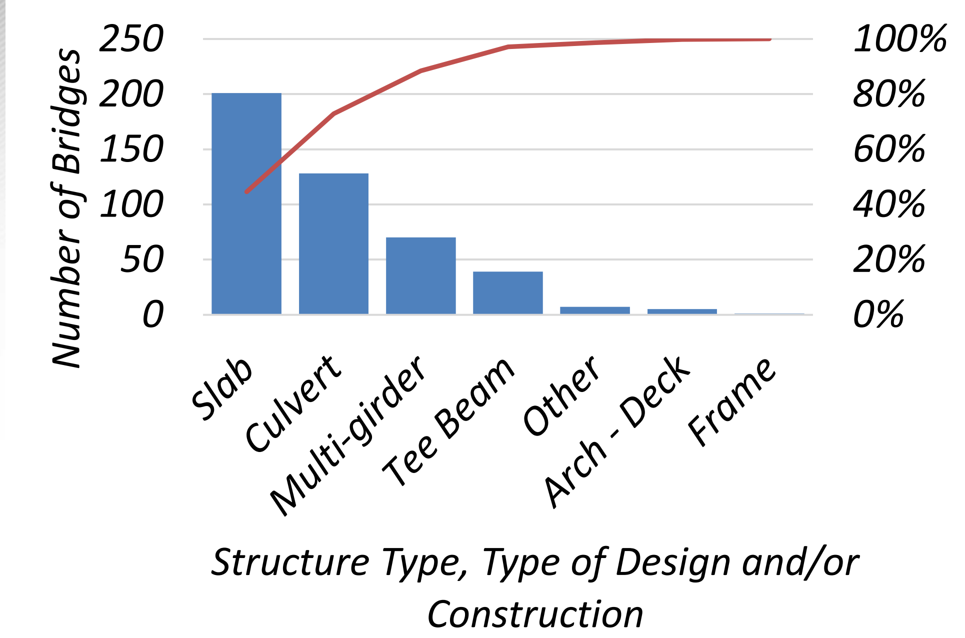
SSLO Bridges



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

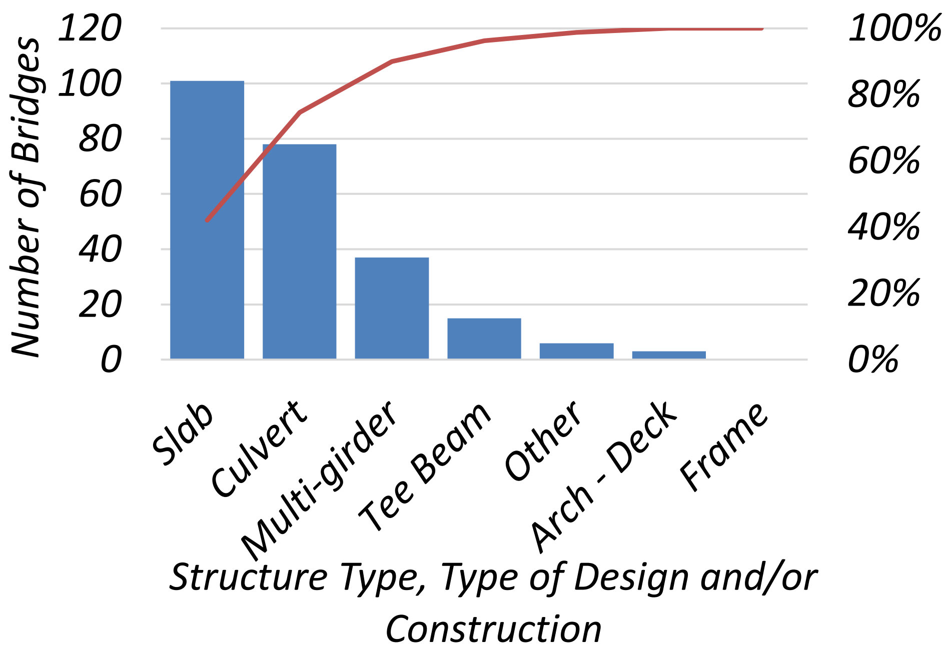
Distribution of Concrete Bridges

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%

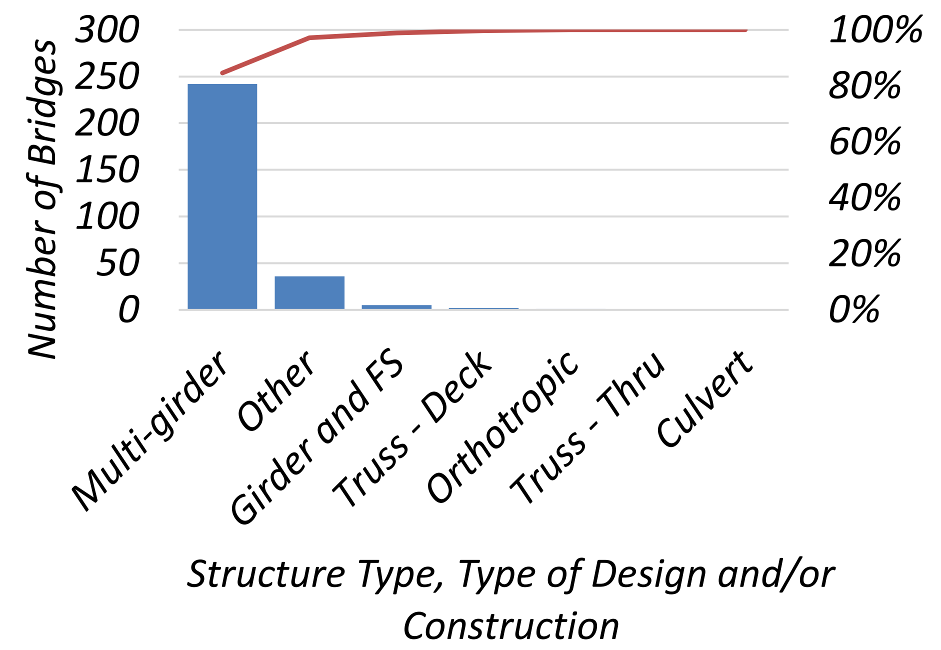
SSLO Bridges



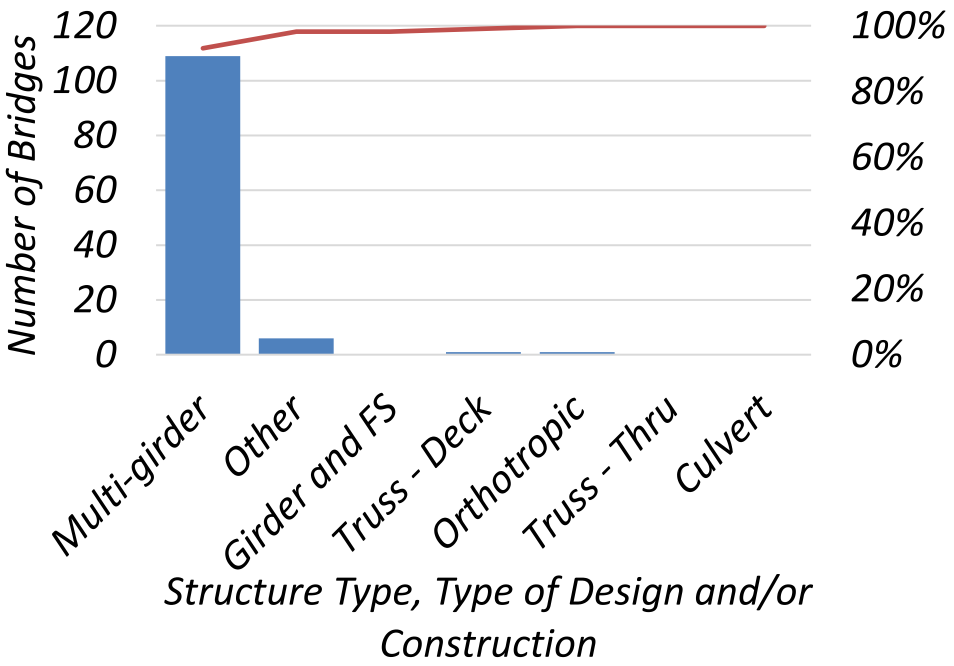
Type of Design/Construction	No. of Bridges	Percentage
Slab	101	42%
Culvert	78	33%
Multi-girder	37	15%
Tee Beam	15	6%

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

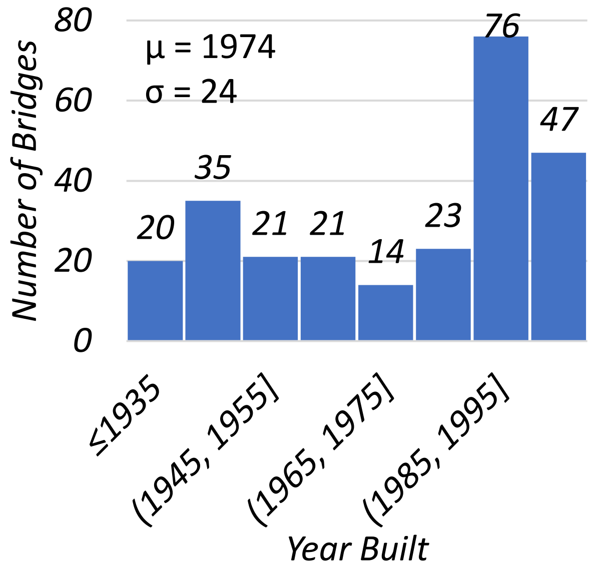
Material/Design	Bridge Type	No. of Bridges		
		On System	Off System	Total
Steel	Stringer/Multi-beam or Girder	14	243	257
Concrete	Slab	42	59	101
Concrete	Stringer/Multi-beam or Girder	2	35	37
Steel Continuous	Stringer/Multi-beam or Girder	6	103	109
Prestressed	Other	0	68	68
Concrete Continuous	Slab	4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

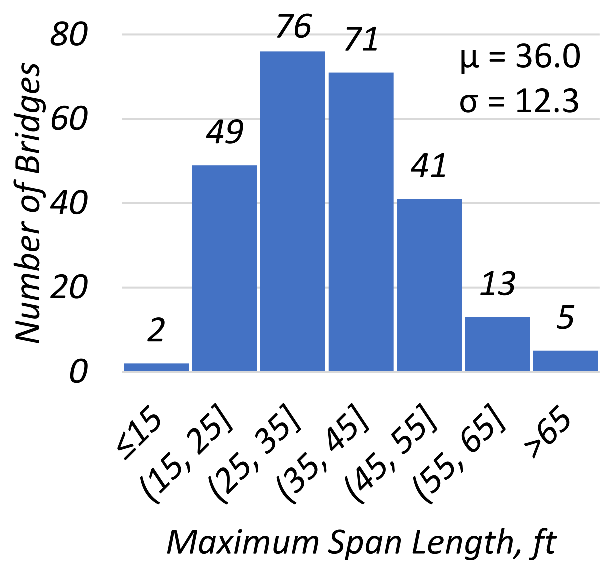
Of the 969 SSLO bridges:

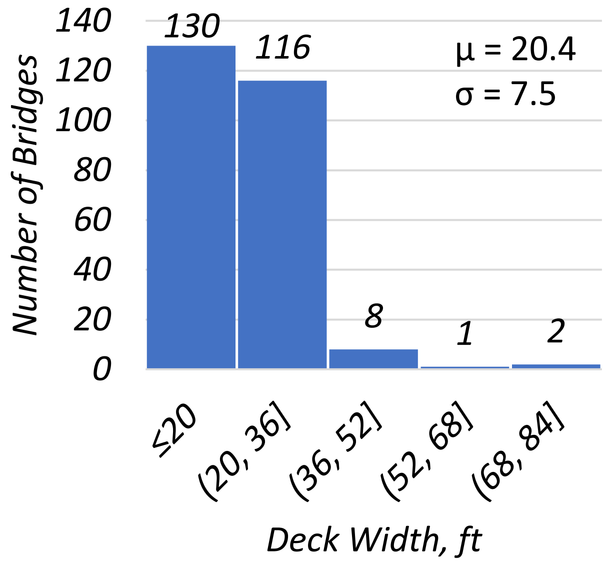
- 27% are steel multi-girder
- 11% are steel continuous multi-girder
- 10% are concrete slab
- 4% are concrete multi-girder

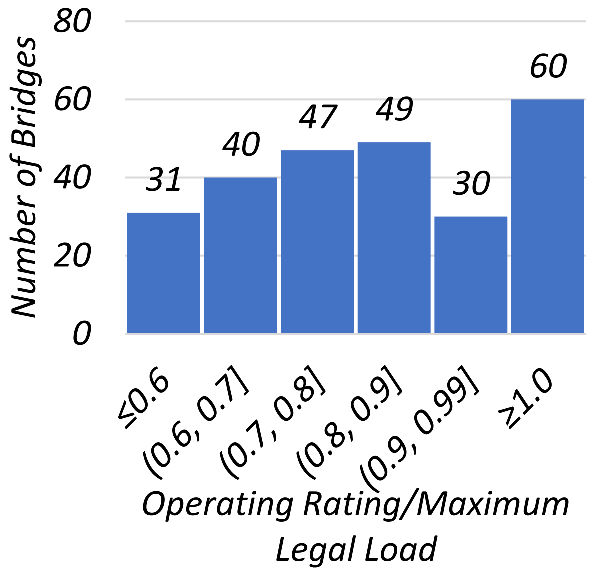
SSLO Steel Multi-Girder Bridges

All SSLO

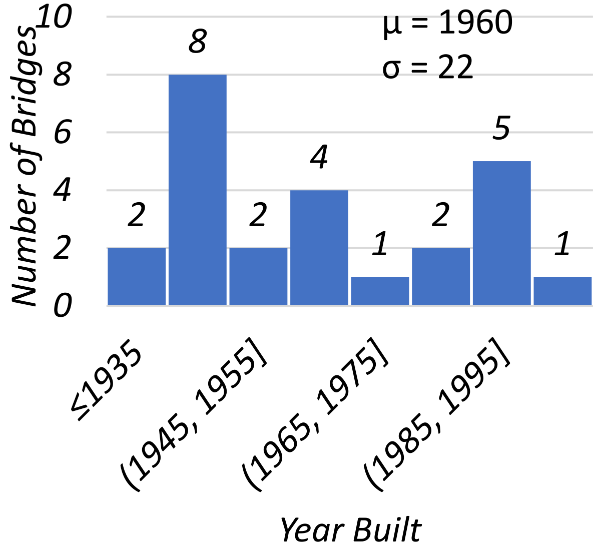


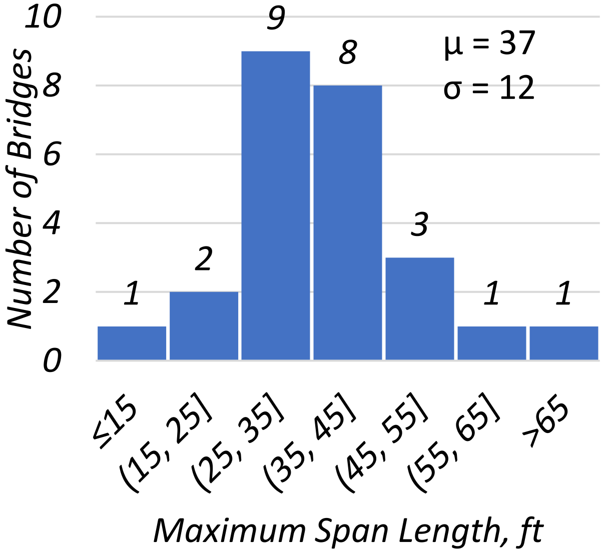


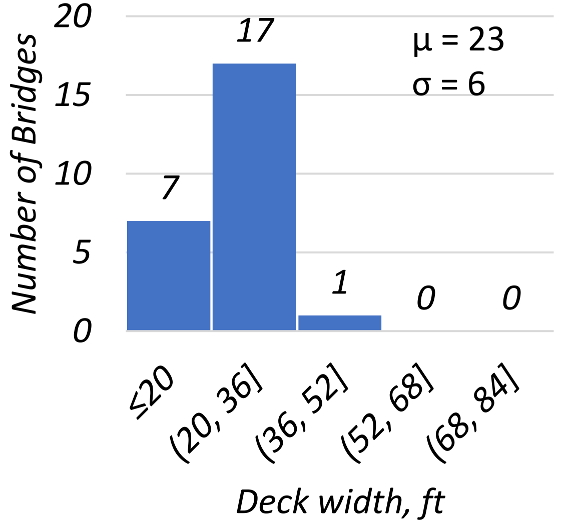


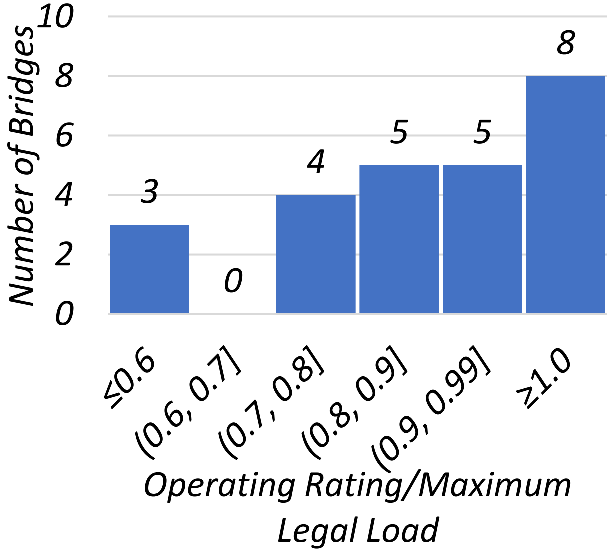


Selected

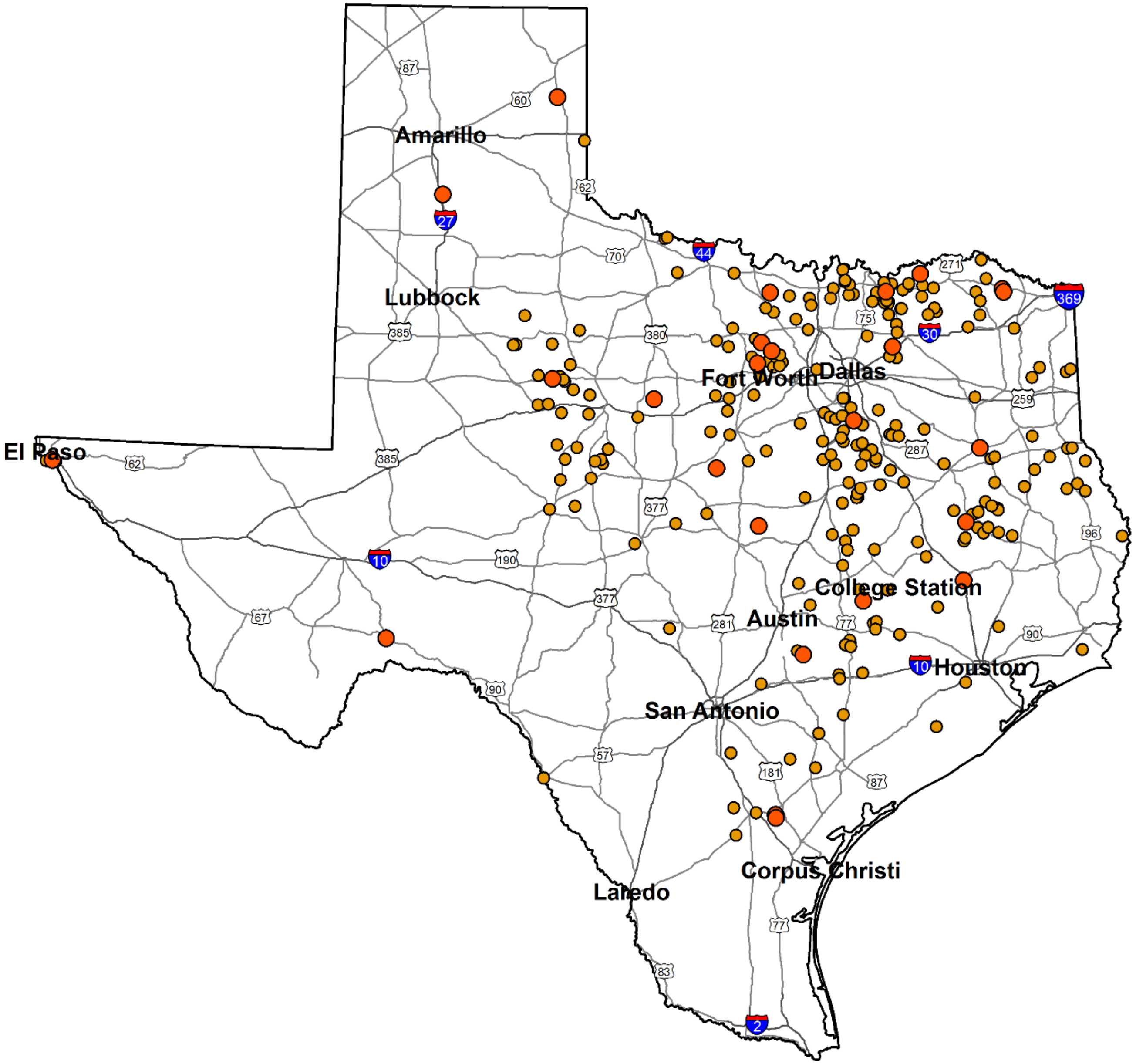








Location of Selected SSLO Steel Multi-Girder Bridges


Amarillo
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Houston
San Antonio
Corpus Christi
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369
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380
75
30
259
287
377
96
10
190
67
281
77
90
57
181
83
2

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

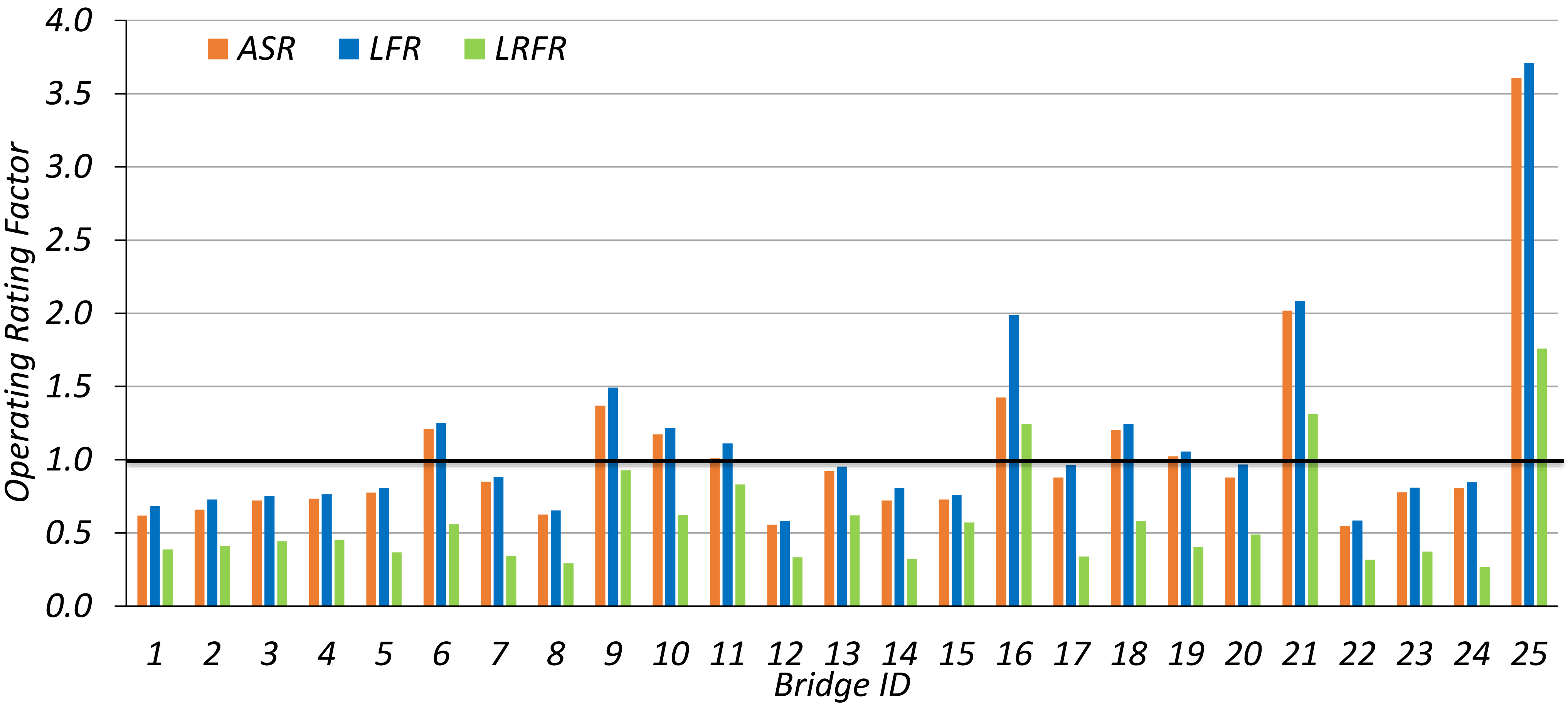
Basic Load Rating and Identification of Areas of Opportunity

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



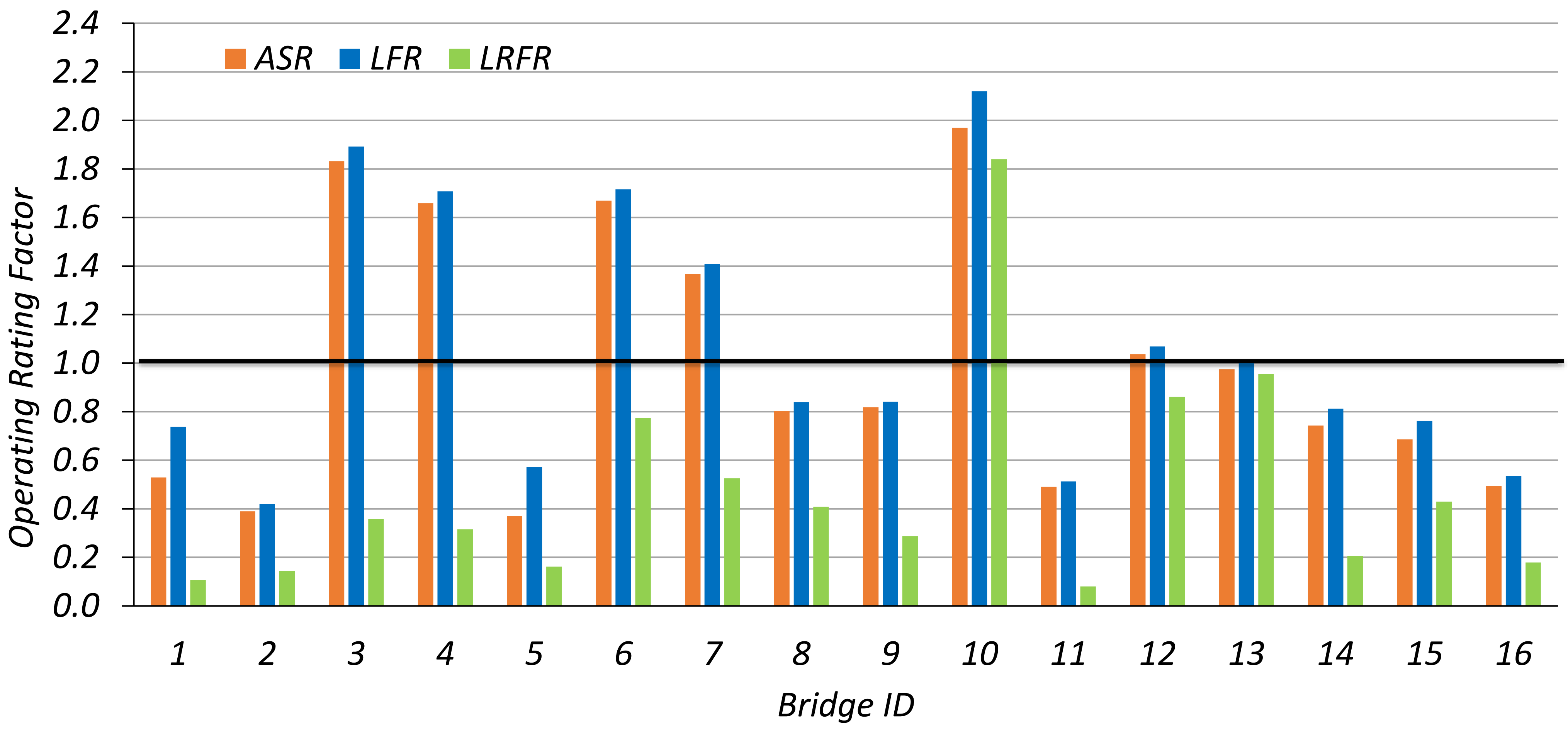
- LFR produced higher Operating RFs than ASR
- LRFR resulted in lowest RFs for all analyzed bridges

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



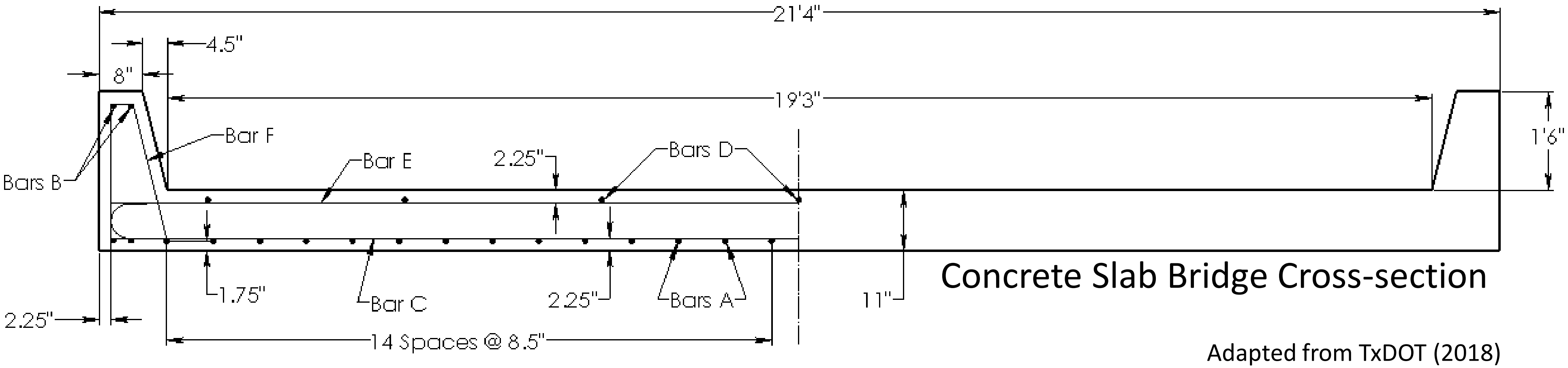
- LFR method consistently provided higher RFs than ASR
- LRFR method tends to give much lower RFs

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**

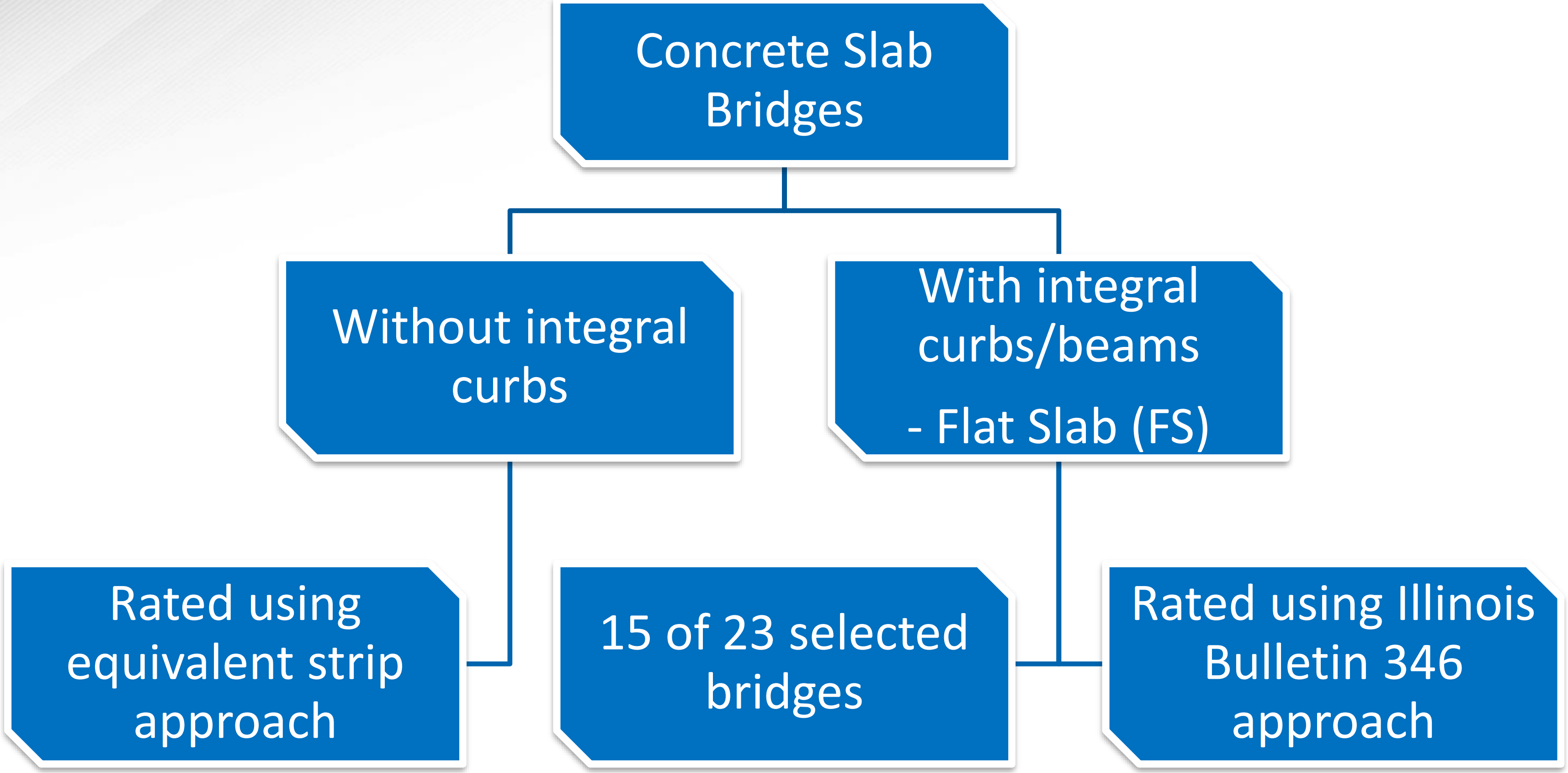
Bridge CS-9


21'4"
4.5"
8"
19'3"
1'6"
Bar F
Bar E
2.25"
Bars D
Bars B
1.75"
Bar C
2.25"
Bars A
11"
2.25"
14 Spaces @ 8.5"

Concrete Slab Bridge Cross-section

Adapted from TxDOT (2018)

Concrete Slab Bridge Types



Concrete Slab Bridges

Without integral curbs

With integral curbs/beams

- Flat Slab (FS)

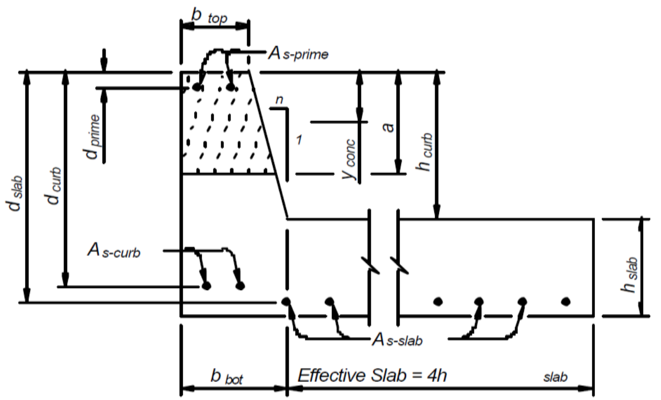
Rated using equivalent strip approach

15 of 23 selected bridges

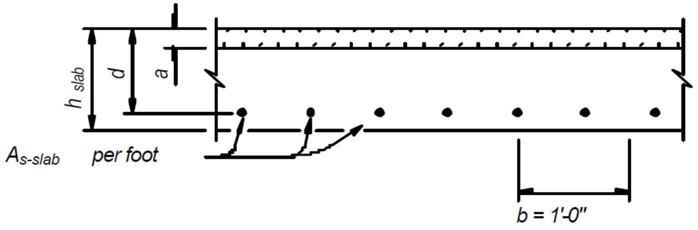
Rated using Illinois Bulletin 346 approach

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
  - $E = 6.89 + 0.23L \leq \frac{W}{N_L}$
  - $C_{edge} = 1.0 + 0.5\left(\frac{d_1}{3.28} - 0.15\right) \geq 1.0$


b_{top}
$A_{s\text{-}prime}$
n
1
d_{prime}
y_{conc}
a
h_{curb}
d_{slab}
d_{curb}
$A_{s\text{-}curb}$
$A_{s\text{-}slab}$
h_{slab}
b_{bot}
Effective Slab = 4h slab

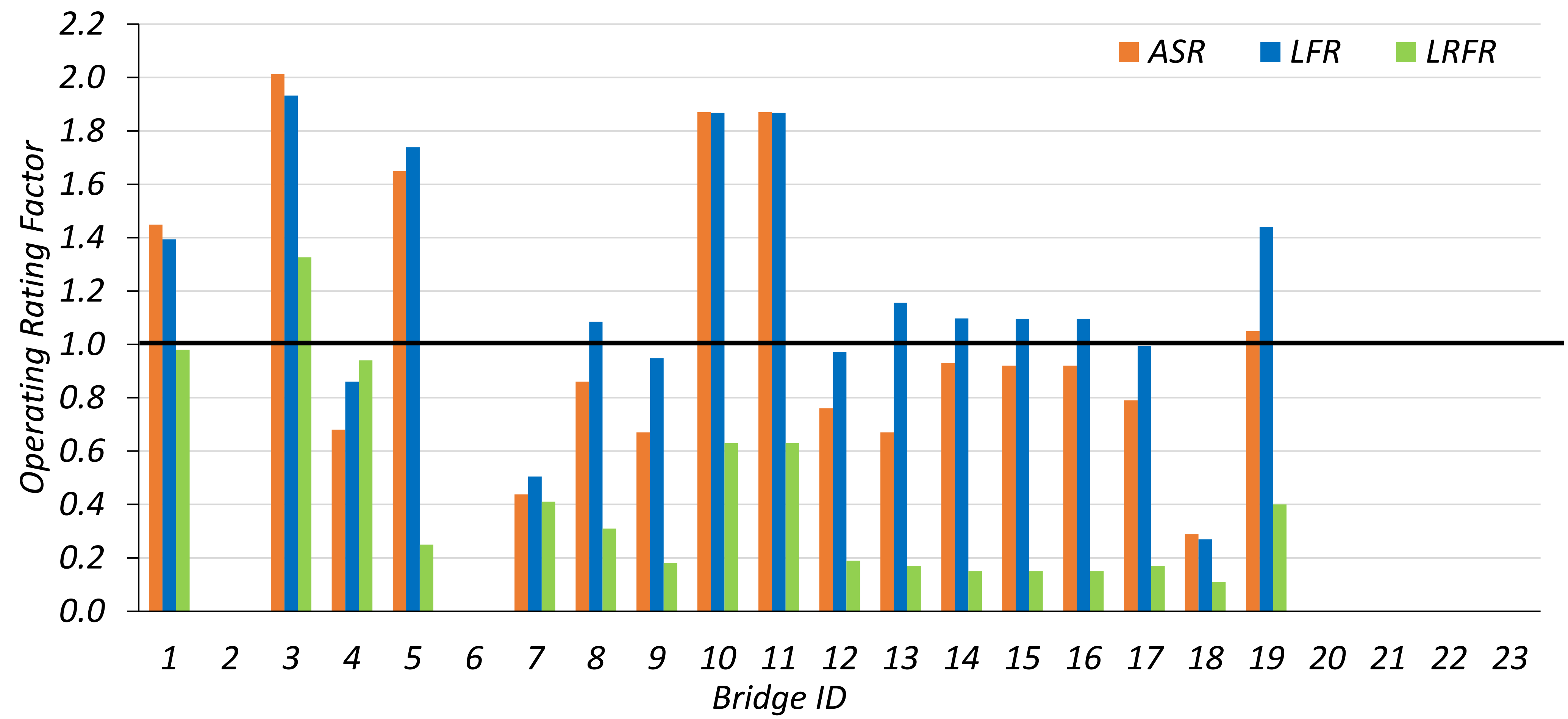
L-curb component


h_{slab}
d
a
$A_{s\text{-}slab}$ per foot
b = 1'-0"

Interior slab

Adapted from TxDOT (2001)

CS Bridge Flexure Operating RFs

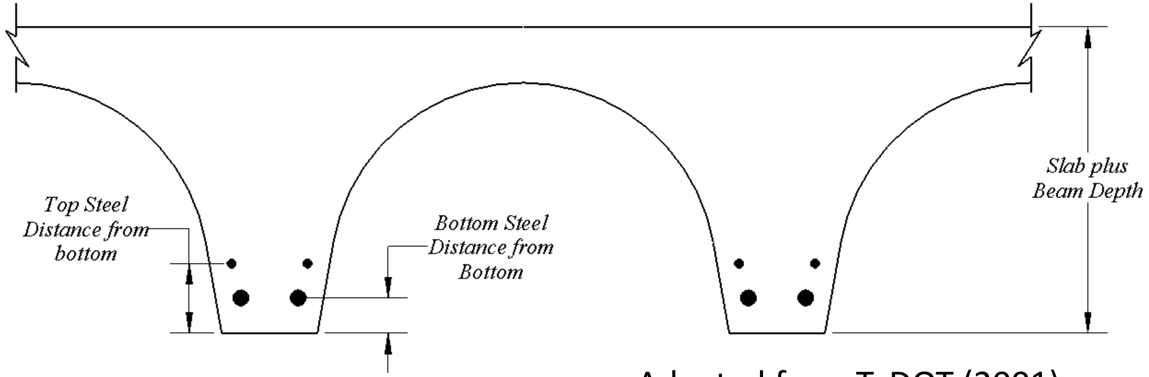


- LRFR provided low flexure RFs than ASR and LFR except for Bridge CS-4

Simple Span Concrete Multi-Girder Bridges

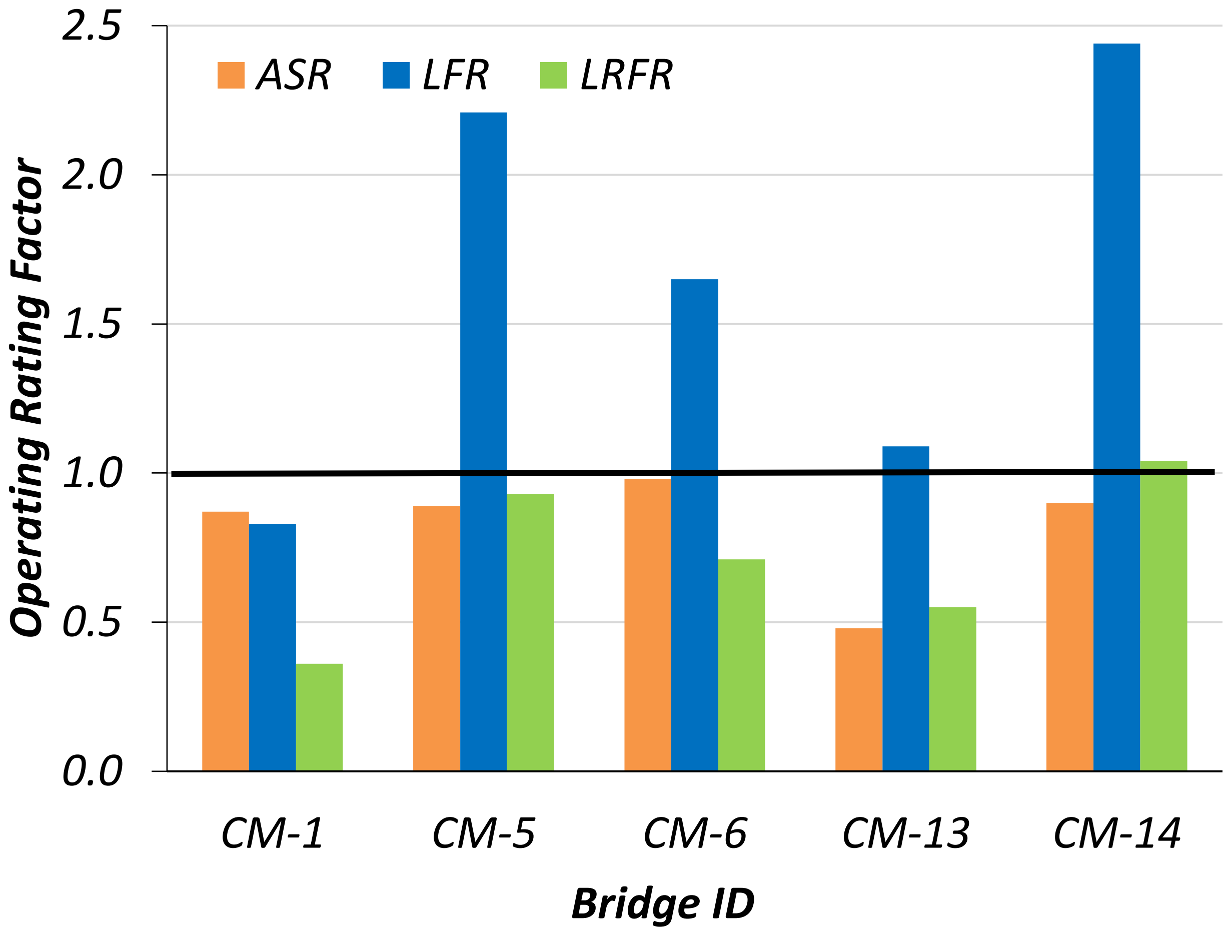
Subset for Basic Load Rating Analysis

- **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**


Top Steel
Distance from
bottom
Bottom Steel
Distance from
Bottom
Slab plus
Beam Depth

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

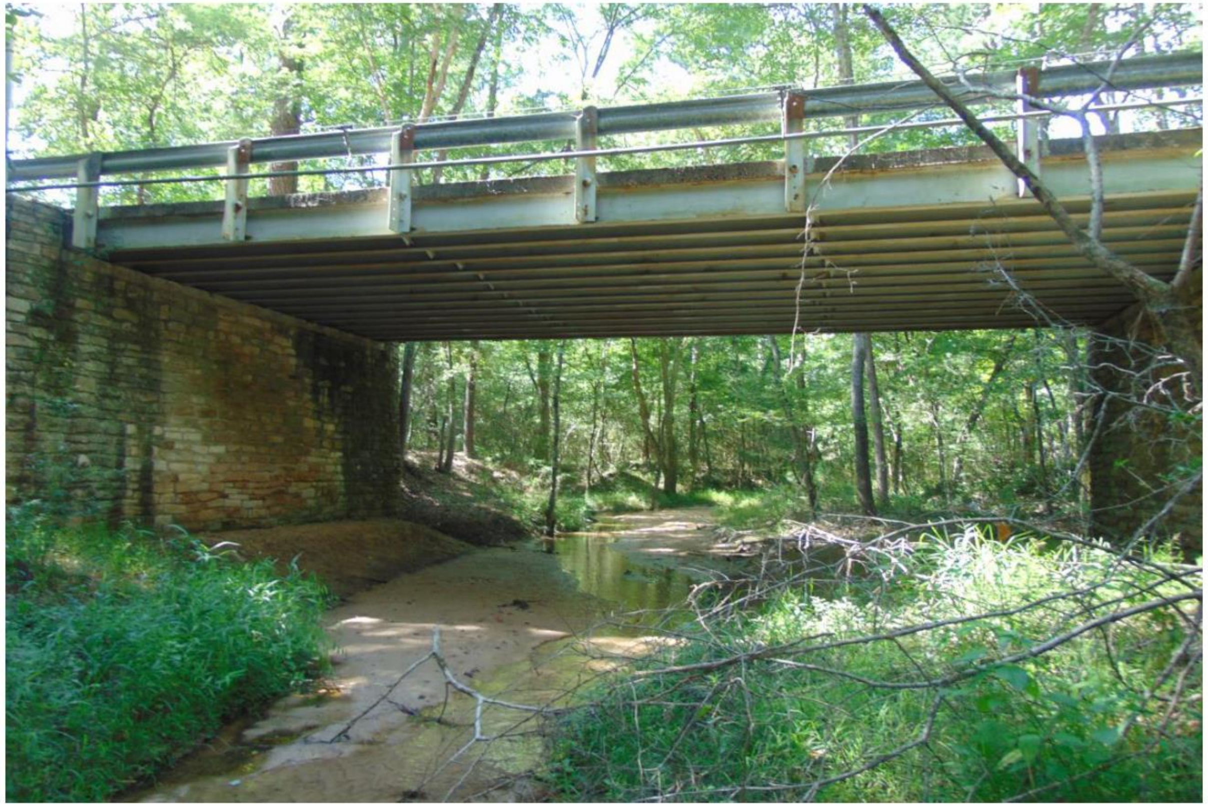
Refined Analysis of Selected Typical Bridges

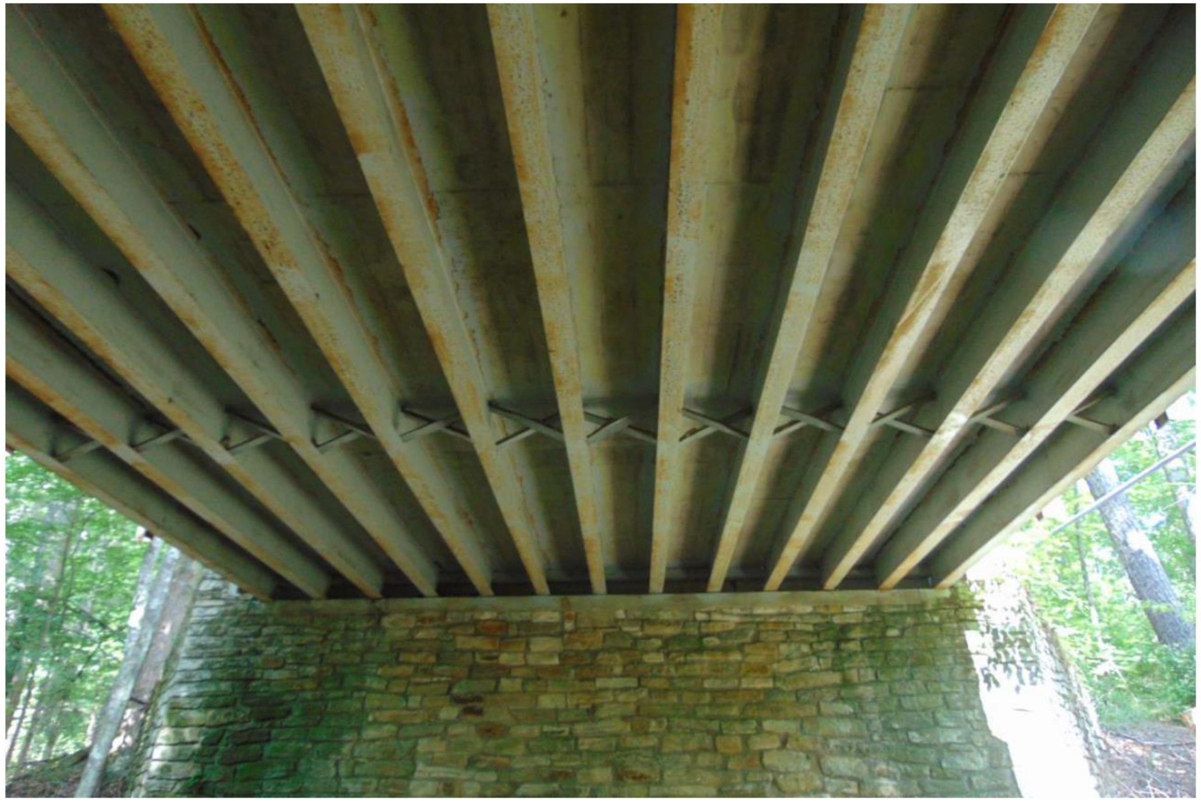
Steel Multi-Girder Bridge

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

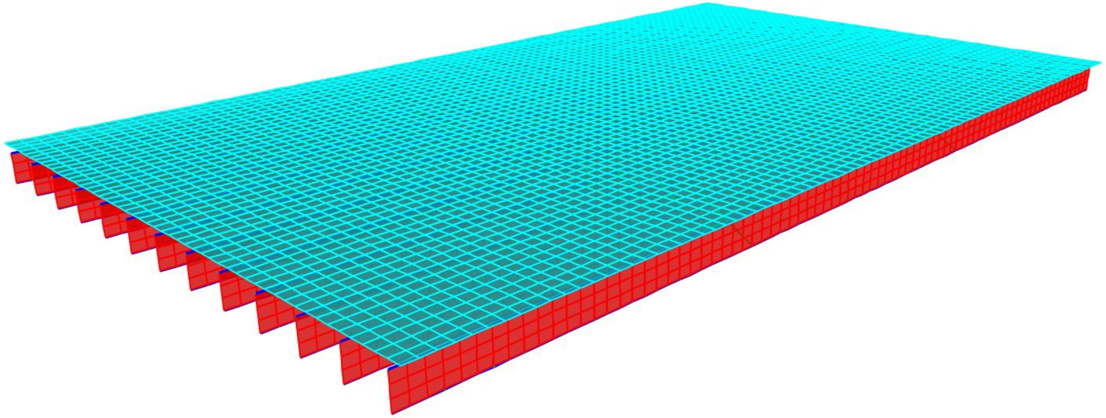


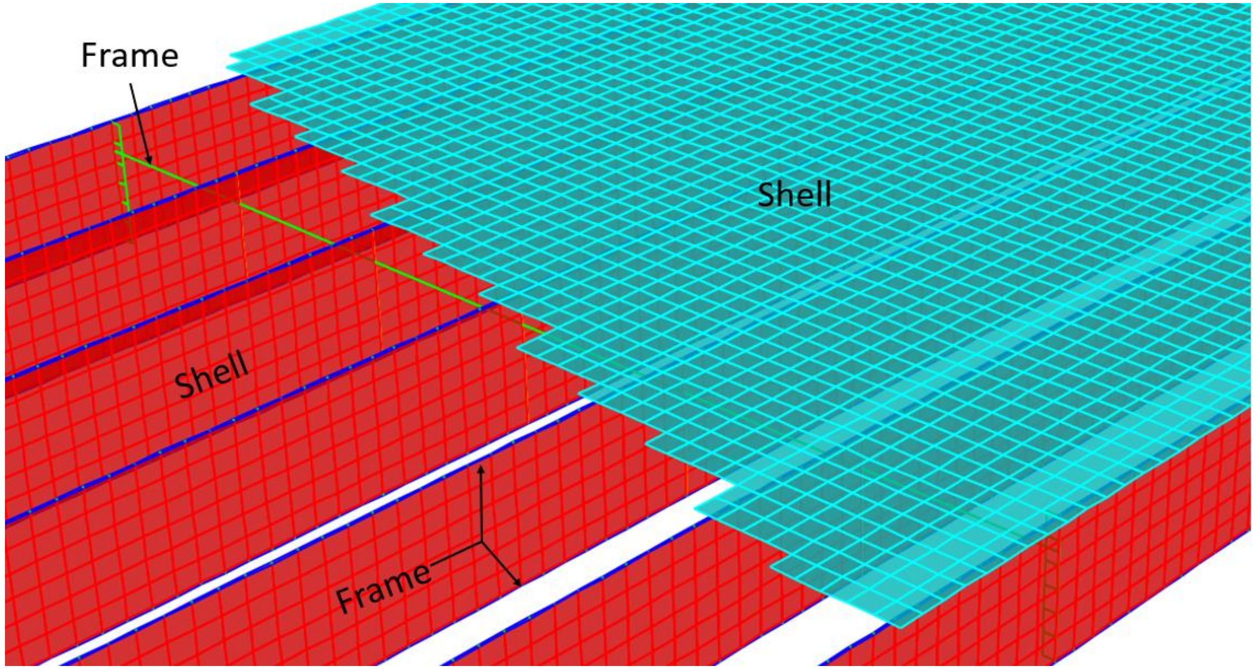


Model Development

Bridge SM-5

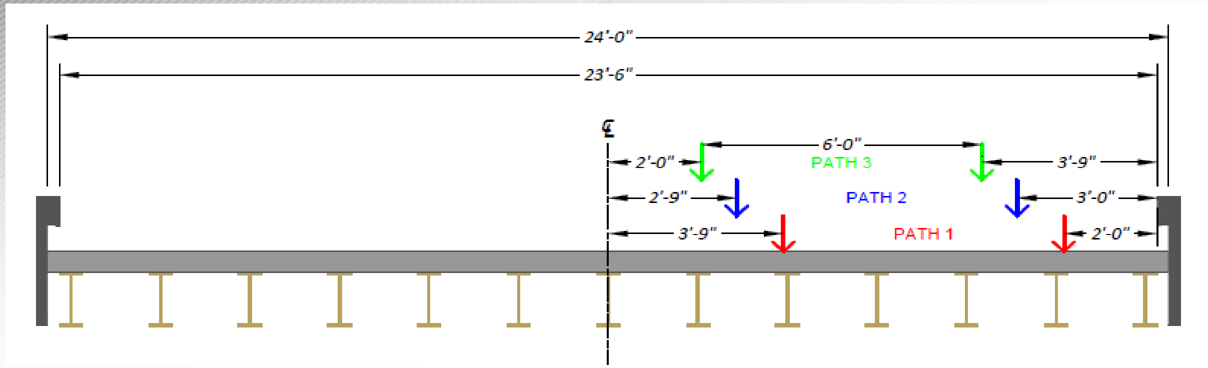
- SM-5 was modeled using the commercial software CSiBridge
- Mesh sensitivity analysis was conducted, and a maximum mesh size of 6 in. was used
- Model was verified by comparing midspan moments and end shears to expected values from structural analysis



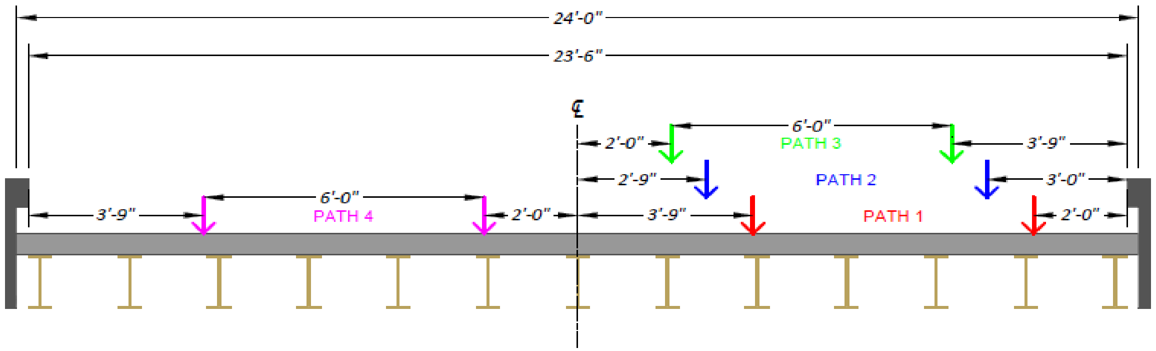


Load Paths

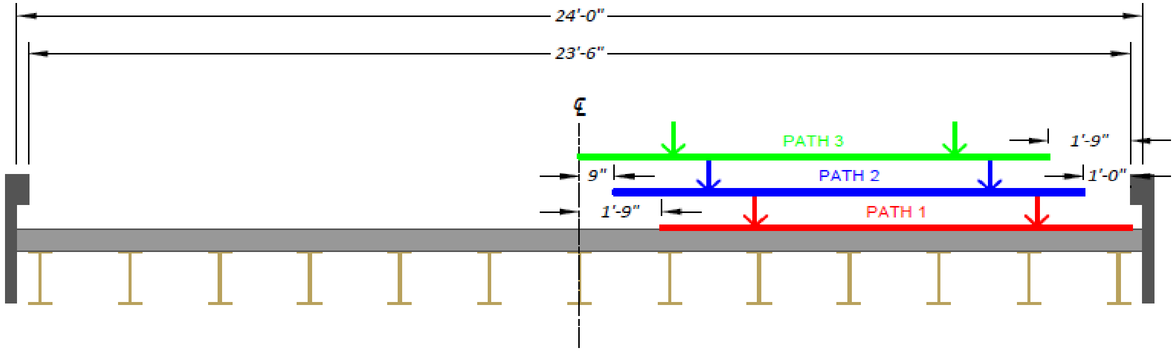
Bridge SM-5


24'-0"
23'-6"
℄
2'-0"
6'-0"
PATH 3
3'-9"
2'-9"
PATH 2
3'-0"
3'-9"
PATH 1
2'-0"

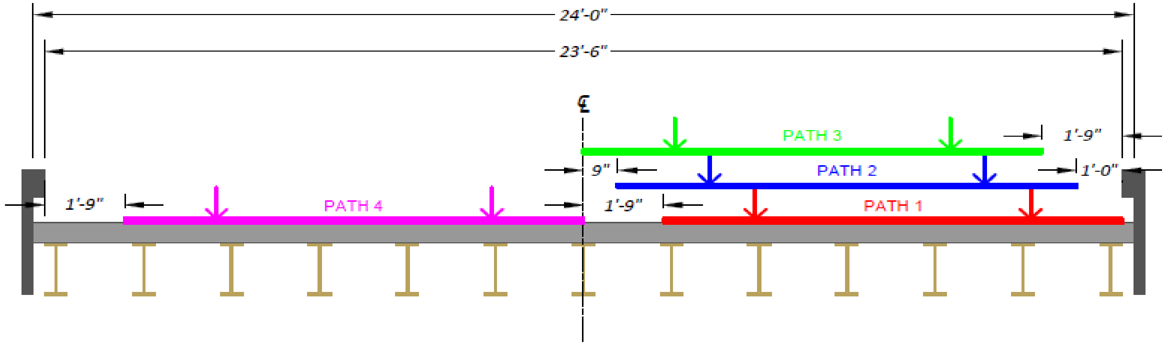
One-Lane HS20


24'-0"
23'-6"
℄
2'-0"
6'-0"
PATH 3
3'-9"
2'-9"
PATH 2
3'-0"
3'-9"
6'-0"
PATH 4
2'-0"
3'-9"
PATH 1
2'-0"

Two-Lane HS20


24'-0"
23'-6"
℄
PATH 3
1'-9"
9"
PATH 2
1'-0"
1'-9"
PATH 1

One-Lane HL93


24'-0"
23'-6"
℄
PATH 3
1'-9"
9"
PATH 2
1'-0"
1'-9"
PATH 4
1'-9"
PATH 1

Two-Lane HL93

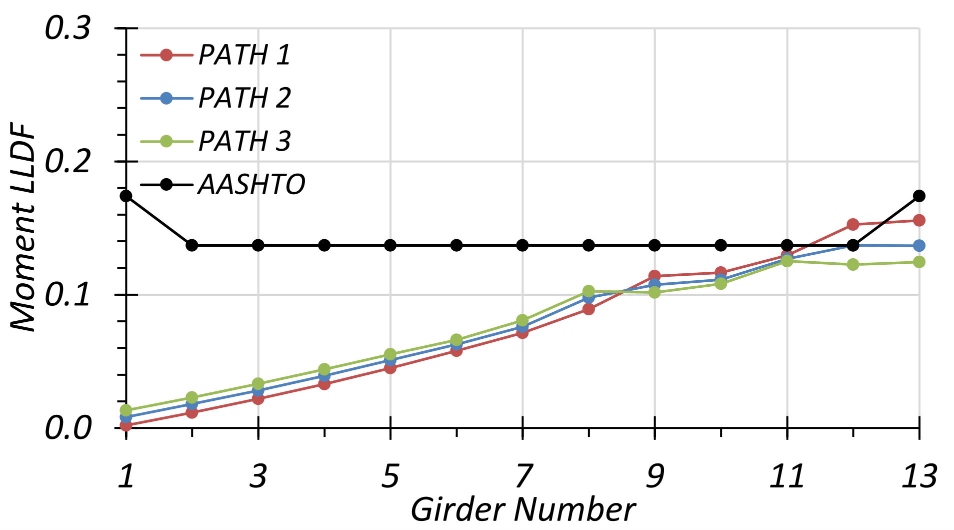
$$LLDF = \frac{M_i}{\sum M_i}$$

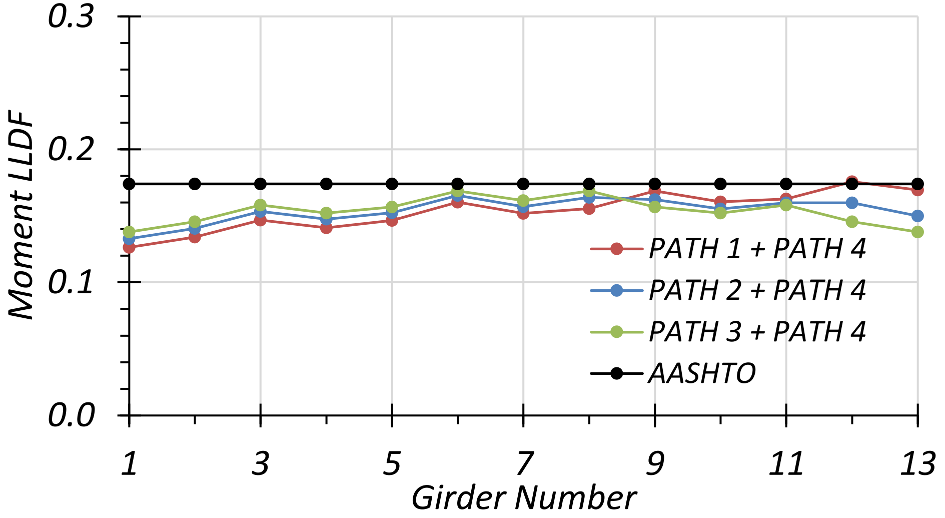
HS20 Moment LLDFs

Bridge SM-5

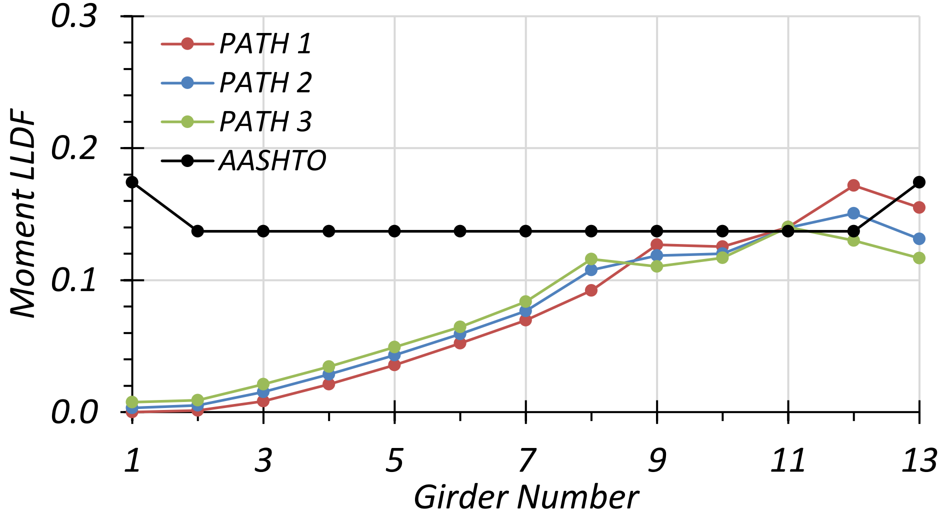
One-Lane **Two-Lane**

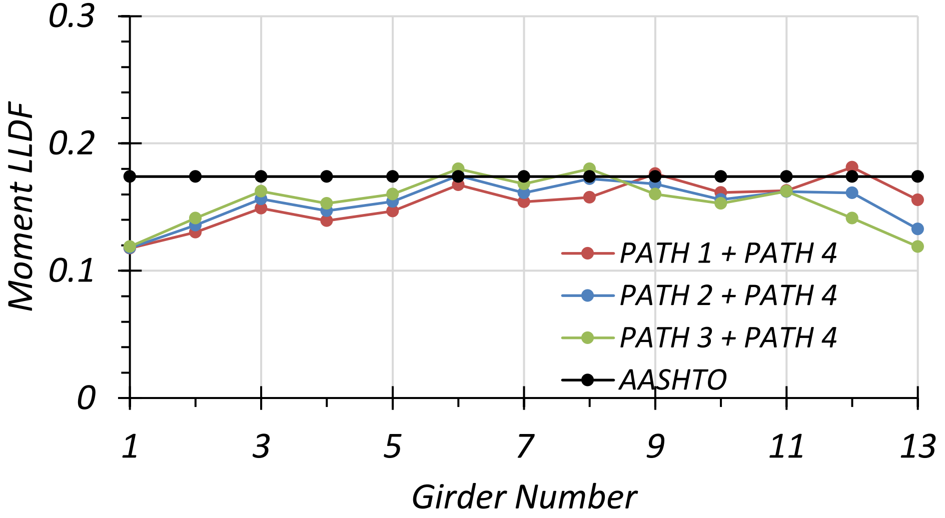
Non-Composite





Composite





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

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

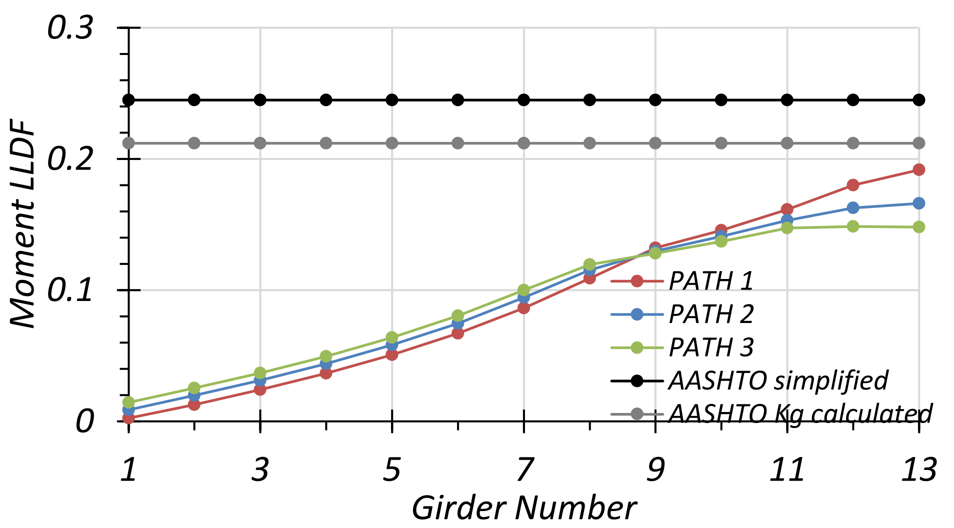
HL93 Moment LLDFs

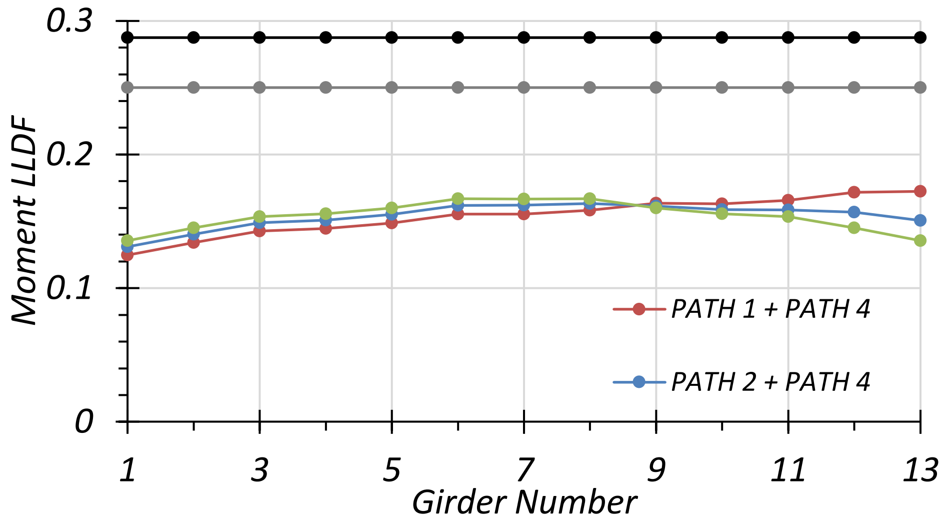
Bridge SM-5

One-Lane

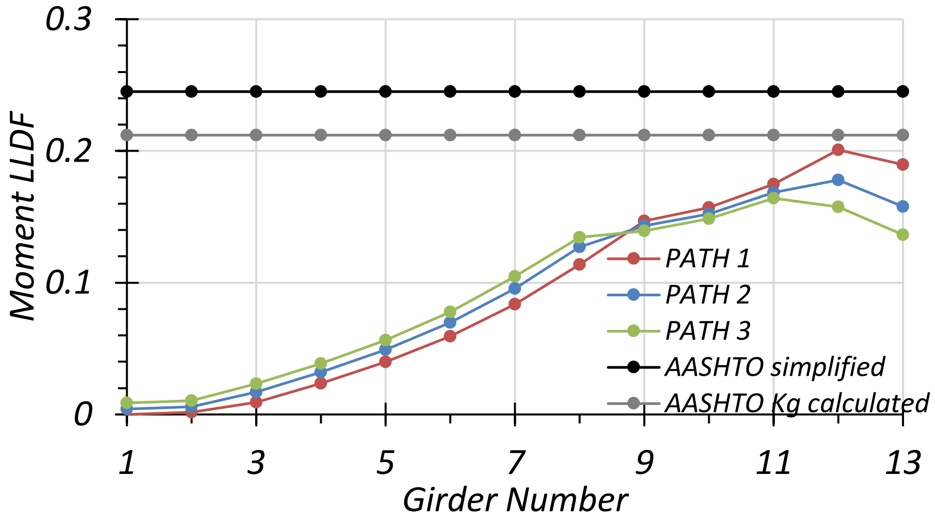
Two-Lane

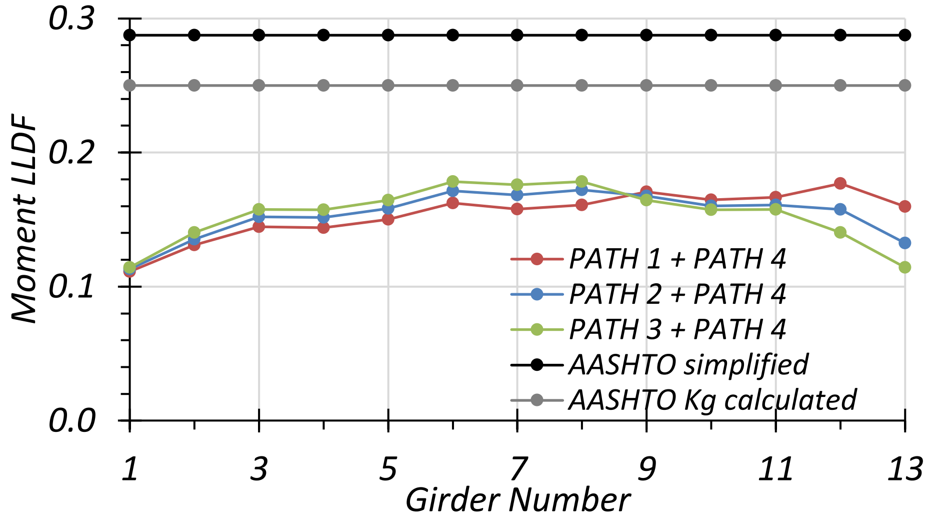
Non-Composite





Composite





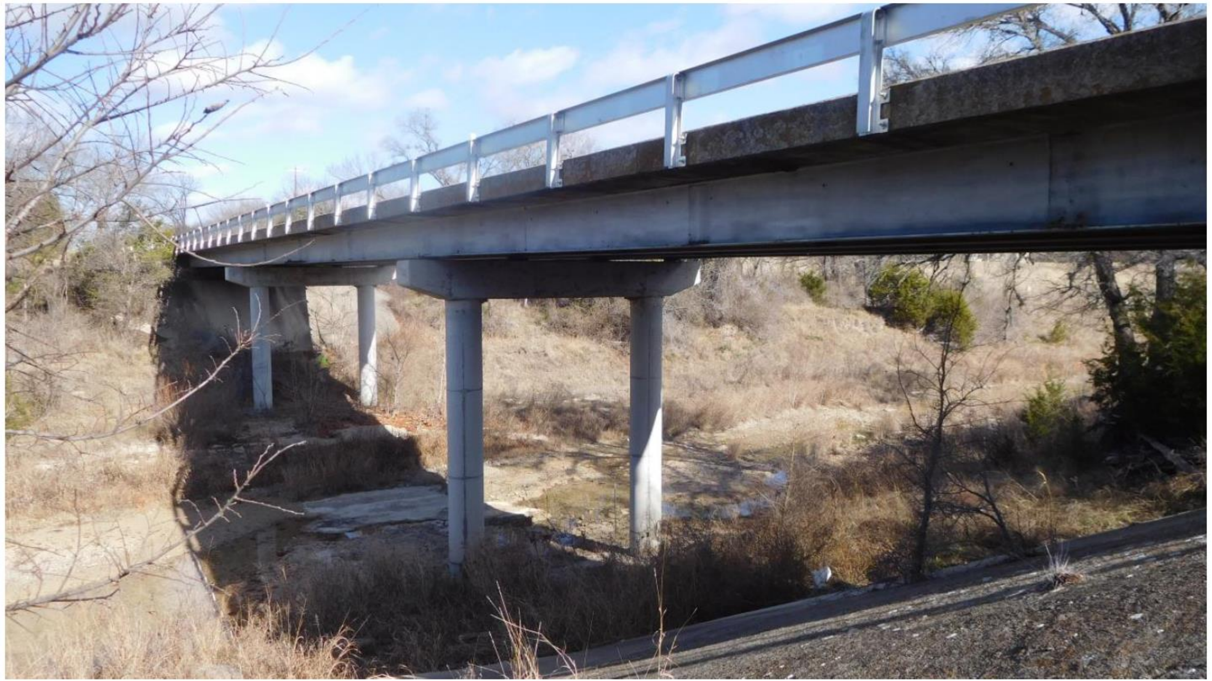
AASHTO LRFD Specifications give conservative LLDFs, especially for two-lane loading

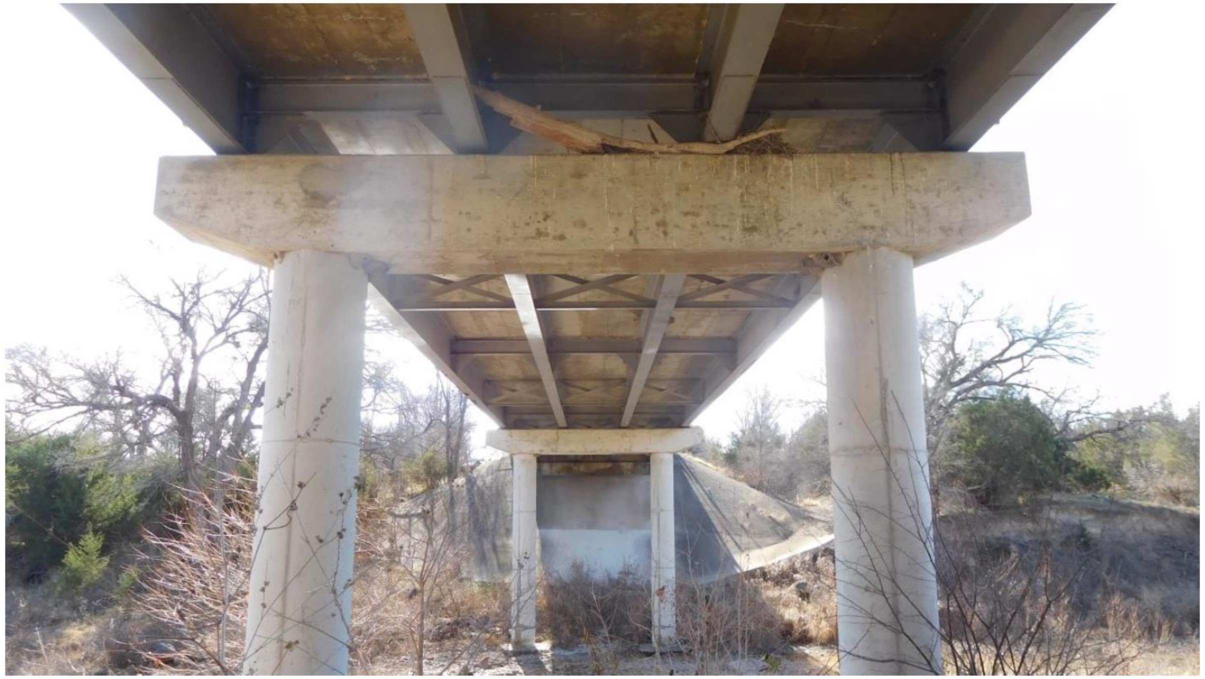
Steel Continuous Multi-Girder Bridge

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

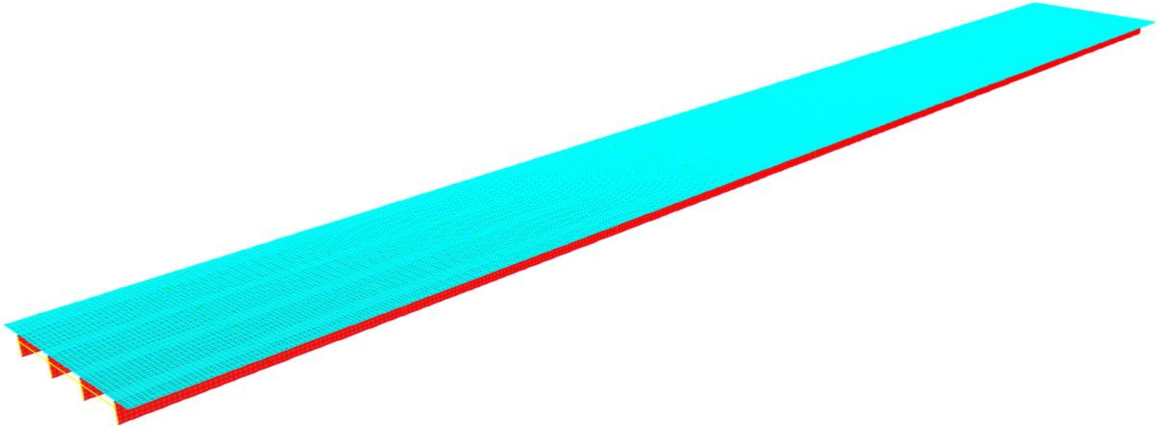


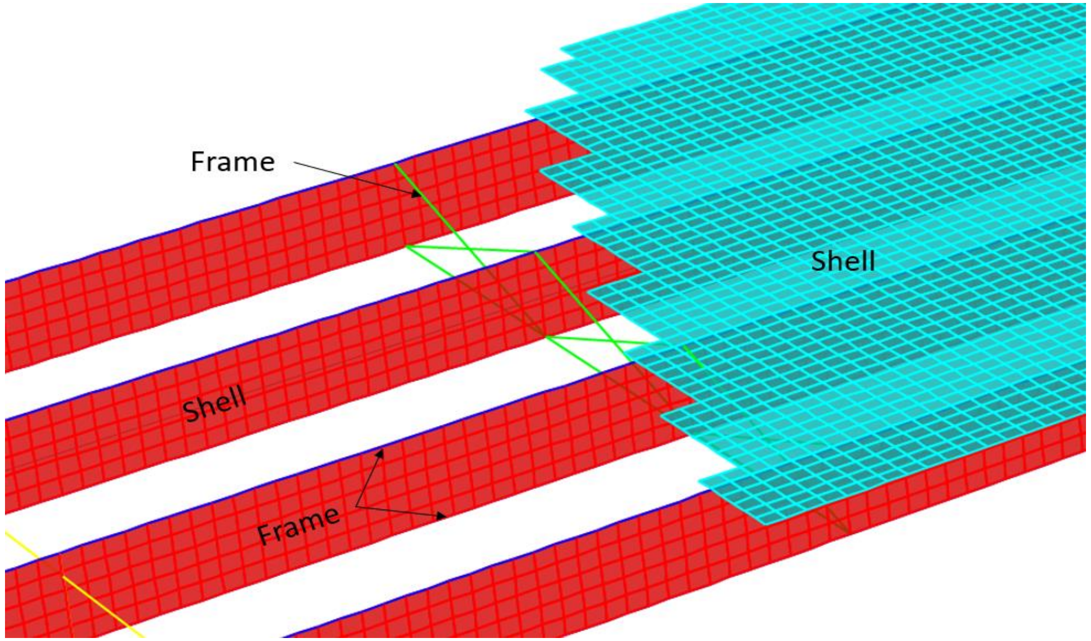


Model Development

Bridge SC-12

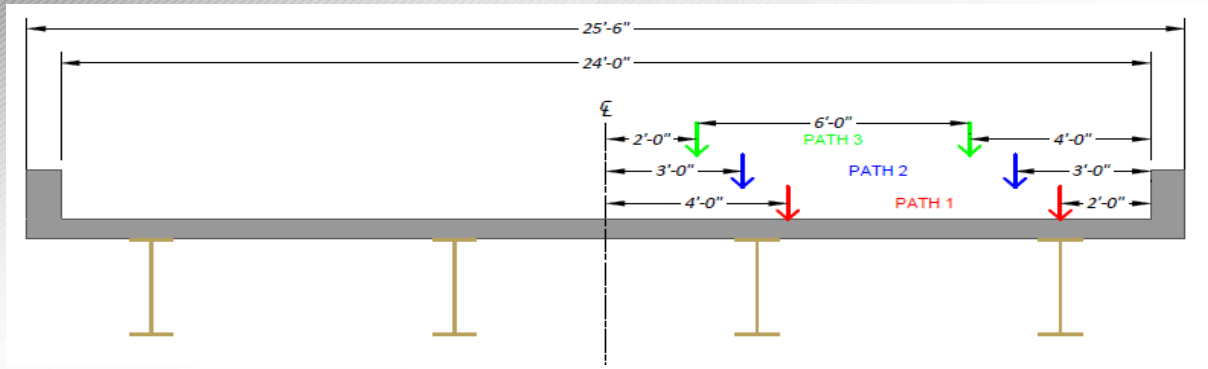
- SC-12 was modeled using the commercial software CSiBridge
- A maximum mesh size of 6 in. was used based on the mesh sensitivity analysis performed for Bridge SM-5
- Models were verified by comparing midspan moments and end shears to expected values from structural analysis



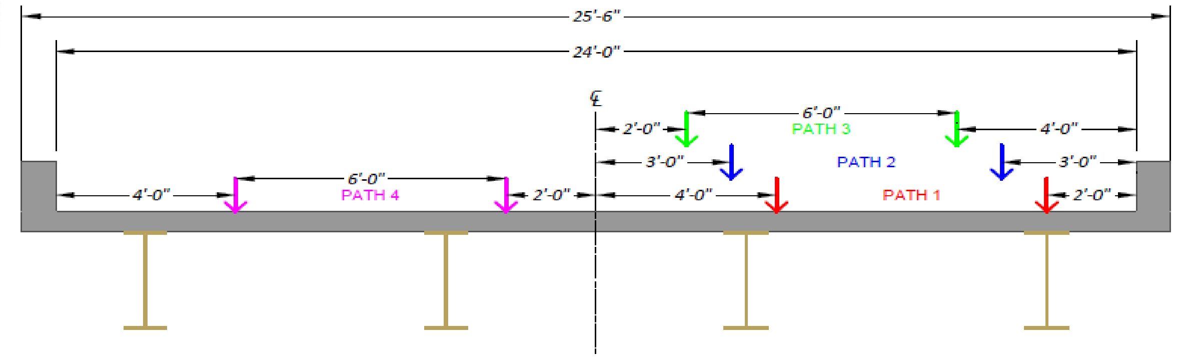


Load Paths

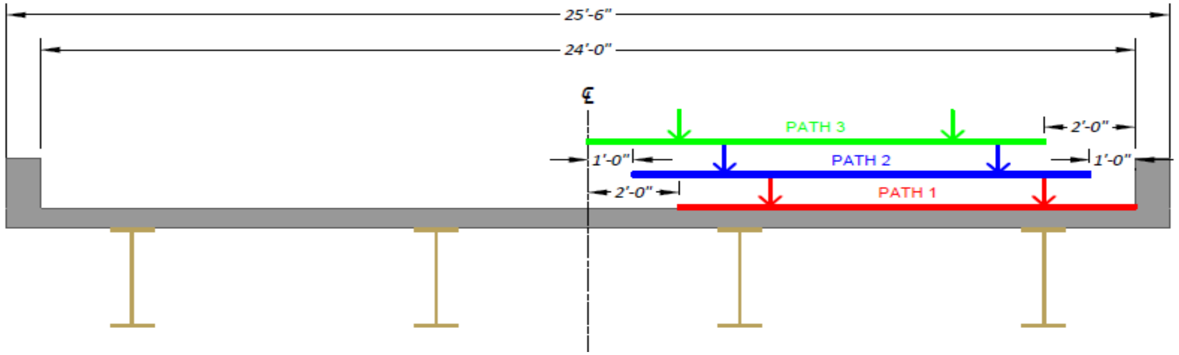
Bridge SC-12


25'-6"
24'-0"
℄
6'-0"
2'-0"
PATH 3
4'-0"
3'-0"
PATH 2
3'-0"
4'-0"
PATH 1
2'-0"

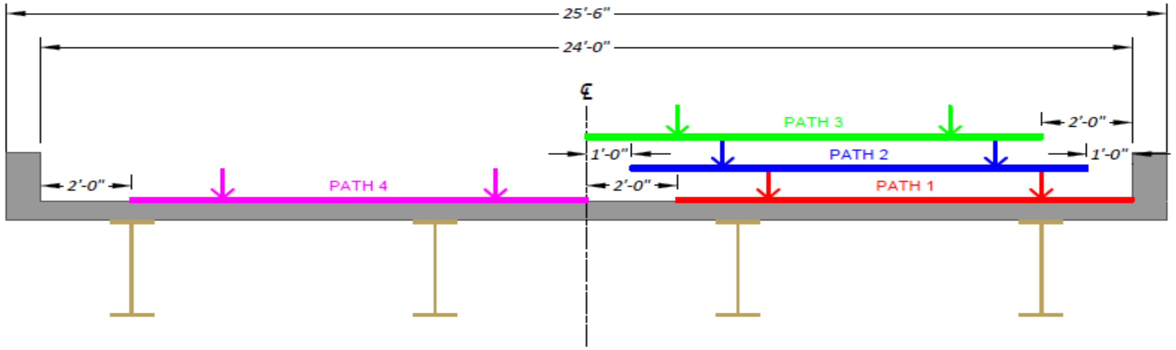
One-Lane HS20


25'-6"
24'-0"
℄
6'-0"
2'-0"
PATH 3
4'-0"
3'-0"
PATH 2
3'-0"
6'-0"
4'-0"
PATH 4
2'-0"
4'-0"
PATH 1
2'-0"

Two-Lane HS20


25'-6"
24'-0"
℄
PATH 3
2'-0"
1'-0"
PATH 2
1'-0"
2'-0"
PATH 1

One-Lane HL93


25'-6"
24'-0"
℄
PATH 3
2'-0"
1'-0"
PATH 2
1'-0"
2'-0"
PATH 4
2'-0"
PATH 1

Two-Lane HL93

HS20 Positive Moment LLDFs

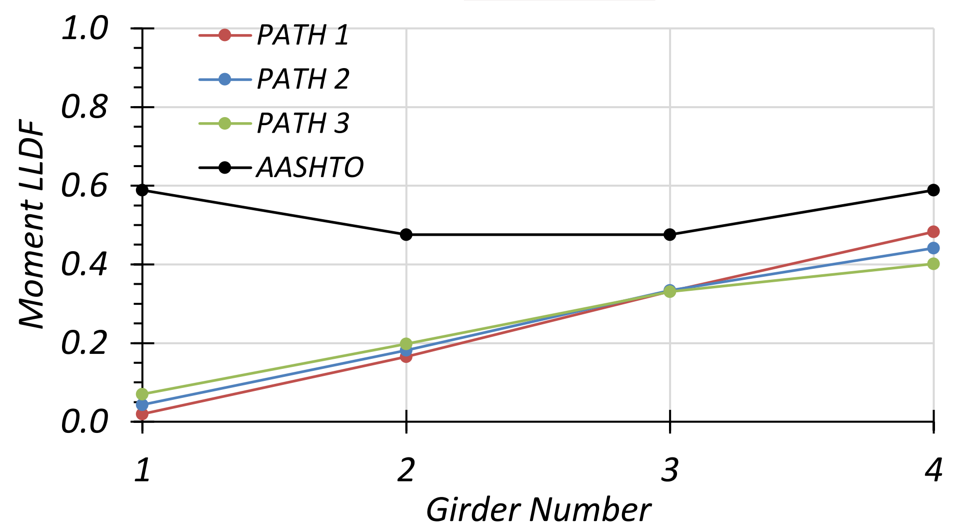
Bridge SC-12

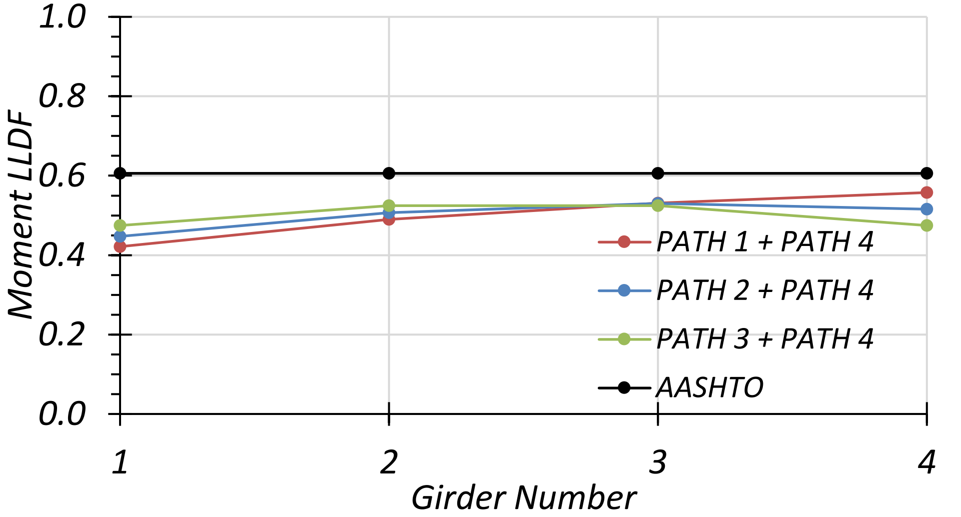
$$LLDF = \frac{M_i}{\sum M_i}$$

One-Lane

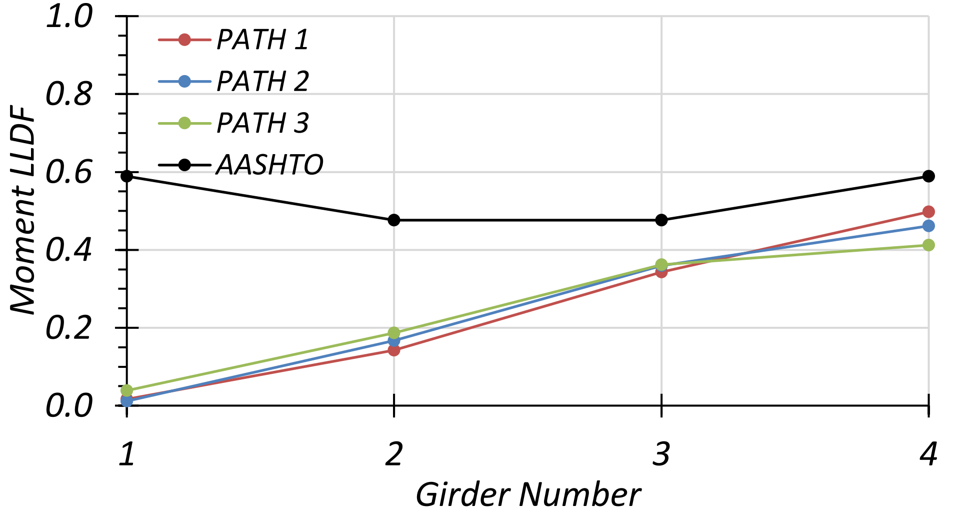
Two-Lane

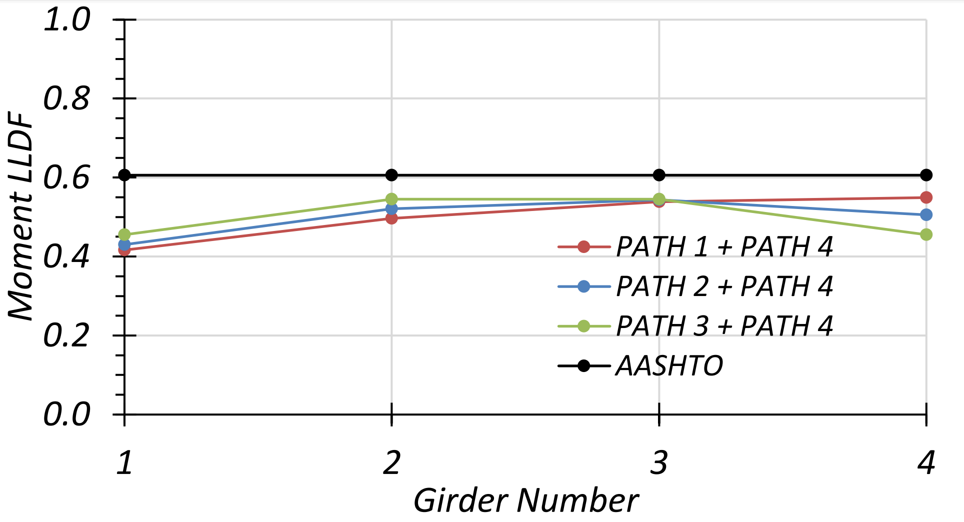
Non-Composite





Composite





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

HS20 Negative Moment LLDFs

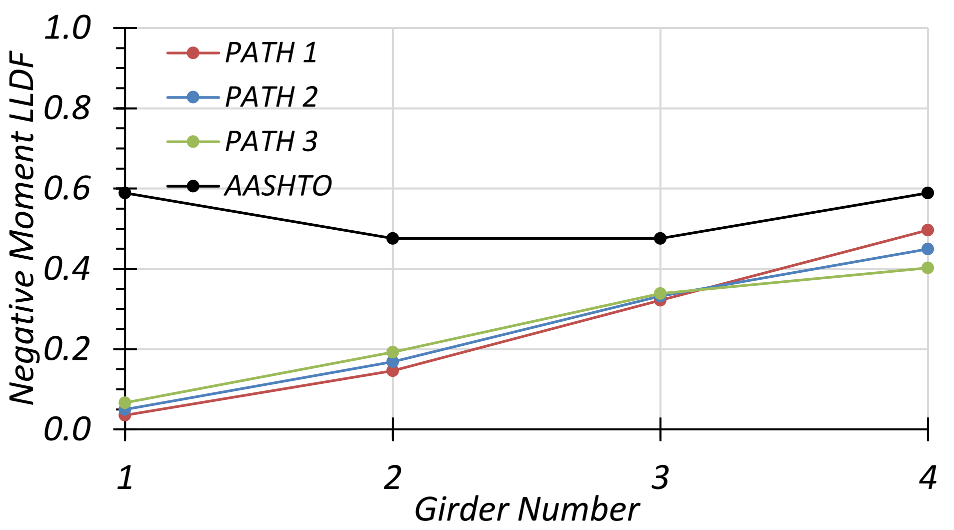
Bridge SC-12

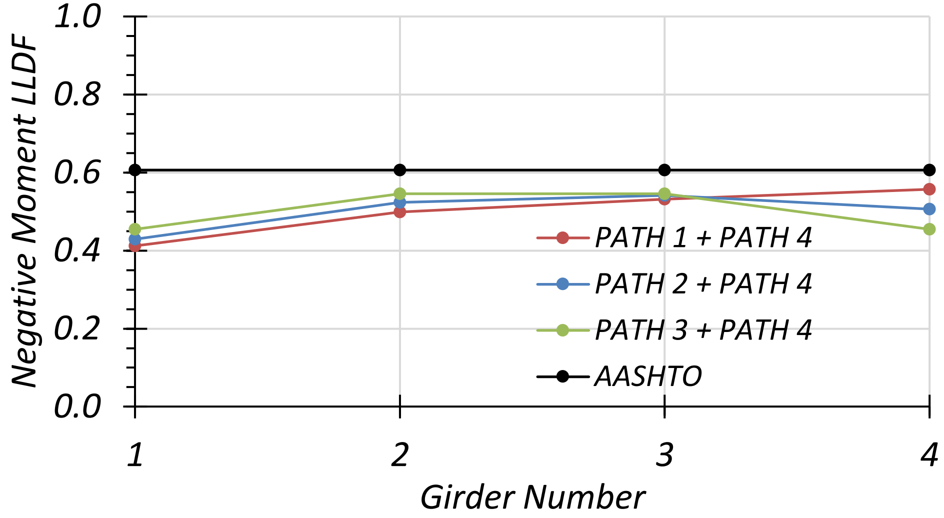
$$LLDF = \frac{M_i}{\sum M_i}$$

One-Lane

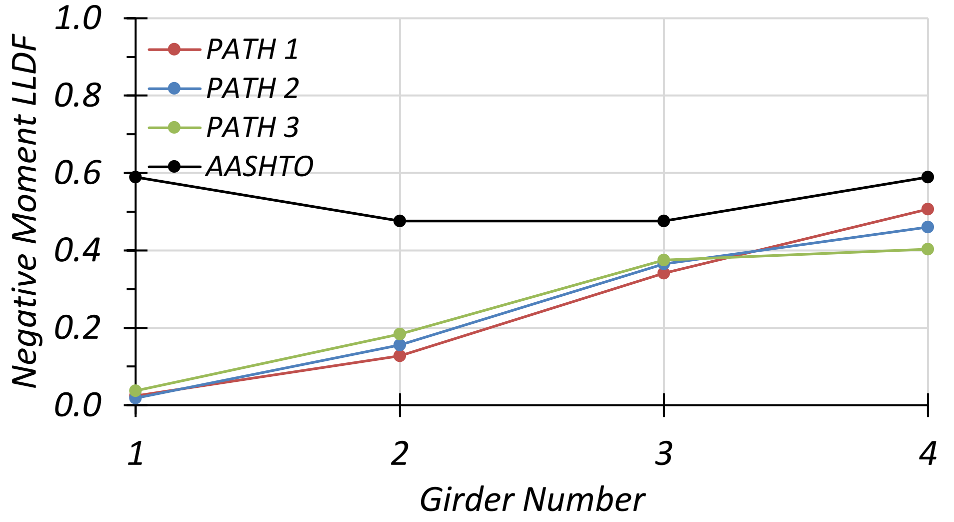
Two-Lane

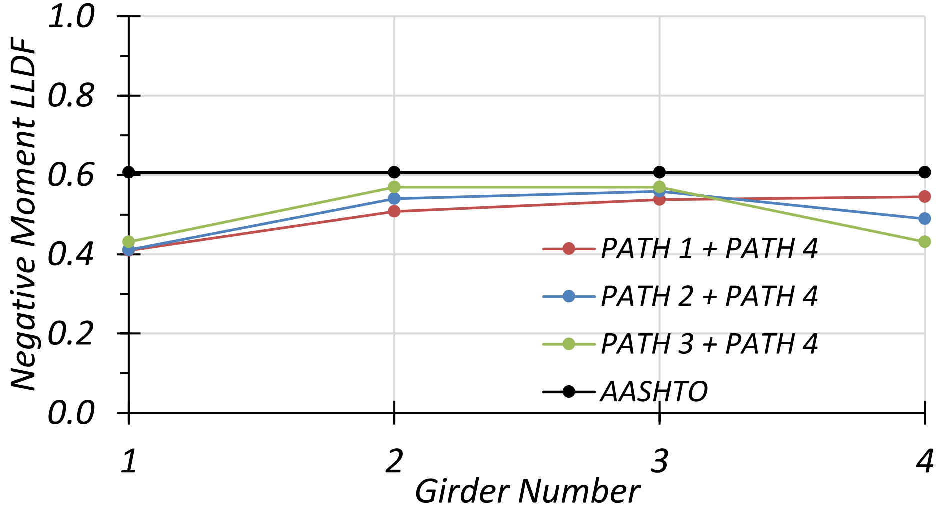
Non-Composite





Composite





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

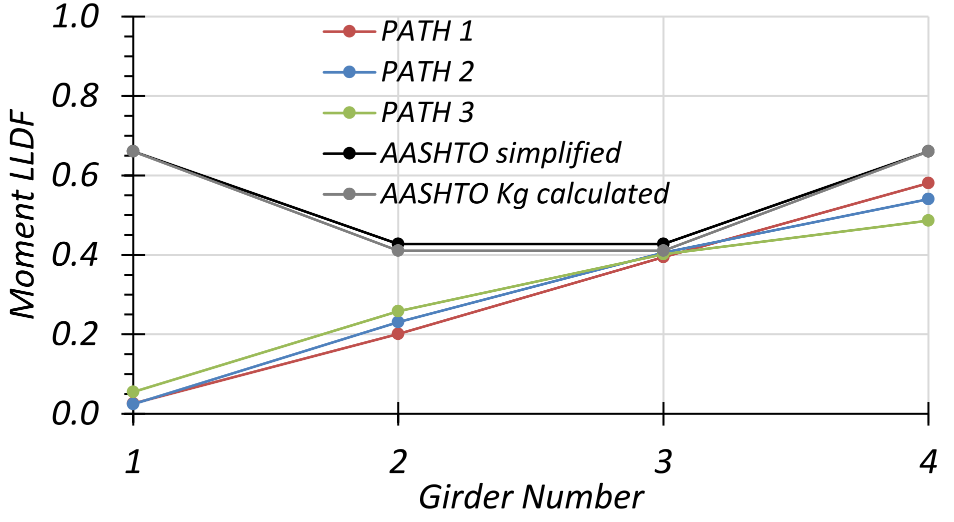
HL93 Positive Moment LLDFs

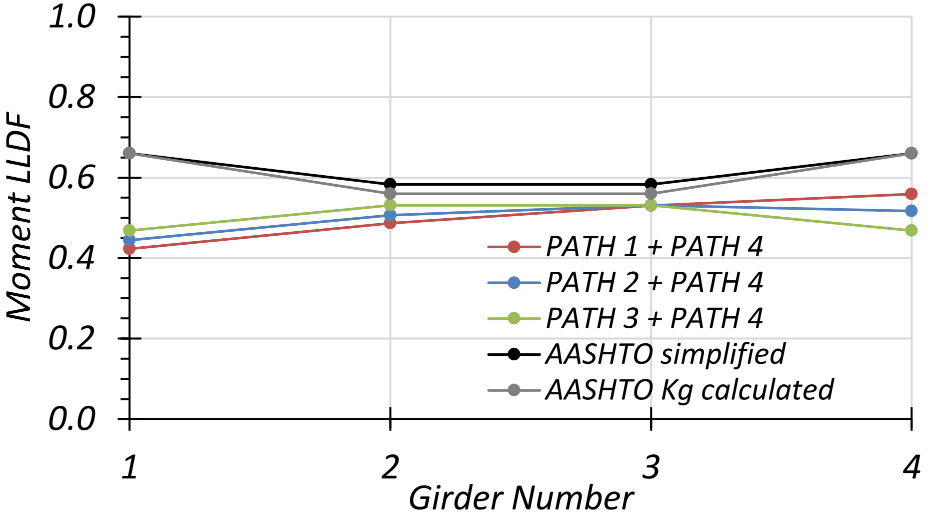
Bridge SC-12

$$LLDF = \frac{\mathrm{M}_i}{\sum \mathrm{M}_i}$$

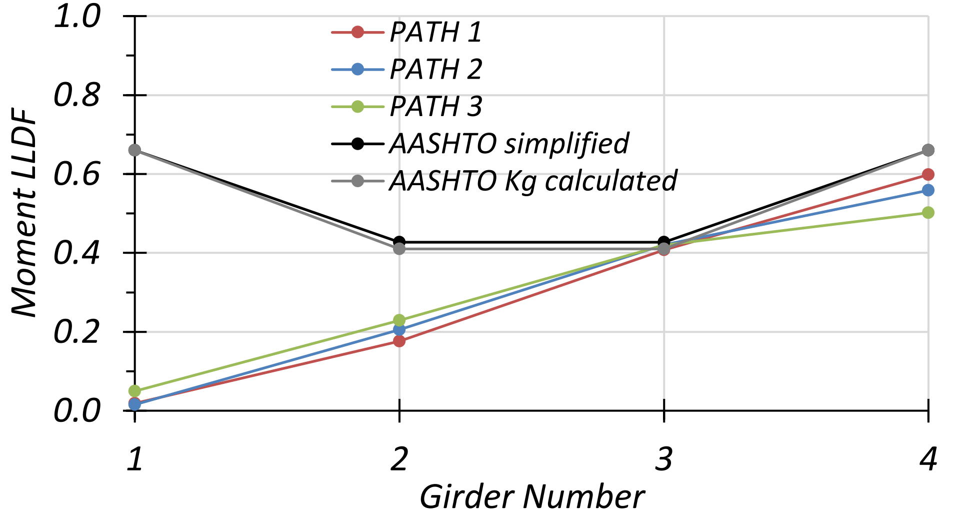
One-Lane **Two-Lane**

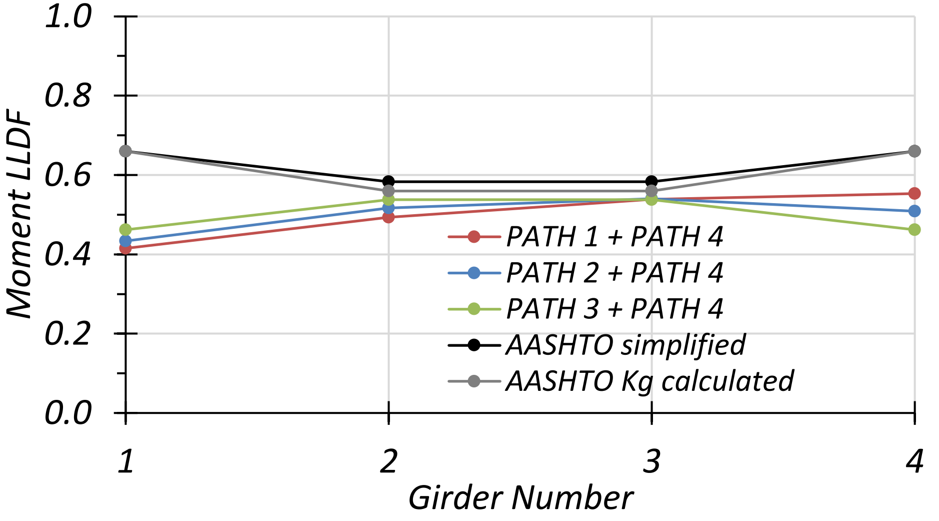
Non-Composite





Composite





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

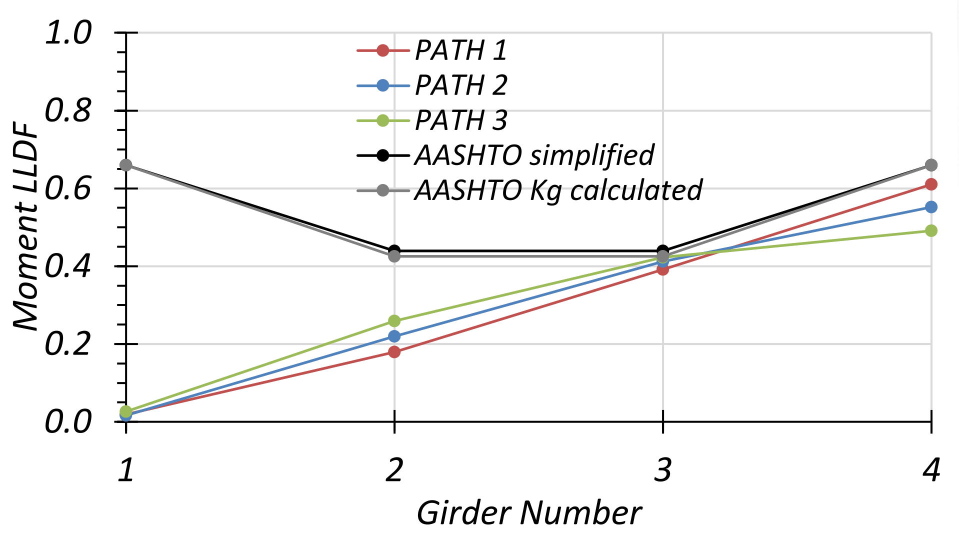
HL93 Negative Moment LLDFs

Bridge SC-12

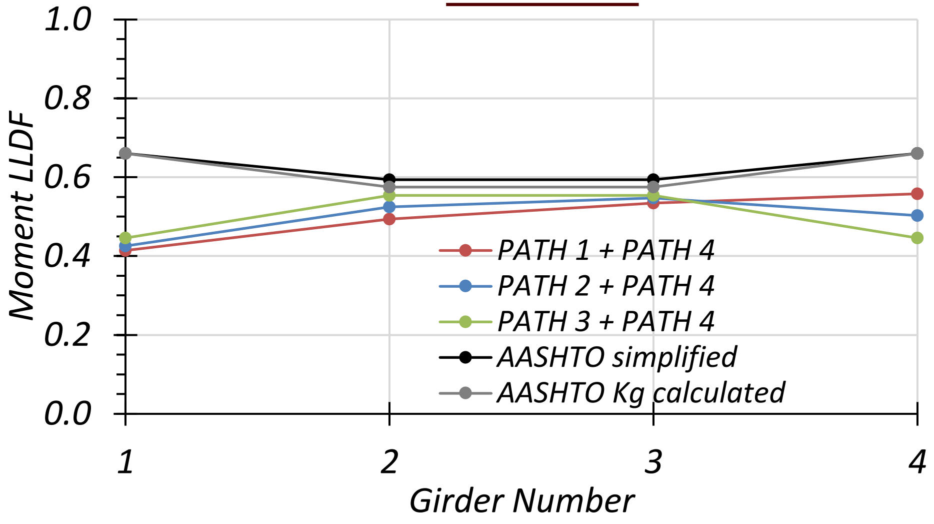
$$LLDF = \frac{M_i}{\sum M_i}$$

Non-Composite

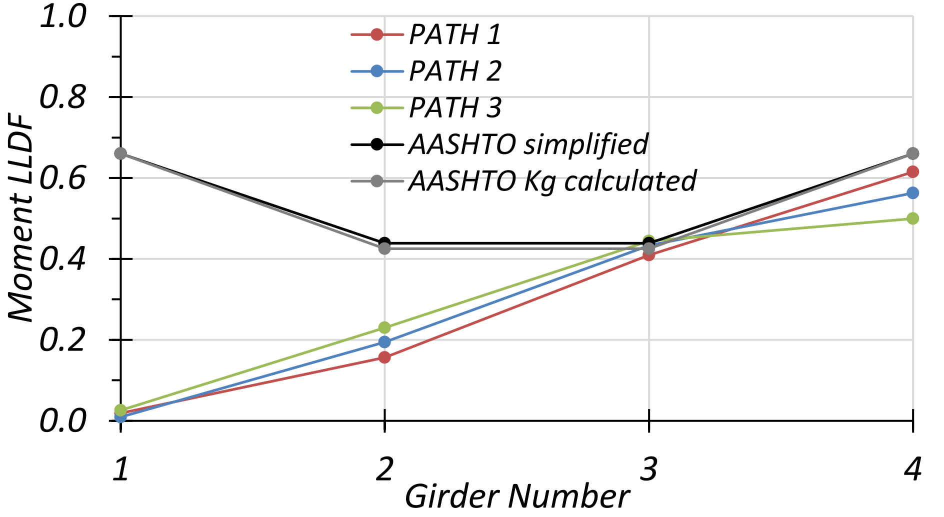
One-Lane

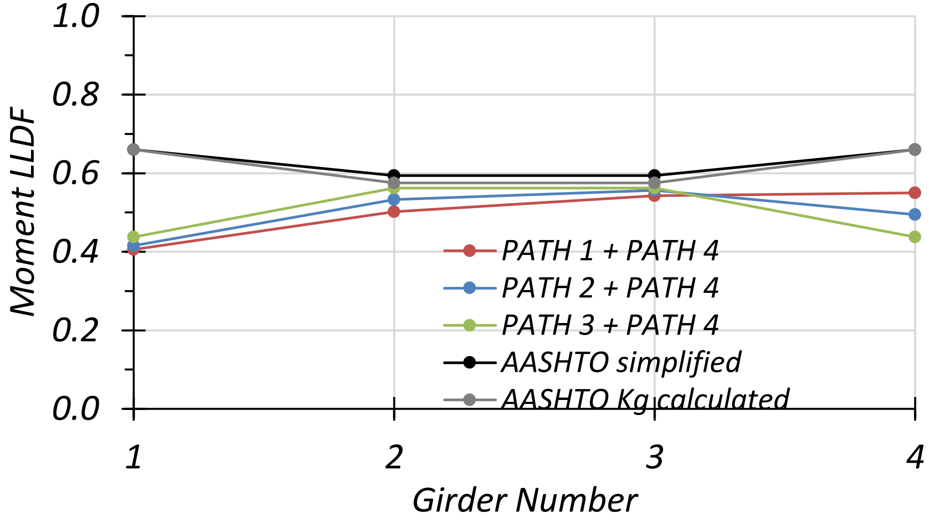


Two-Lane



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

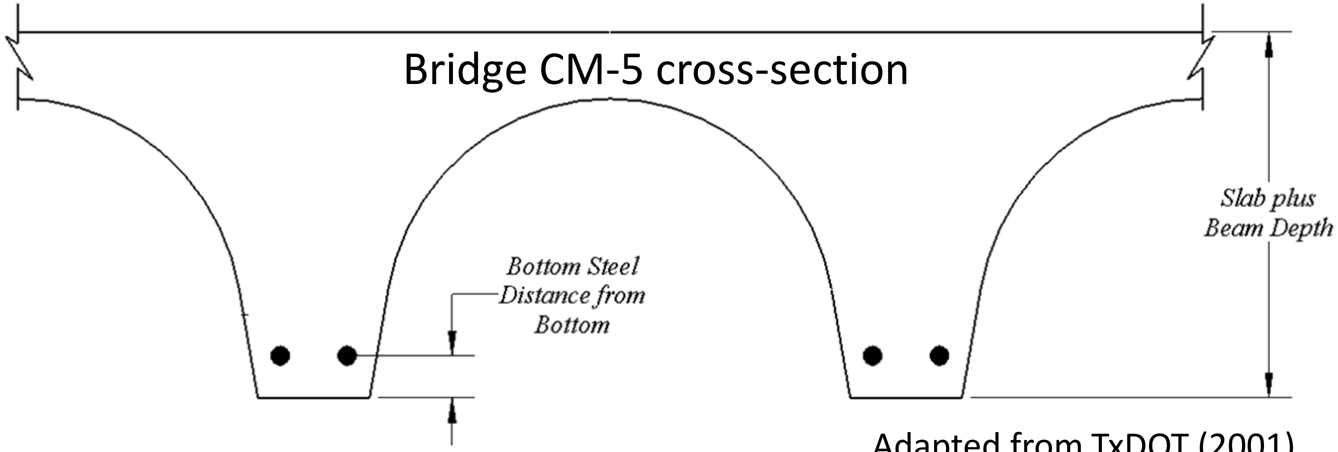
- TxDOT currently rates both steel bridges using the LFR method
  - AASHTO Standard Specification LLDFs
- Changes to LLDF calculations do not significantly affect the rating factors
- Composite action seems to slightly increase the controlling LLDFs, however, not significantly

→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

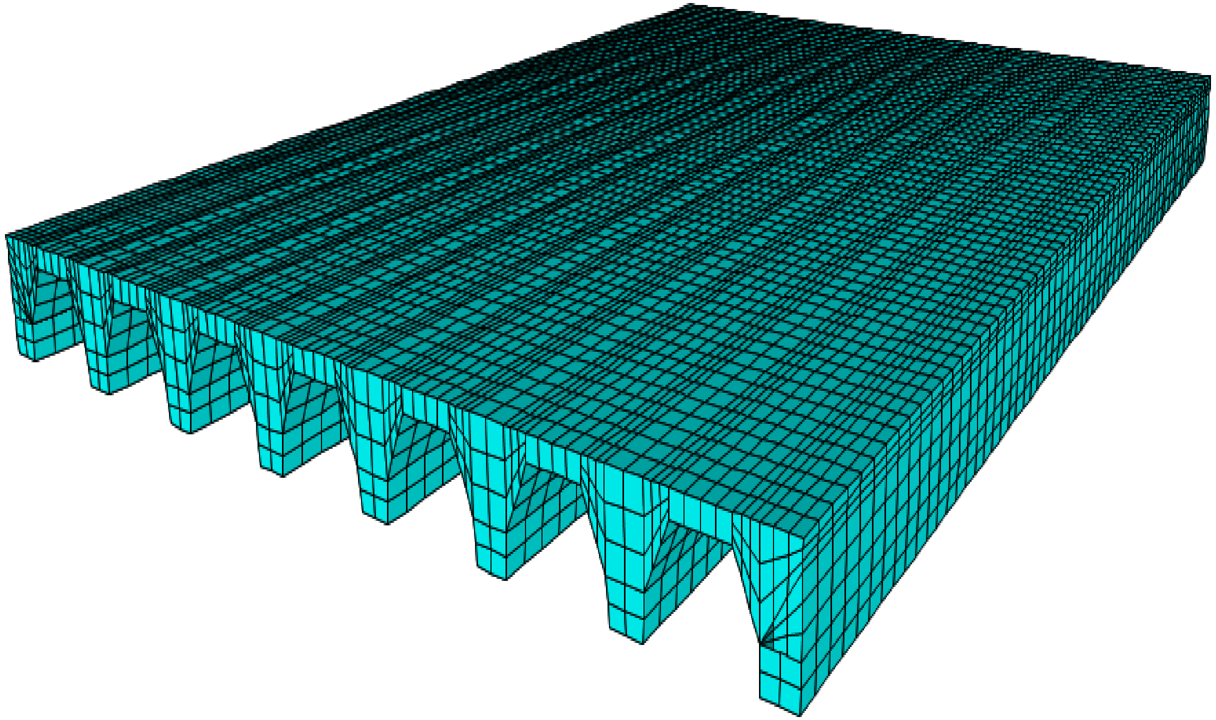

Bridge CM-5 cross-section
Slab plus Beam Depth
Bottom Steel Distance from Bottom

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

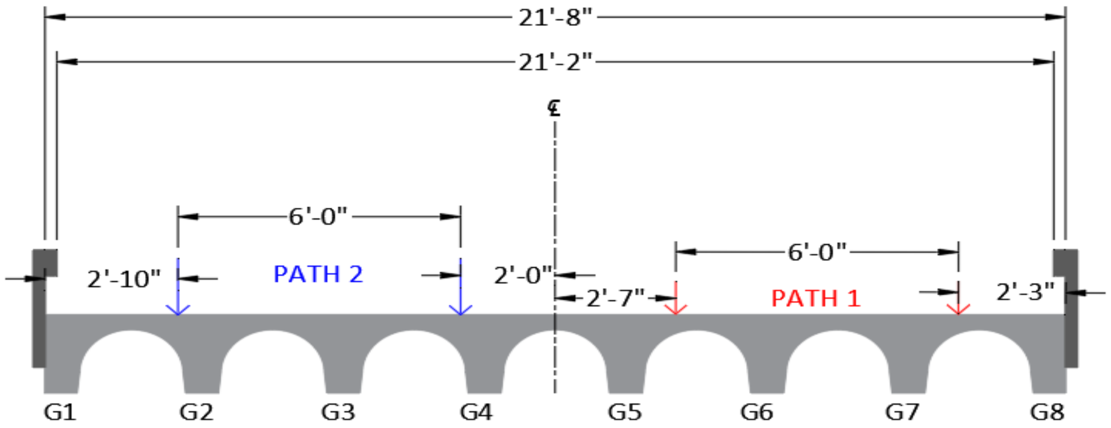


Bridge CM-5 FEM Model (6 in. mesh)

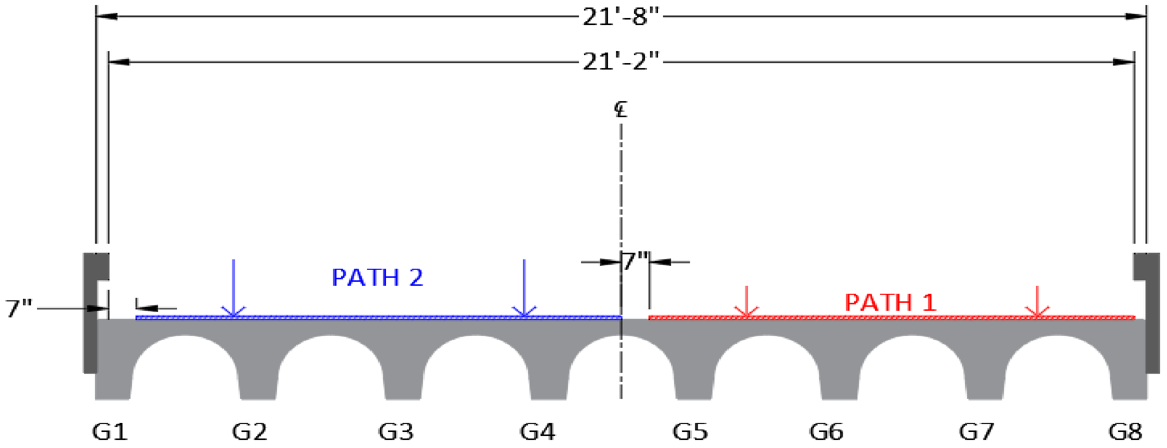
Load Paths

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


21'-8"
21'-2"
℄
6'-0"
2'-10"
PATH 2
2'-0"
2'-7"
6'-0"
PATH 1
2'-3"
G1
G2
G3
G4
G5
G6
G7
G8

HS-20 Truck


21'-8"
21'-2"
℄
7"
PATH 2
7"
PATH 1
G1
G2
G3
G4
G5
G6
G7
G8

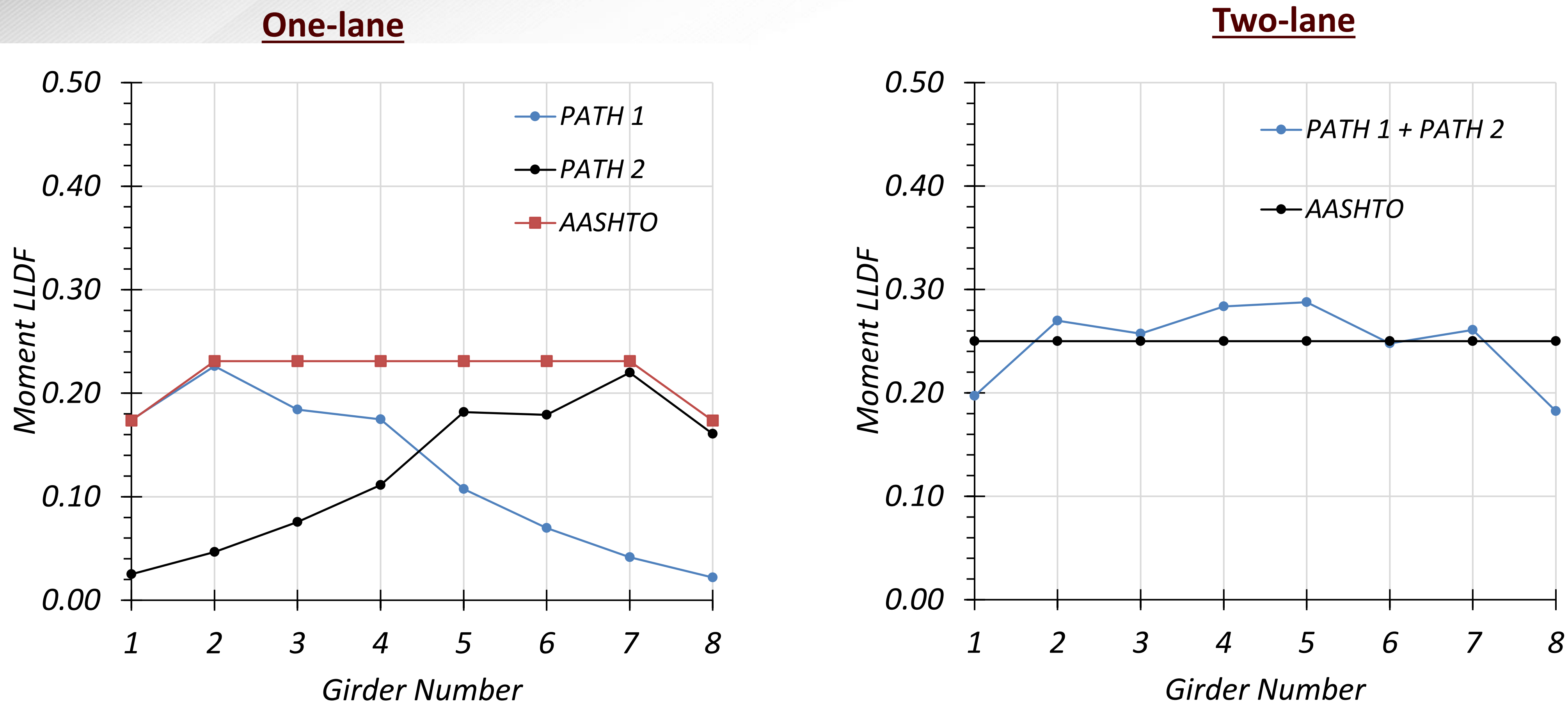
HL93 Design Load

Updated – 08/04/2021

HS-20 Moment LLDFs

Bridge CM-5

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



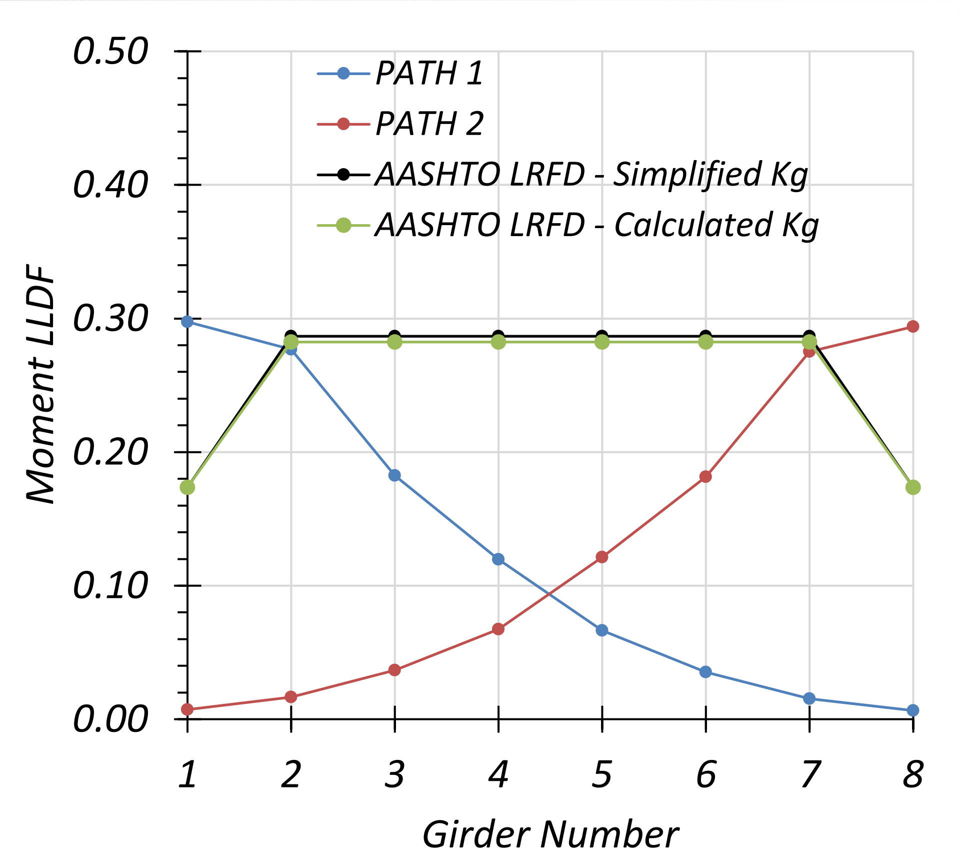
- AASHTO Standard accurately estimate the maximum LLDFs for one-lane loading
- AASHTO Standard slightly unconservative for two-lane LLDFs

Updated – 08/04/2021

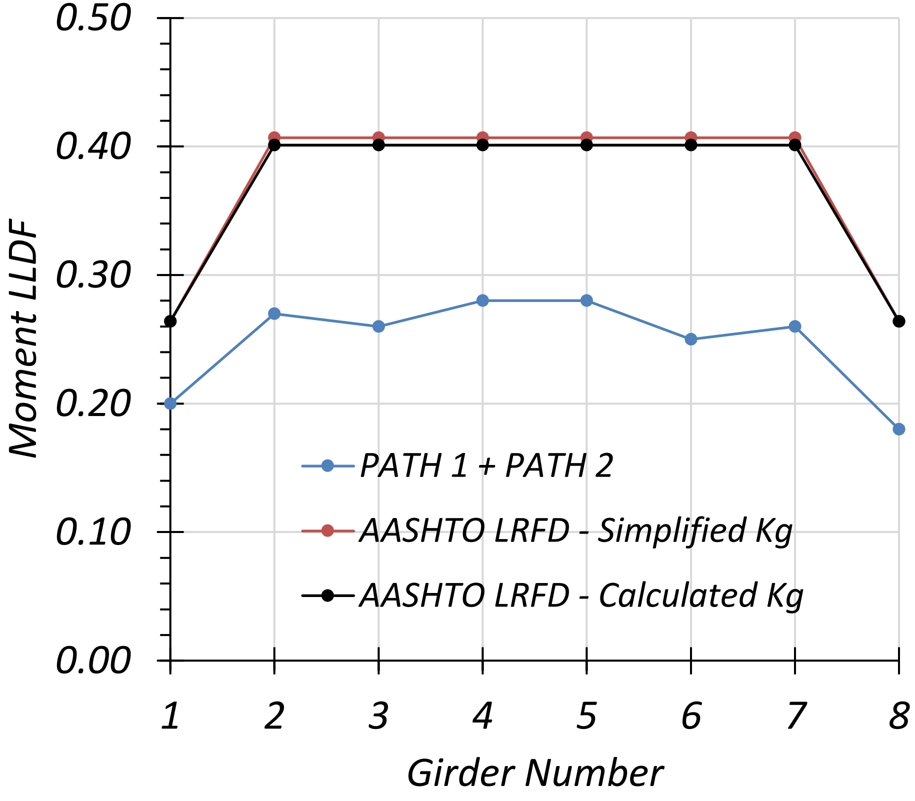
HL-93 Moment LLDFs

Bridge CM-5

One-Lane



Two-Lane



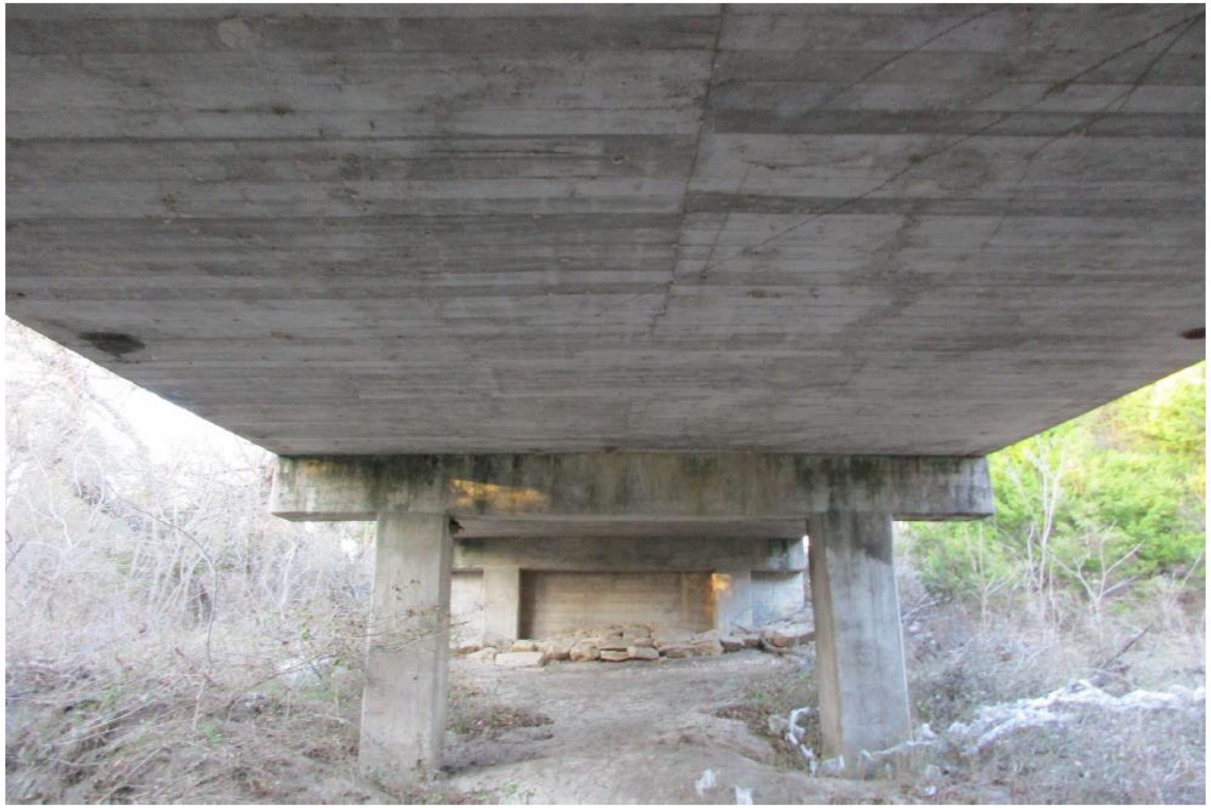
- AASHTO LRFD conservative for interior girder LLDFs for one-lane loading
- AASHTO LRFD unconservative for two-lane LLDFs

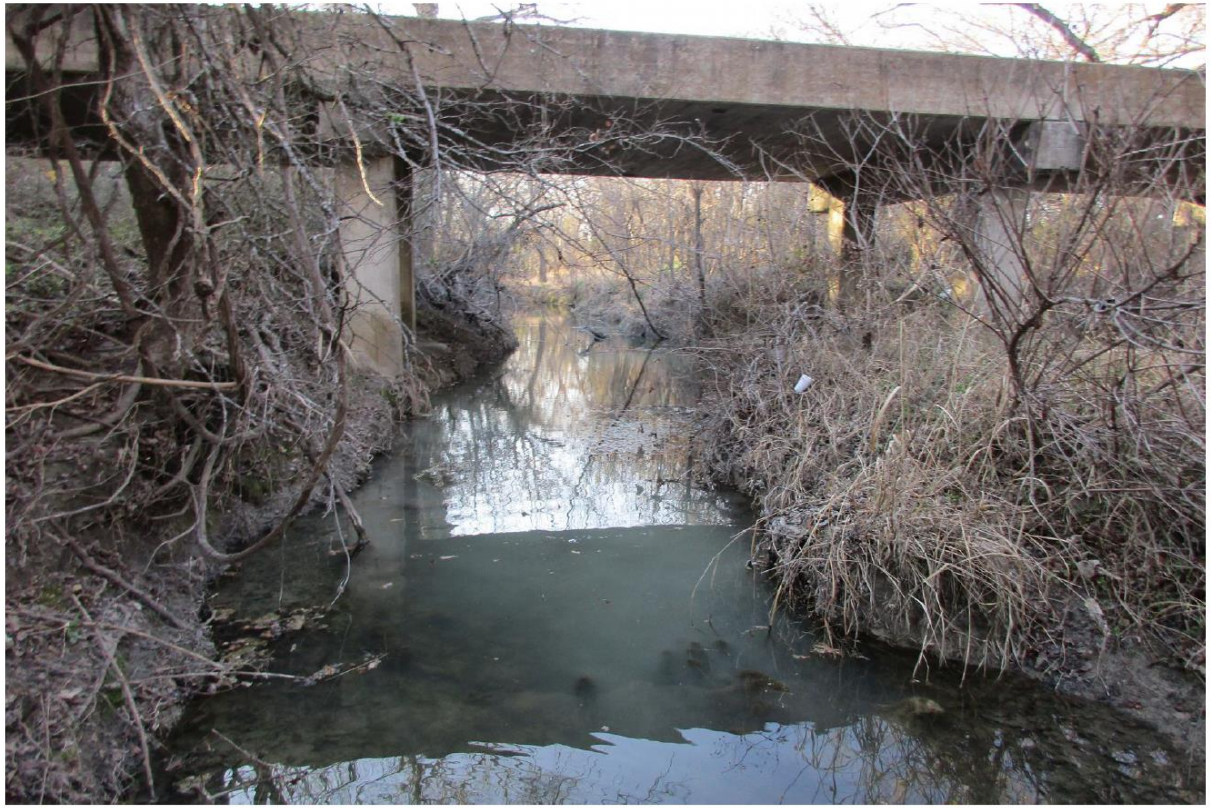
Concrete Slab Bridge

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

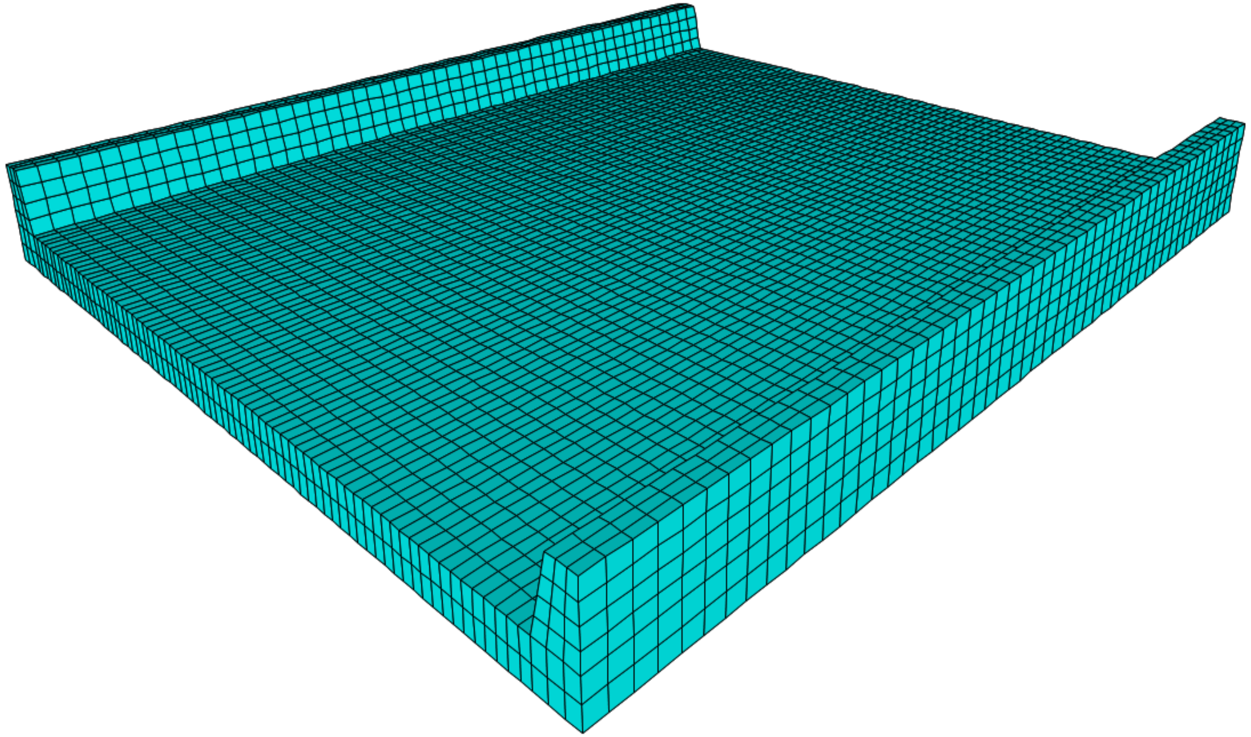




Model Development

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

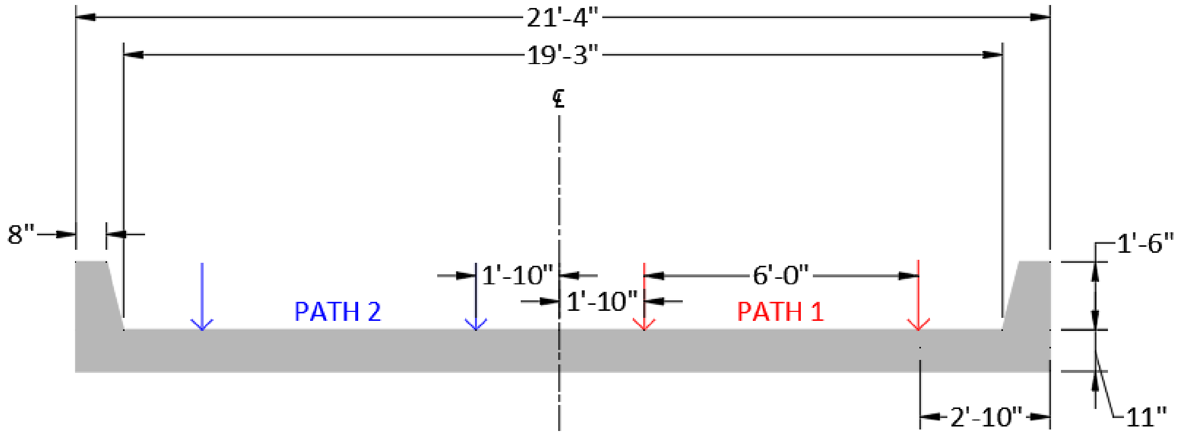


Bridge CS-9 FEM Model (6 in. mesh)

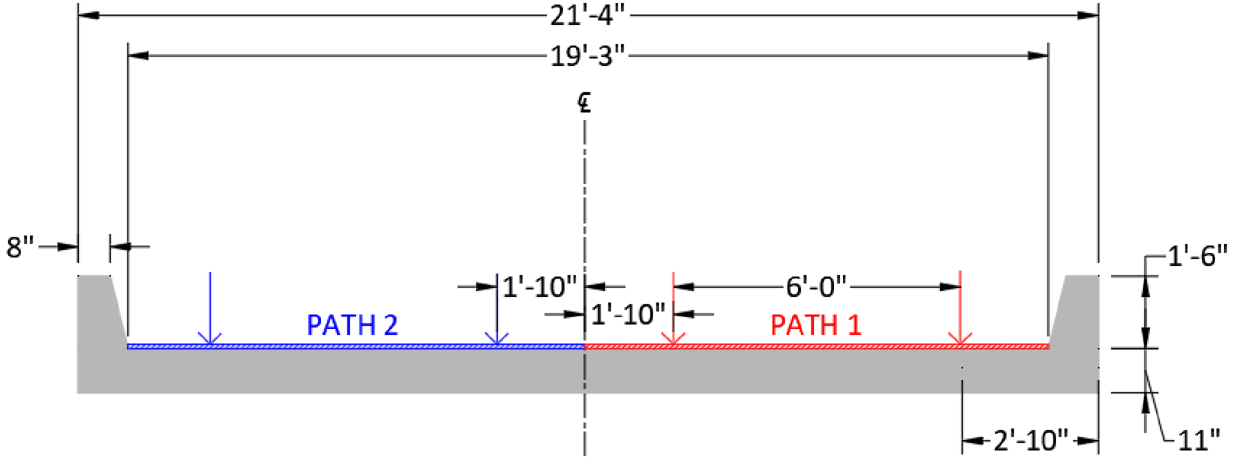
Load Paths

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


21'-4"
19'-3"
℄
8"
1'-6"
1'-10"
1'-10"
6'-0"
PATH 2
PATH 1
2'-10"
11"

HS-20 Truck


21'-4"
19'-3"
℄
8"
1'-6"
1'-10"
1'-10"
6'-0"
PATH 2
PATH 1
2'-10"
11"

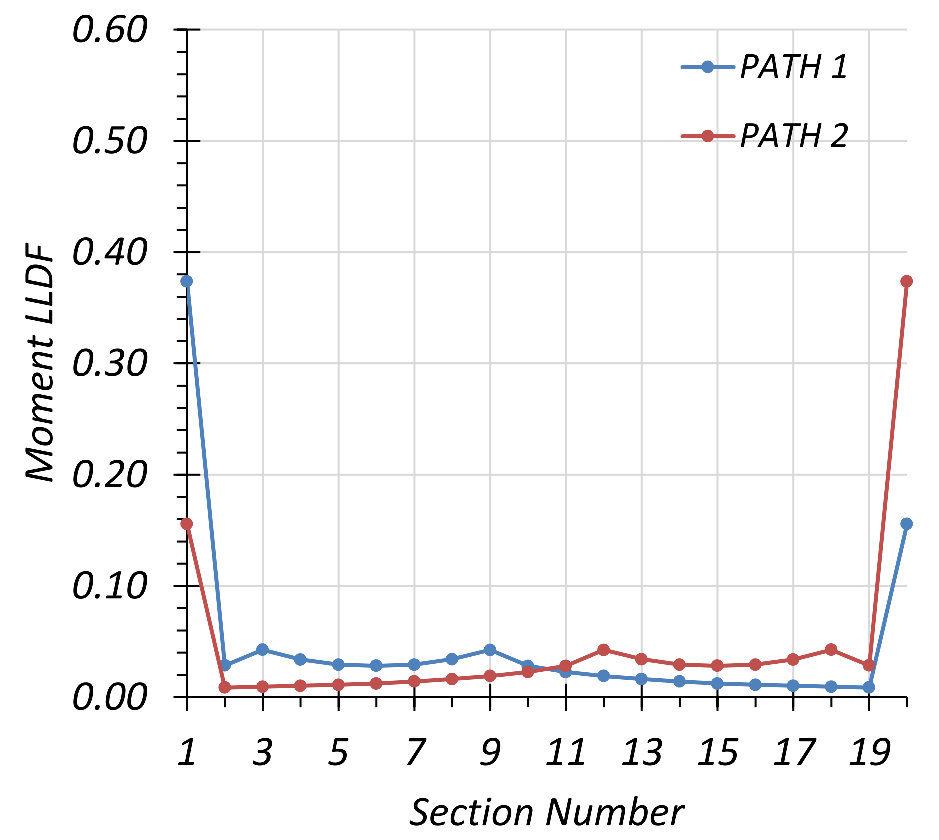
HL93 Design Load

HS-20 Moment LLDFs

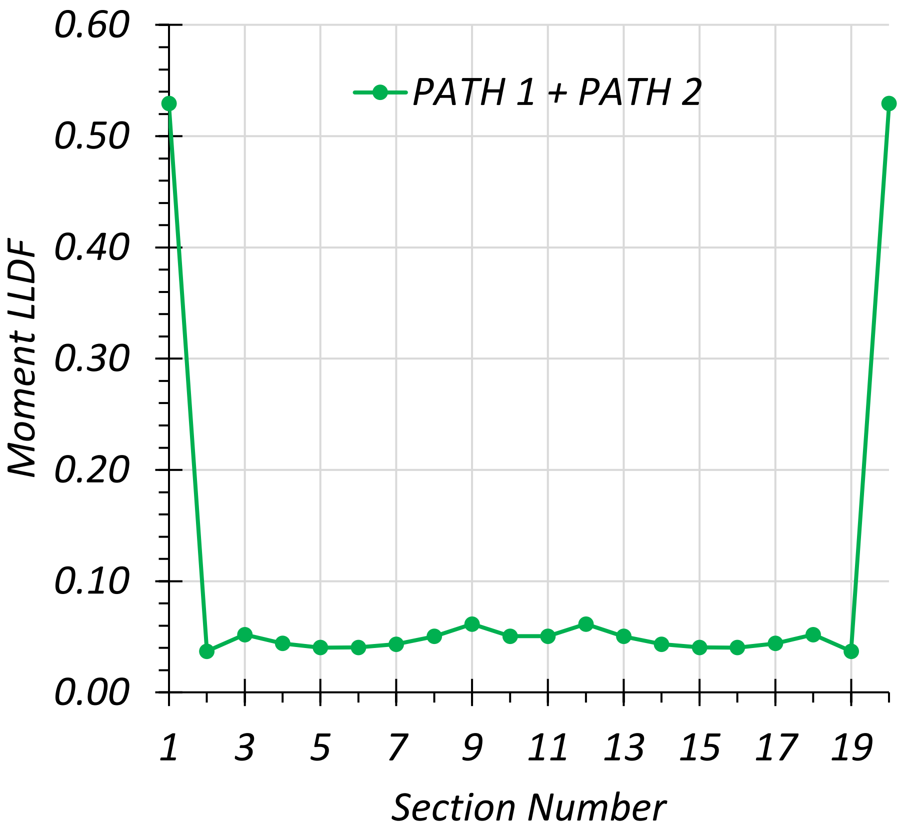
Bridge CS-9

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

One-Lane



Two-Lane

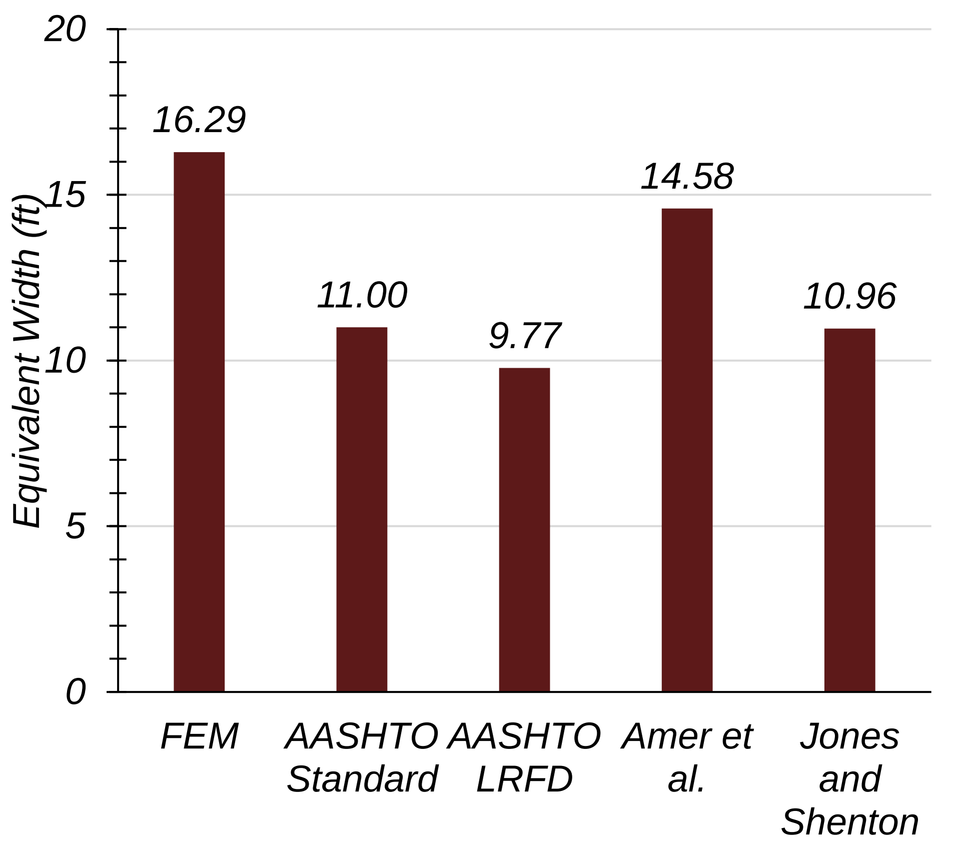


- Above results correspond to bridge width divided into 20 sections
- Stiffer curb sections attract significant portion of load

HS-20 Equivalent Width

Bridge CS-9

Two-Lane Equivalent Width



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

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

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.				

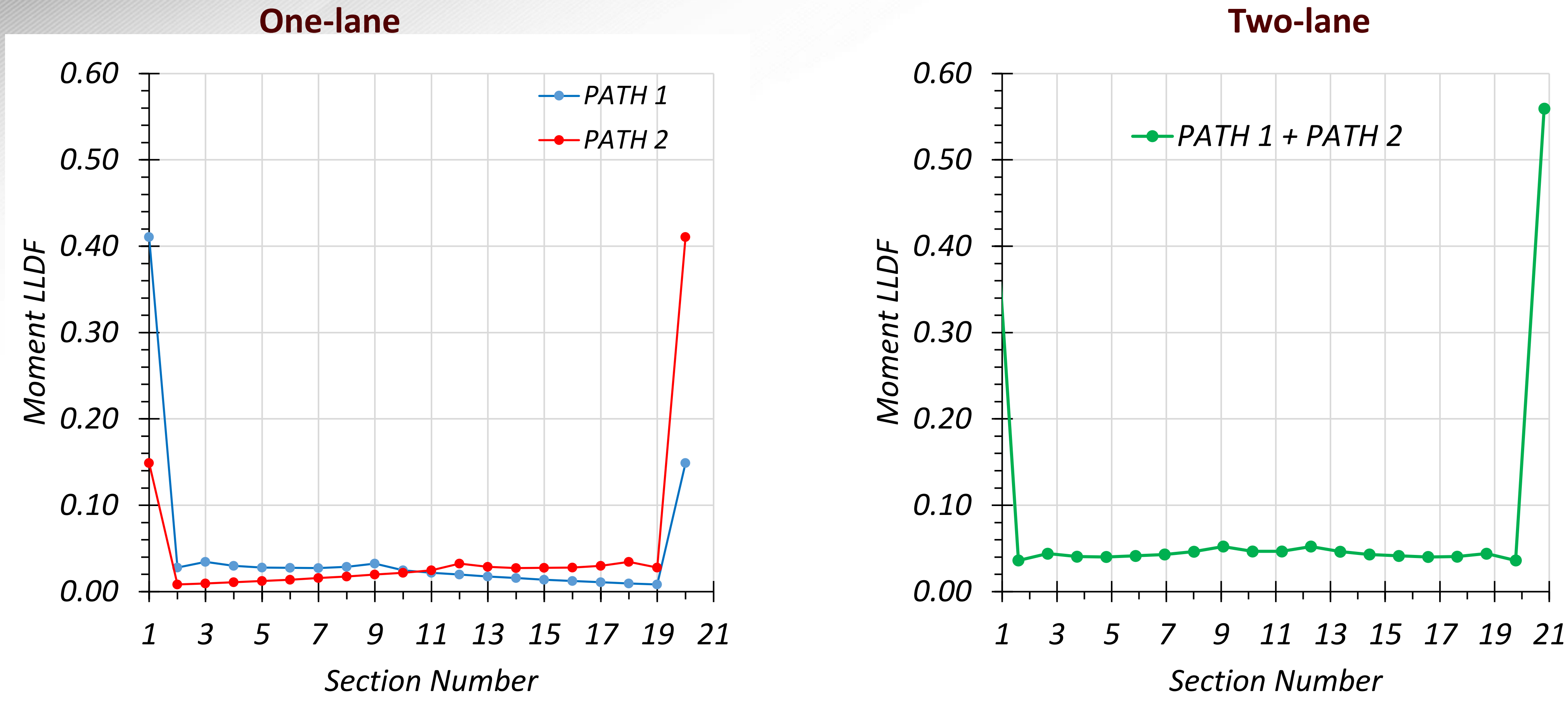
Comparison with various studies

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

- 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

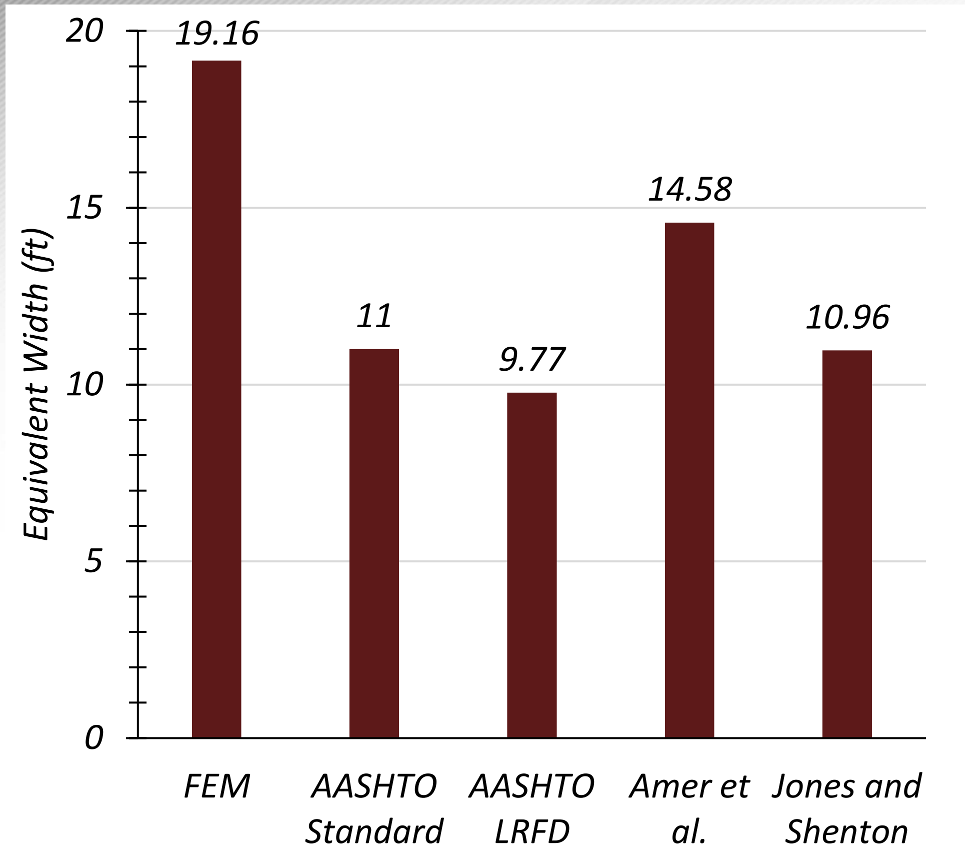


- Above results correspond to bridge width divided into 20 sections
- Stiffer curb sections attract greater load

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.

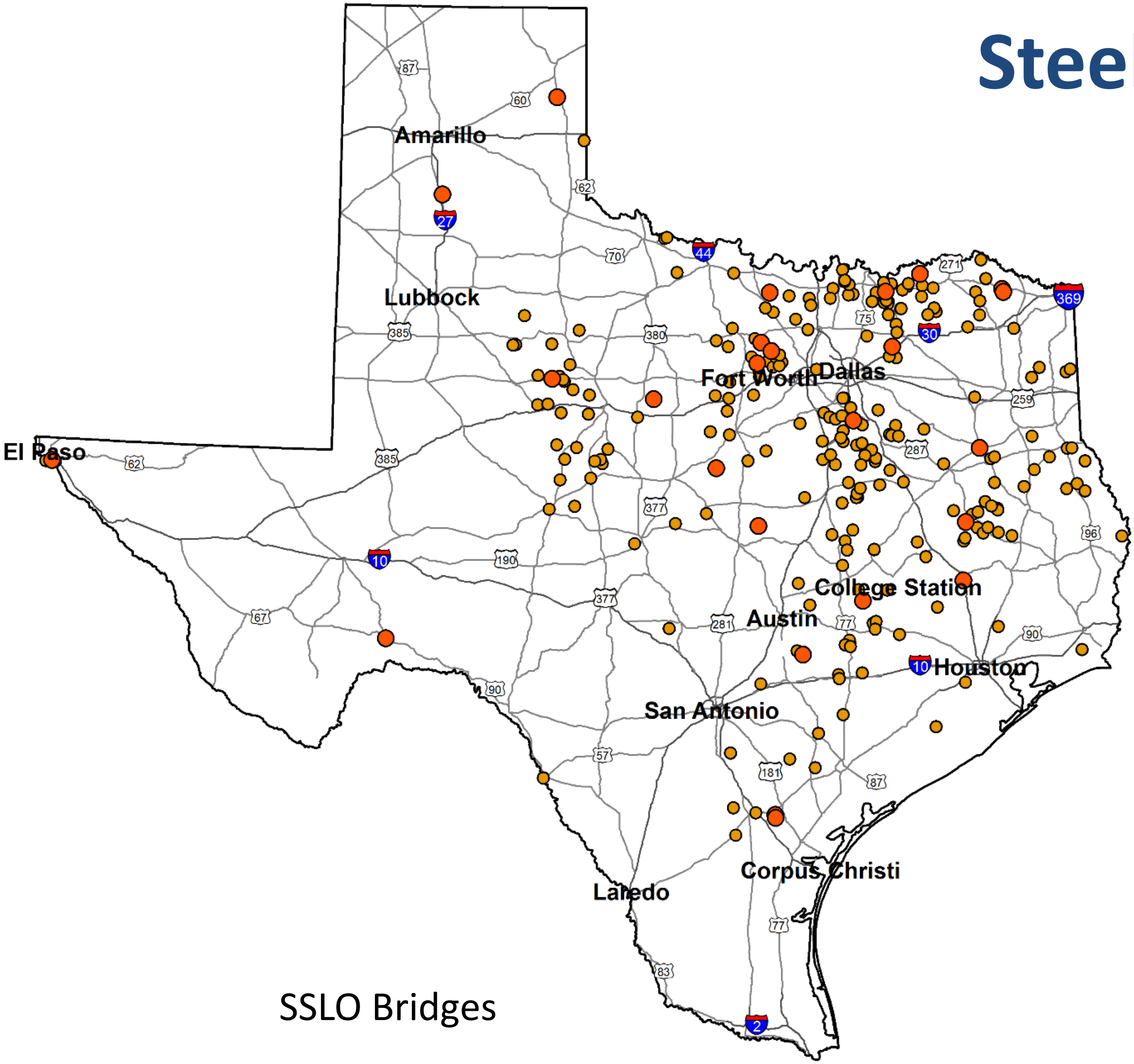
Concrete Slab Bridge with Integral Curb (CS-9)

- 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


Amarillo
Lubbock
El Paso
Fort Worth
Dallas
College Station
Austin
Houston
San Antonio
Corpus Christi
Laredo
87
60
62
27
70
44
271
75
30
369
385
380
259
287
377
96
10
190
67
90
281
77
57
181
83
2

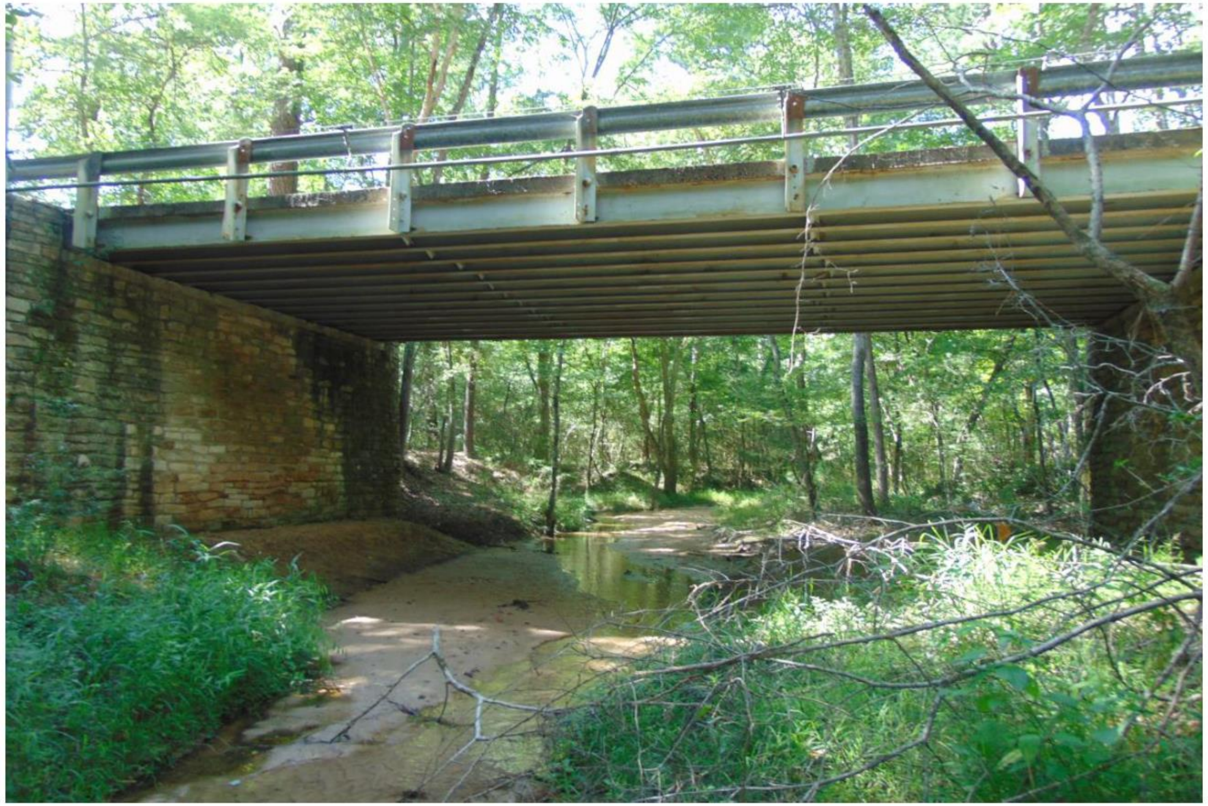
SSLO Bridges

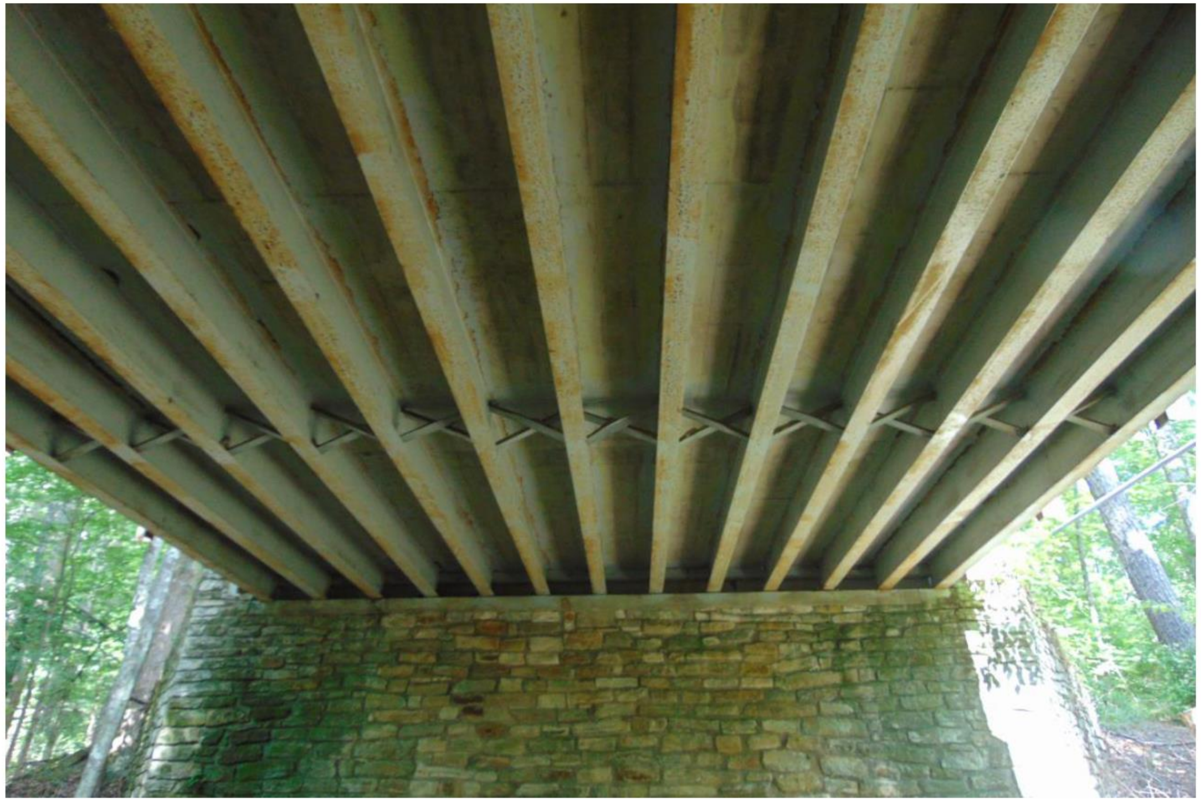
Steel Multi-Girder Bridge

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

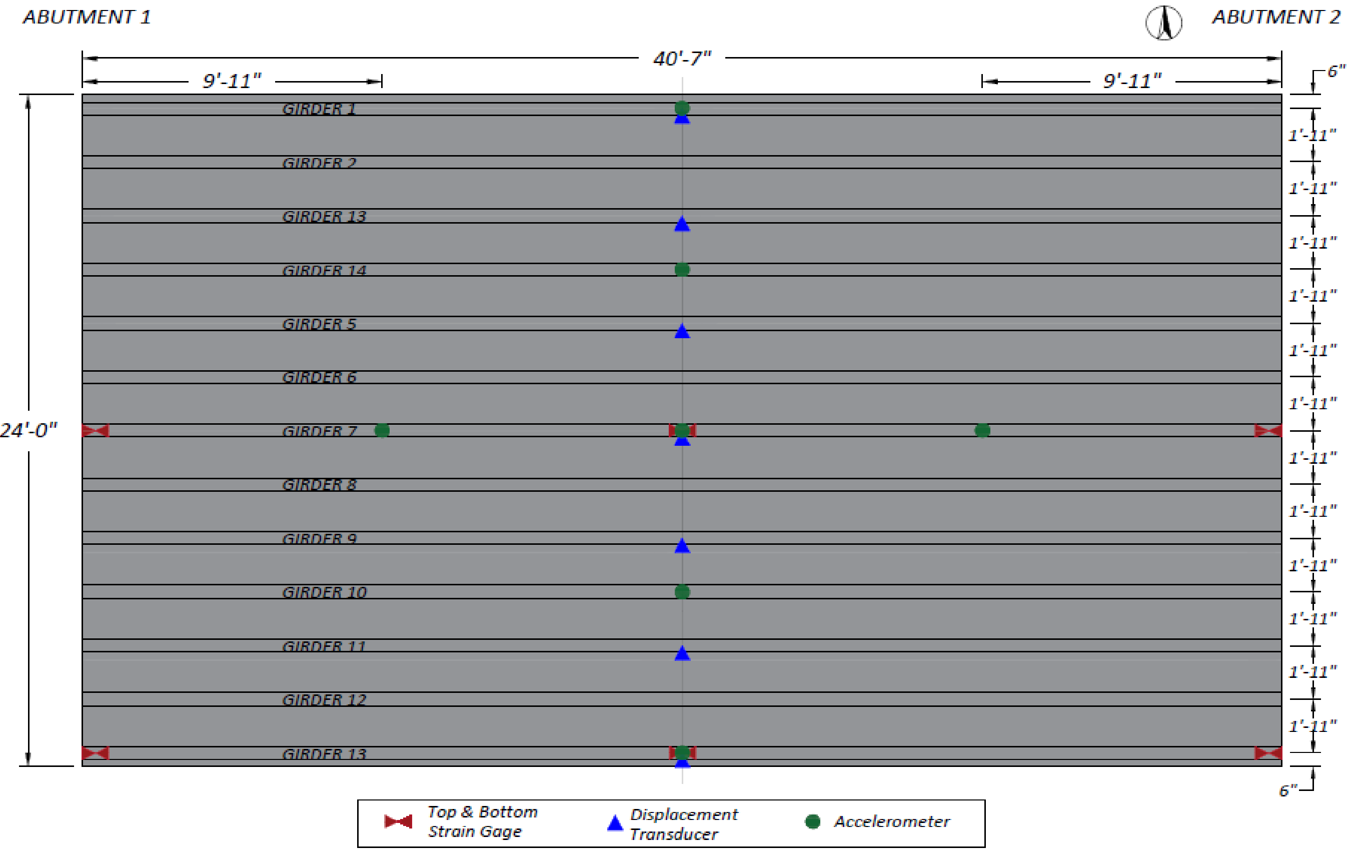
Carries PR 40 and traverses Big Chinquapin Creek near Huntsville, approximately 1.0 mi southwest of I-45

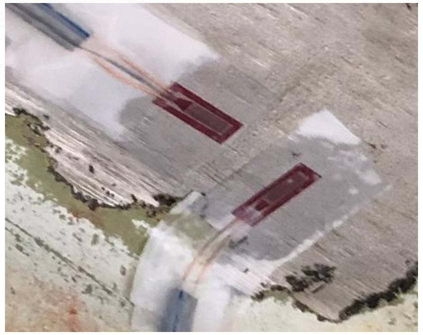


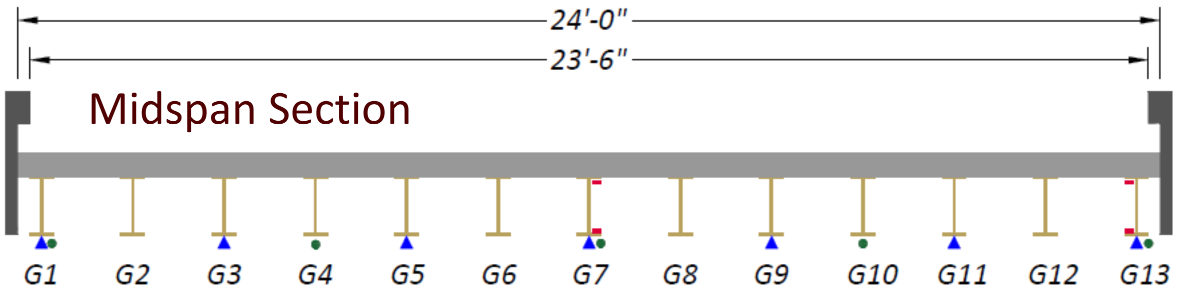


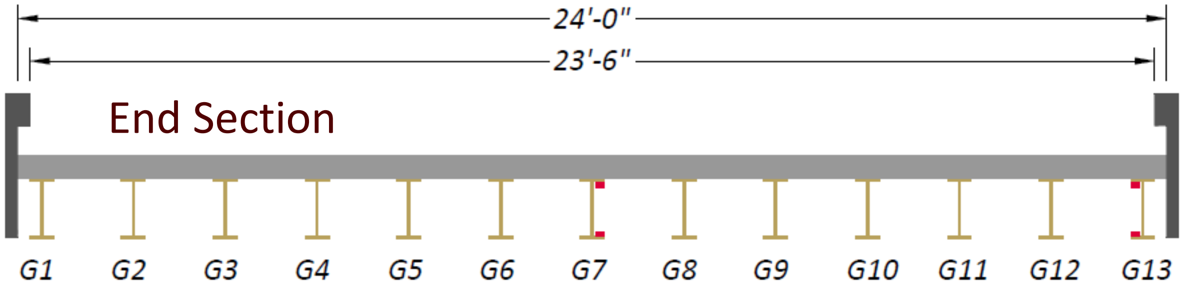
Instrumentation

Bridge SM-5


ABUTMENT 1
ABUTMENT 2
40'-7"
9'-11"
9'-11"
6"
GIRDER 1
GIRDER 2
GIRDER 13
GIRDER 14
GIRDER 5
GIRDER 6
GIRDER 7
GIRDER 8
GIRDER 9
GIRDER 10
GIRDER 11
GIRDER 12
GIRDER 13
1'-11"
1'-11"
1'-11"
1'-11"
1'-11"
1'-11"
1'-11"
1'-11"
1'-11"
1'-11"
1'-11"
1'-11"
24'-0"
6"
Top & Bottom Strain Gage
Displacement Transducer
Accelerometer

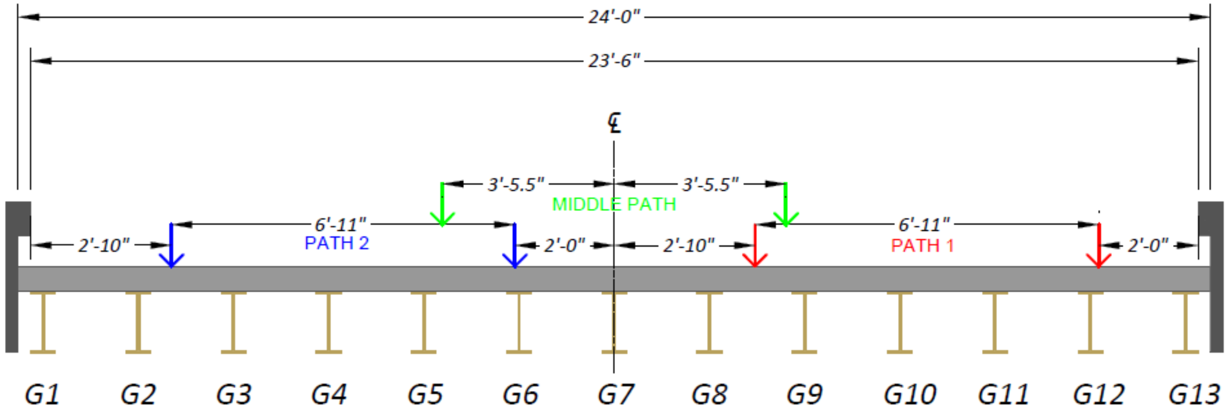



24'-0"
23'-6"
Midspan Section
G1
G2
G3
G4
G5
G6
G7
G8
G9
G10
G11
G12
G13


24'-0"
23'-6"
End Section
G1
G2
G3
G4
G5
G6
G7
G8
G9
G10
G11
G12
G13

Test Sequence

Bridge SM-5

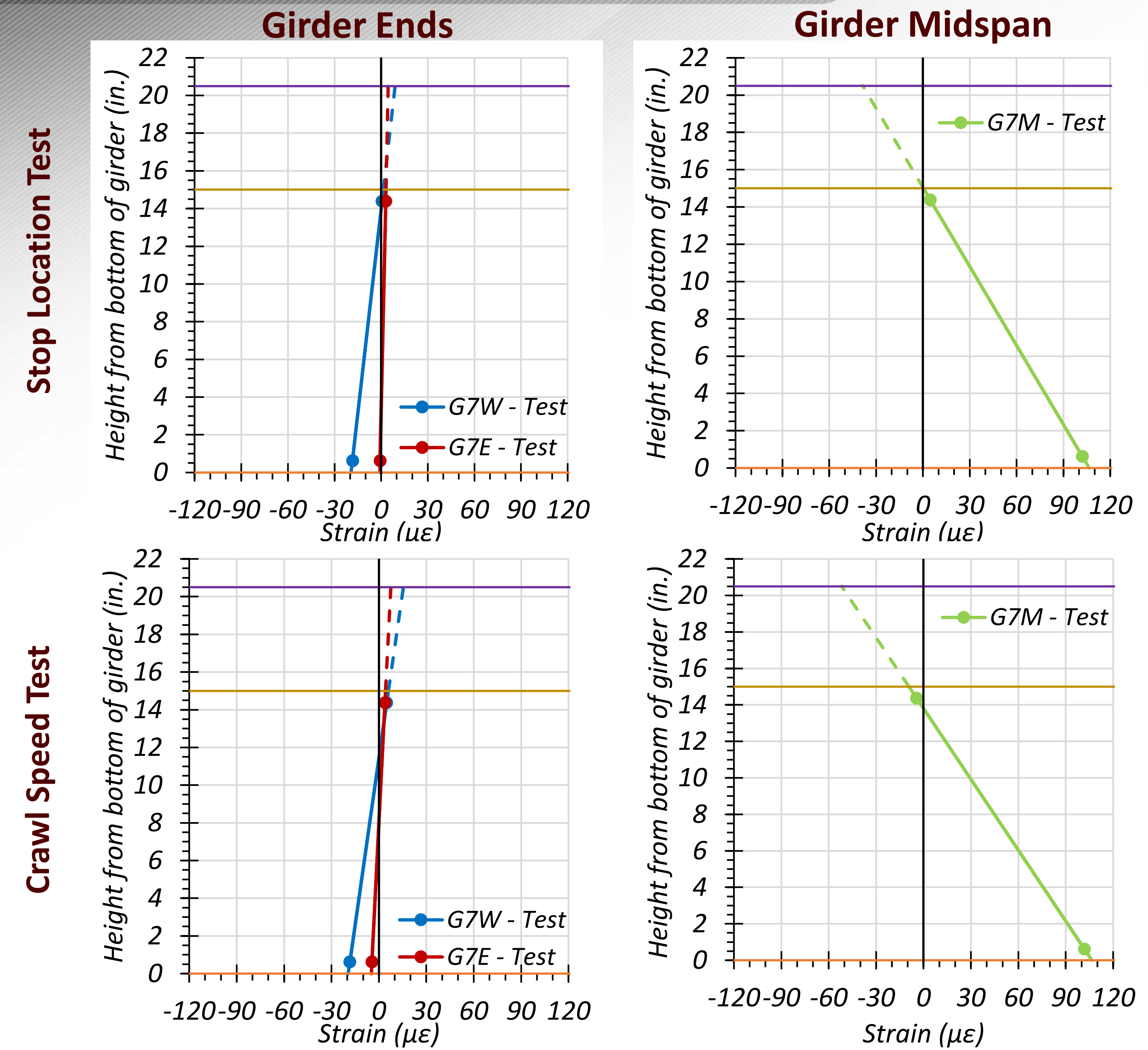

24'-0"
23'-6"
℄
3'-5.5"
3'-5.5"
MIDDLE PATH
2'-10"
6'-11"
PATH 2
2'-0"
2'-10"
6'-11"
PATH 1
2'-0"
G1
G2
G3
G4
G5
G6
G7
G8
G9
G10
G11
G12
G13

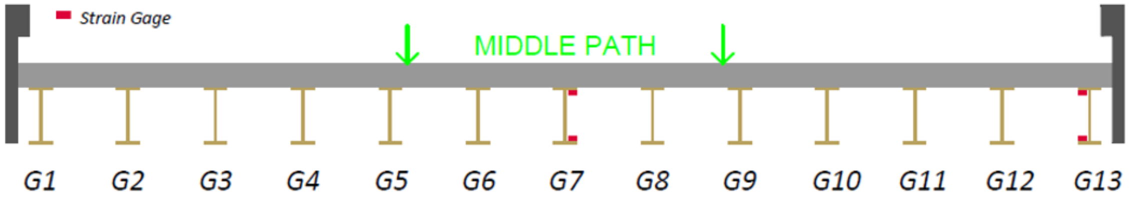
Test Number	Test Location	Test Type
1	Path 1	Static – Stop Location (Engine Running)
2	Path 2	Static – Stop Location (Engine Running)
3	Path 1	Static – Crawl Speed (5 mph)
4	Path 2	Static – Crawl Speed (2 mph)
5	Path 1	Dynamic (30 mph)
6	Path 2	Dynamic (35 mph)
7	Path 1	Dynamic (23 mph)
8	Path 2	Dynamic (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

Interior Girder G7 Strain Results Middle Path – Static Tests

Bridge SM-5




Strain Gage
MIDDLE PATH
G1
G2
G3
G4
G5
G6
G7
G8
G9
G10
G11
G12
G13

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

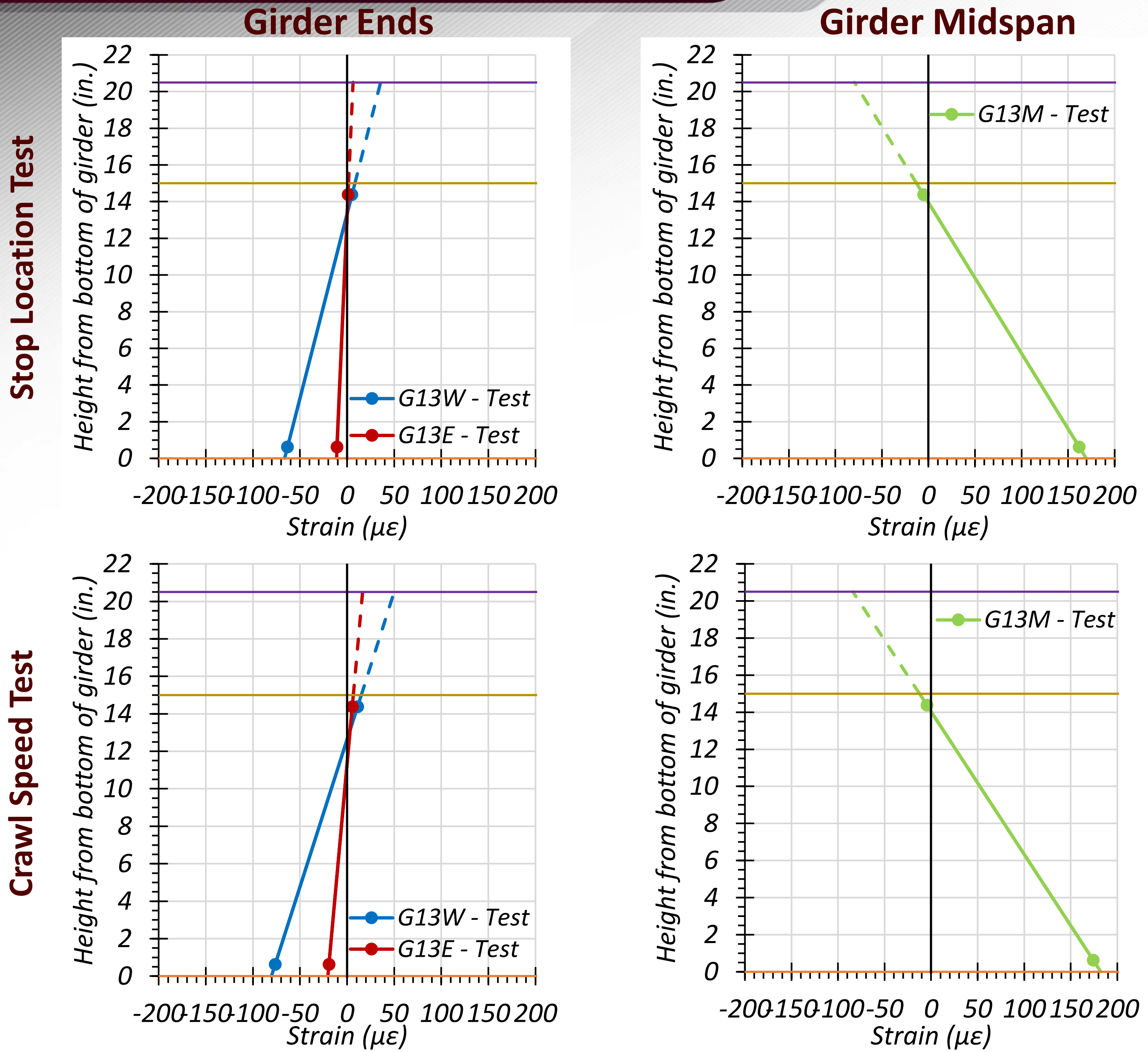
Nearly full composite action

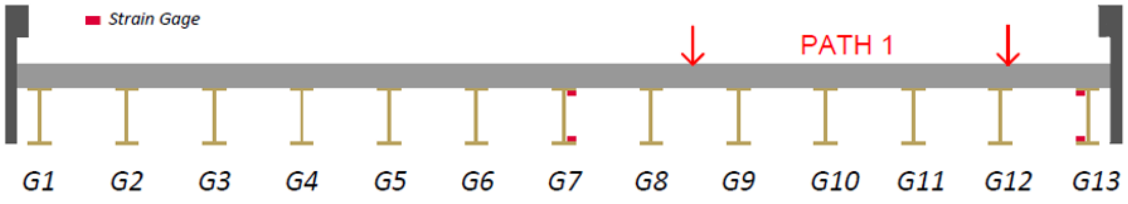
- Maximum Bottom Flange Strains/Stresses
  - Midspan: 102 με → 2.96 ksi
  - West end: -18.5 με → -0.54 ksi
  - East end: -4.4 με → -0.13 ksi

Tension is positive

Exterior Girder G13 Strain Results Path 1 – Static Tests

Bridge SM-5




Strain Gage
PATH 1
G1
G2
G3
G4
G5
G6
G7
G8
G9
G10
G11
G12
G13

- 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

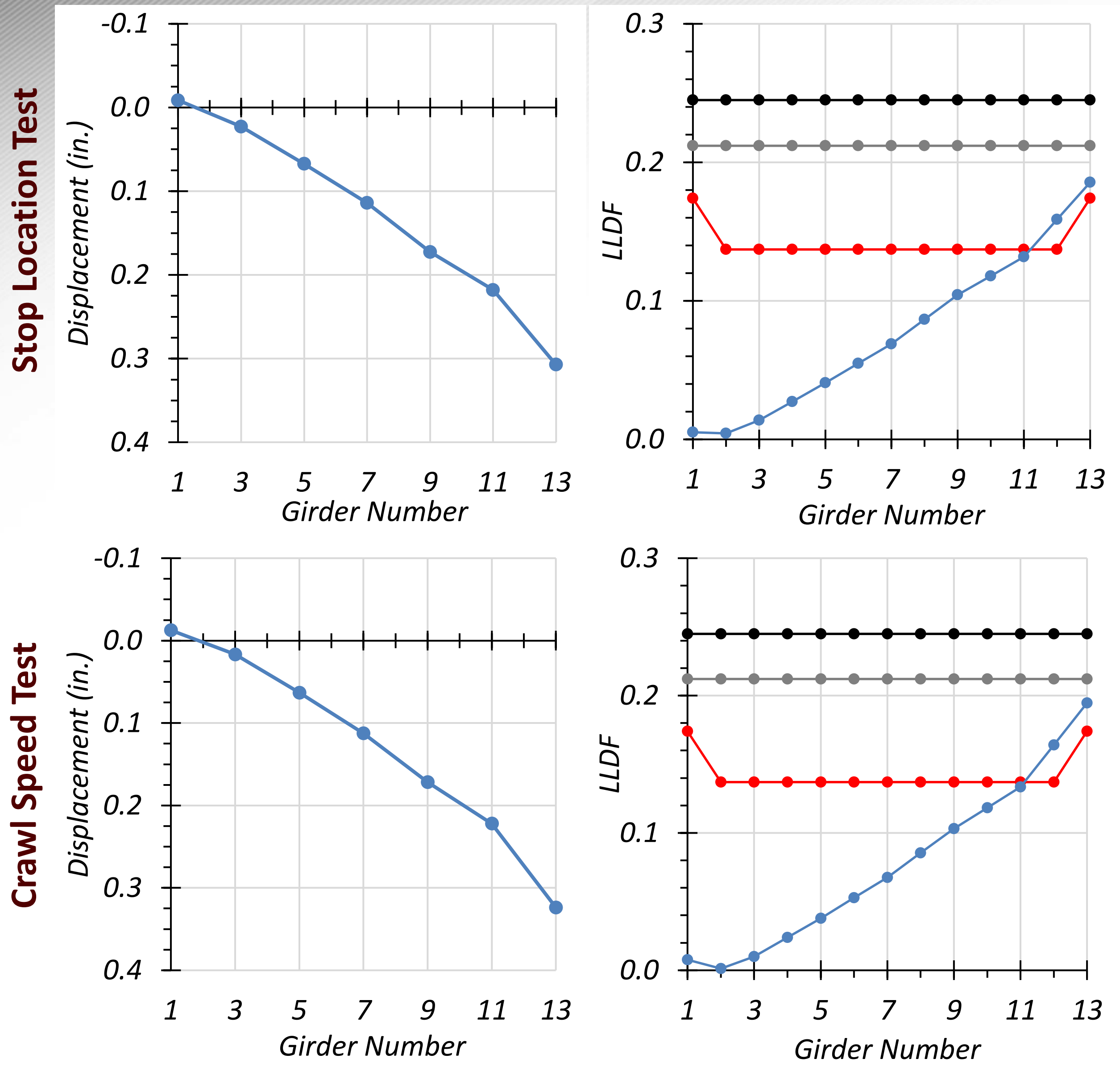
Tension is positive

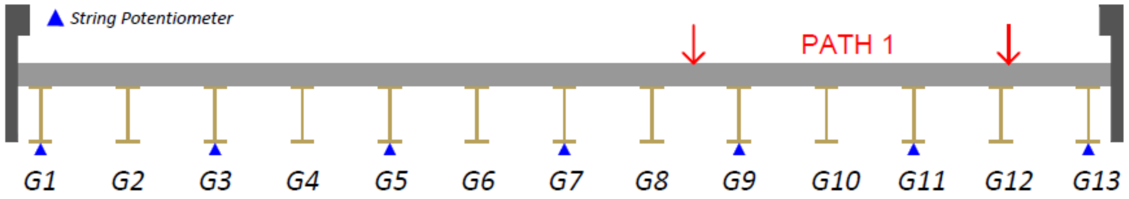
Deflection Results Path 1 – Static Tests

Bridge SM-5

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

Deflections **LLDFs**





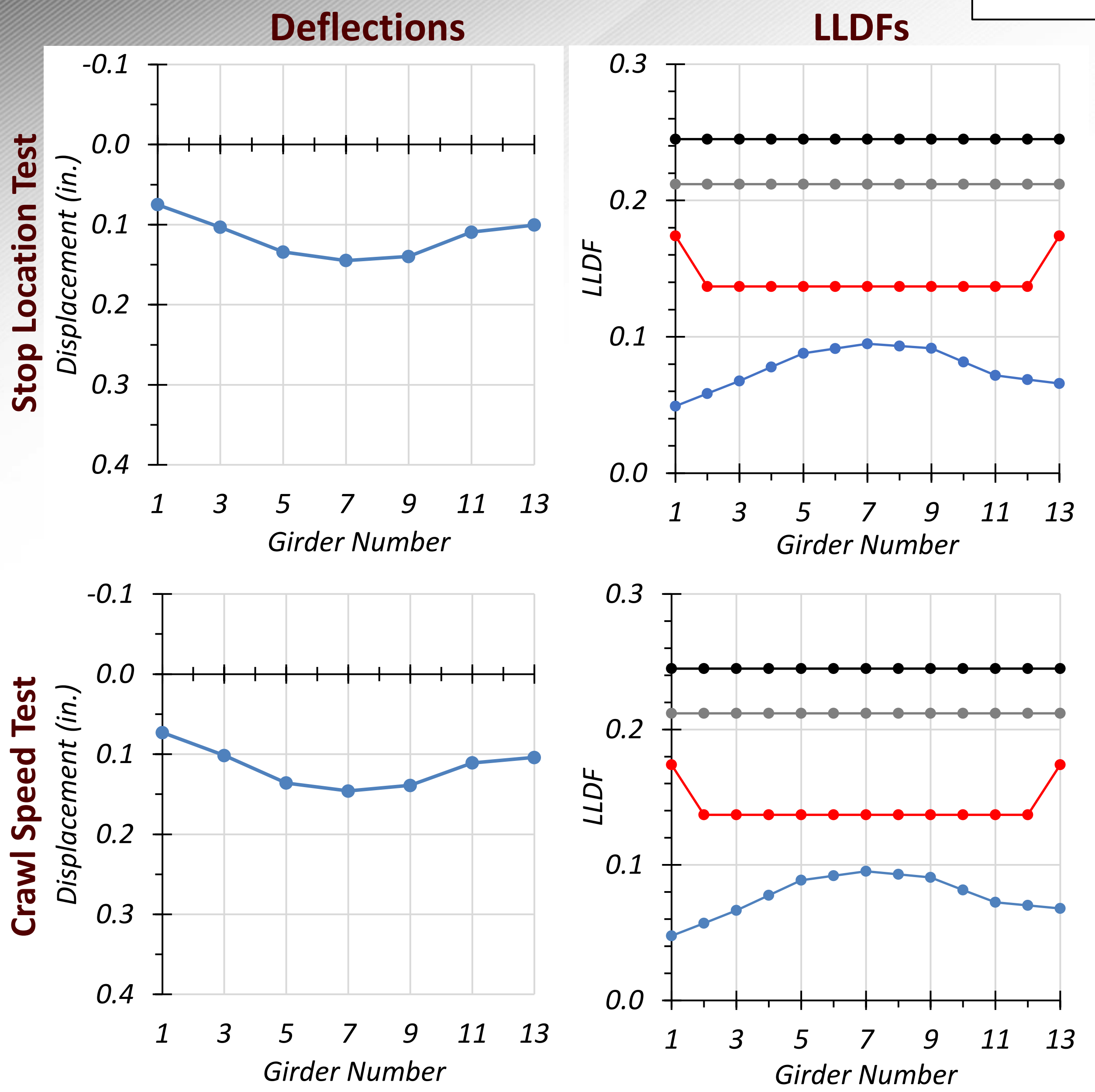
Test and Girder Type	AASHTO Standard Specs ($g^m_{AASHTO\_Std}$)	AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$)	AASHTO LRFD K_g Calculated ($g^m_{AASHTO\_K}$)	Test (g^m_{test})	$g^m_{AASHTO\_Std}/g^m_{test}$	$g^m_{AASHTO\_S}/g^m_{test}$	$g^m_{AASHTO\_K}/g^m_{test}$
Stop Location Interior	0.137	0.245	0.212	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

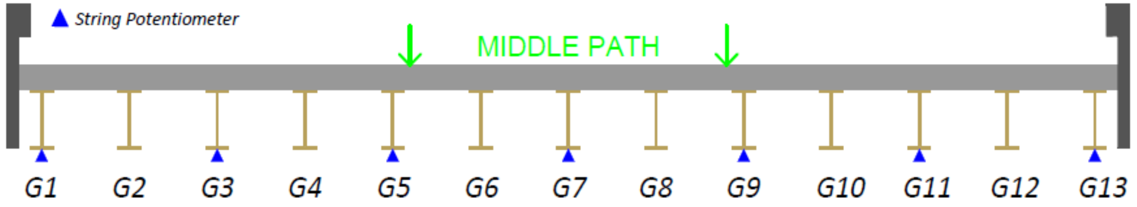
● Test ● AASHTO Standard ● AASHTO LRFD simplified
● AASHTO LRFD K_g calculated

Deflection Results
Middle Path – Static Tests

Bridge SM-5

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



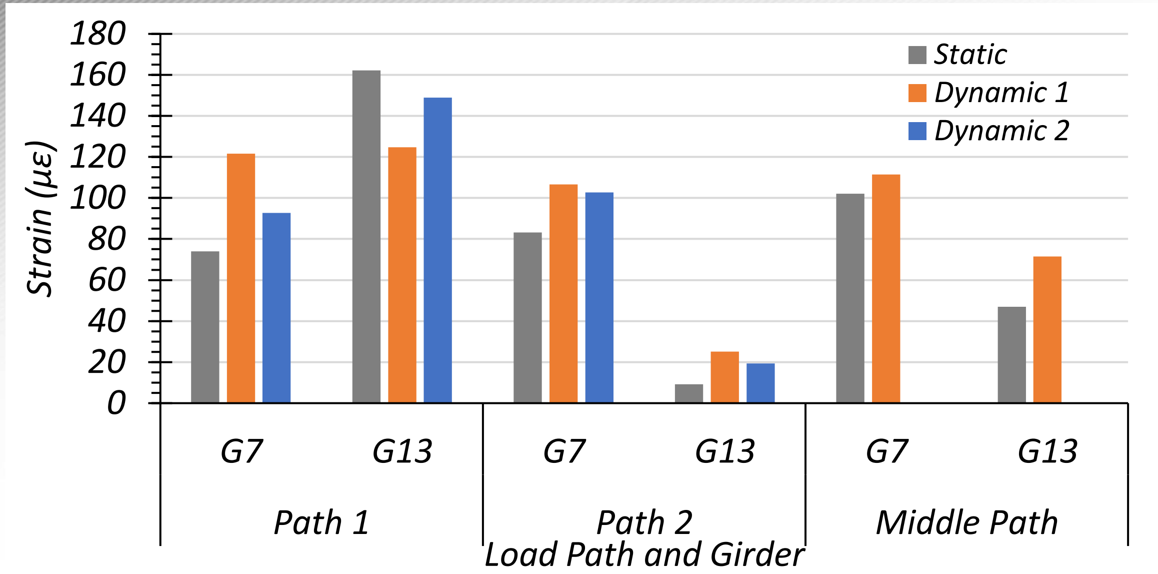


Test and Girder Type	AASHTO Standard Specs ($g^m_{AASHTO\_Std}$)	AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$)	AASHTO LRFD K_g Calculated ($g^m_{AASHTO\_K}$)	Test (g^m_{test})	$g^m_{AASHTO\_Std}/g^m_{test}$	$g^m_{AASHTO\_S}/g^m_{test}$	$g^m_{AASHTO\_K}/g^m_{test}$
Stop Location Interior	0.137	0.245	0.212	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

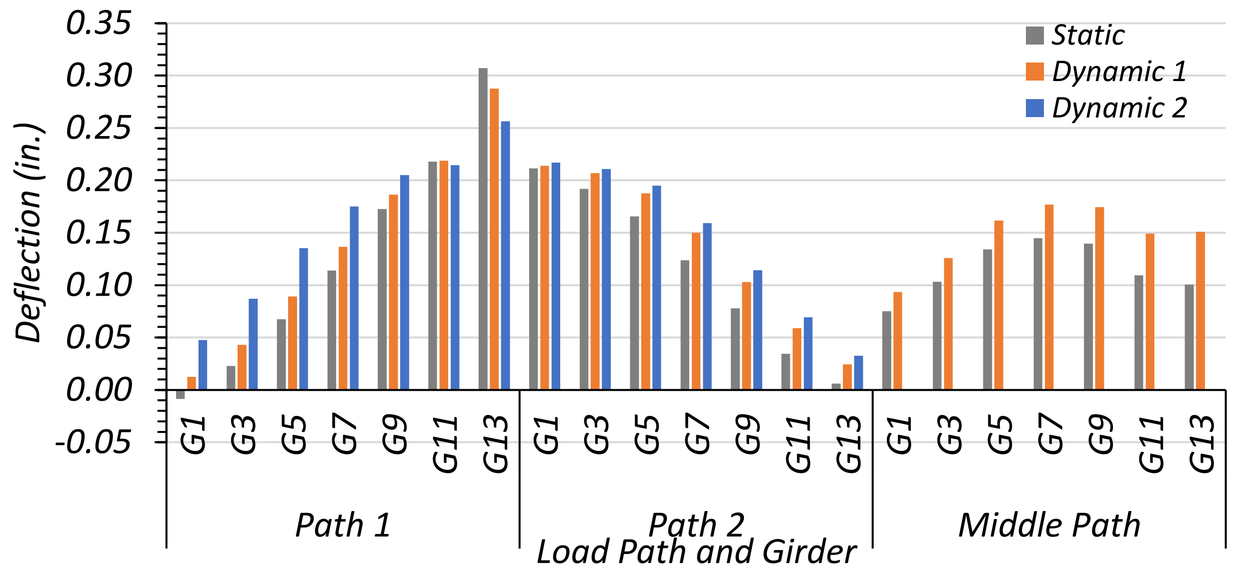
● Test ● AASHTO Standard ● AASHTO LRFD simplified
● AASHTO LRFD K_g calculated

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*

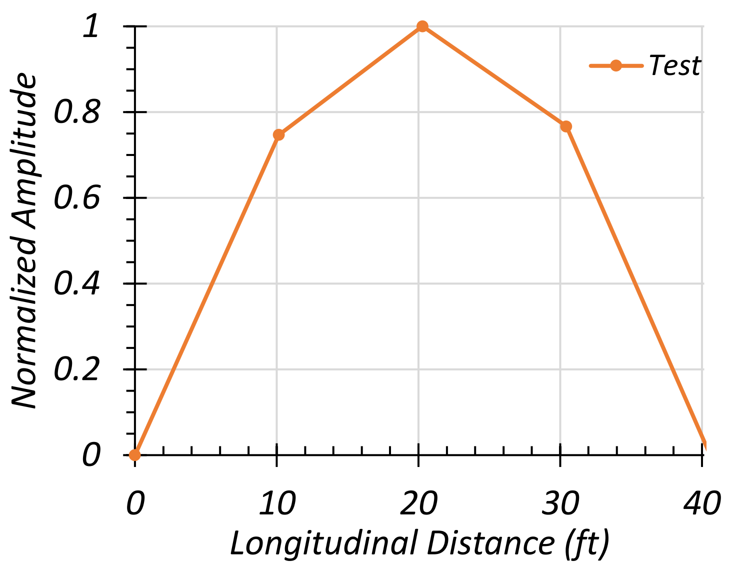
Dynamic Bridge Characteristics

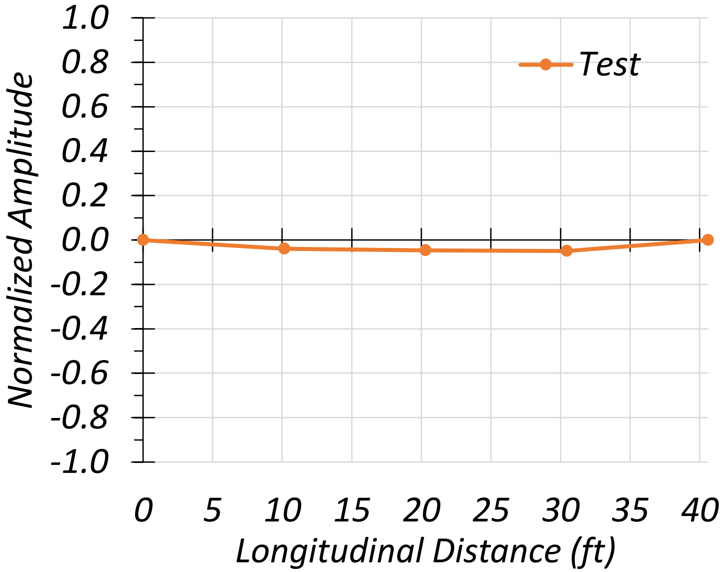
Bridge SM-5

Mode Shape 1 (f_1=7.57 Hz)

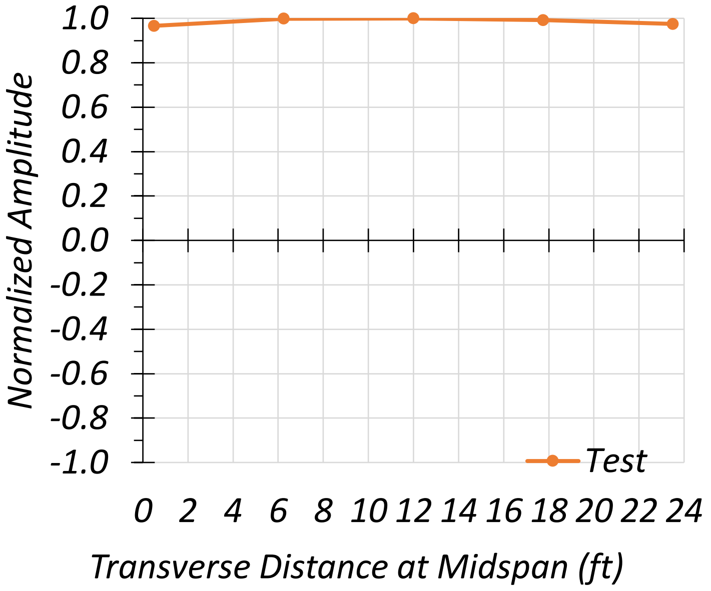
Mode Shape 2 (f_2 = 9.03 Hz)

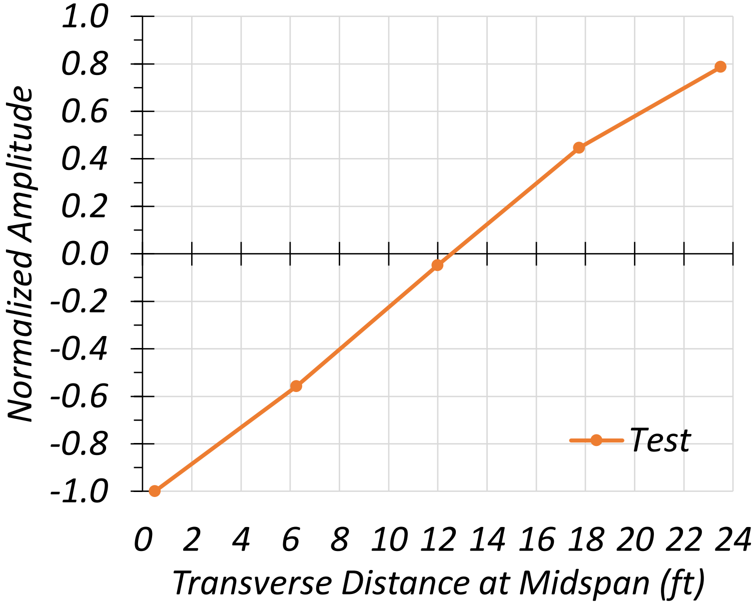
Longitudinal Section





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

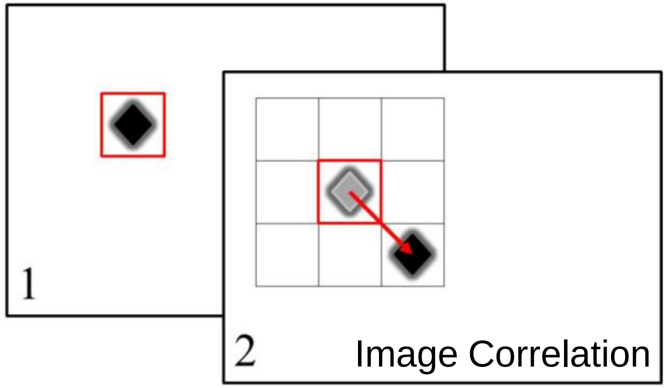
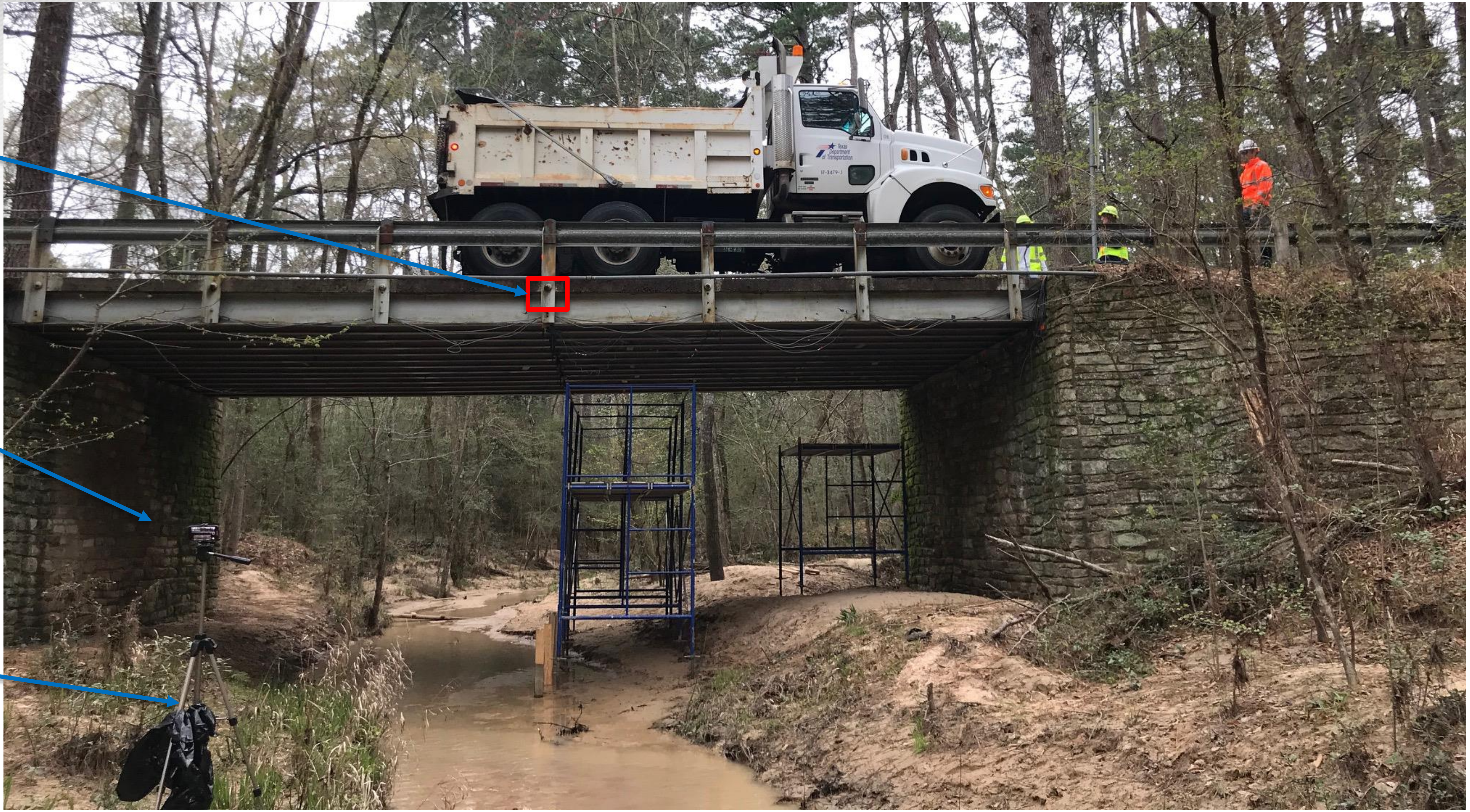


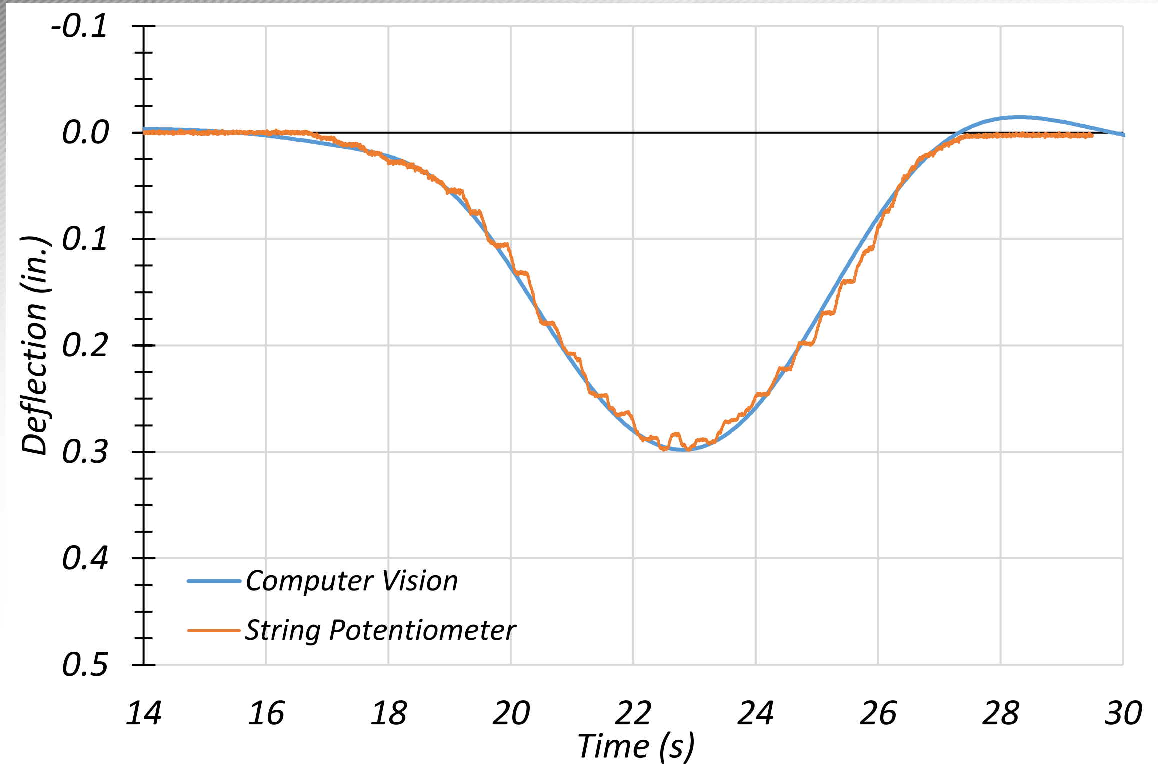
Image Correlation

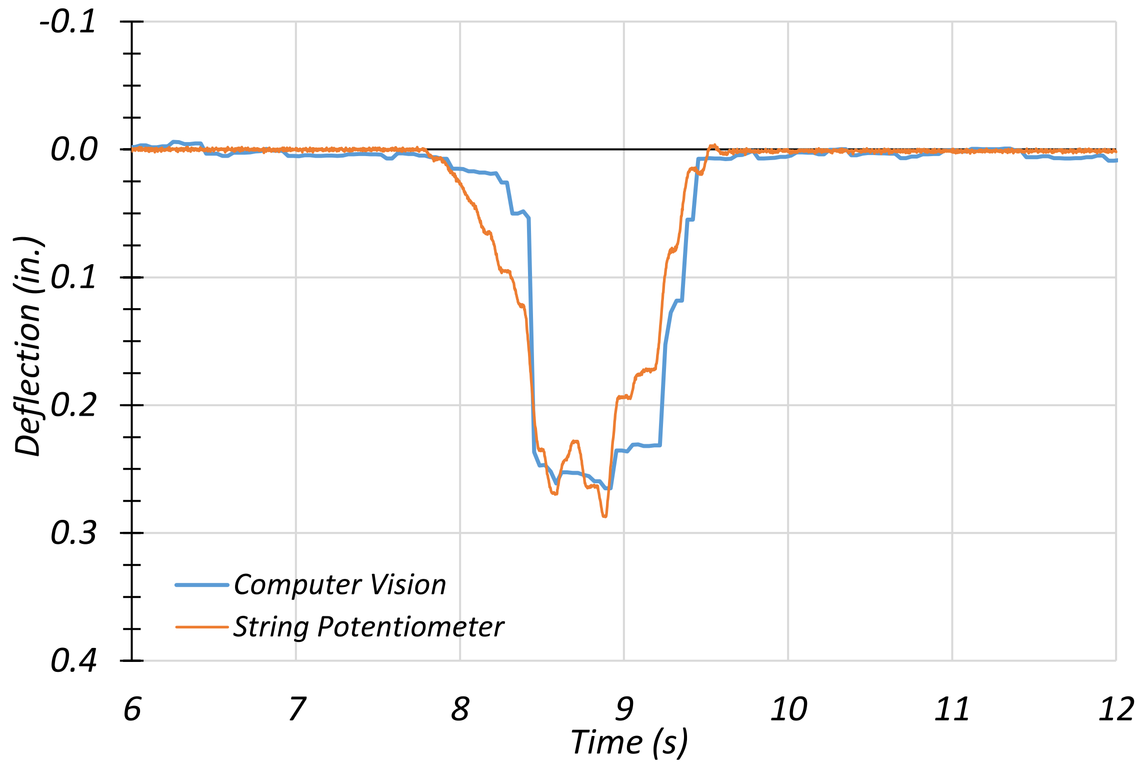
Targetless Computer Vision


Sub window
Camera
Tripod

Targetless Computer Vision Results

Bridge SM-5





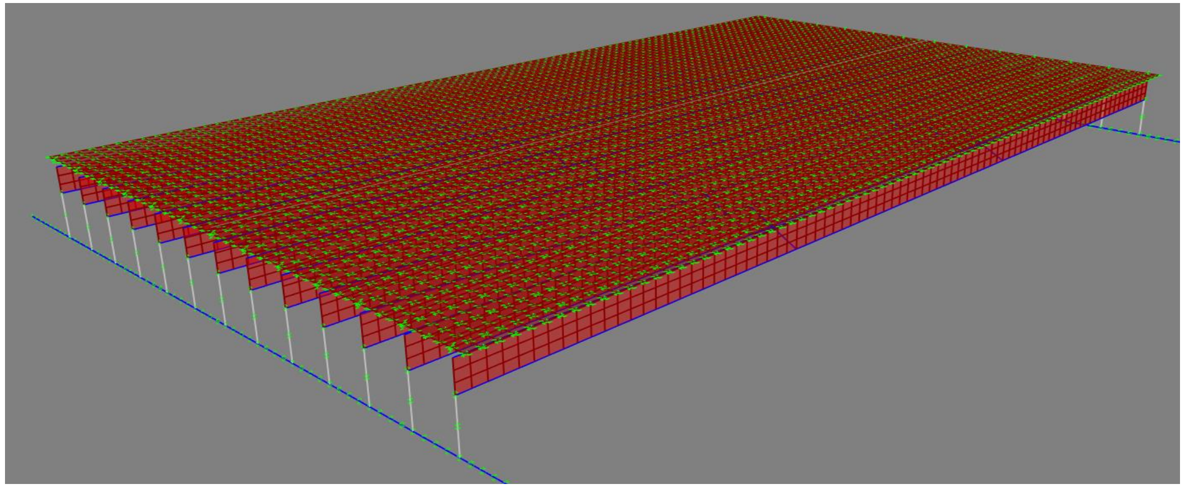
- Exterior Girder 13 – Path 1 – Crawl Speed Test
  - String Pot Deflection: 0.299 in.
  - Computer Vision Deflection: 0.298 in.
  - 0.3% Difference
  - Lowpass Butterworth filter with 600 Hz cutoff frequency

- 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

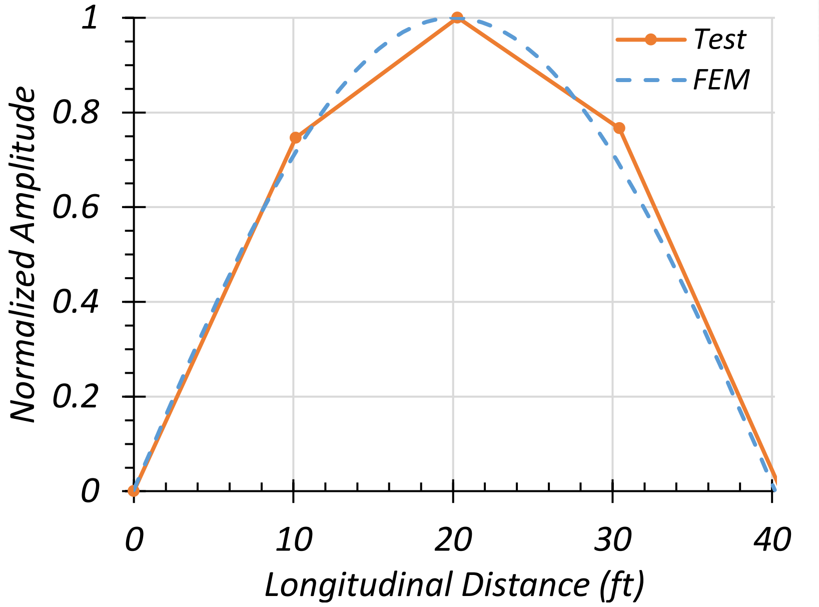


Dynamic Characteristics Comparison

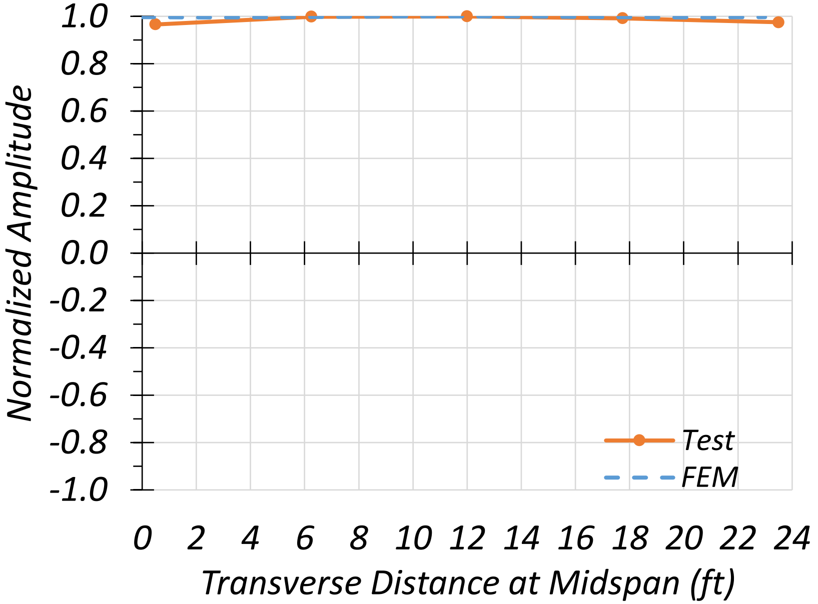
Bridge SM-5

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

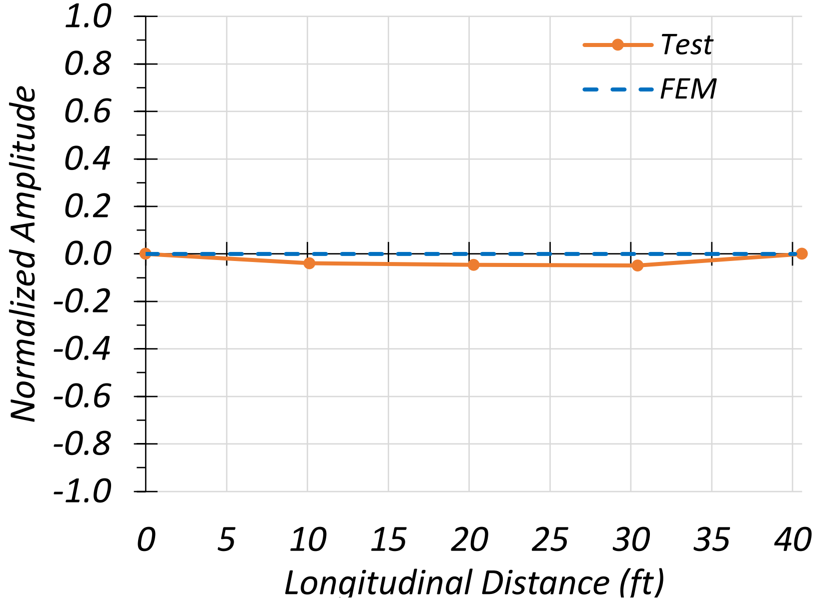
Longitudinal Section

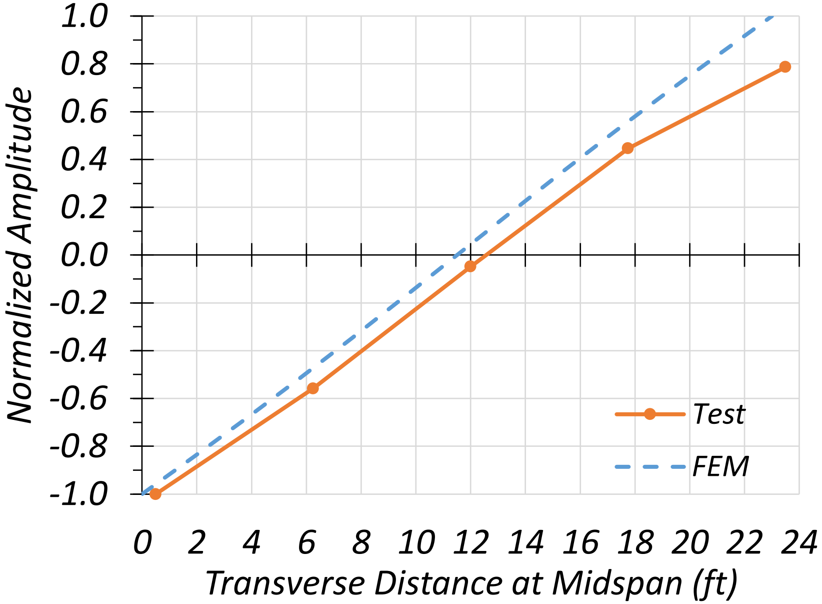


Transverse Section



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

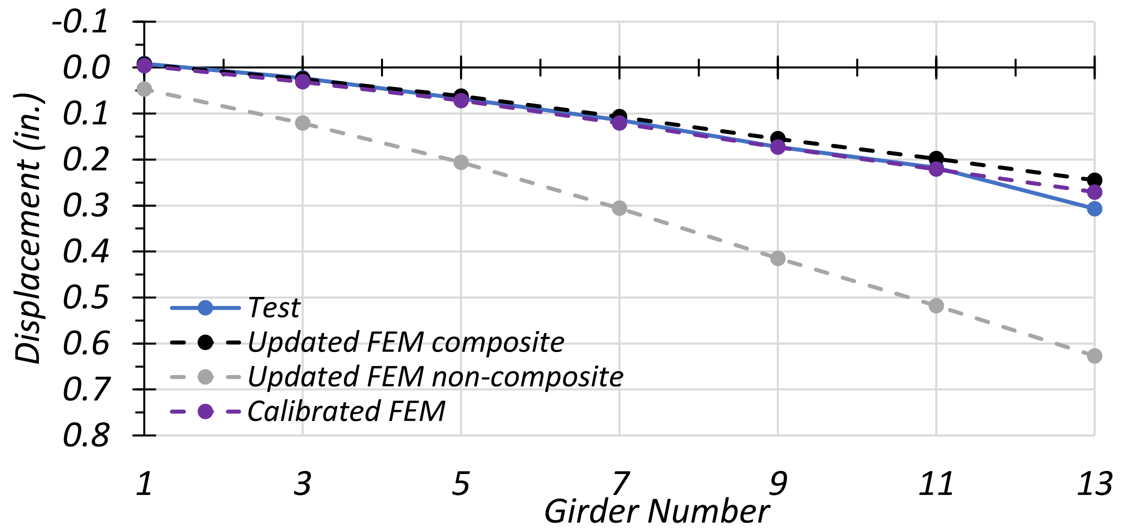




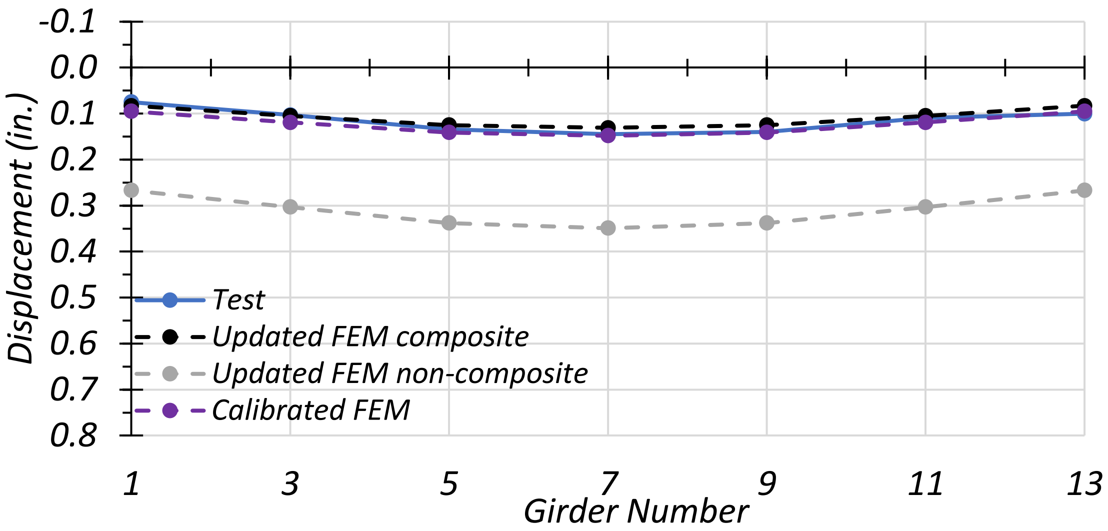
Comparison of Model and Test Results

Bridge SM-5

- Displacements - Crawl Speed Tests



Path 1 Midspan Deflections



Middle Path Midspan Deflections

Comparison of Model and Test Results

Bridge SM-5

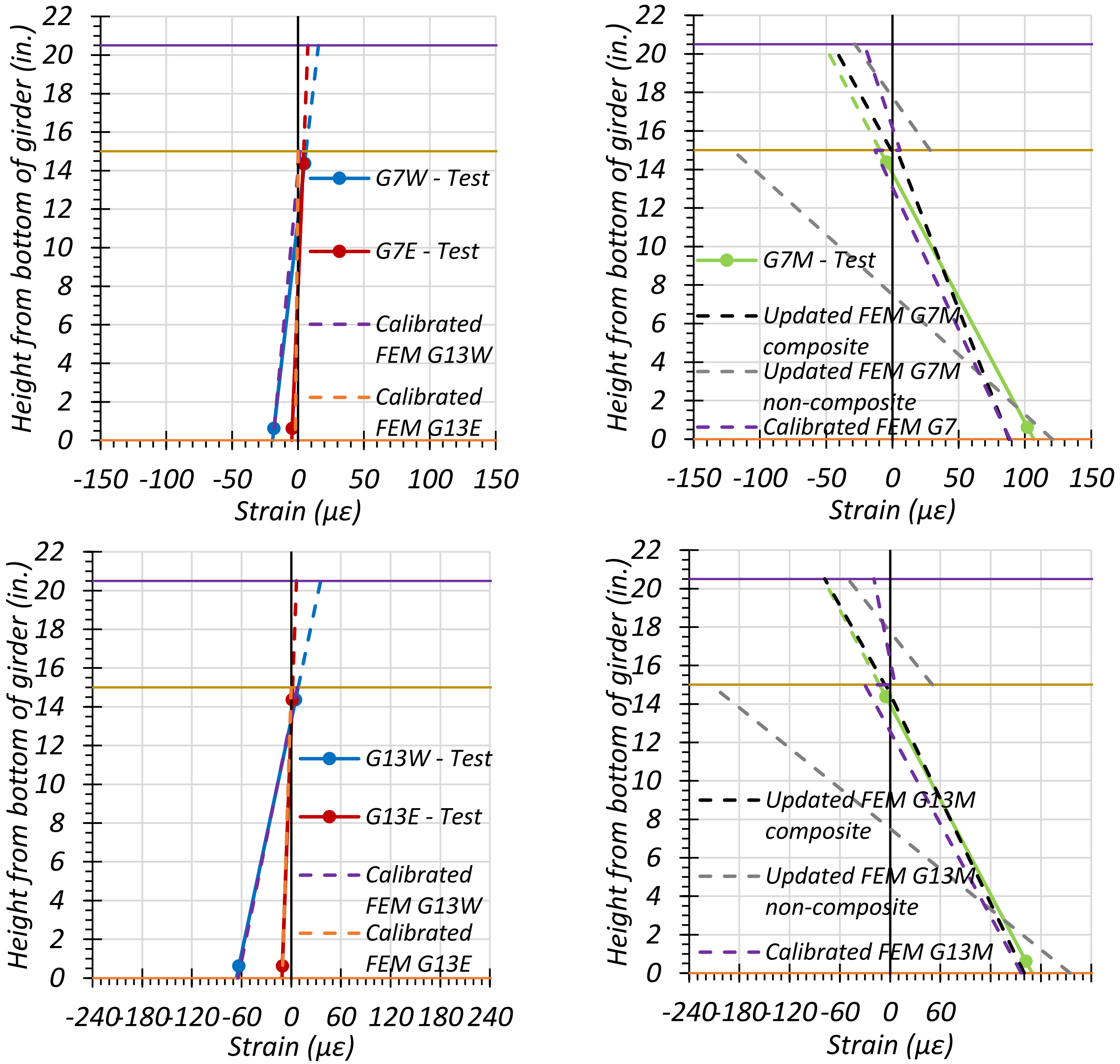
- Strains - Crawl Speed Tests

Girder Ends

Girder Midspan

G7 – Middle Path

G13 – Path 1



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

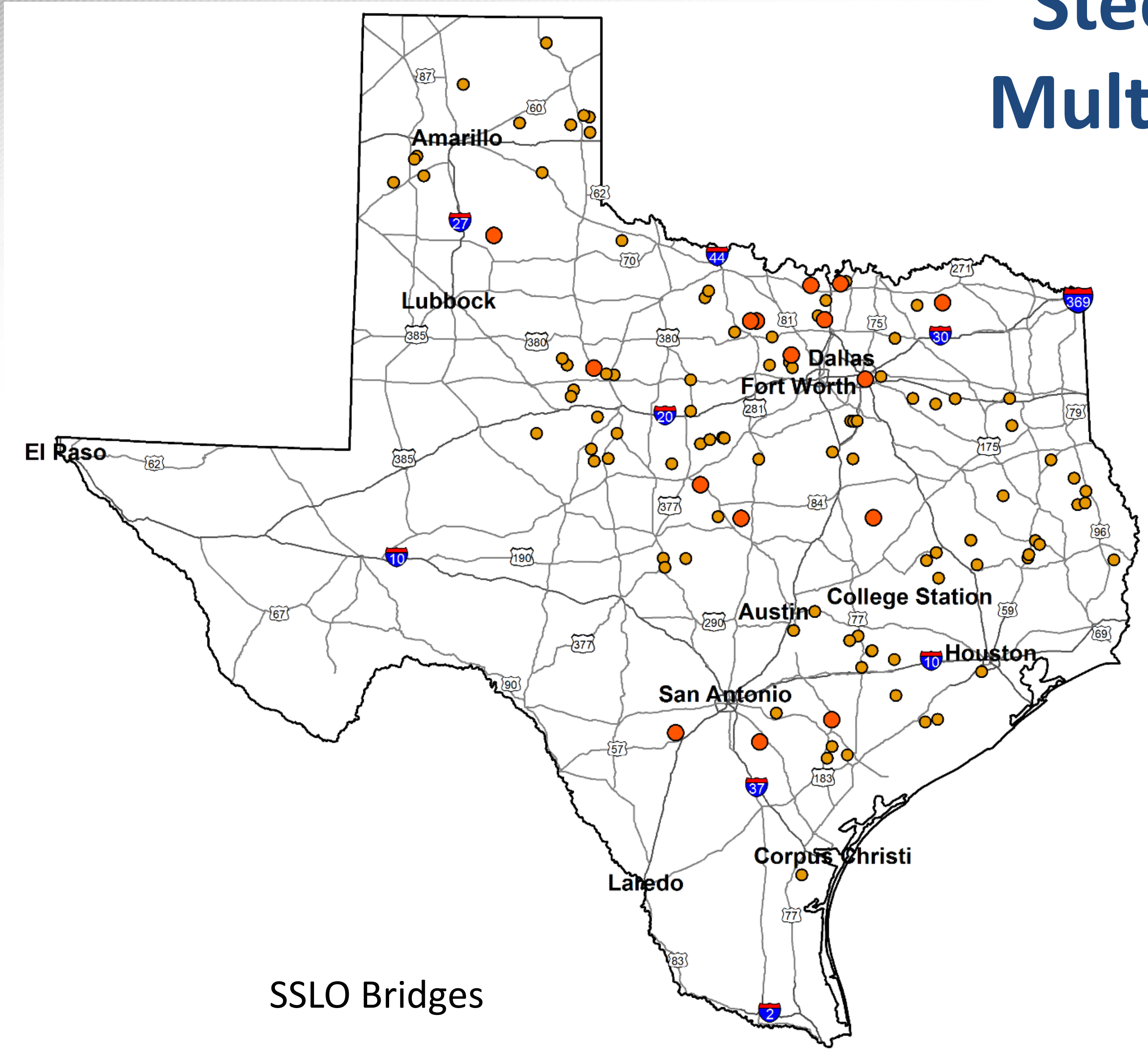
✓ *The updated RFs would allow for removal of the posting per TxDOT's load rating flowchart*

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


Amarillo
Lubbock
El Paso
Dallas
Fort Worth
Austin
College Station
Houston
San Antonio
Corpus Christi
Laredo
87
60
62
27
70
44
271
369
81
75
30
385
380
20
281
79
175
84
377
96
10
190
59
67
290
77
69
90
57
37
183
83
2

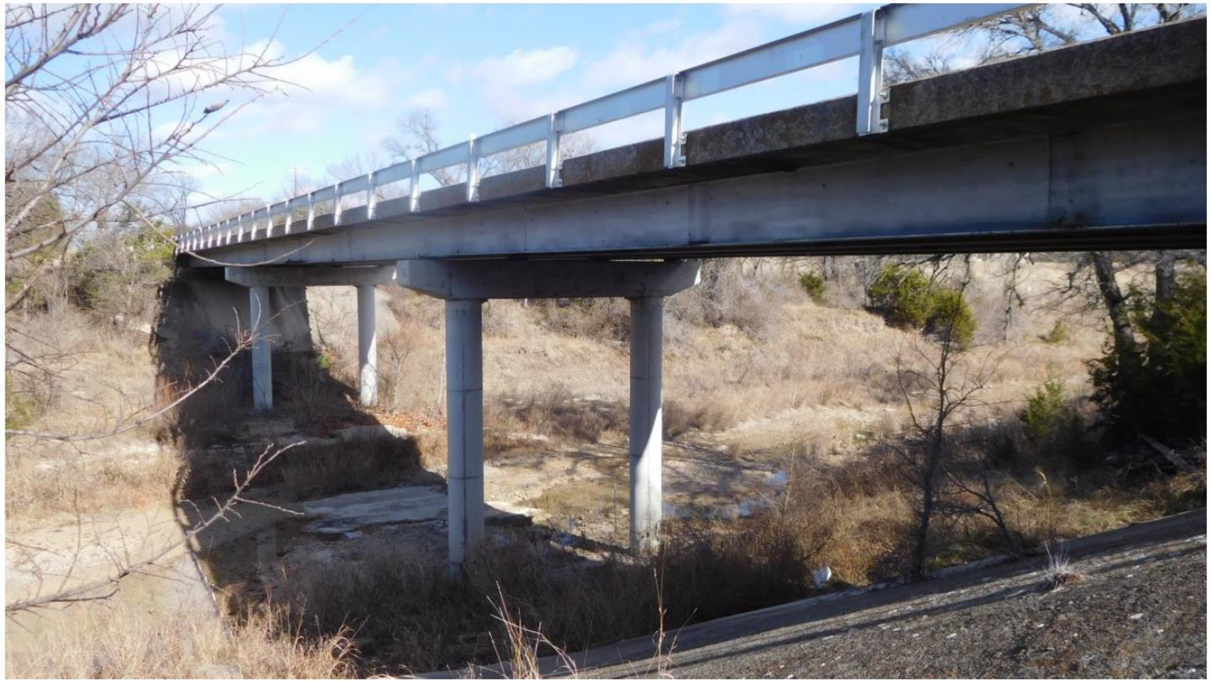
SSLO Bridges

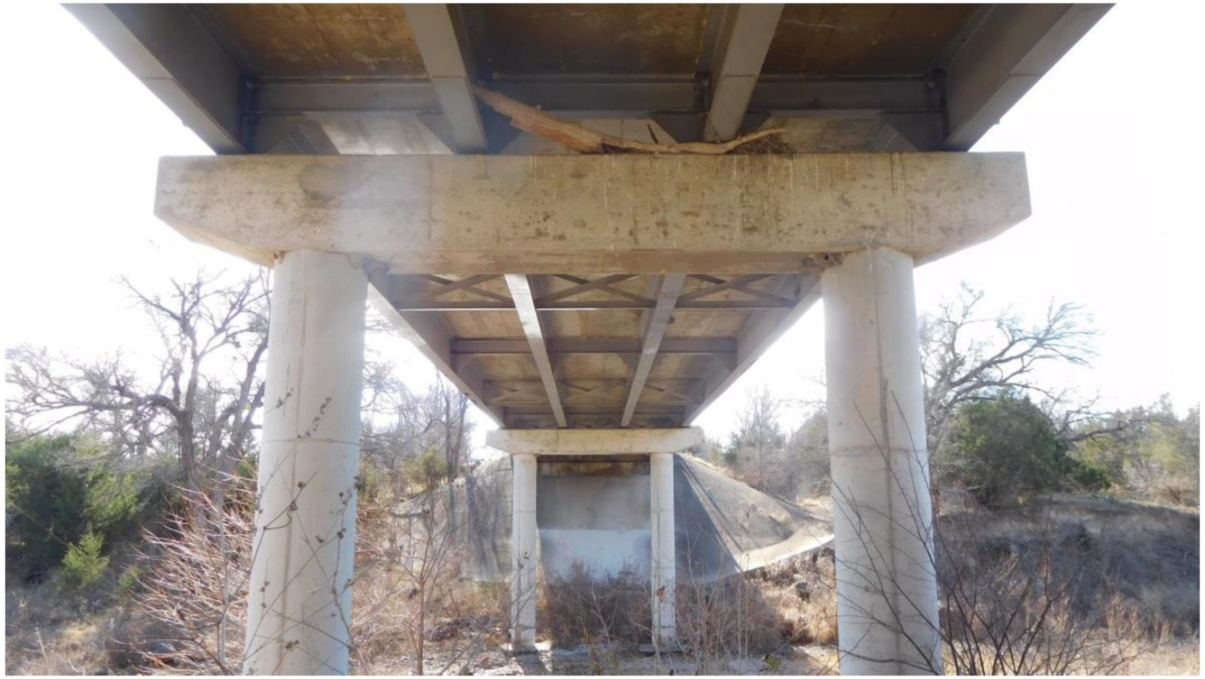
Steel Continuous Multi-Girder Bridge

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

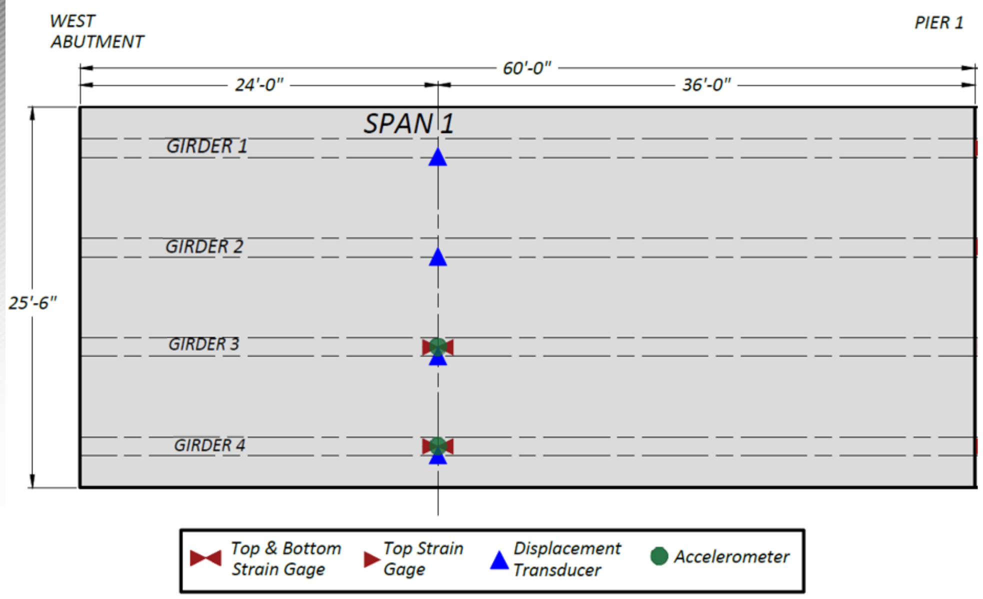
Carries FM 1047 and traverses Simms Creek near Lometa, approximately 0.9 miles northwest of FM 581

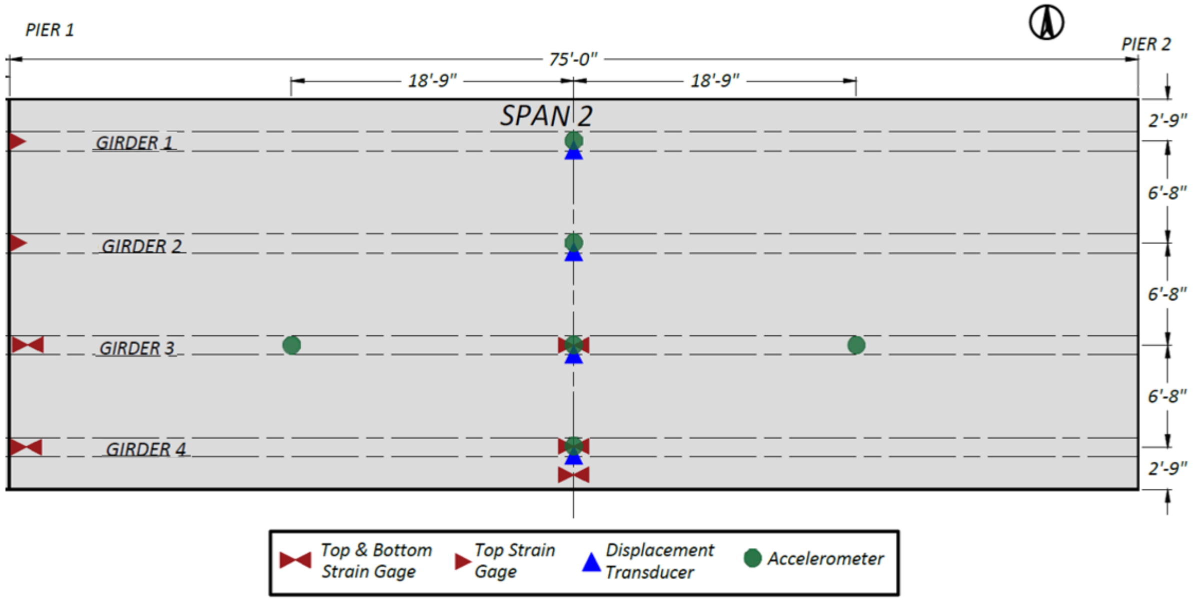




Instrumentation

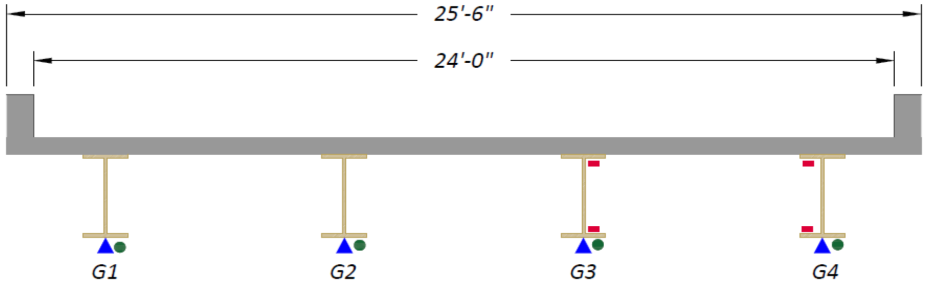
Bridge SC-12


WEST
ABUTMENT
PIER 1
60'-0"
24'-0"
36'-0"
SPAN 1
GIRDER 1
GIRDER 2
GIRDER 3
GIRDER 4
25'-6"
Top & Bottom Strain Gage
Top Strain Gage
Displacement Transducer
Accelerometer

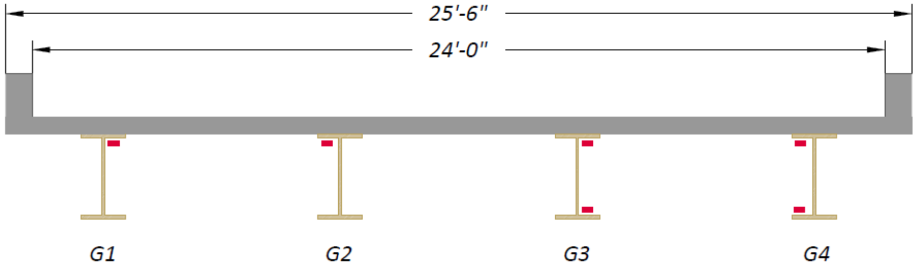

PIER 1
PIER 2
75'-0"
18'-9"
18'-9"
SPAN 2
GIRDER 1
GIRDER 2
GIRDER 3
GIRDER 4
2'-9"
6'-8"
6'-8"
6'-8"
2'-9"
Top & Bottom Strain Gage
Top Strain Gage
Displacement Transducer
Accelerometer

Span 3 not shown

Midspan – Span 2

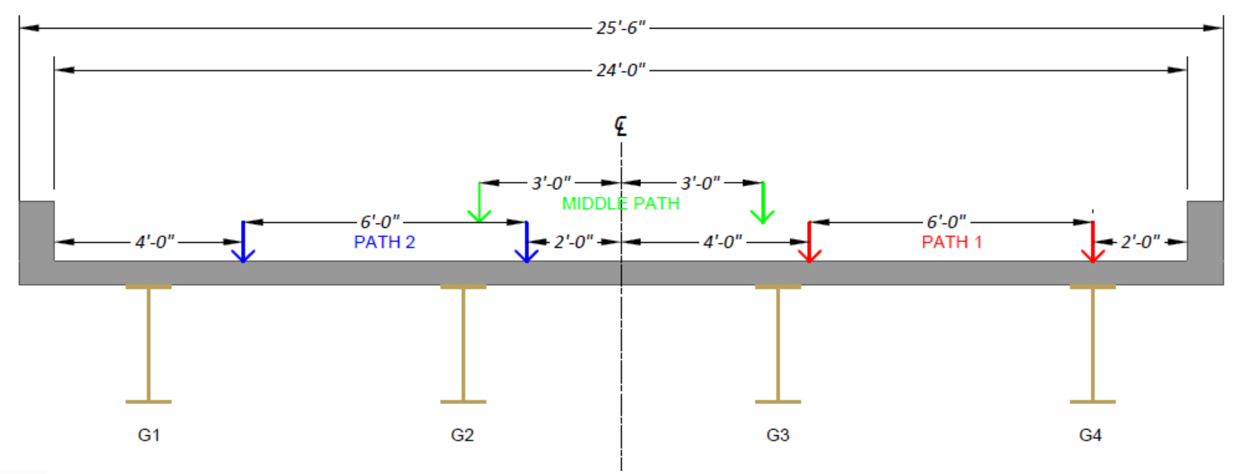

25'-6"
24'-0"
G1
G2
G3
G4

Pier 1


25'-6"
24'-0"
G1
G2
G3
G4

Test Sequence

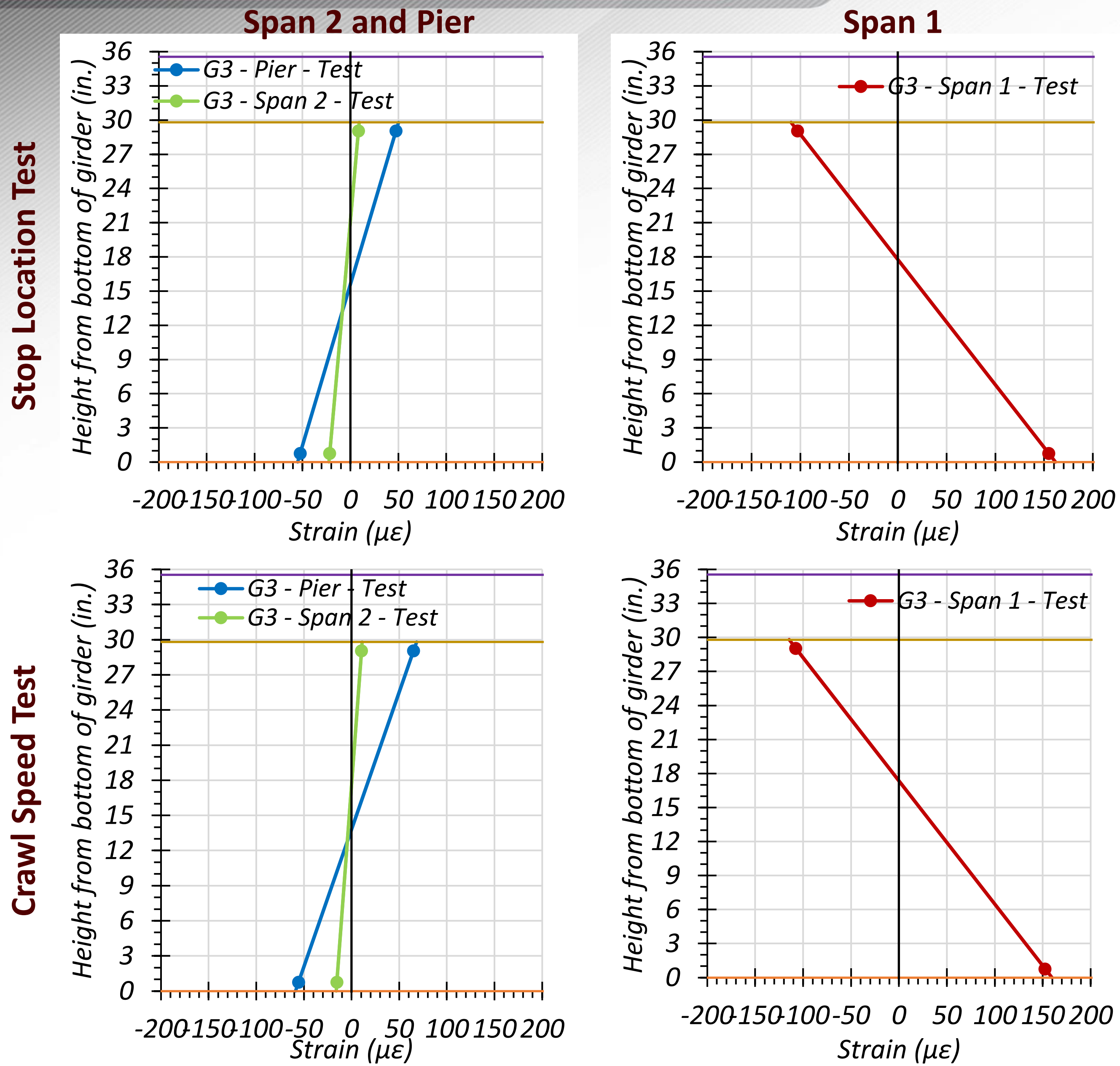
Bridge SC-12

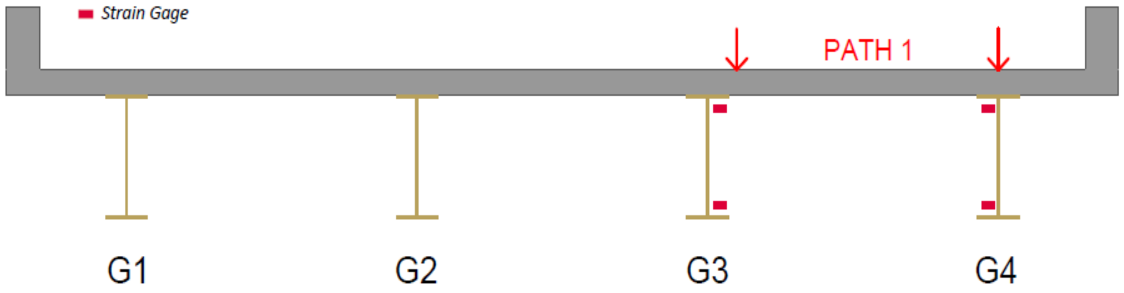


Test Number	Test Location	Test Type
1	Path 1 – Span 1	Static – Stop Location
2	Path 1 – Span 2	Static – Stop Location
3	Path 1	Static – Crawl (2 mph)
4	Path 1	Dynamic (30 mph)
5	Path 1	Dynamic (37 mph)
6	Path 2 – Span 1	Static – Stop Location
7	Path 2 – Span 2	Static – Stop Location
8	Path 2	Static – 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



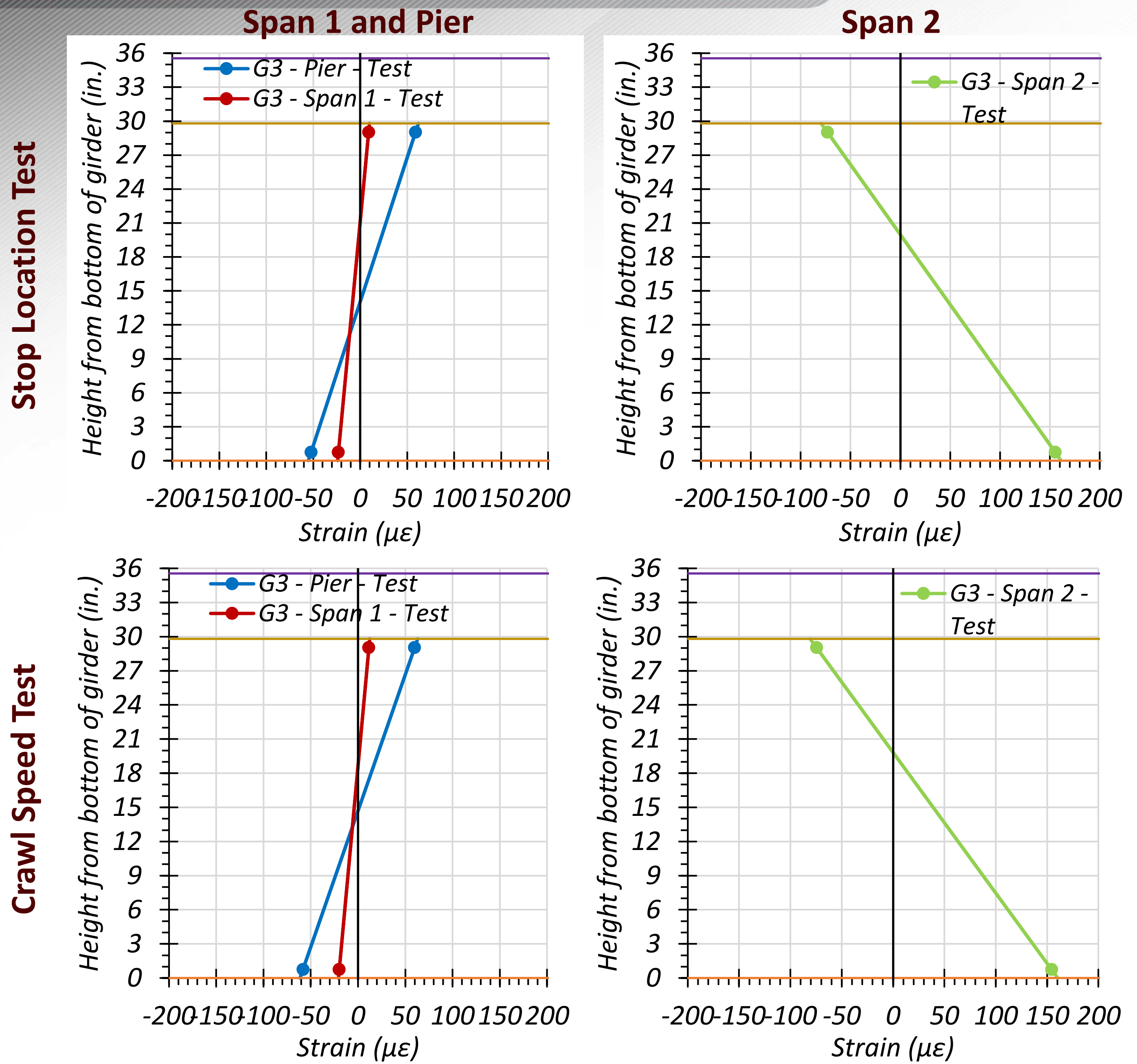


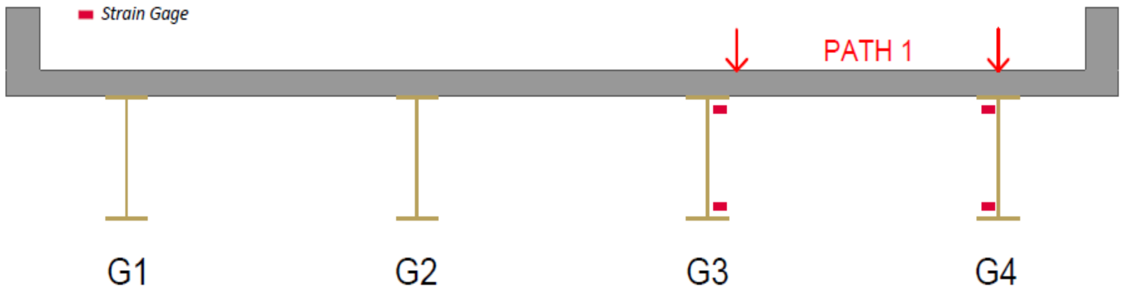
- Positive Bending Neutral Axis Locations
  - Stop Location: 17.77 in.
  - Crawl Speed: 17.34 in.
  - *Theoretical Non-Composite: 14.90 in.*
  - *Theoretical Composite: 26.11 in.*
- Maximum Bottom Flange Strains/Stresses
  - Span 1: 154.9 με → 4.49 ksi
  - Pier 1: -55.6 με → -1.61 ksi
  - Span 2: -21.6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

Tension is positive

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

Bridge SC-12





- 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.*

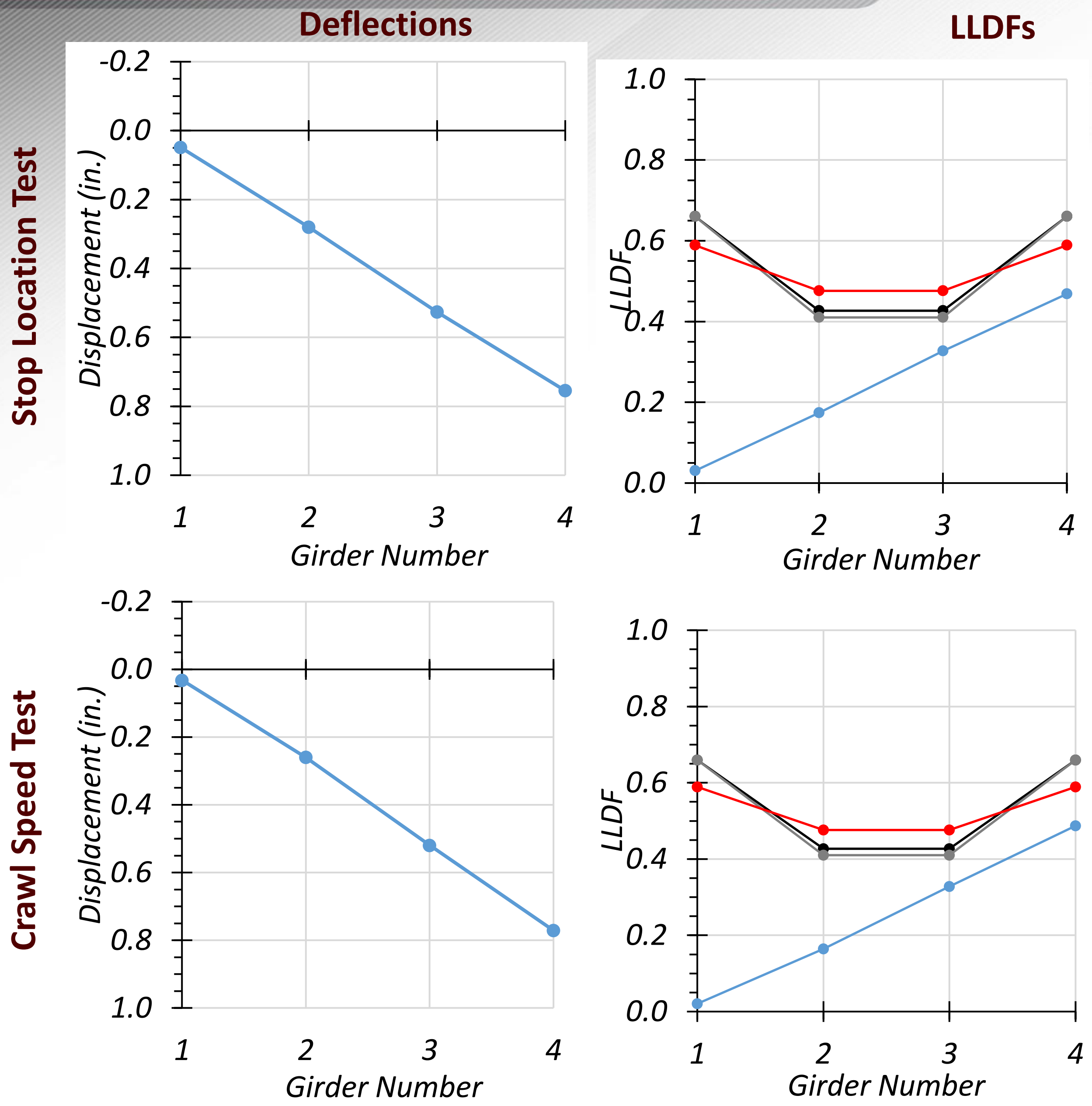
Partial composite action

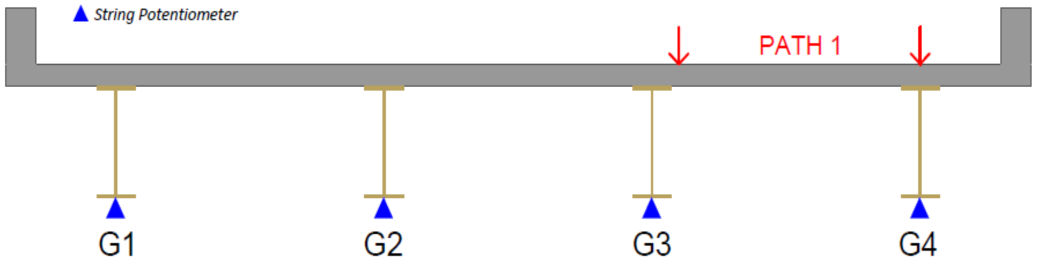
- Maximum Bottom Flange Strains/Stresses
  - Span 2: 155.1 με → 4.50 ksi
  - Pier 1: -58.2 με → -1.69 ksi
  - Span 1: -23.1 με → -0.67 ksi

Tension is positive

Deflection Results
Span 2, Path 1 – Static Tests

Bridge SC-12



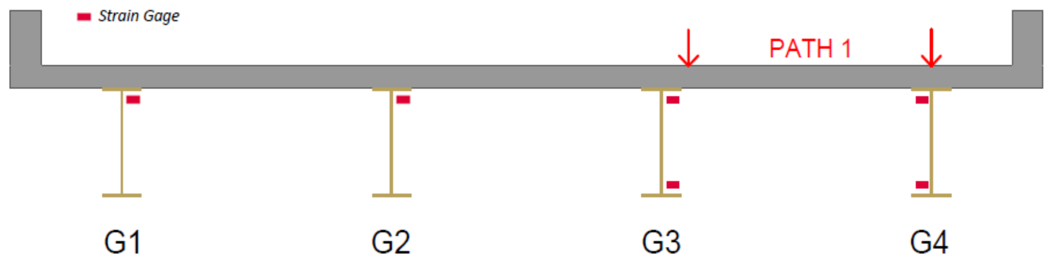


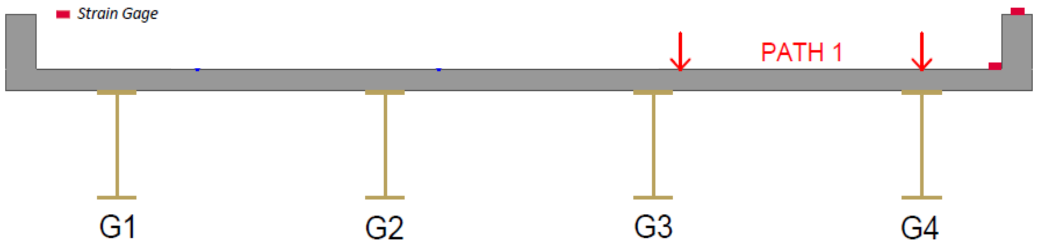
Test and Girder Type	AASHTO Standard Specs ($g^m_{AASHTO\_Std}$)	AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$)	AASHTO LRFD K_g Calculated ($g^m_{AASHTO\_K}$)	Test (g^m_{test})	$g^m_{AASHTO\_Std}/g^m_{test}$	$g^m_{AASHTO\_S}/g^m_{test}$	$g^m_{AASHTO\_K}/g^m_{test}$
Stop Location Interior	0.476	0.427	0.410	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

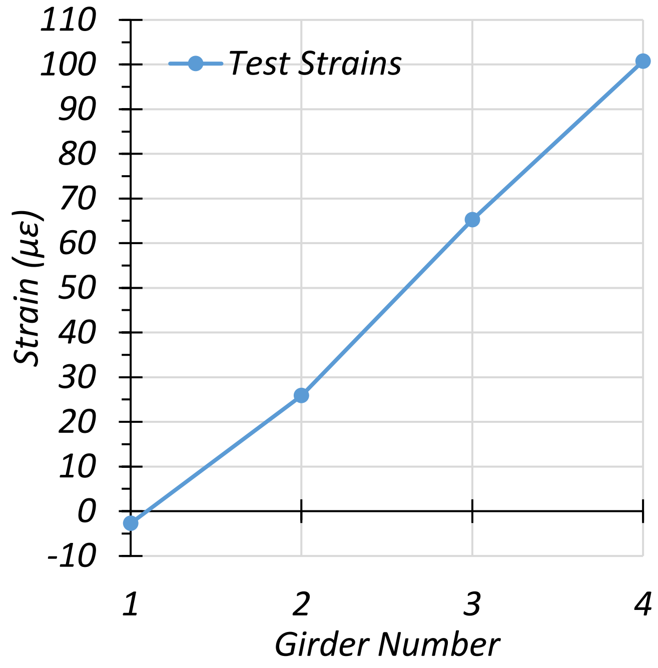
● Test ● AASHTO Standard ● AASHTO LRFD simplified
● AASHTO LRFD K_g calculated

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

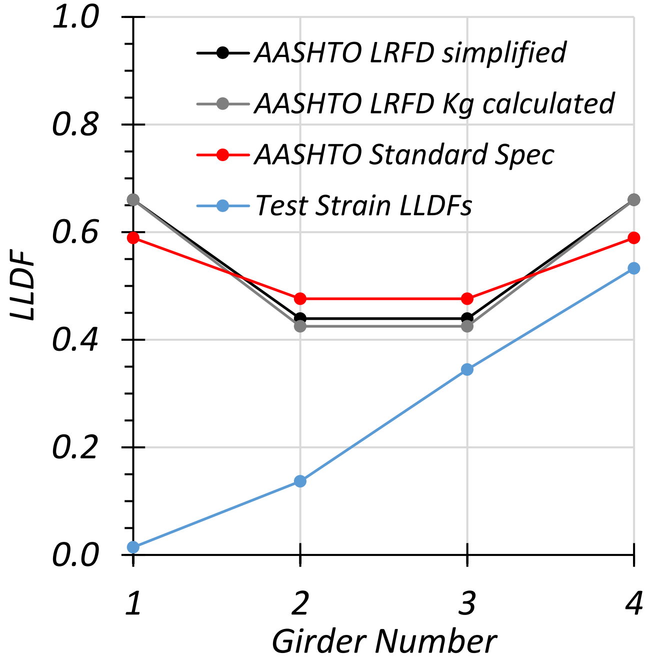
Bridge SC-12


Strain Gage
PATH 1
G1
G2
G3
G4

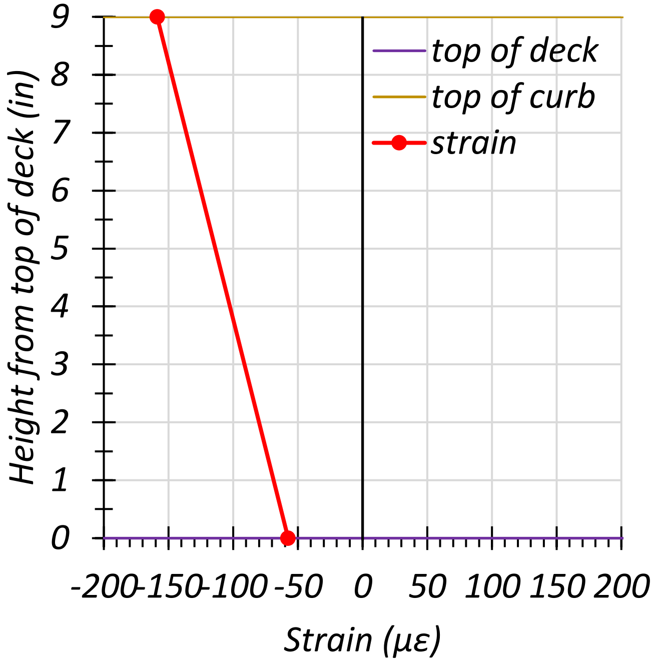

Strain Gage
PATH 1
G1
G2
G3
G4



Top Flange Strains



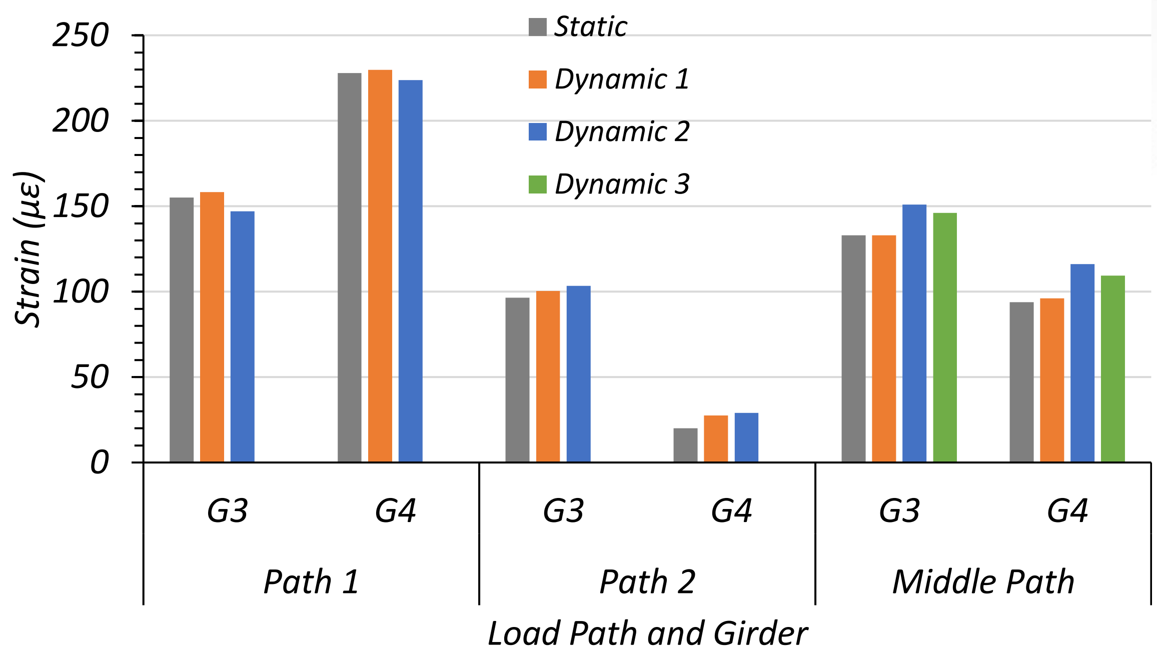
Negative Moment LLDFs

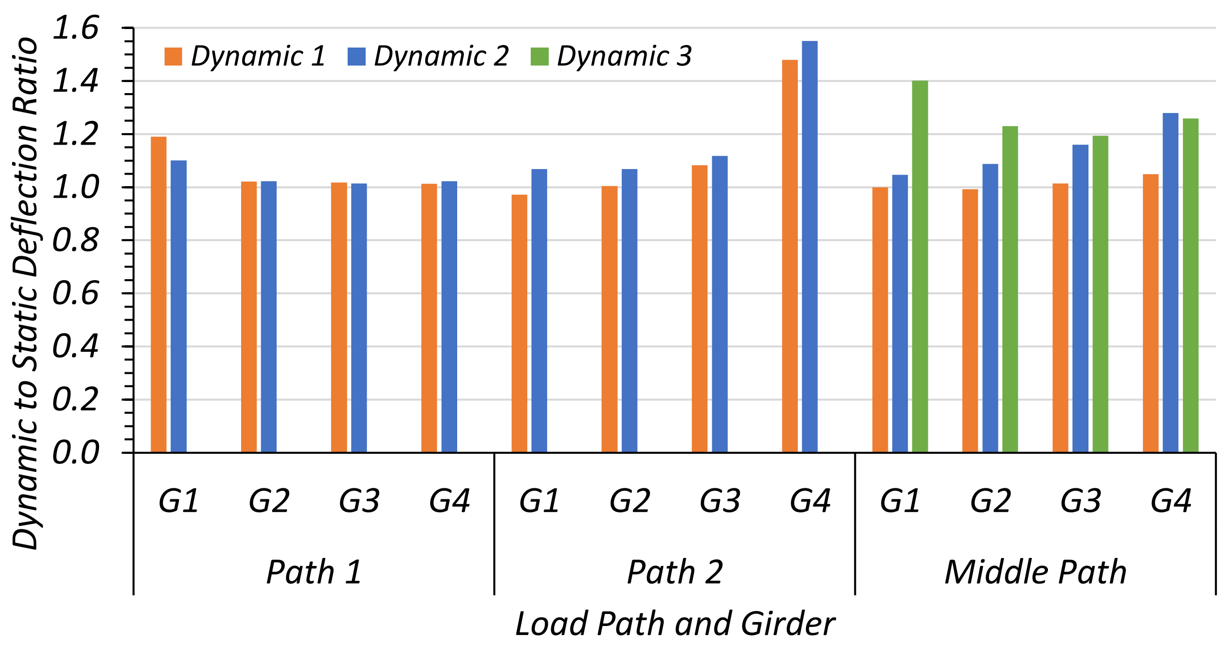


Curb Strain Results

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%

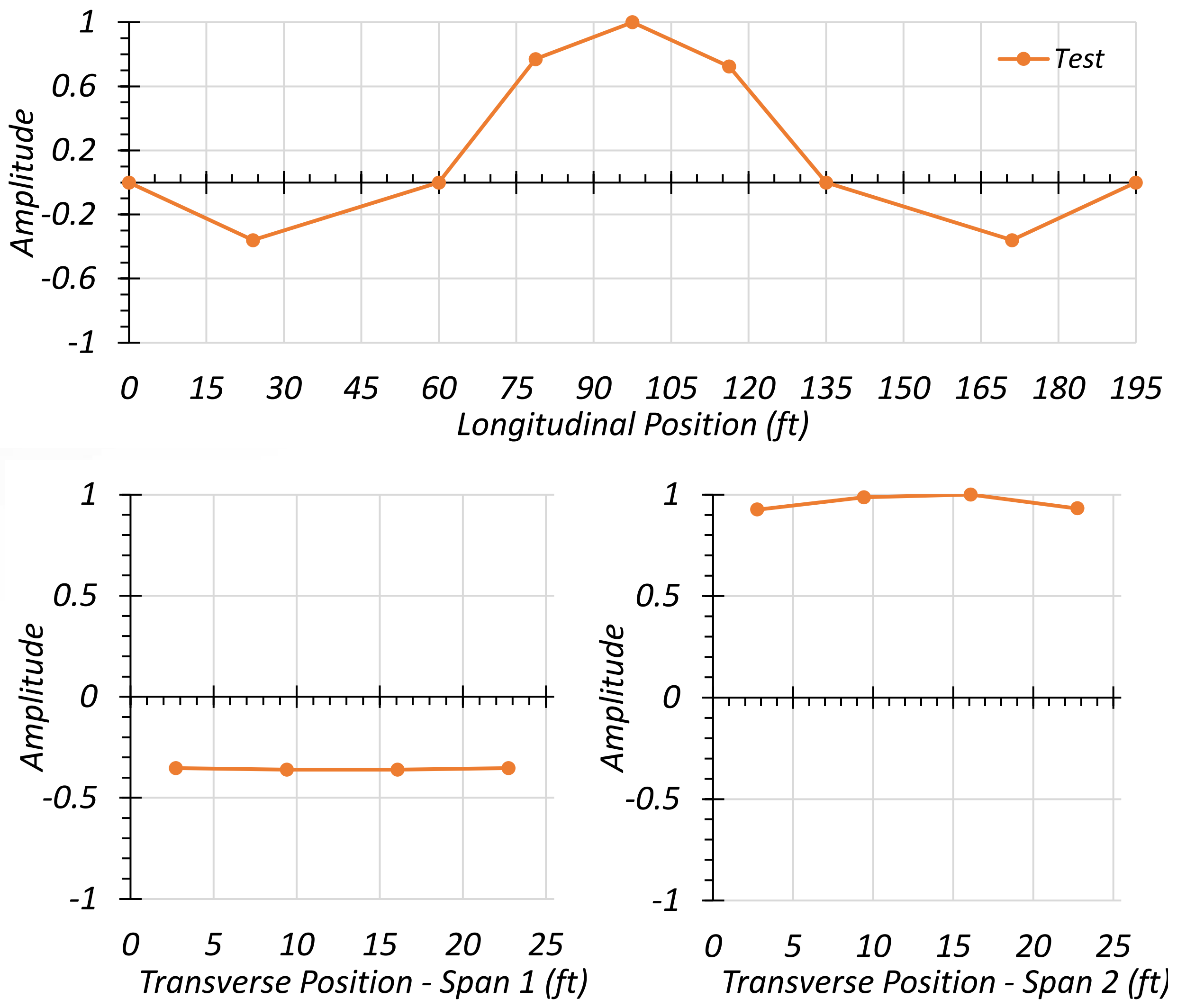
- Average dynamic increase for both girders: 12%
- AASHTO Standard Specifications IM:25%
- AASHTO LRFD Specifications IM: 33%

Note:

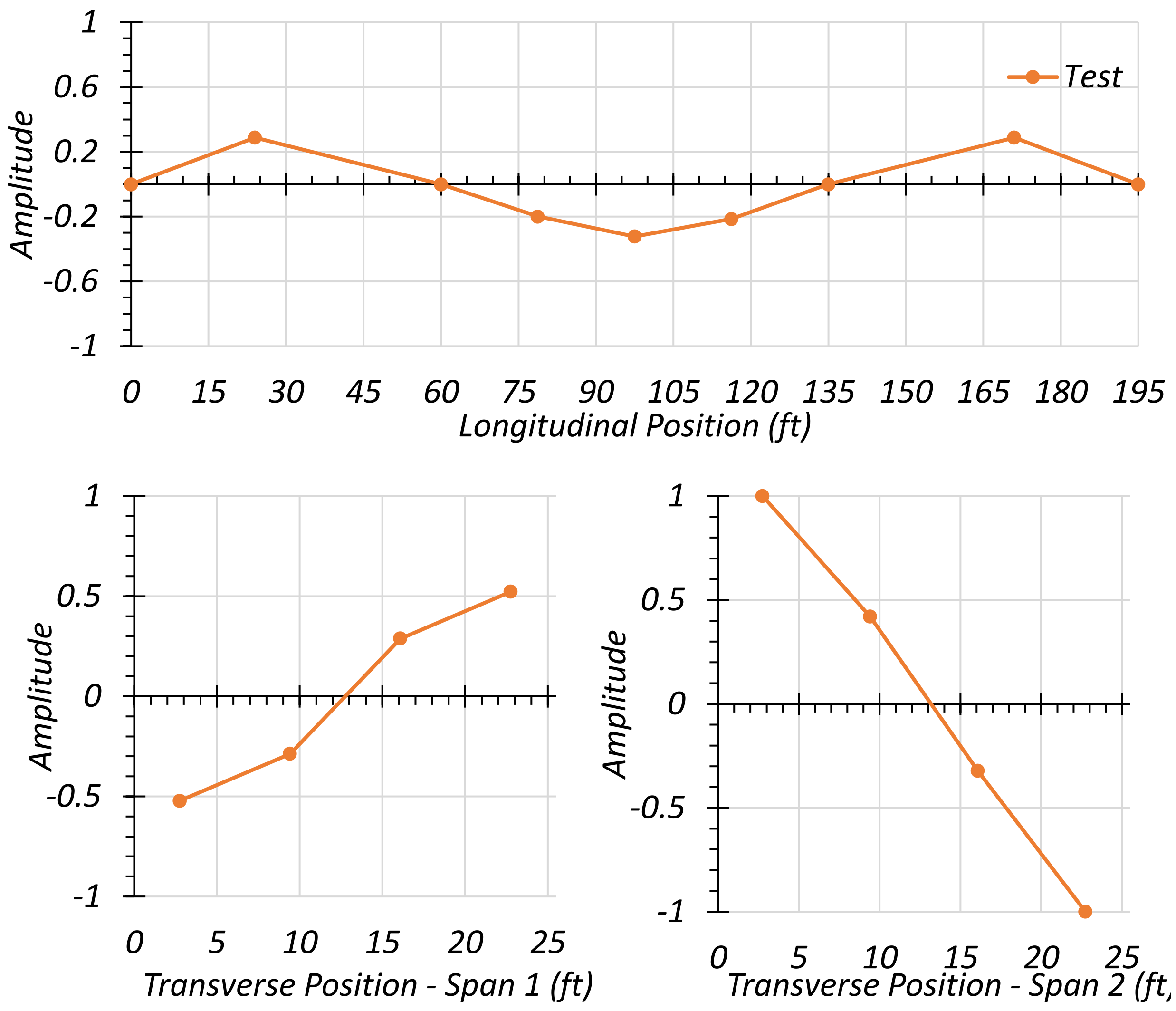
- *Path 1: Dynamic 1 = 30 mph, Dynamic 2 = 37 mph*
- *Path 2: Dynamic 1 = 29 mph, Dynamic 2 = 44 mph*
- *Middle Path: Dynamic 1 = 30 mph, Dynamic 2 = 44 mph, Dynamic 3 = 57 mph*

Dynamic Bride Characteristics

Bridge SC-12



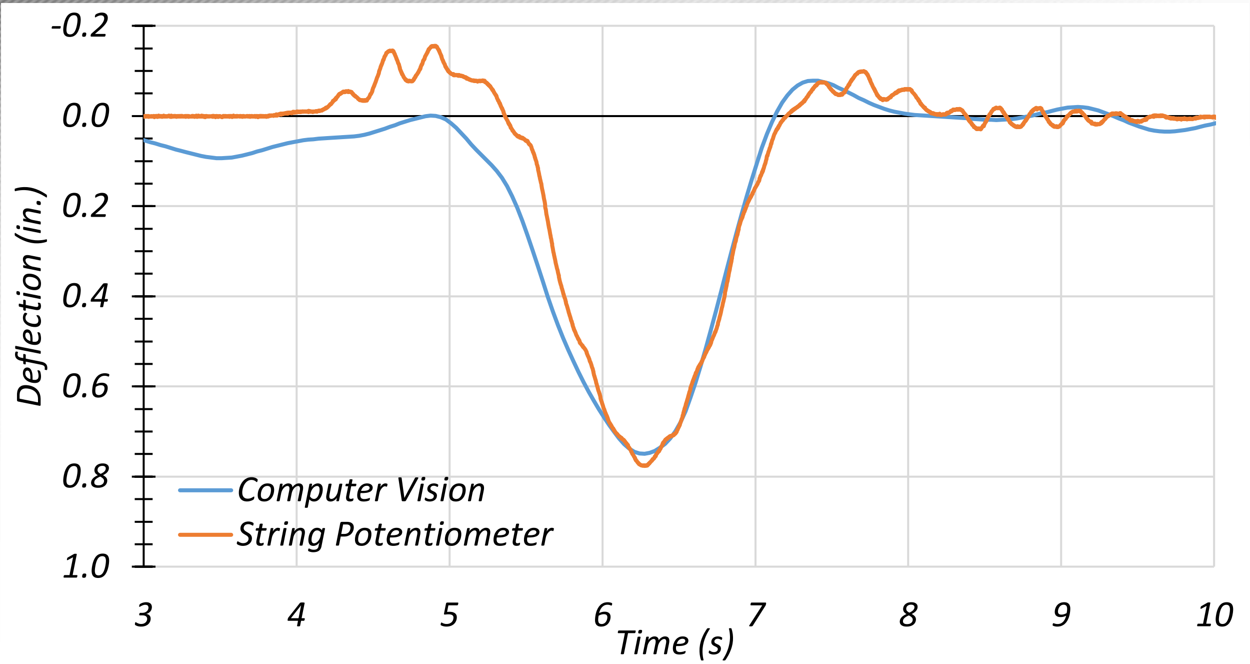
Mode Shape 1 (3.78 Hz)

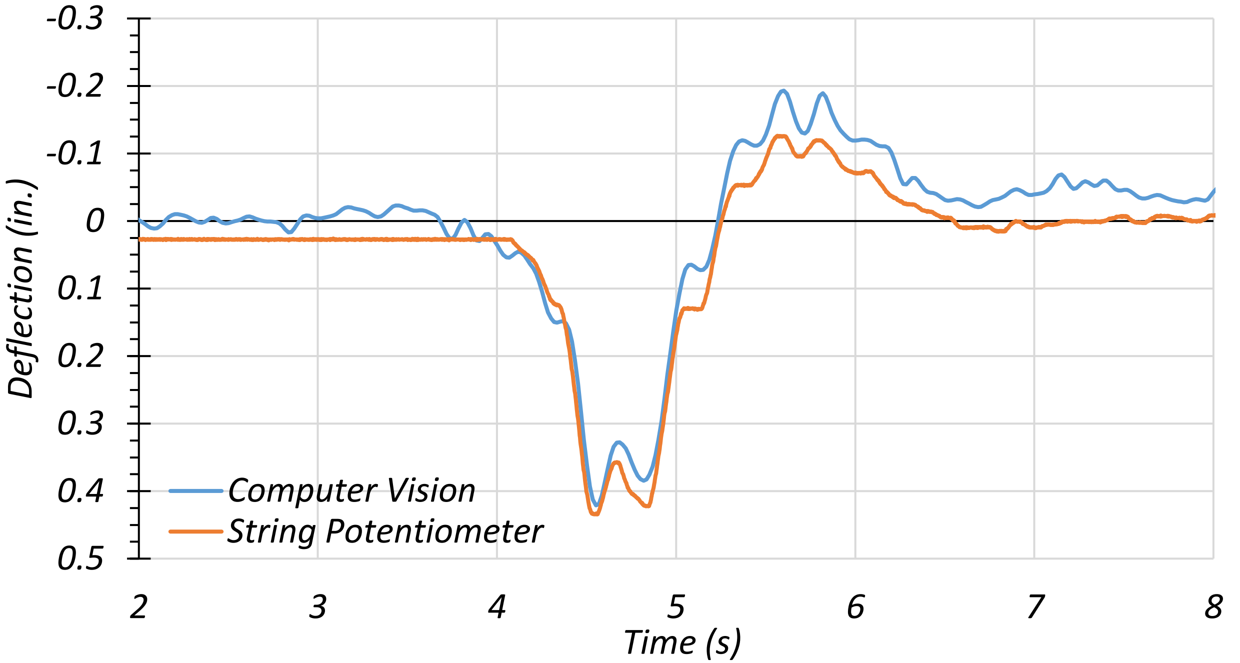


Mode Shape 2 (6.71 Hz)

Computer Vision Results

Bridge SC-12





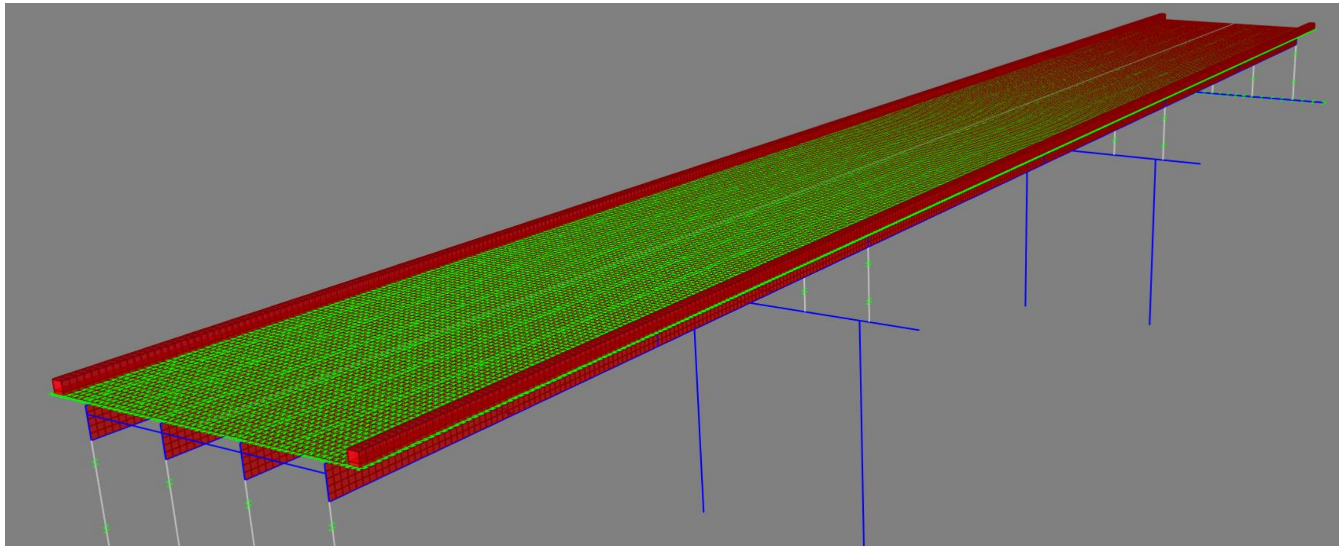
- Girder 4 – Path 1 – Span 2 – Dynamic Test at 30 mph
  - String Pot Deflection: 0.776 in.
  - Computer Visions Deflection: 0.750 in.
  - 3.4% Difference
  - Lowpass Butterworth filter with 300 Hz cutoff frequency

- 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

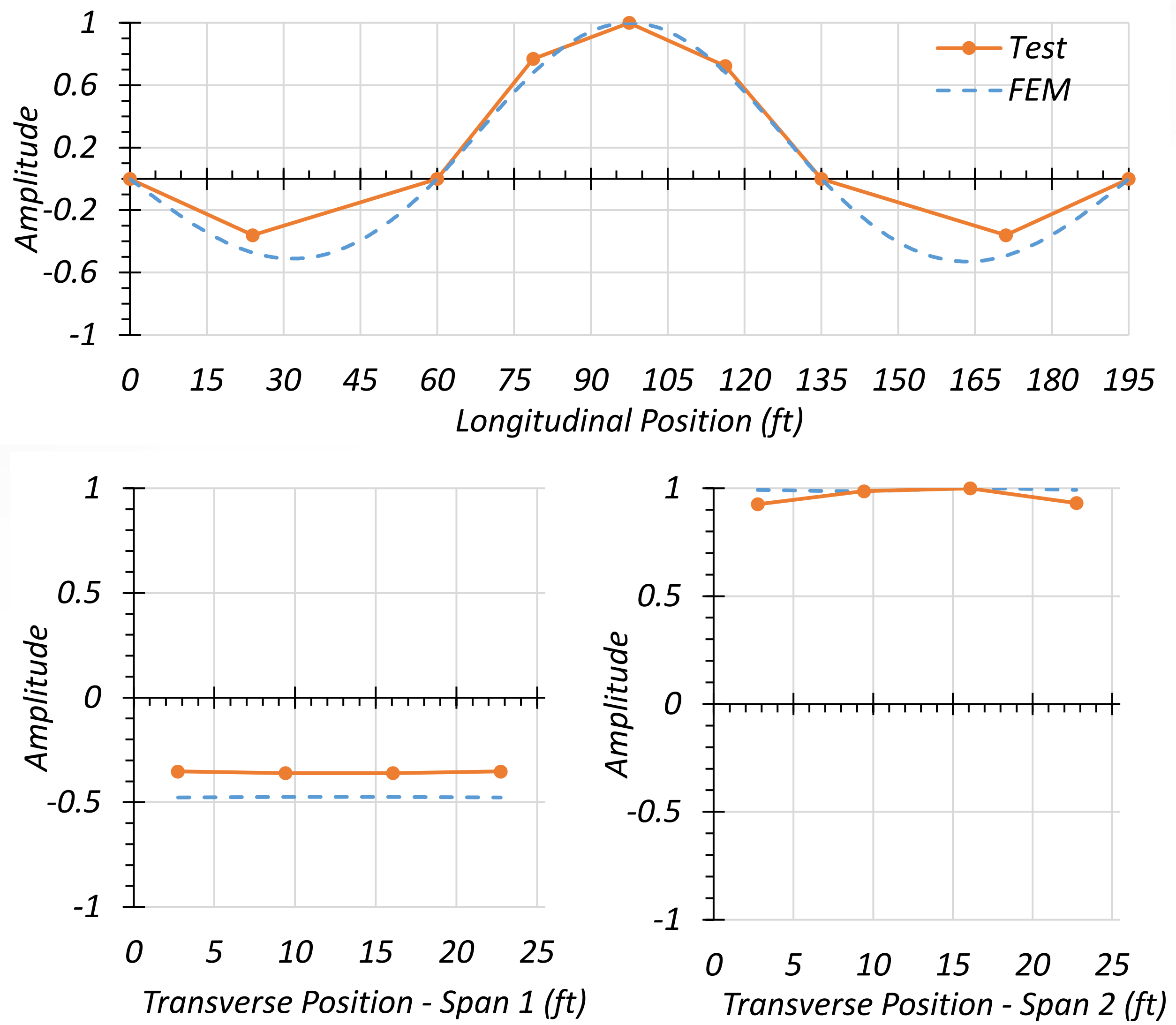
Bridge SC-12

- 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

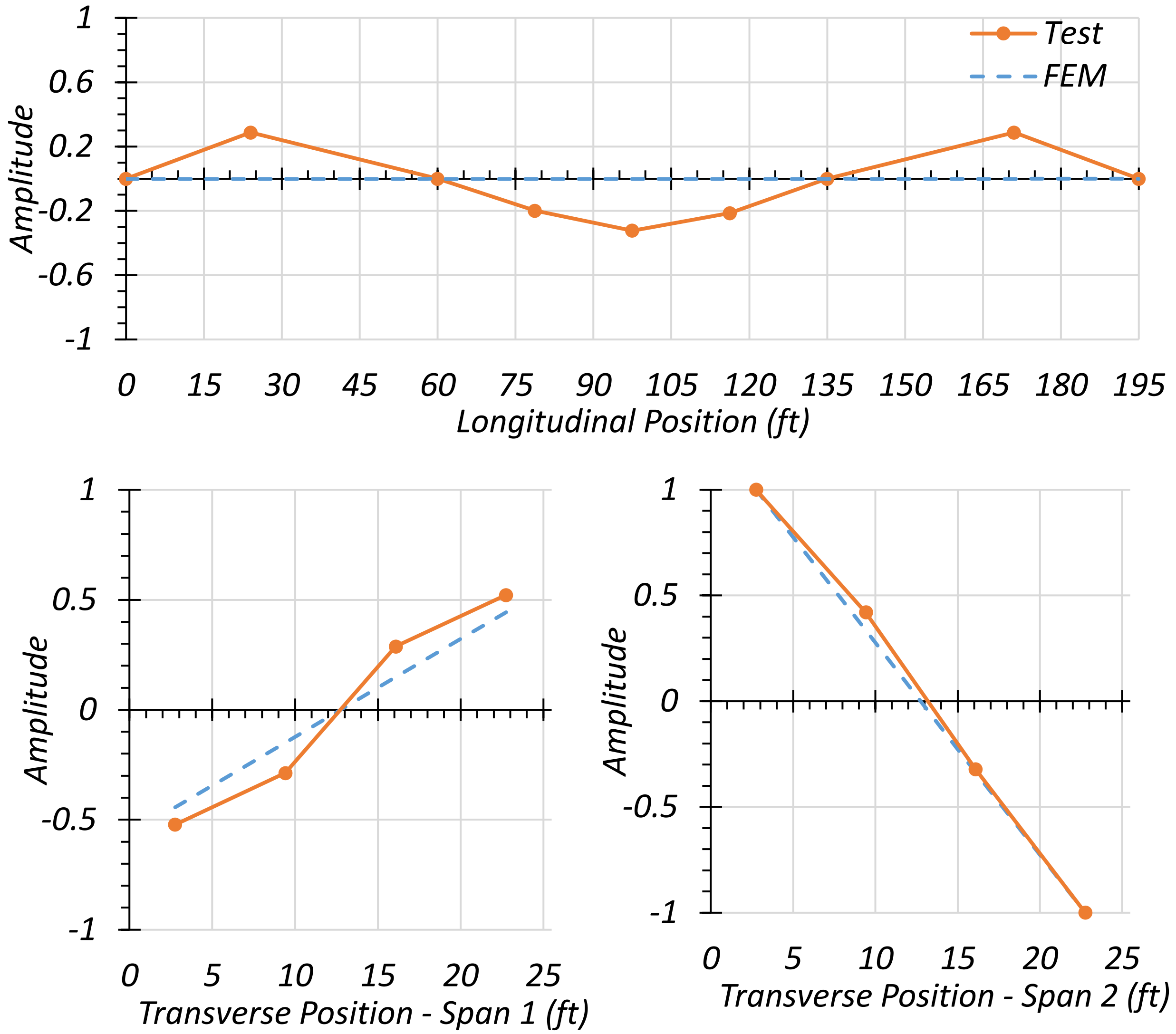


Dynamic Characteristics Comparison

Bridge SC-12



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



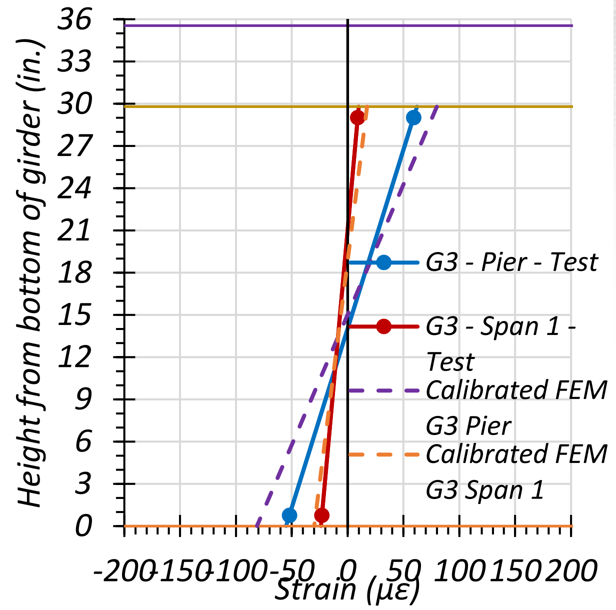
2nd Mode (Test = 6.71 Hz, FEM = 5.95 Hz)

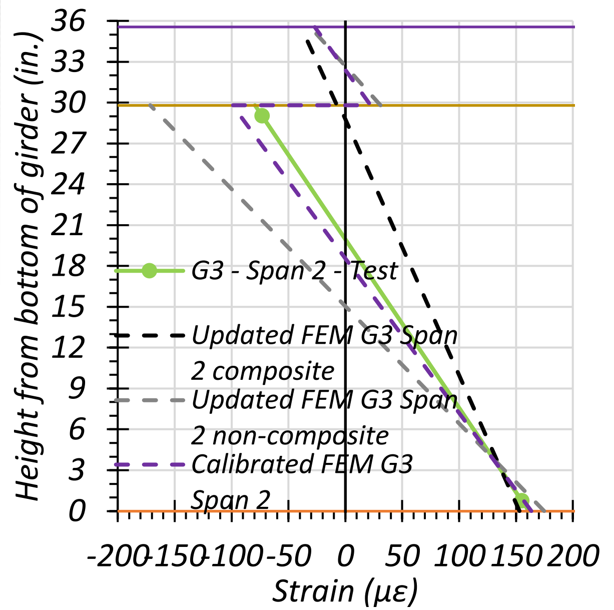
Comparison of Model and Test Results – Span 2

Span 1 and Pier

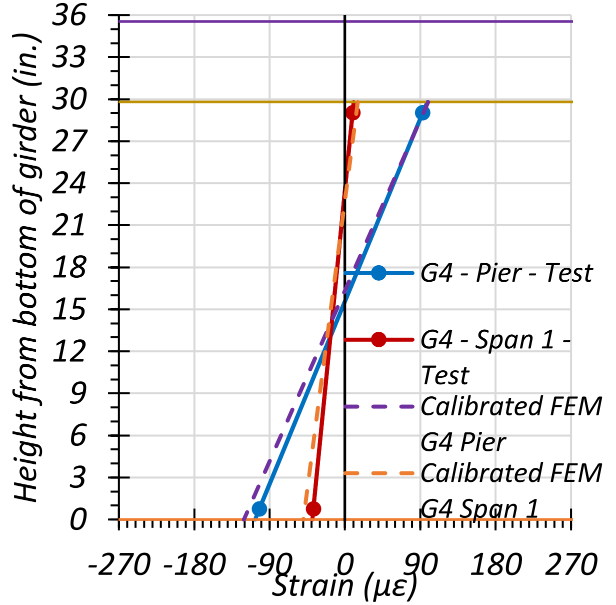
Span 2

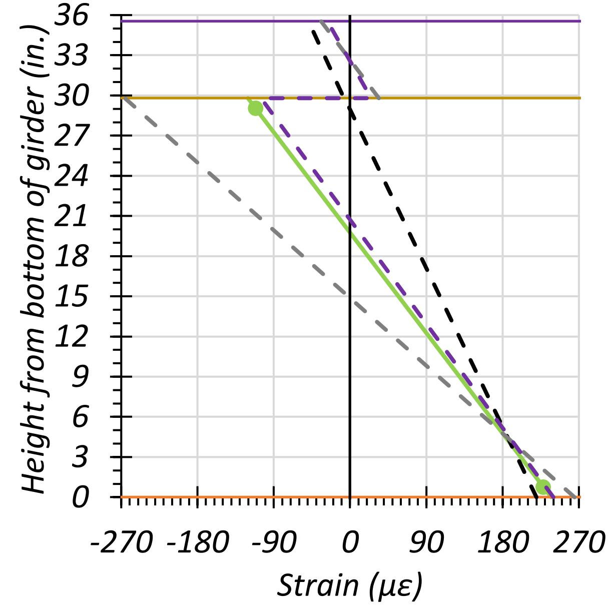
G3 – Path 1

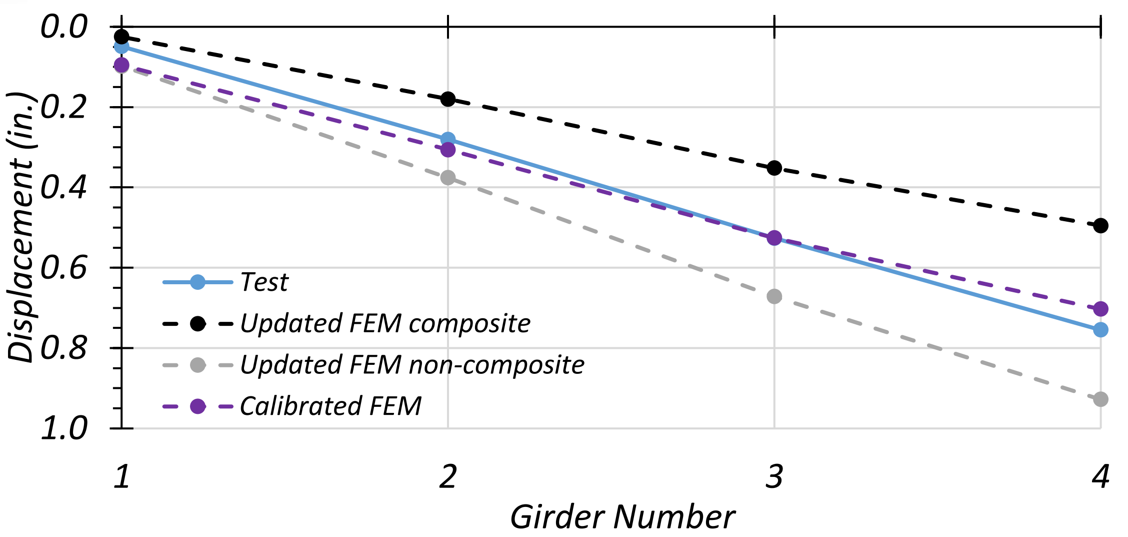




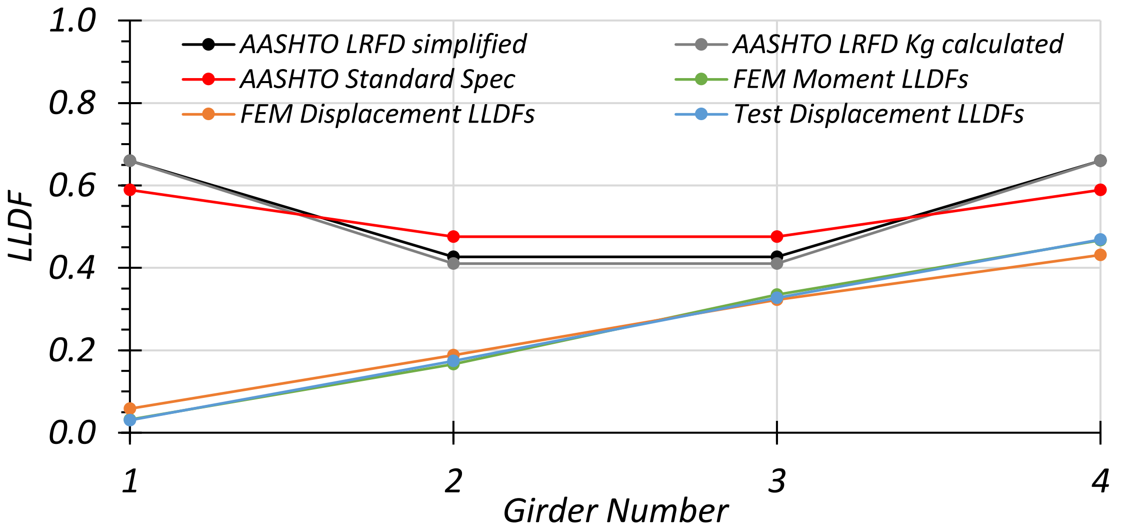
G4 – Path 1







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	0.73	1.34

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

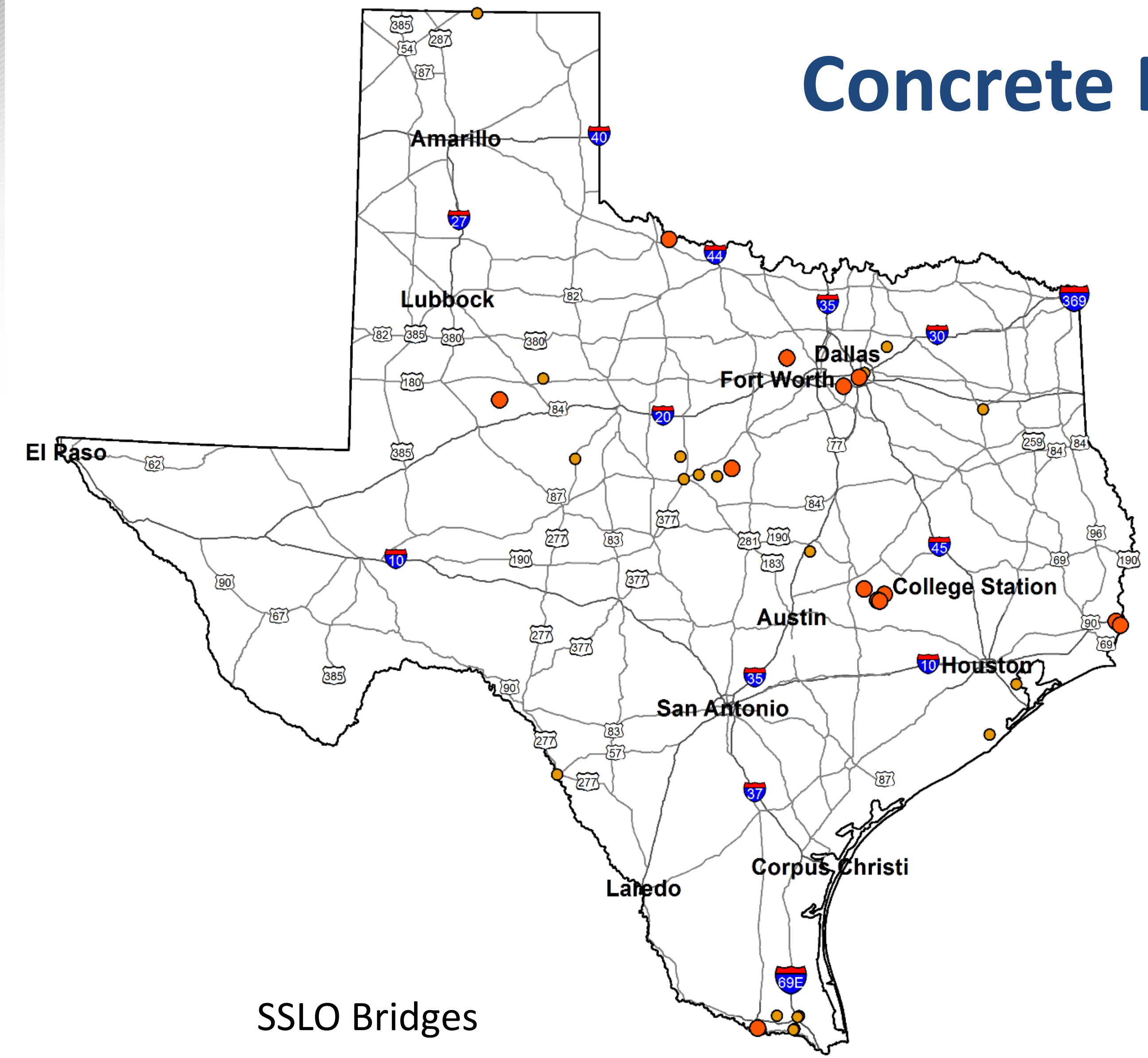
✓ The proposed RFs would allow for removal of the posting per TxDOT's load rating flowchart

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

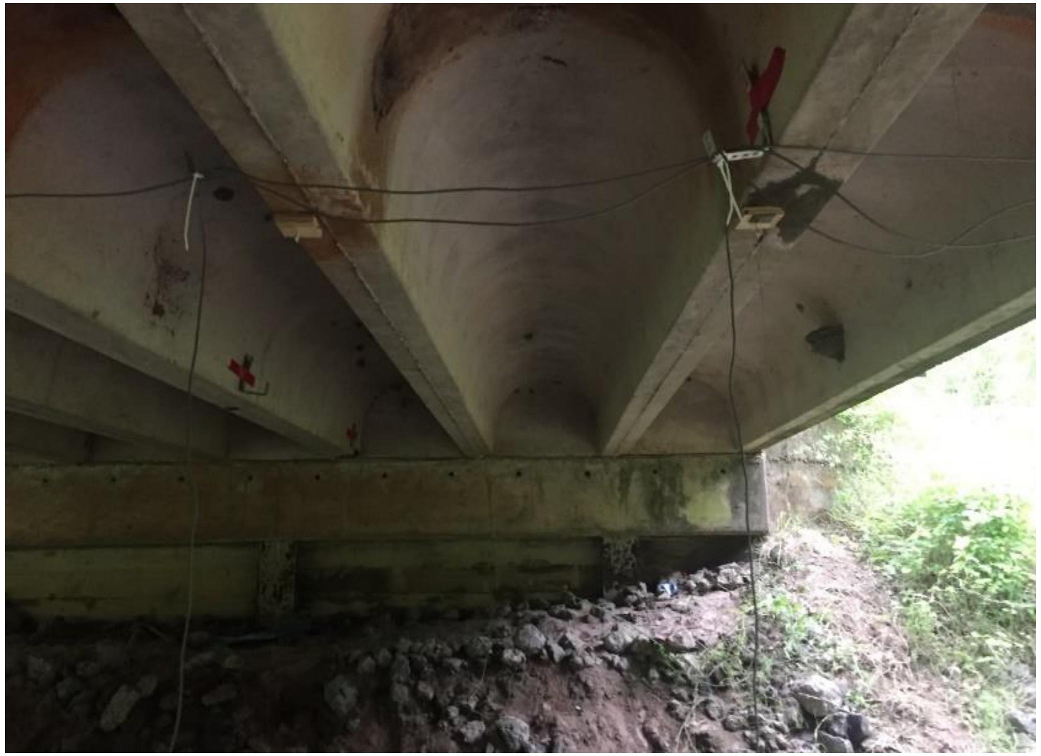

Amarillo
Lubbock
El Paso
Dallas
Fort Worth
College Station
Austin
Houston
San Antonio
Corpus Christi
Laredo

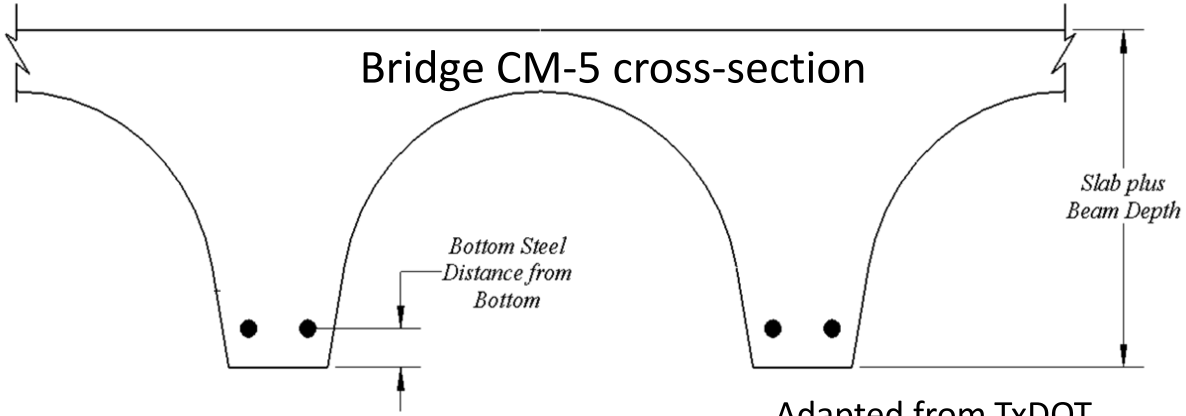
SSLO Bridges

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



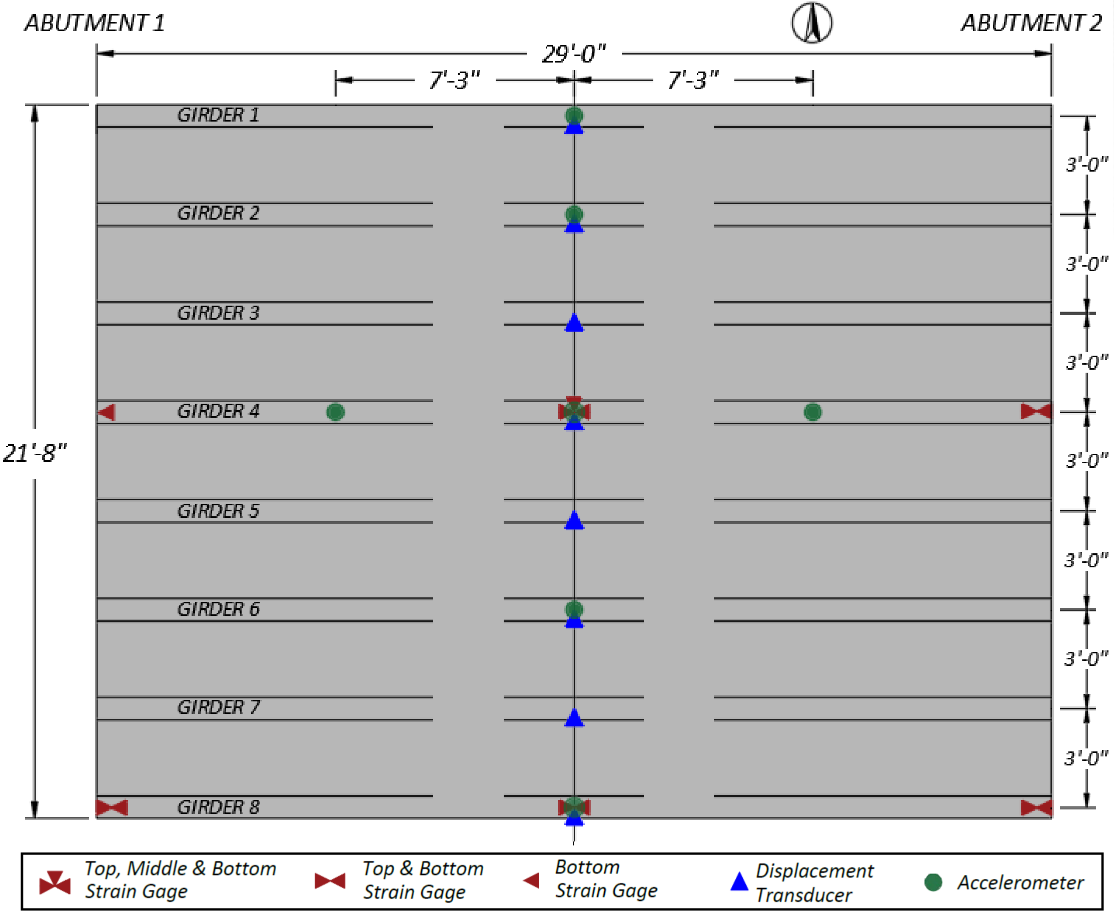


Bridge CM-5 cross-section

Adapted from TxDOT (2001)

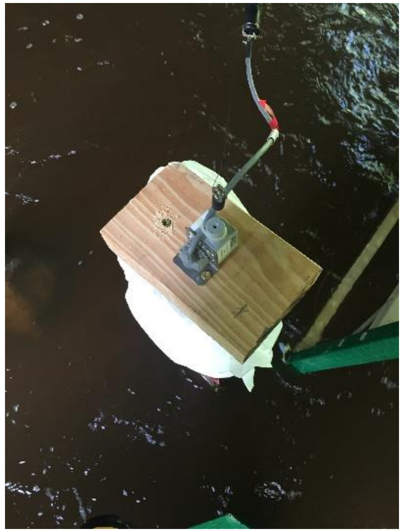
Instrumentation

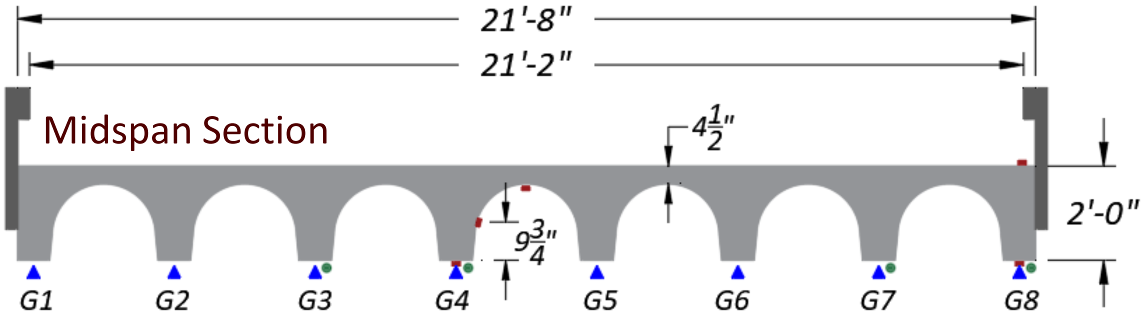
Bridge CM-5

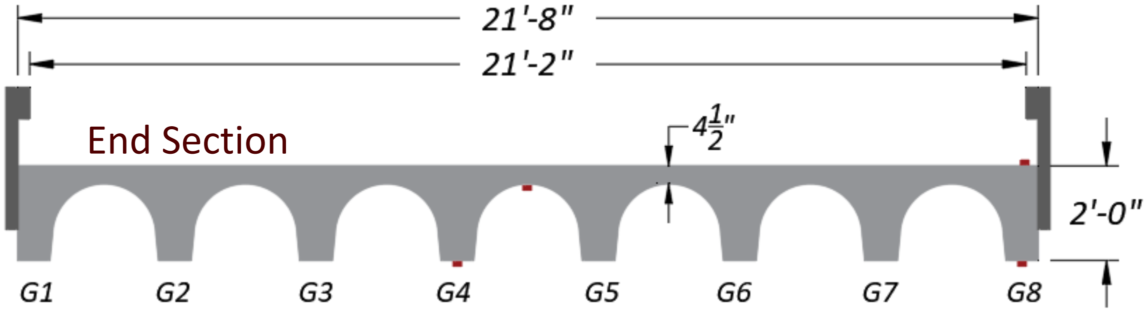

ABUTMENT 1
ABUTMENT 2
29'-0"
7'-3"
7'-3"
GIRDER 1
GIRDER 2
GIRDER 3
GIRDER 4
GIRDER 5
GIRDER 6
GIRDER 7
GIRDER 8
3'-0"
3'-0"
3'-0"
3'-0"
3'-0"
3'-0"
3'-0"
21'-8"
Top, Middle & Bottom Strain Gage
Top & Bottom Strain Gage
Bottom Strain Gage
Displacement Transducer
Accelerometer

Strain Gauge

Accelerometer

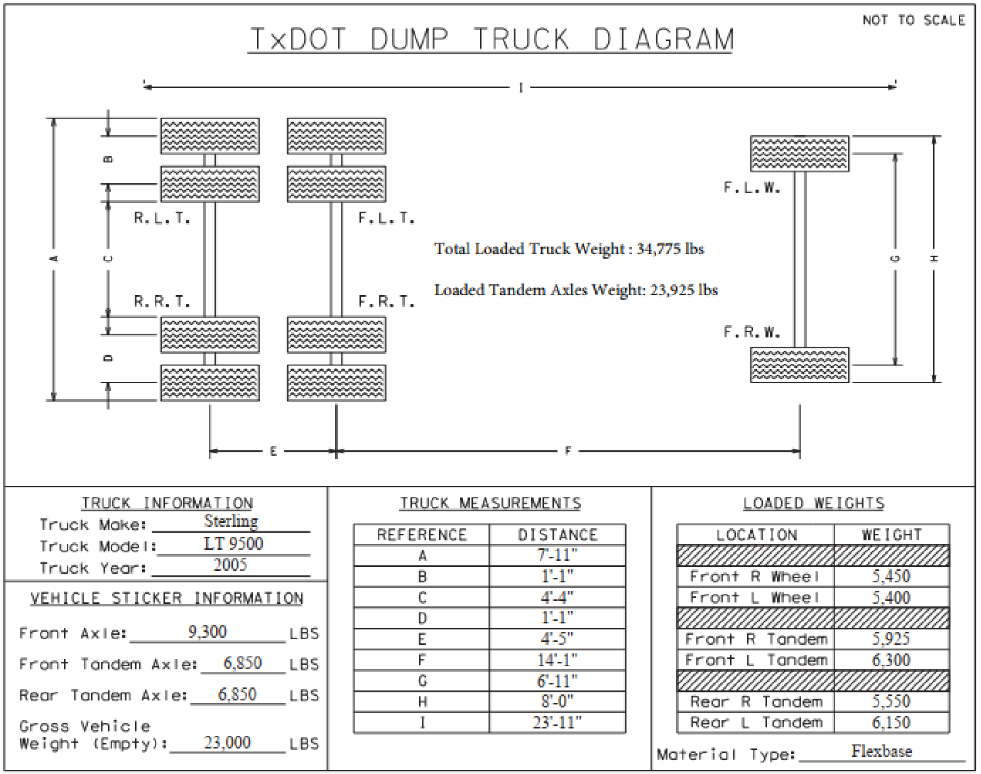

String Potentiometer


Midspan Section
21'-8"
21'-2"
$4\frac{1}{2}$"
$9\frac{3}{4}$"
2'-0"
G1
G2
G3
G4
G5
G6
G7
G8


End Section
21'-8"
21'-2"
$4\frac{1}{2}$"
2'-0"
G1
G2
G3
G4
G5
G6
G7
G8

Testing

Bridge CM-5


NOT TO SCALE
I
A
B
C
D
R.L.T.
R.R.T.
F.L.T.
F.R.T.
F.L.W.
F.R.W.
G
H
E
F

TxDOT DUMP TRUCK DIAGRAM

Total Loaded Truck Weight : 34,775 lbs

Loaded Tandem Axles Weight: 23,925 lbs

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

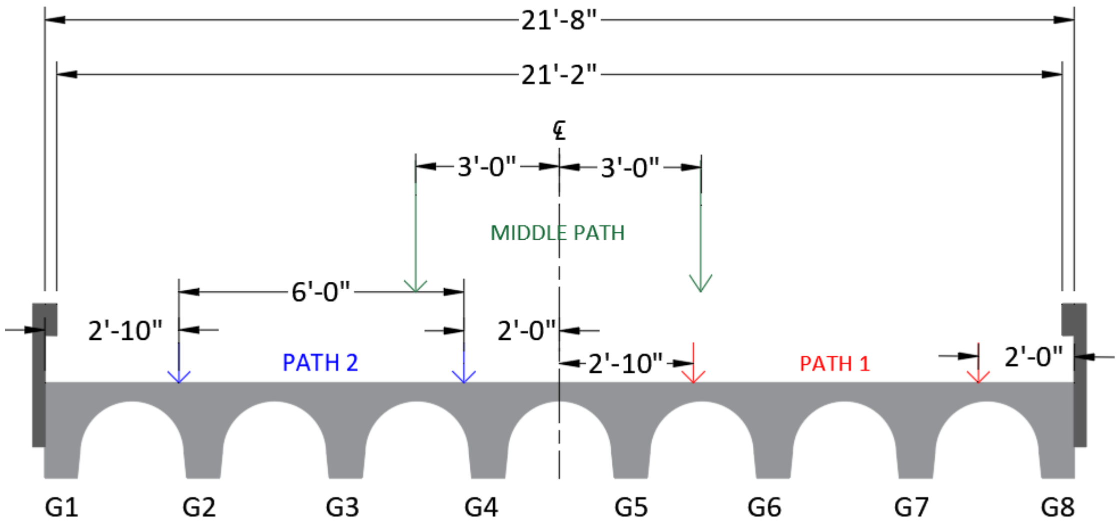
LOCATION	WEIGHT
▨	▨
Front R Wheel	5,450
Front L Wheel	5,400
▨	▨
Front R Tandem	5,925
Front L Tandem	6,300
▨	▨
Rear R Tandem	5,550
Rear L Tandem	6,150

Material Type: Flexbase

WEIGHT
LIMIT
TANDEM
AXLE
24000LBS

Load Posting

TxDOT Dump Truck

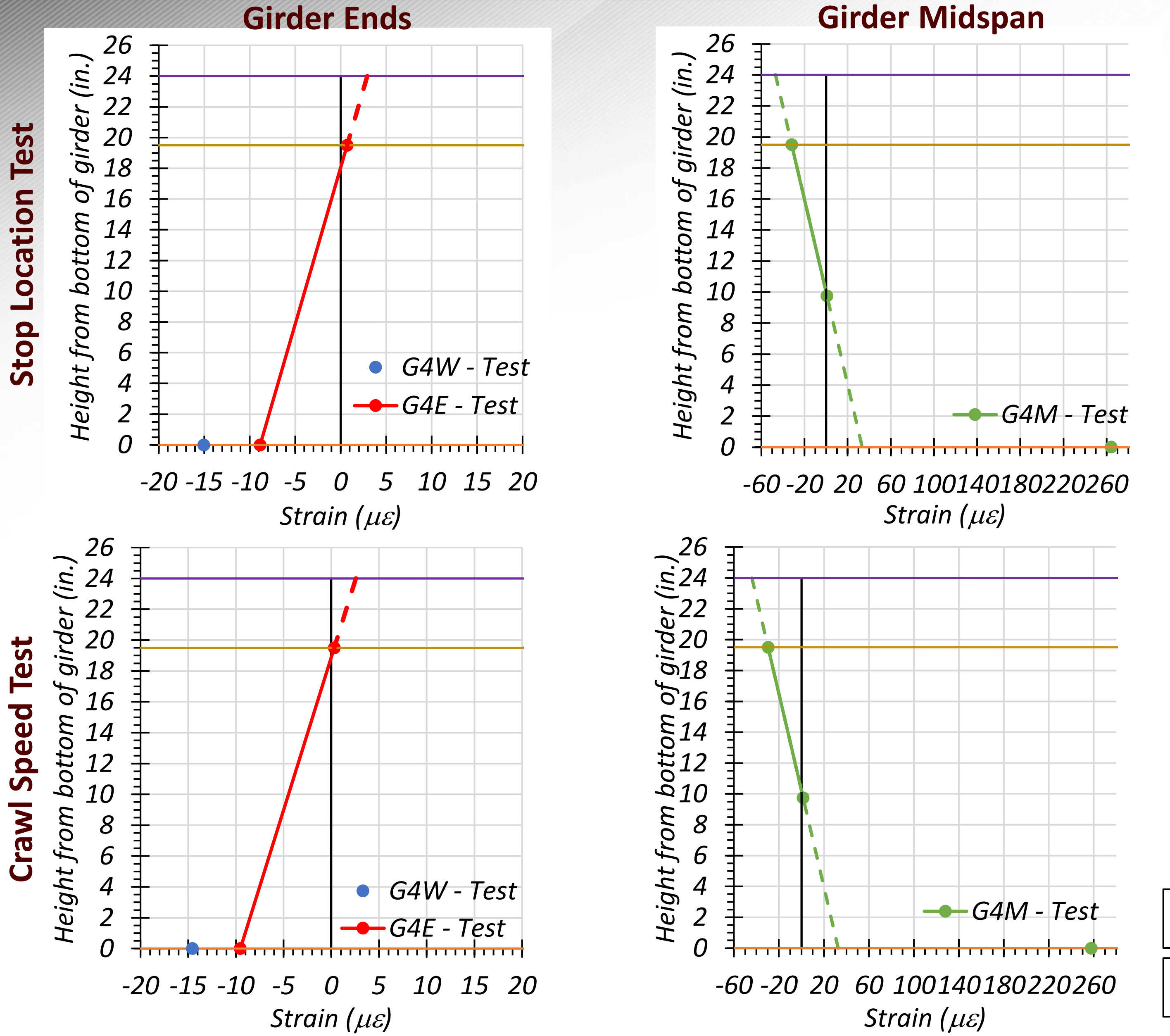

21'-8"
21'-2"
℄
3'-0"
3'-0"
MIDDLE PATH
6'-0"
2'-10"
2'-0"
PATH 2
2'-10"
PATH 1
2'-0"
G1
G2
G3
G4
G5
G6
G7
G8

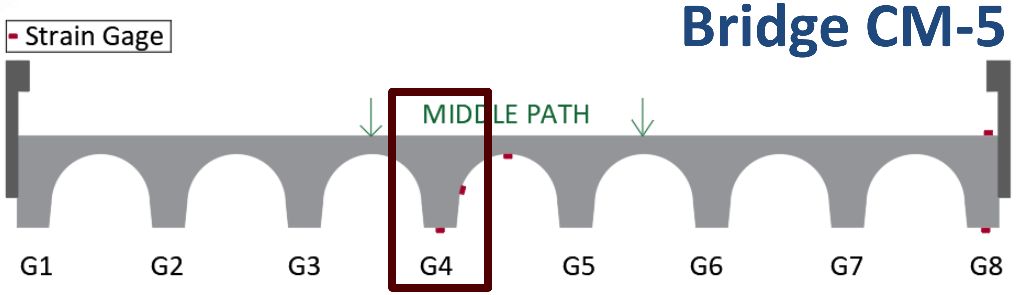
Test Load Paths

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

Interior Girder G4 Strain Results, Middle Path – Static Tests

Bridge CM-5



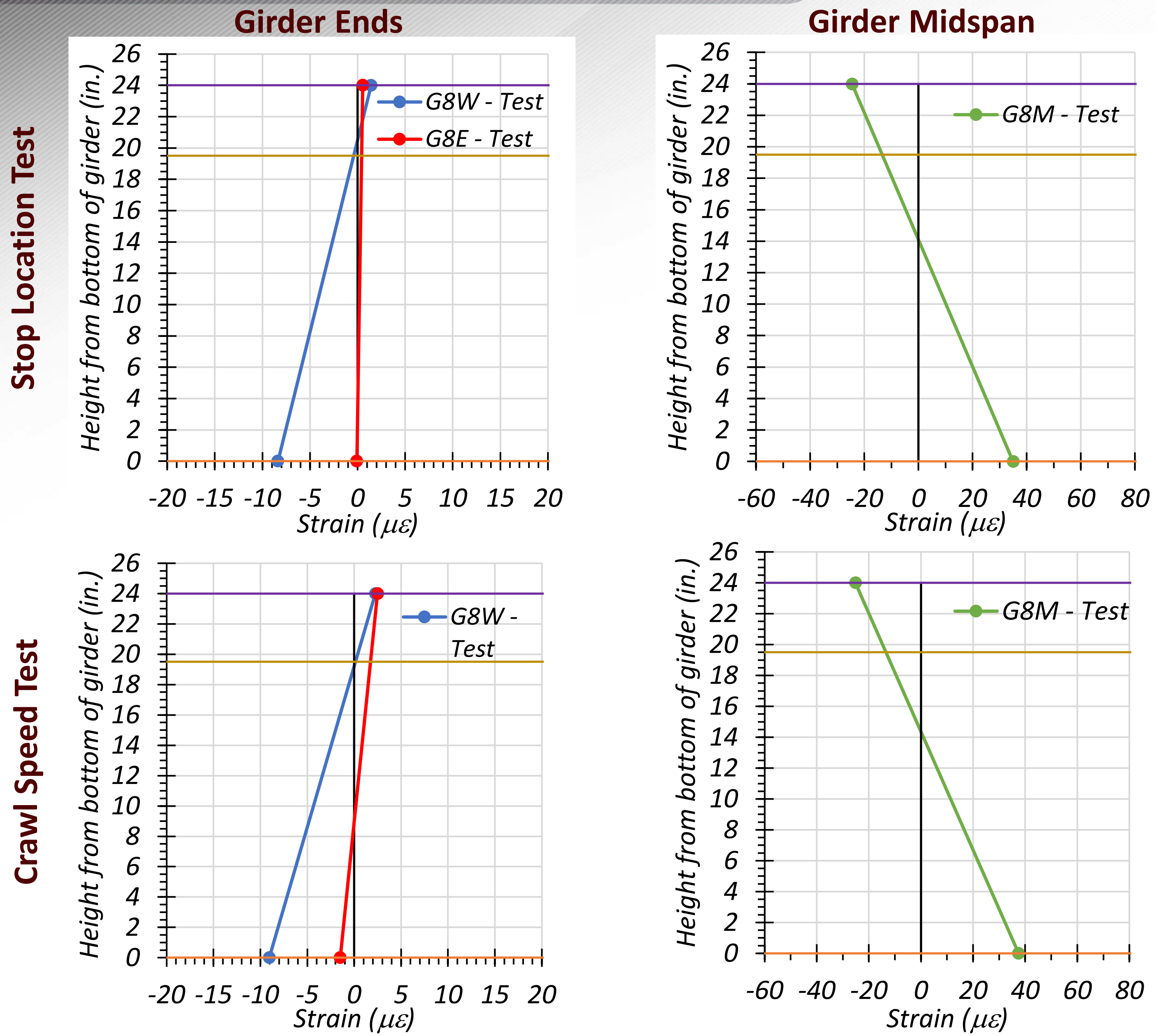


- Neutral Axis Location - Midspan
  - Stop location N.A. = 10.40 in.
  - Crawl speed N.A. = 10.65 in.
  - *Theoretical cracked N.A. = 19.91 in.*
  - *Theoretical uncracked N.A. = 14.05 in.*
  - *Issue with bottom strain gauge at midspan.*
- End Restraint?
  - Compressive strains at bottom of girder ends→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

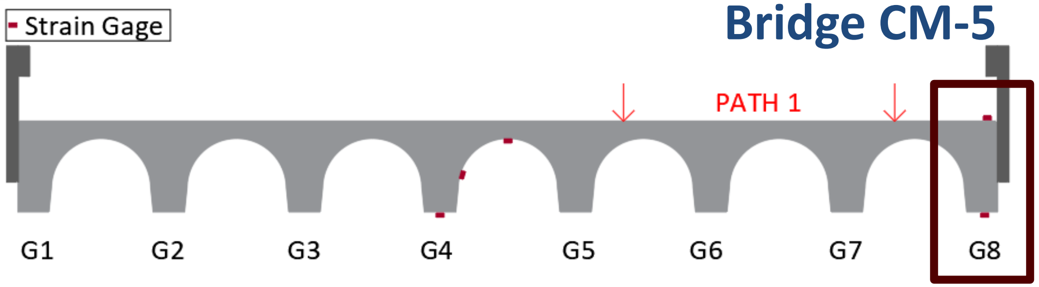
▬ top of slab ▬ bottom of slab ▬ bottom of girder

Tension is positive

Exterior Girder G8 Strain Results
Path 1 – Static Tests



Bridge CM-5



- 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

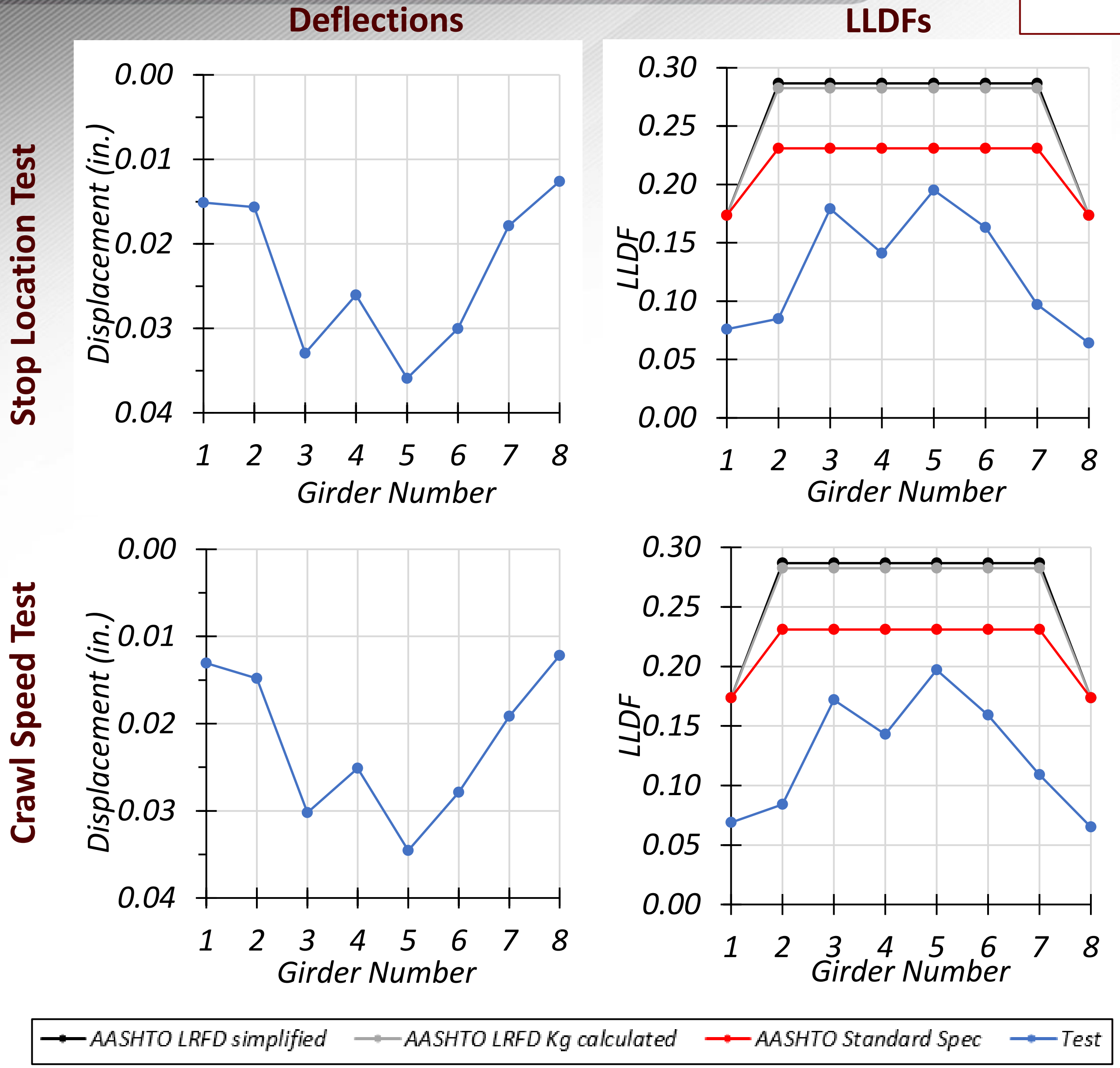
TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

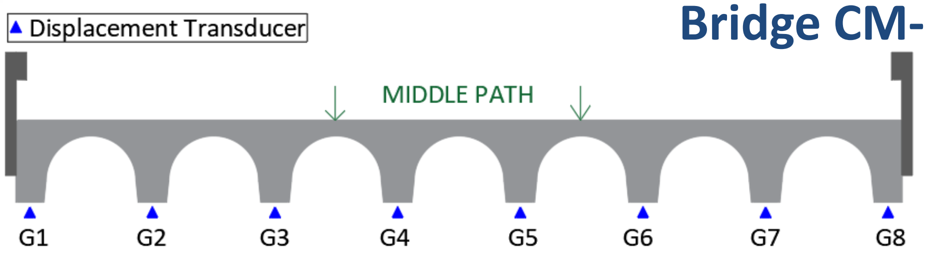
Updated – 08/04/2021

Deflection Results
Middle Path – Static Tests

Bridge CM-5

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





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

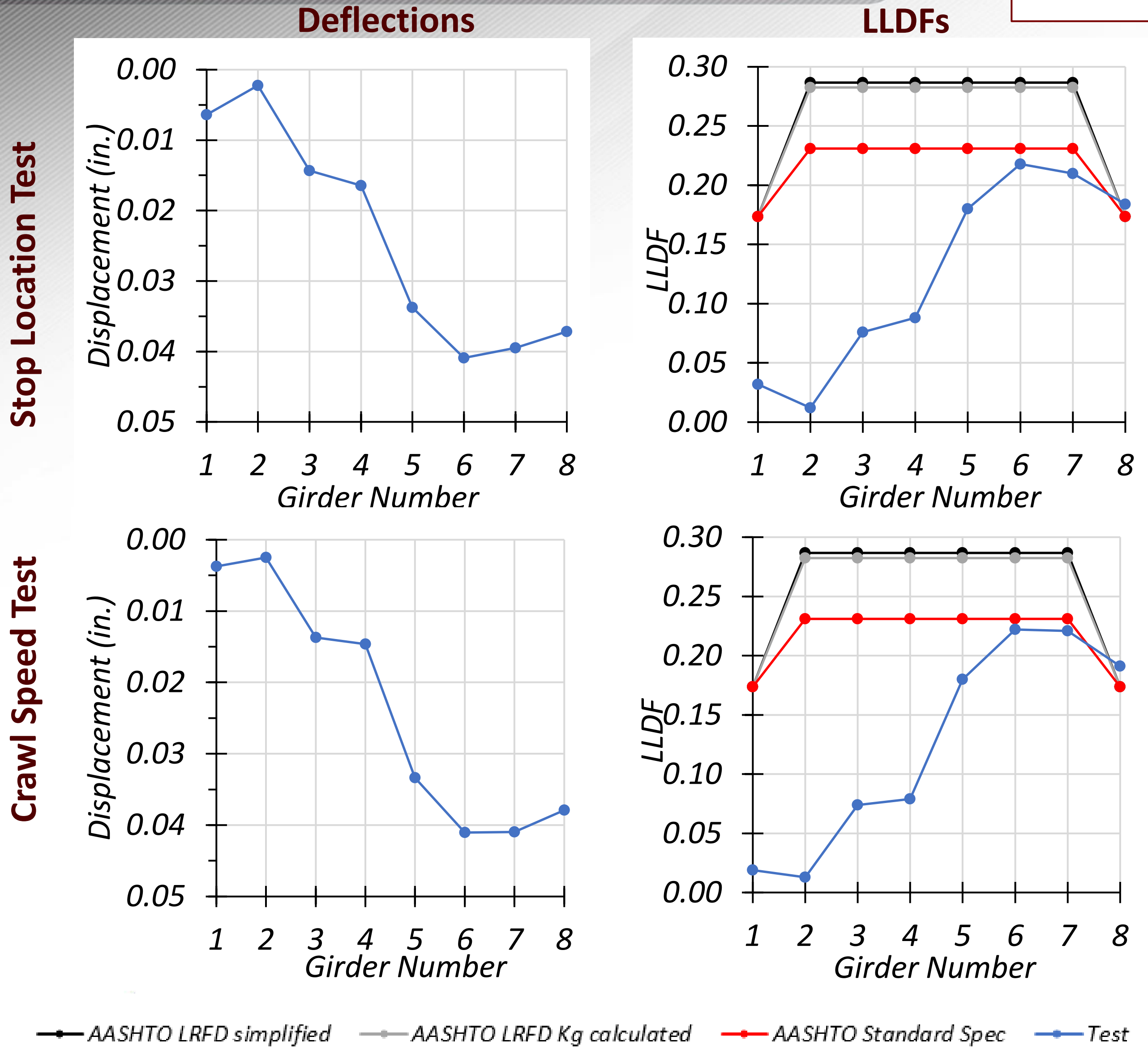
- AASHTO Standard Specifications provide conservative LLDFs
- AASHTO LRFD Specifications provide highly conservative LLDFs

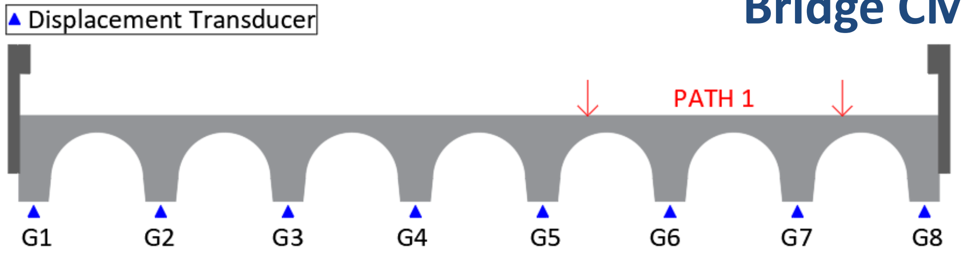
Updated – 08/04/2021

Deflection Results
Path 1 – Static Tests

Bridge CM-5

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





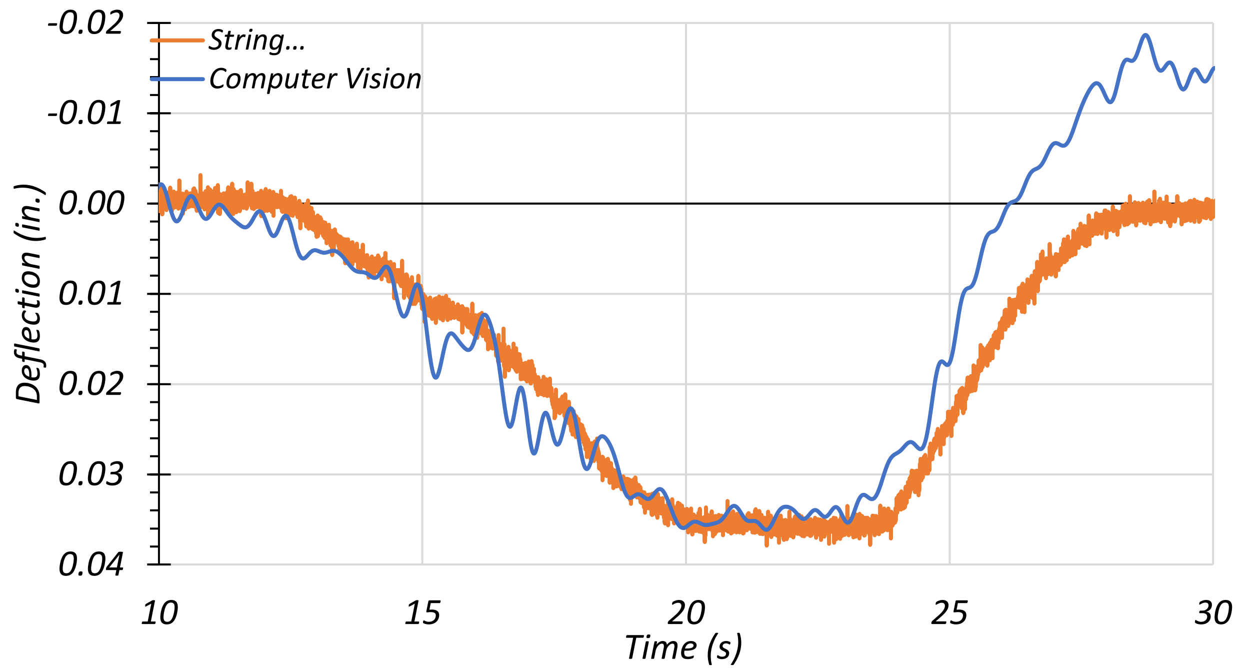
Test and Girder Type	AASHTO Standard Specs ($g^m_{AASHTO\_Std}$)	AASHTO LRFD Simplified ($g^m_{AASHTO\_S}$)	AASHTO LRFD K_g Calculated ($g^m_{AASHTO\_K}$)	Test (g^m_{test})	$g^m_{AASHTO\_Std}/g^m_{test}$	$g^m_{AASHTO\_S}/g^m_{test}$	$g^m_{AASHTO\_K}/g^m_{test}$
Stop Location Interior	0.231	0.287	0.283	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

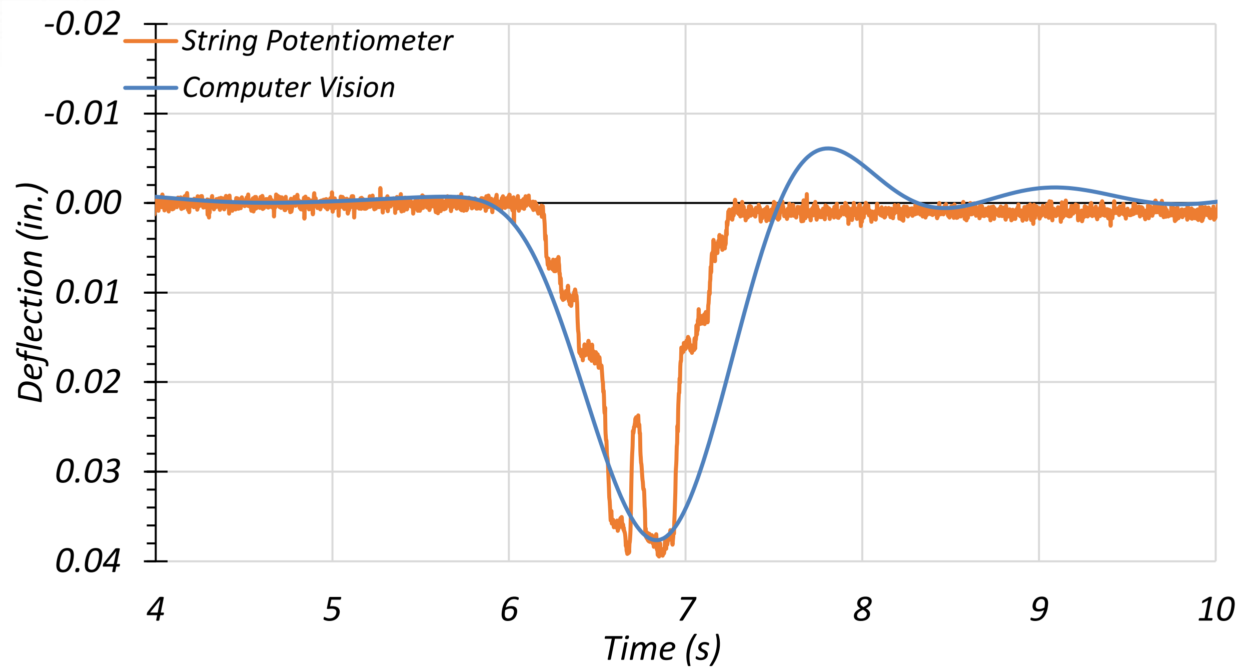
Computer Vision Results

Bridge CM-5

G8 – Path 1 – Crawl test



G1 – Path 2 – Dynamic test



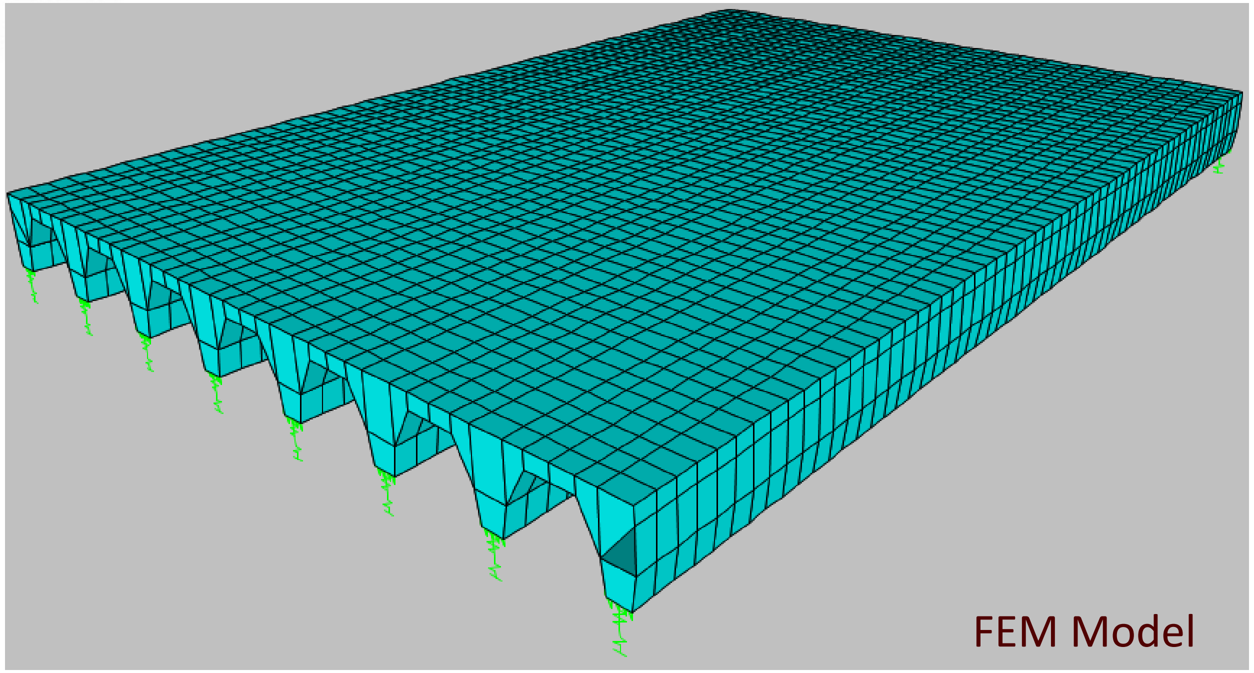
- Girder G8 – Path 1 – Crawl test
- String potentiometer deflection = 0.036 in.
- Computer vision deflection = 0.037 in.
- Difference = 5%
- Bandpass filter, Cut-off frequency = 0.001 Hz to 3 Hz

- 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)



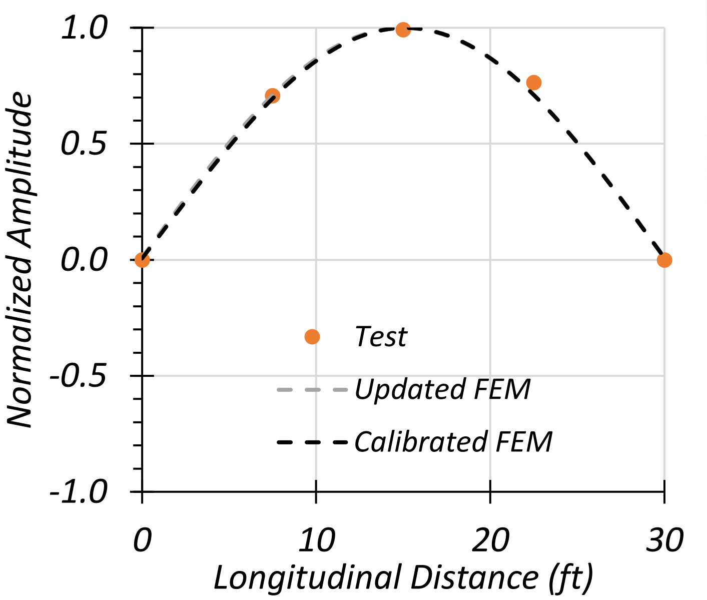
Dynamic Characteristics Comparison

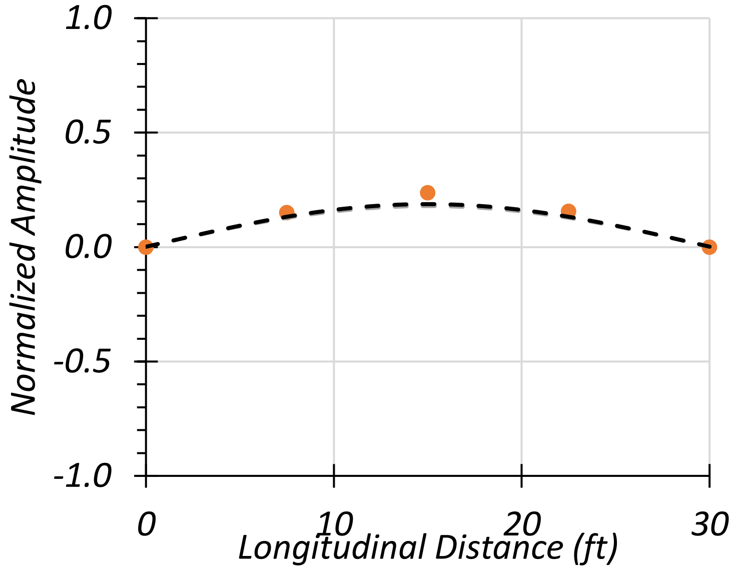
Bridge CM-5

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

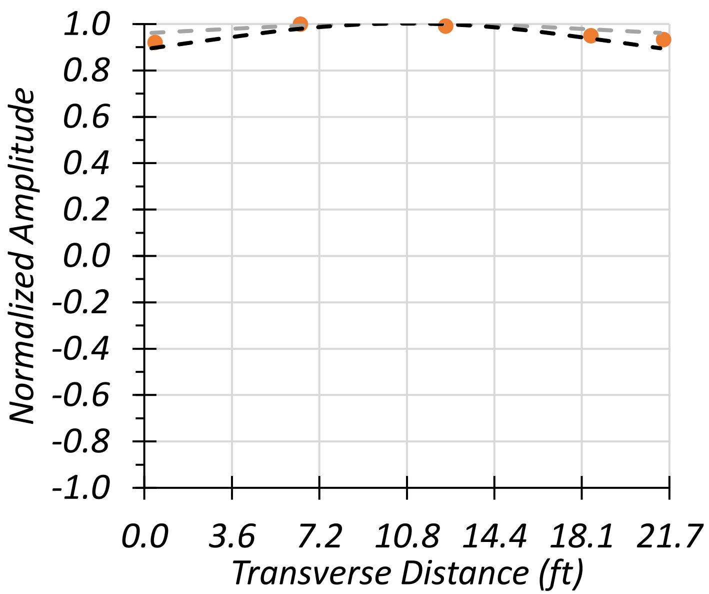
2nd Mode (Test=16.6 Hz, FEM=16.9 Hz)

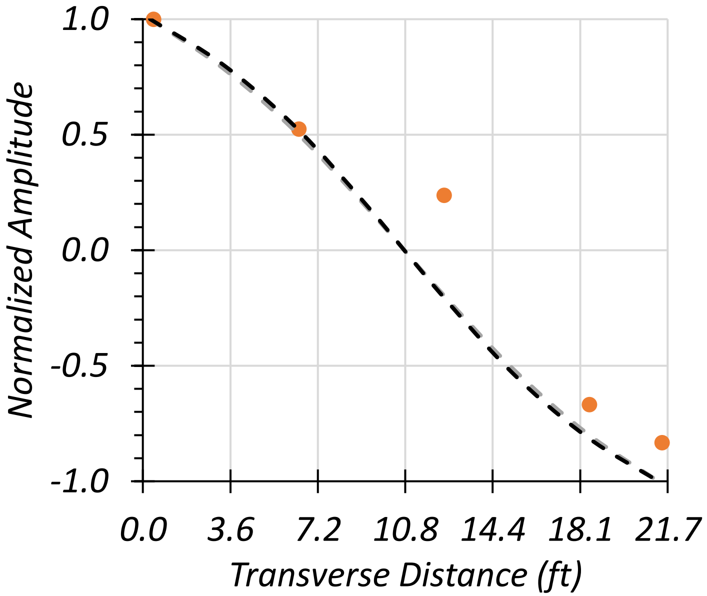
Longitudinal Section





Transverse Section





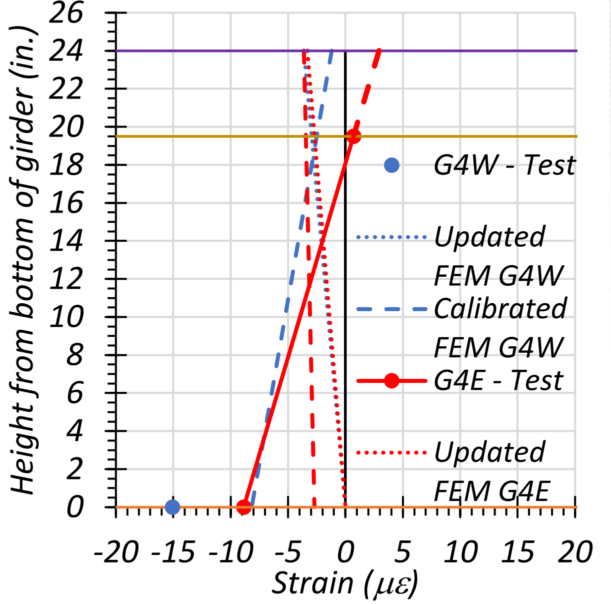
Comparison Model and Test Results

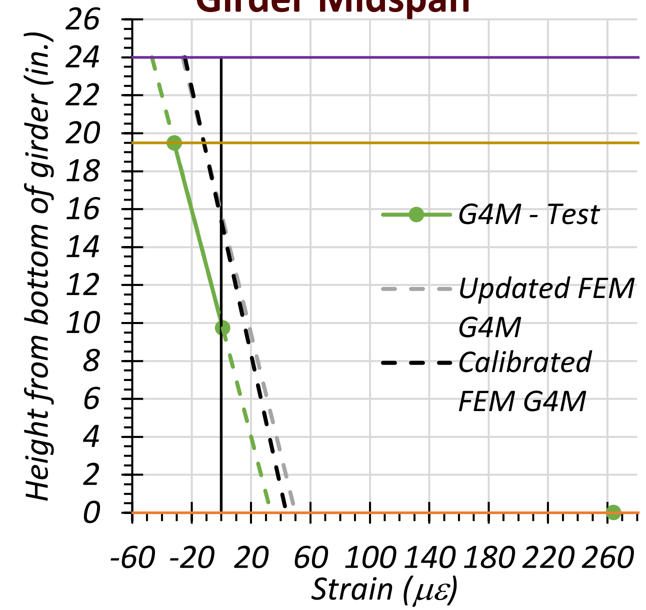
Bridge CM-5

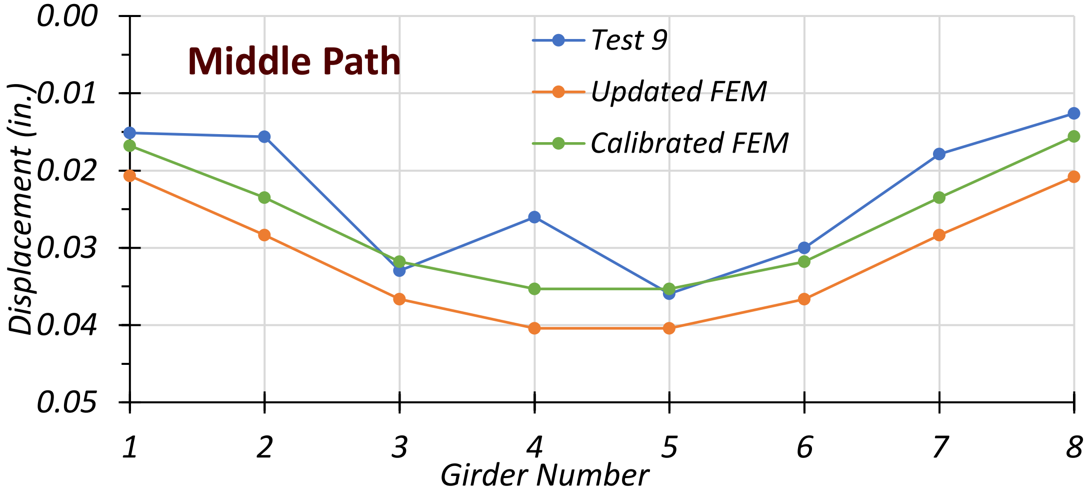
Girder Ends

Girder Midspan

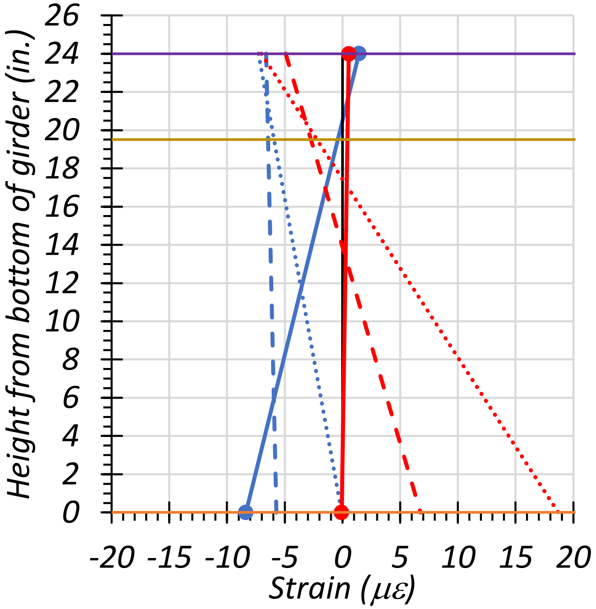
G4 – Middle Path

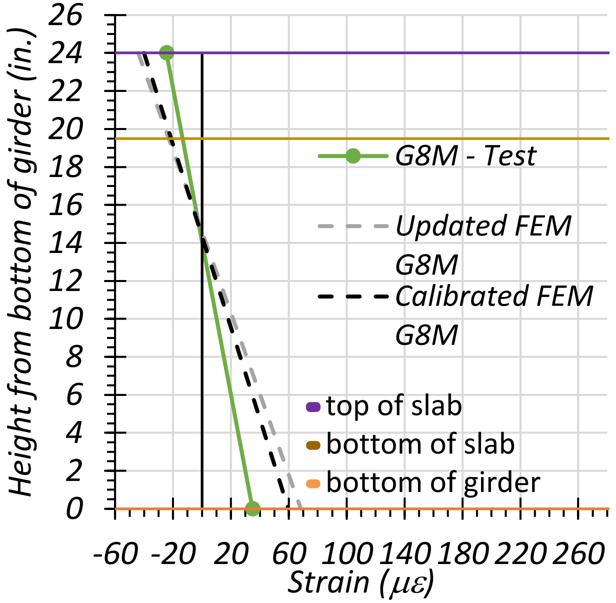


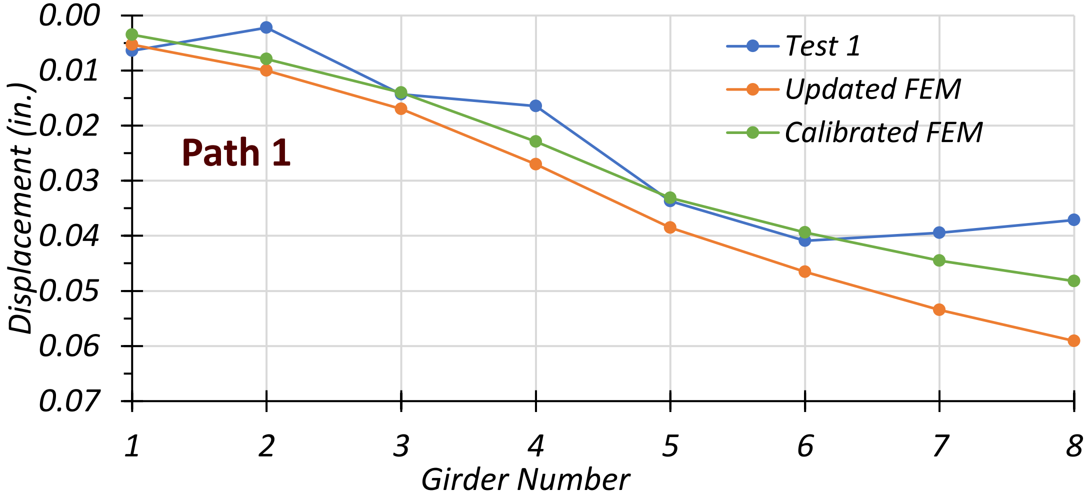




G8 – Path 1







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

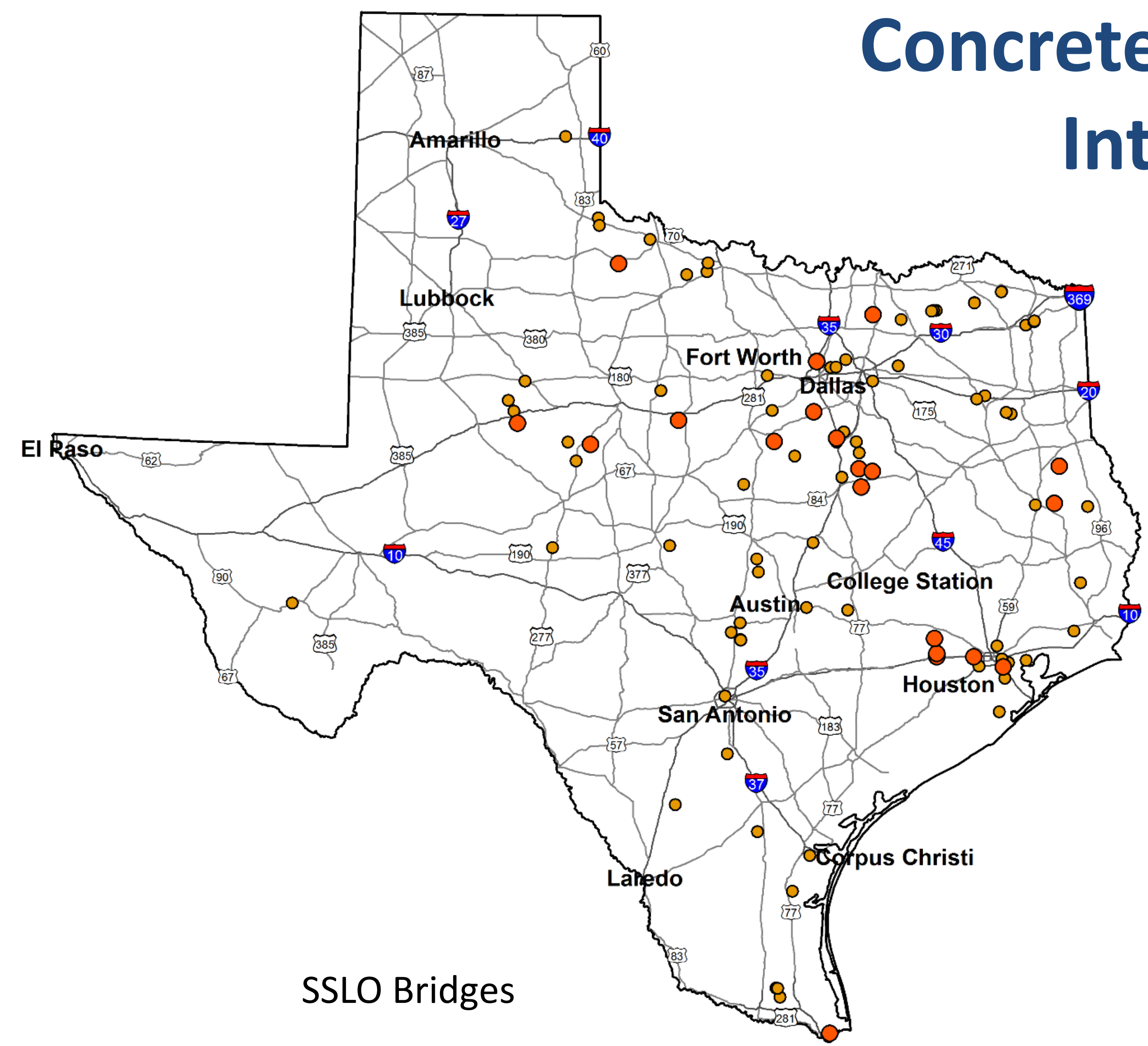
End Fixity

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


Amarillo
Lubbock
El Paso
Fort Worth
Dallas
Austin
College Station
Houston
San Antonio
Corpus Christi
Laredo
60
87
40
83
27
70
271
369
35
30
385
380
180
281
20
175
62
385
67
84
190
96
45
10
190
377
90
59
385
277
77
10
35
67
183
57
37
77
77
83
281

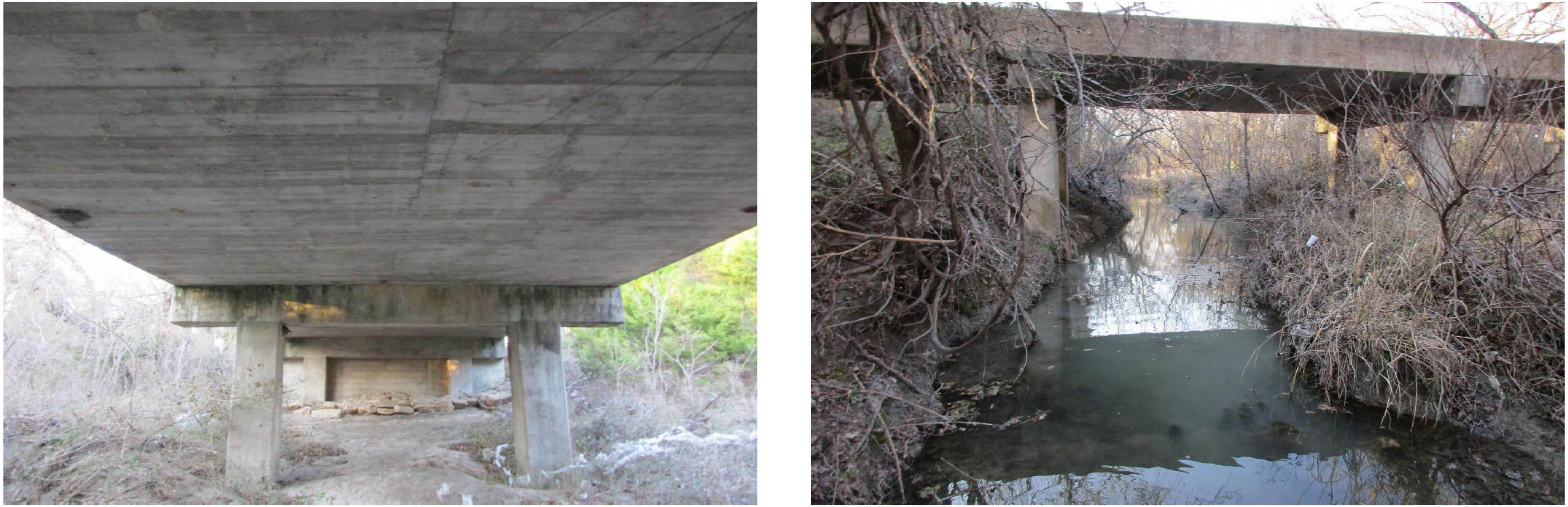
SSLO Bridges

Concrete Slab Bridge

Bridge CS-9

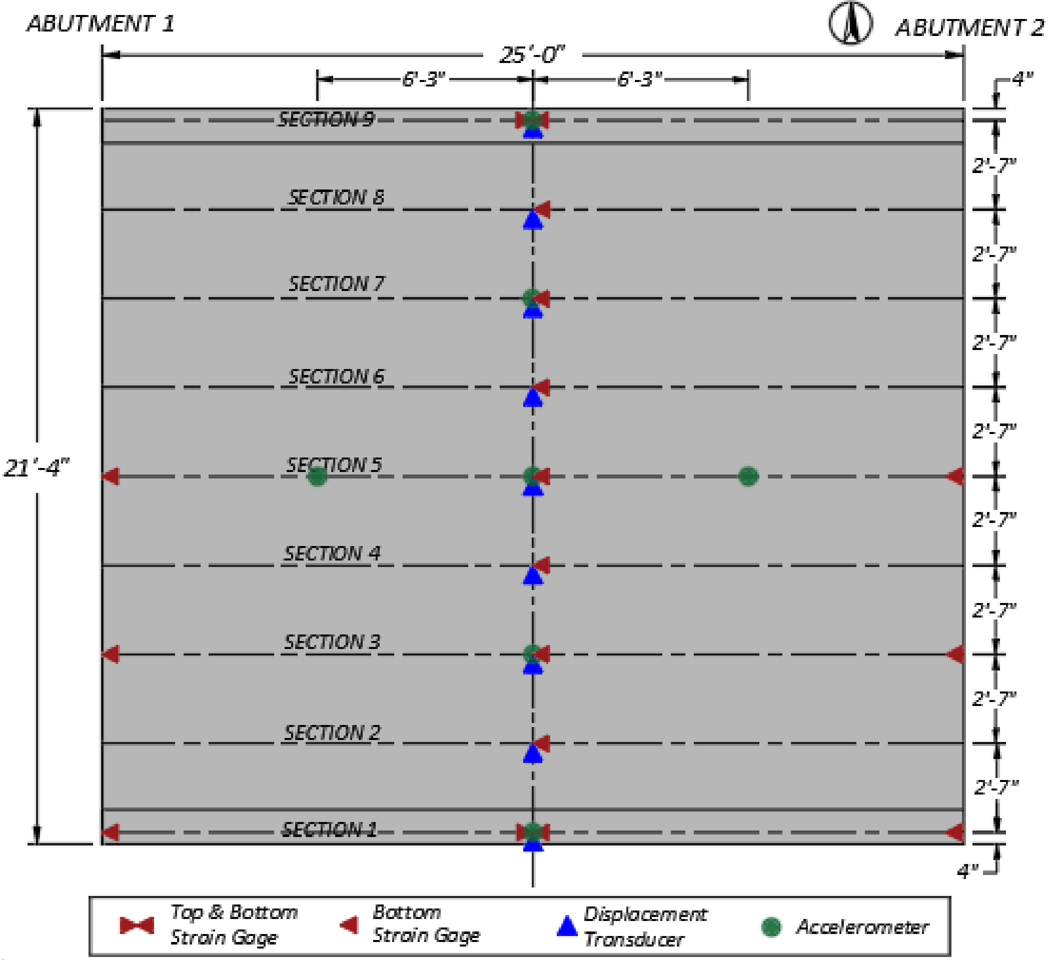
ID	Dist. to CS (mi)	Route Prefix	Year Built	ADT	Max. Span Length (ft)	Deck Width (ft)	Condition Rating			Operating HS20 Rating Factor
							Deck	Super-structure	Sub-structure	
Avrg.	-	-	1949	795	22	28	6 (Satisfactory)	6 (Satisfactory)	6 (Satisfactory)	0.98
CS-9	157	3 (On-system)	1948	30	25	21	6 (Satisfactory)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

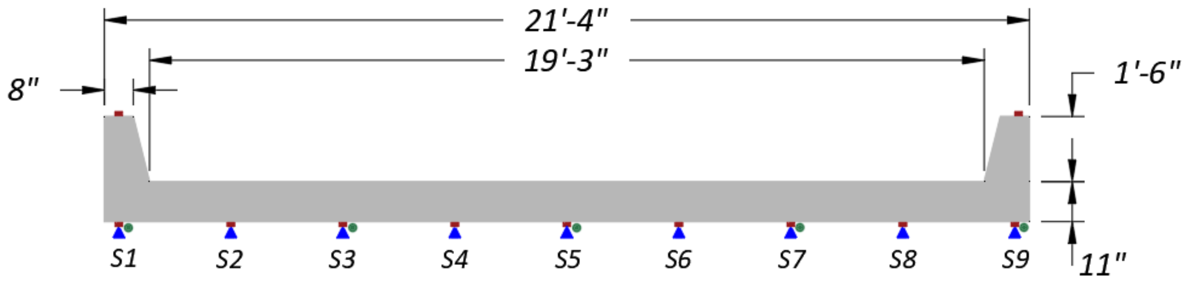
Bridge CS-9


ABUTMENT 1
ABUTMENT 2
25'-0"
6'-3"
6'-3"
4"
SECTION 9
SECTION 8
SECTION 7
SECTION 6
SECTION 5
SECTION 4
SECTION 3
SECTION 2
SECTION 1
21'-4"
2'-7"
2'-7"
2'-7"
2'-7"
2'-7"
2'-7"
2'-7"
2'-7"
4"
Top & Bottom Strain Gage
Bottom Strain Gage
Displacement Transducer
Accelerometer

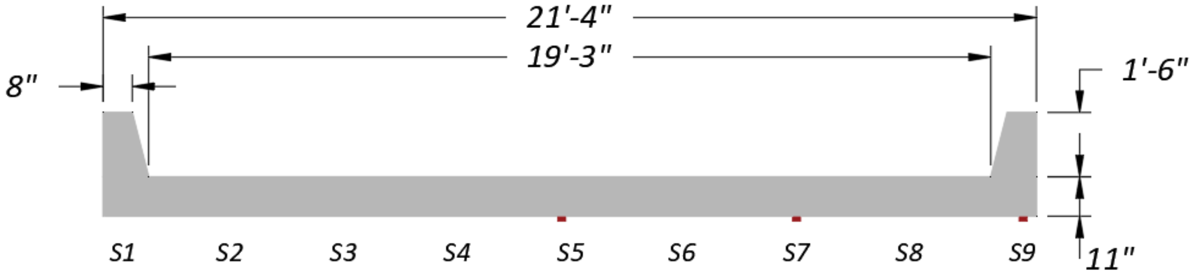
Strain Gauge

Accelerometer

String Potentiometers


21'-4"
19'-3"
8"
1'-6"
11"
S1
S2
S3
S4
S5
S6
S7
S8
S9

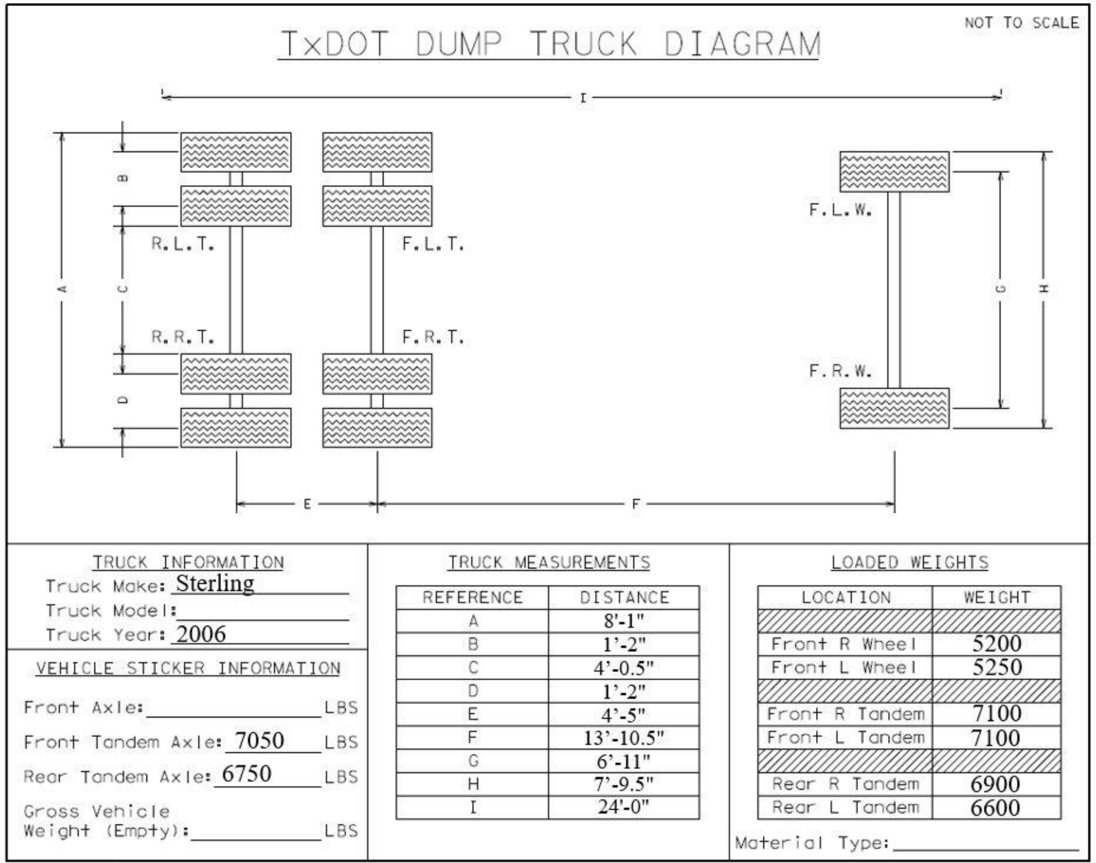
Midspan Section


21'-4"
19'-3"
8"
1'-6"
11"
S1
S2
S3
S4
S5
S6
S7
S8
S9

End Section

Testing

Bridge CS-9


NOT TO SCALE
I
B
A
C
D
R.L.T.
F.L.T.
R.R.T.
F.R.T.
F.L.W.
F.R.W.
G
H
E
F

TXDOT DUMP TRUCK DIAGRAM

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:

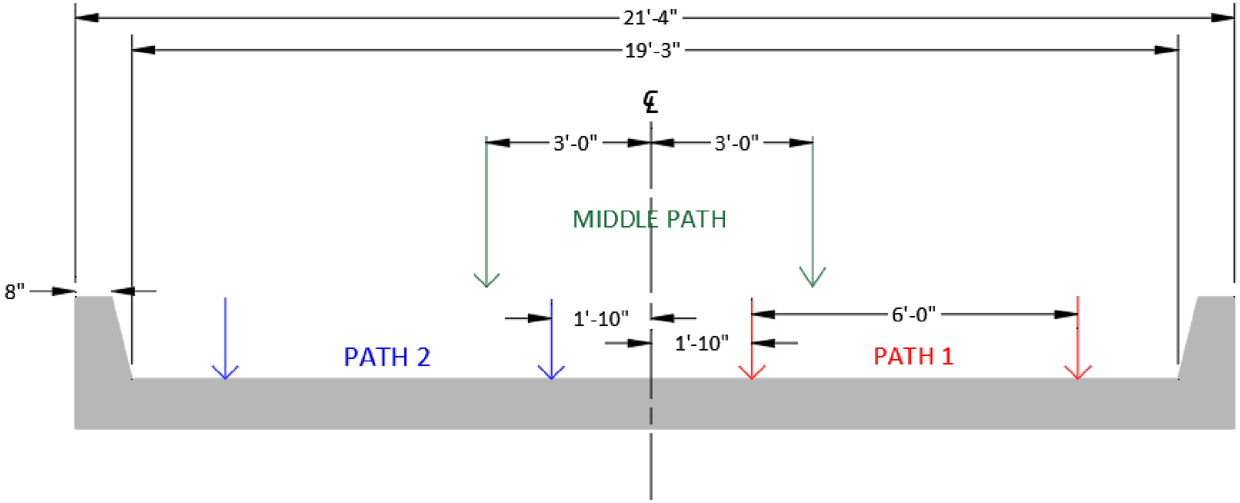
TxDOT Dump Truck

WEIGHT LIMIT
TANDEM AXLE
28000 LBS

Load Posting

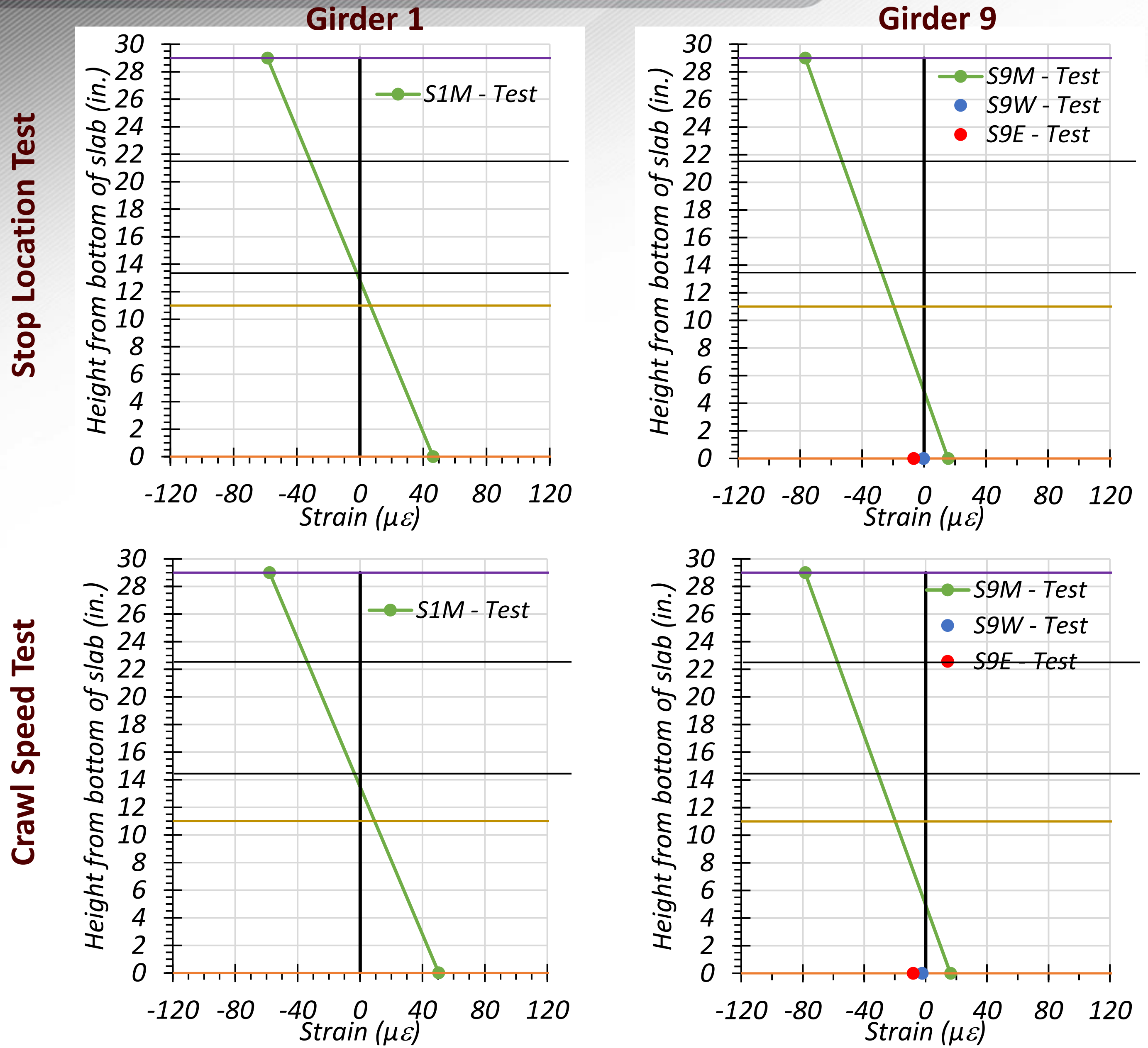
Test Protocol

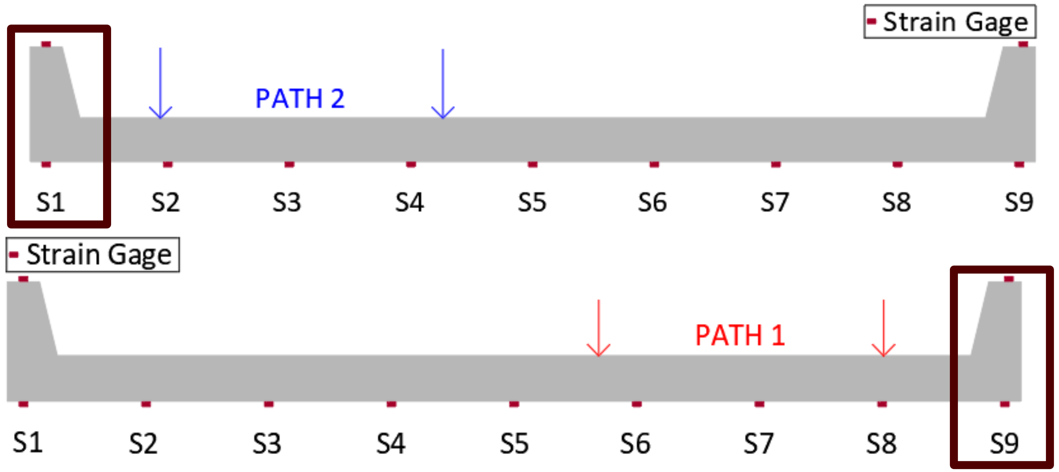
Static Tests	Dynamic Tests
• Stop Location	• 30 & 40 mph
• Crawl Speed	• Impact Tests


21'-4"
19'-3"
℄
3'-0"
3'-0"
MIDDLE PATH
8"
1'-10"
1'-10"
6'-0"
PATH 2
PATH 1

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

Bridge CS-9





- 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

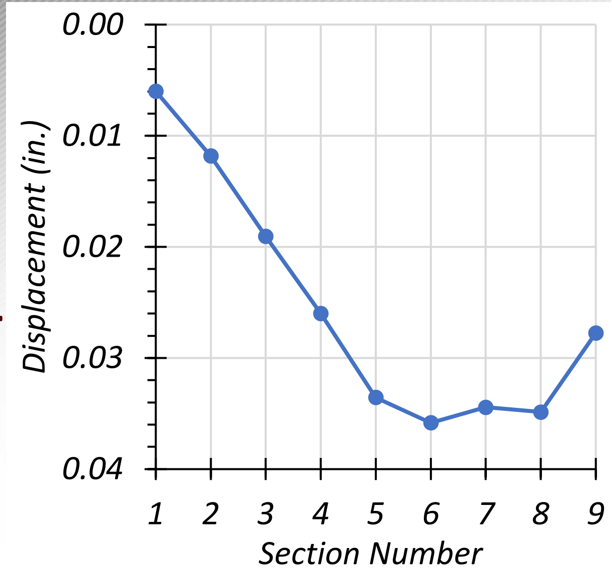
Deflection Results Path 1 –Static Tests

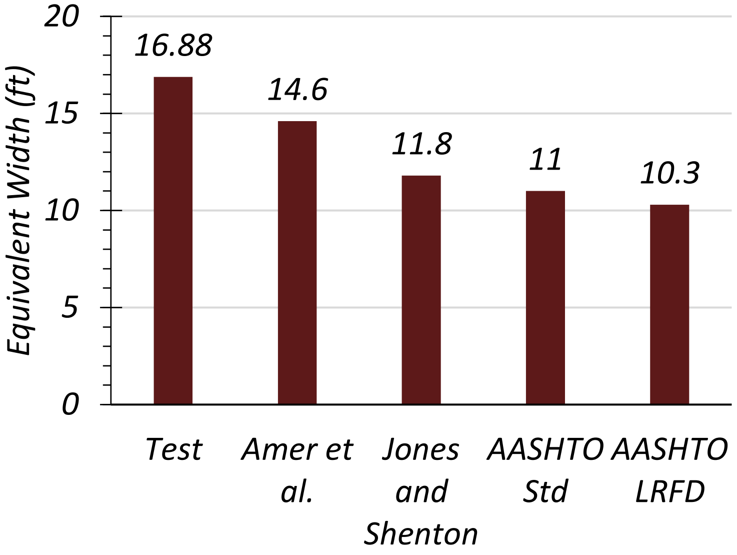
Bridge CS-9

Deflections

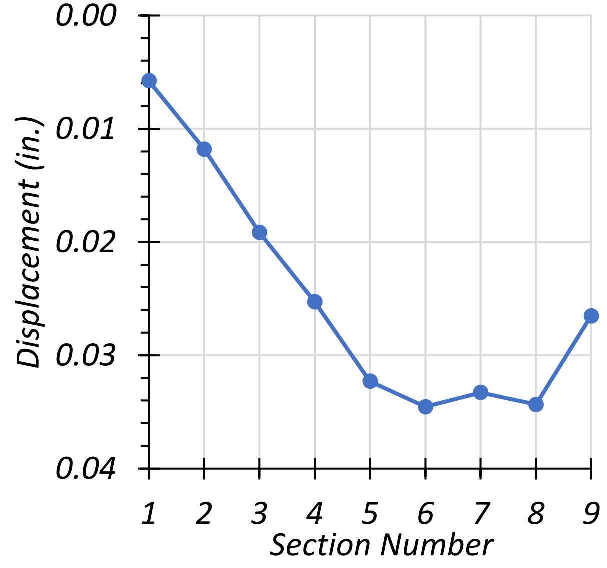
Equivalent Width

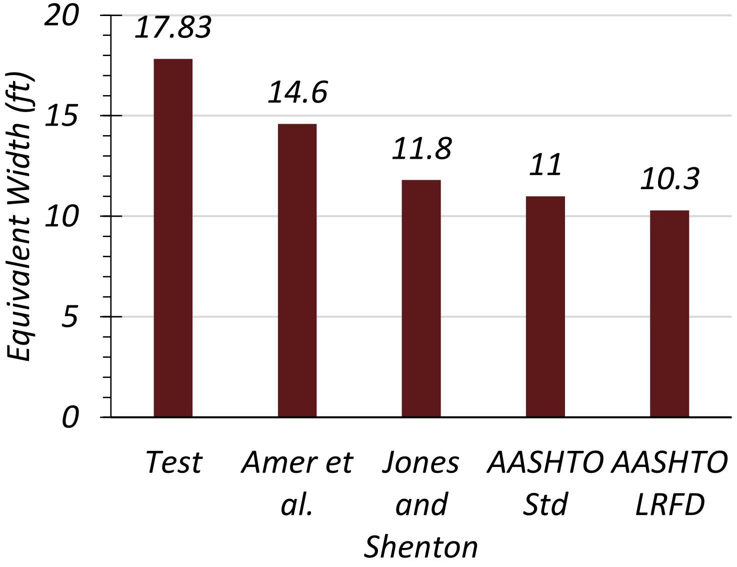
Stop Location Test

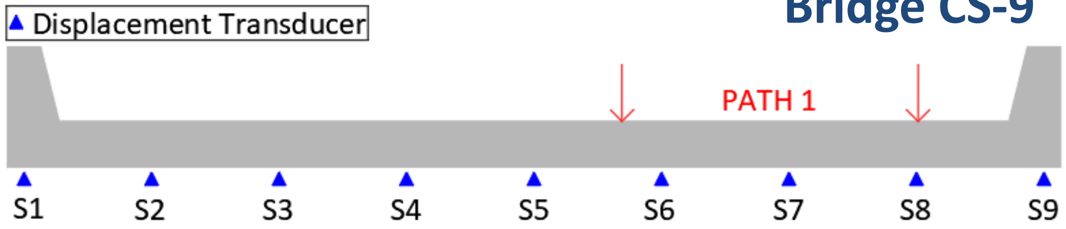




Crawl Speed Test







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.

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

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

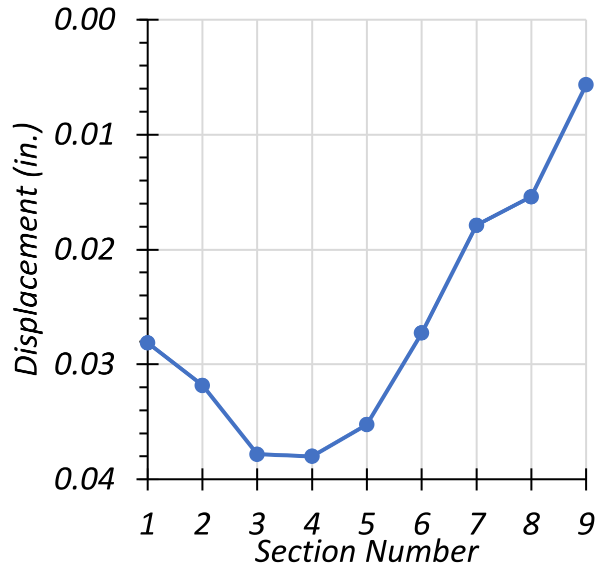
- AASHTO Standard Specifications provide *conservative* equivalent widths
- AASHTO LRFD Specifications provide *highly conservative* equivalent widths

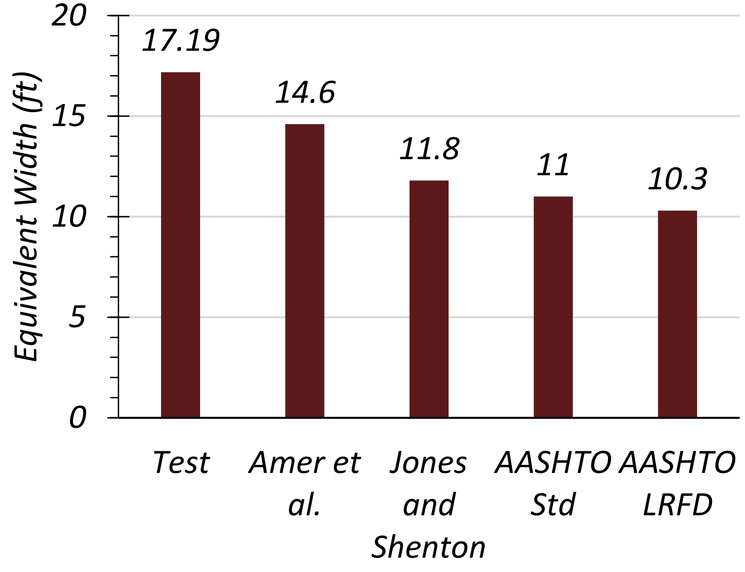
Deflection Results
Path 2 – Static Tests

Bridge CS-9

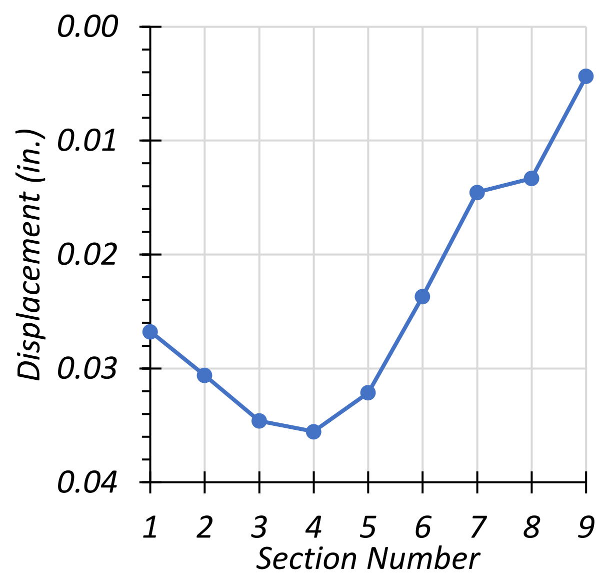
Deflections | **Equivalent Width**

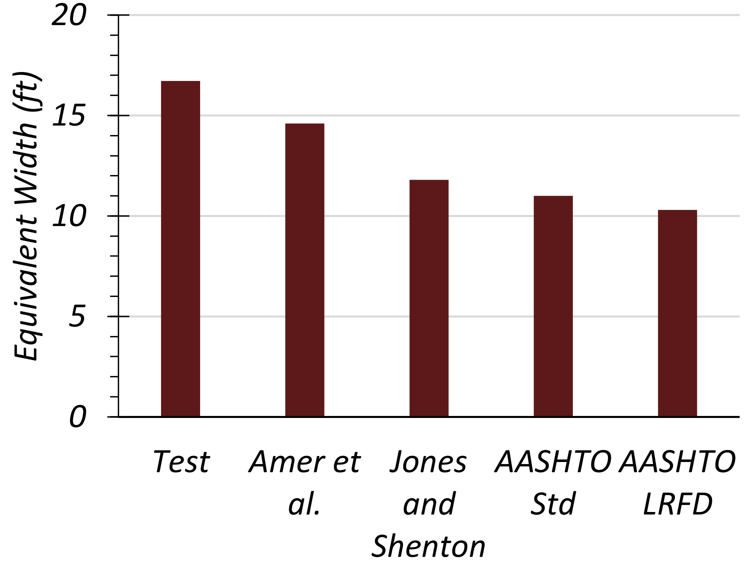
Stop Location Test

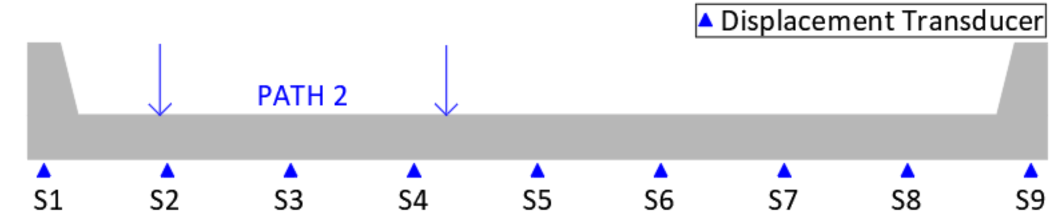




Crawl Speed Test







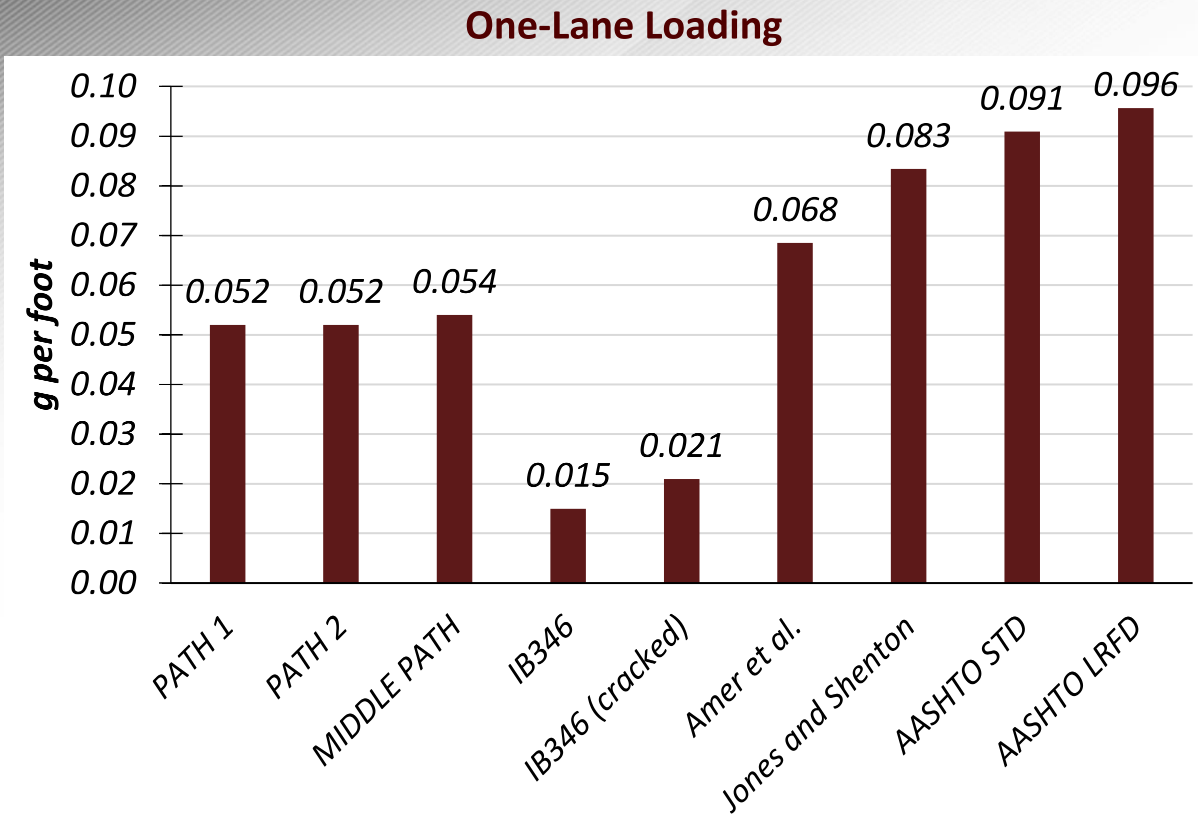
Test	Test (E^m_{Test})	Amer et al. (E^m_{Amer})	Jones and Shenton* ($E^m_{Jones\ \&\ Shenton}$)	AASHTO* (E^m_{AASHTO})	AASHTO LRFD* (E^m_{LRFD})
Stop Location	**17.2**	14.6	11.8	11.0	10.3
Crawl Speed	**16.7**	14.6	11.8	11.0	10.3

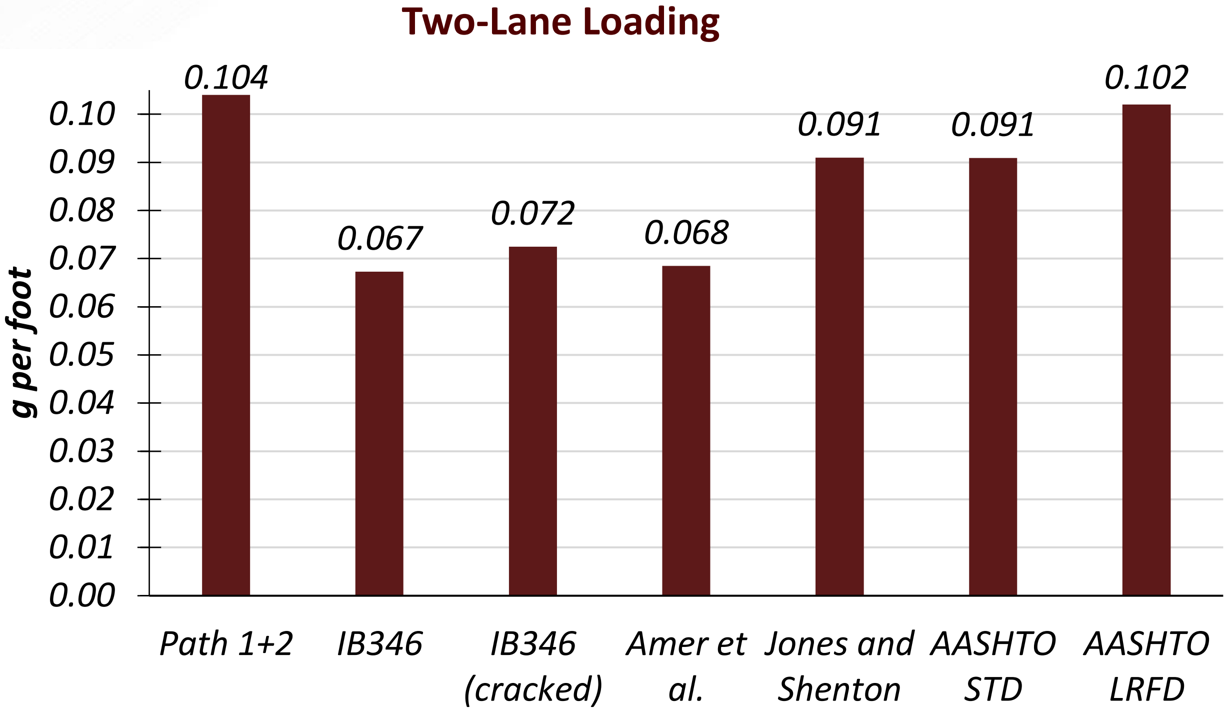
Note: * Approaches do not consider the effect of integral curbs.

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

HS-20 $g_{per\ foot}$

Bridge CS-9





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

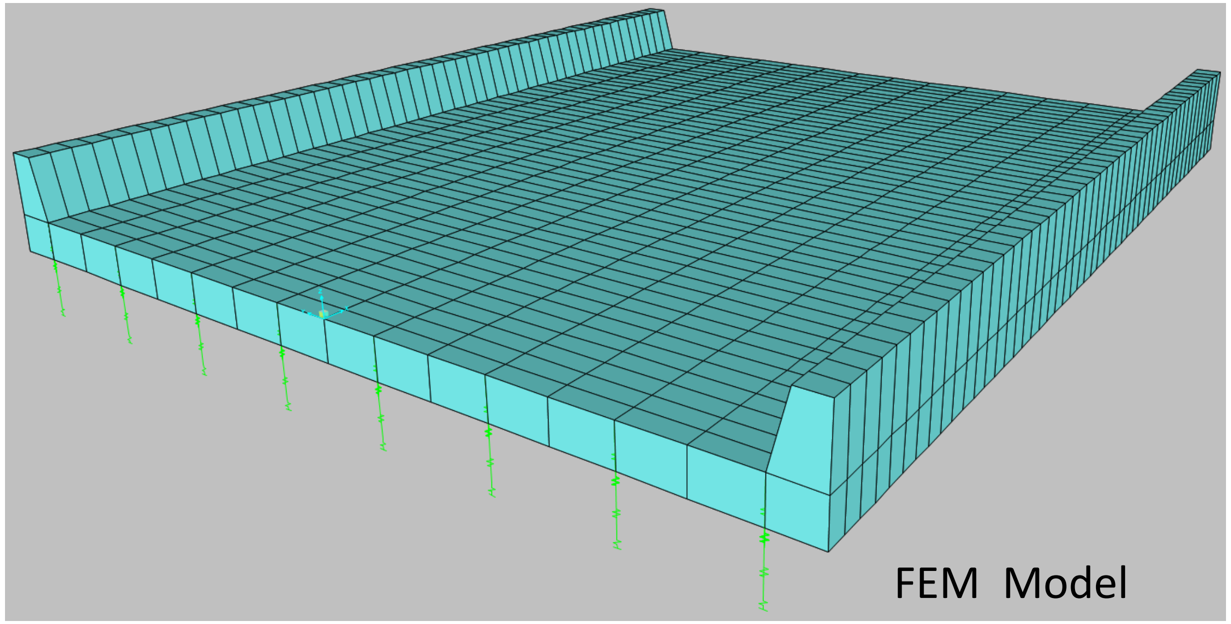
- Amer et al. (1999) provide reasonably good estimate for *g per foot* for one-lane case
- AASHTO LRFD provides better estimate for two-lane loading

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)



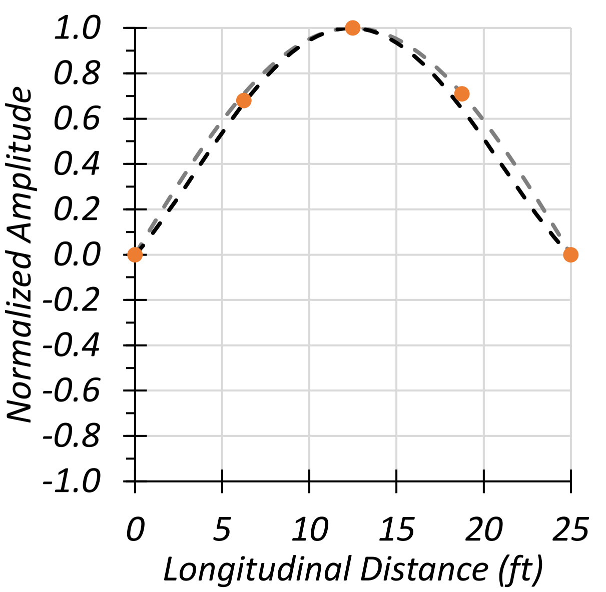
Dynamic Characteristics Comparison

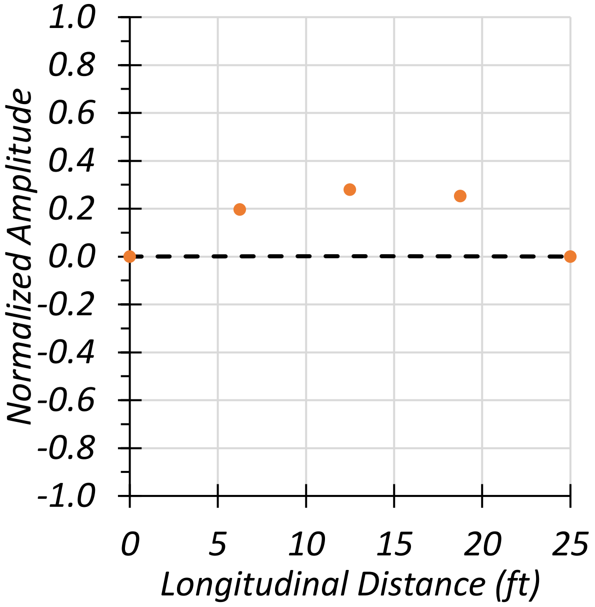
Bridge CS-9

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

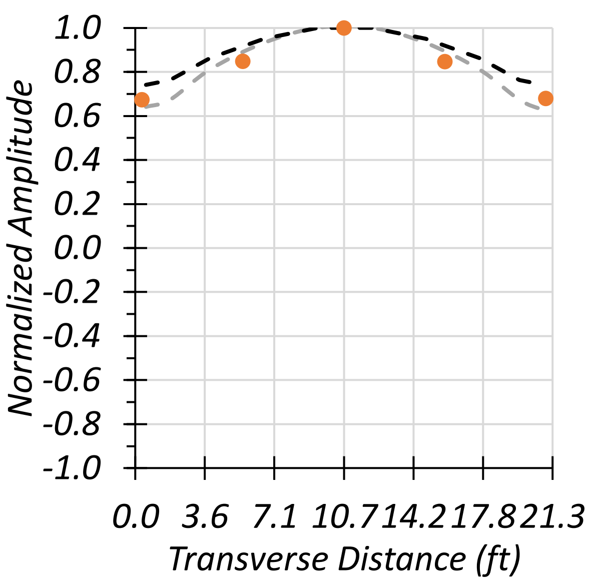
2nd Mode (Test=22.5 Hz, FEM=23.1 Hz)

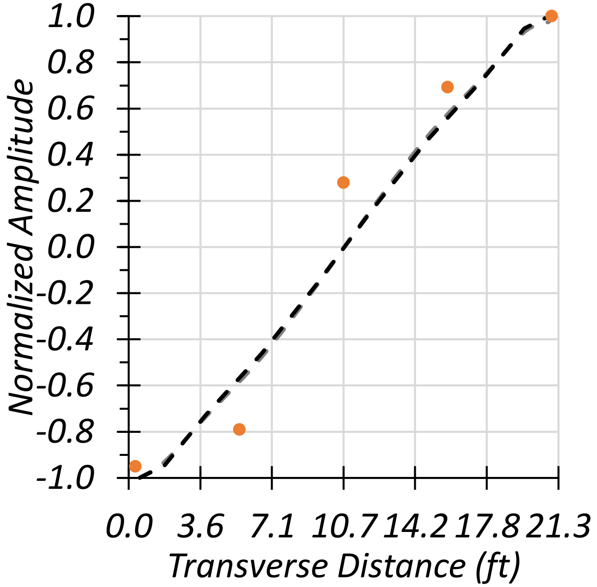
Longitudinal Section





Transverse Section



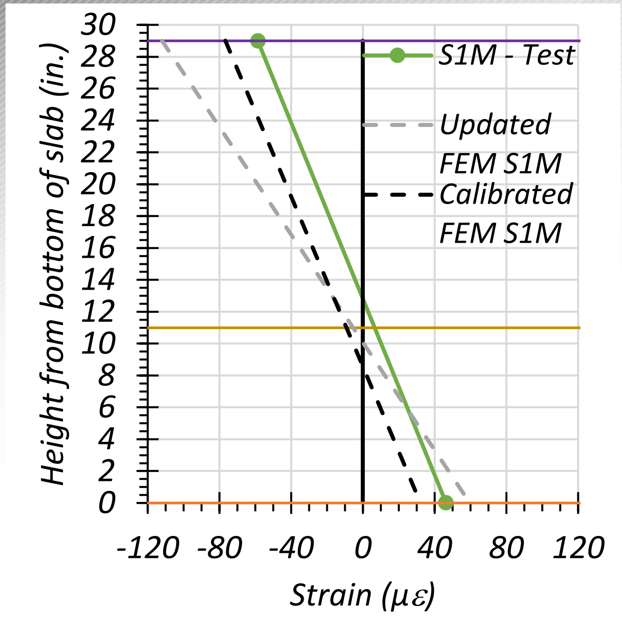


Comparison of Updated and Calibrated Models with Test Results

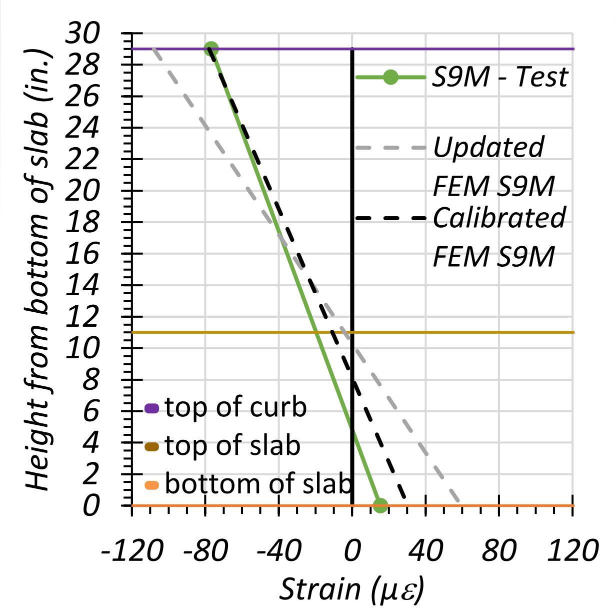
Bridge CS-9

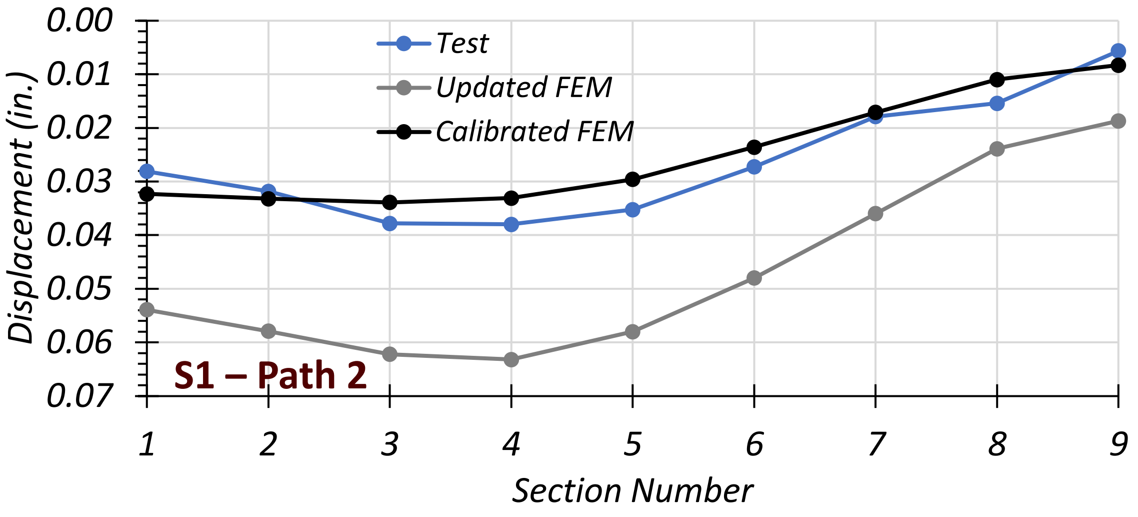
Stop Location Test

S1 – Path 2

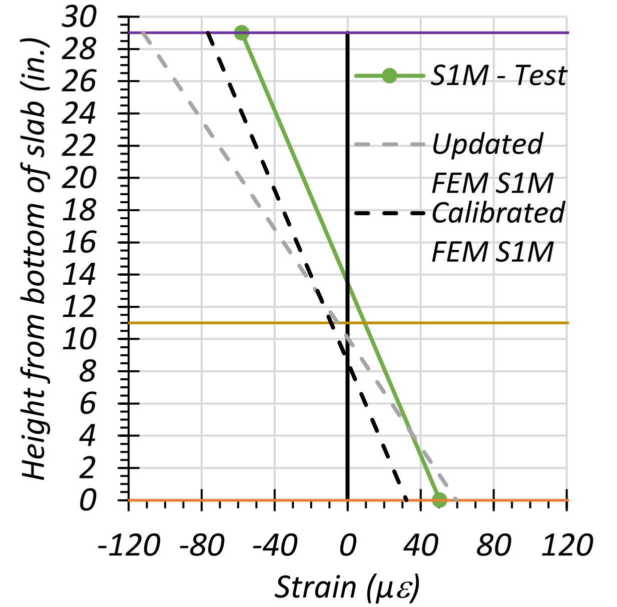


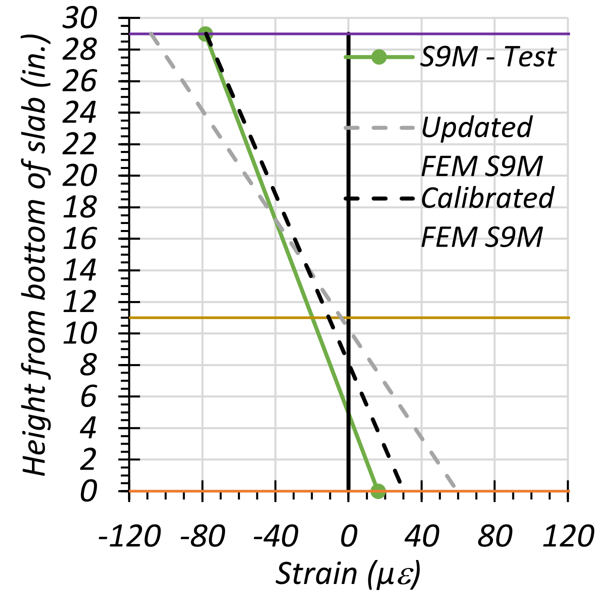
S9 – Path 1

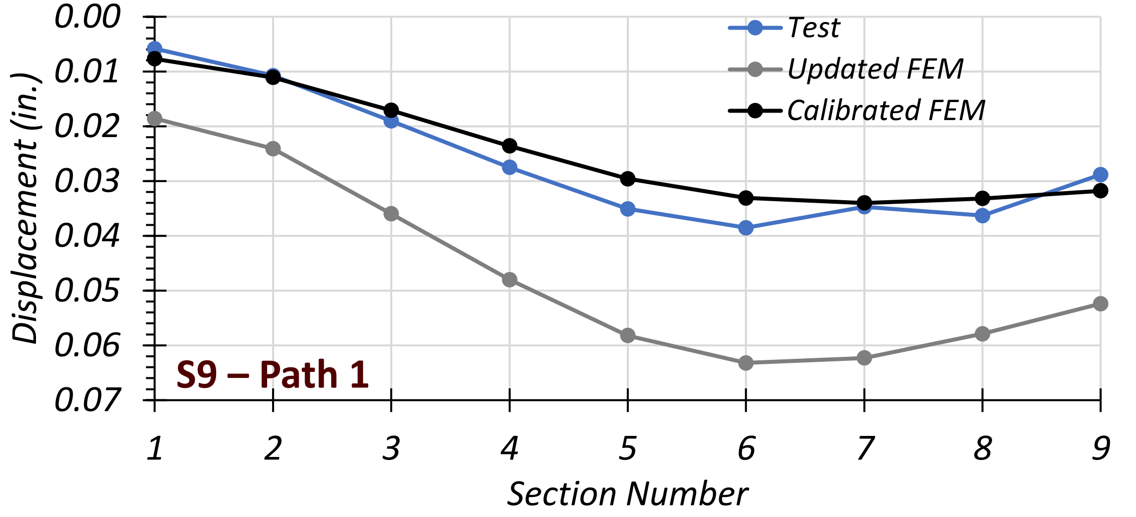




Crawl Speed Test







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*

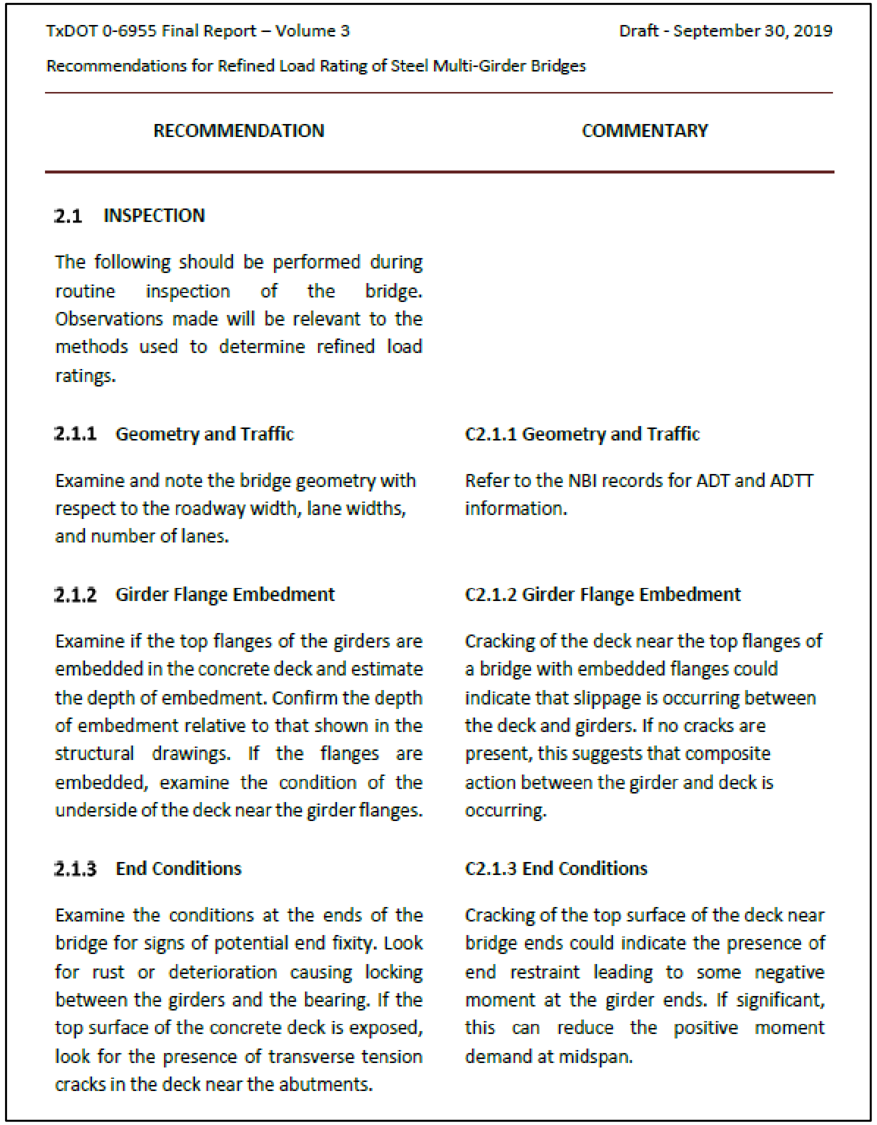
Changes due to:

- 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



TxDOT 0-6955 Final Report – Volume 3 Draft - September 30, 2019

Recommendations for Refined Load Rating of Steel Multi-Girder Bridges

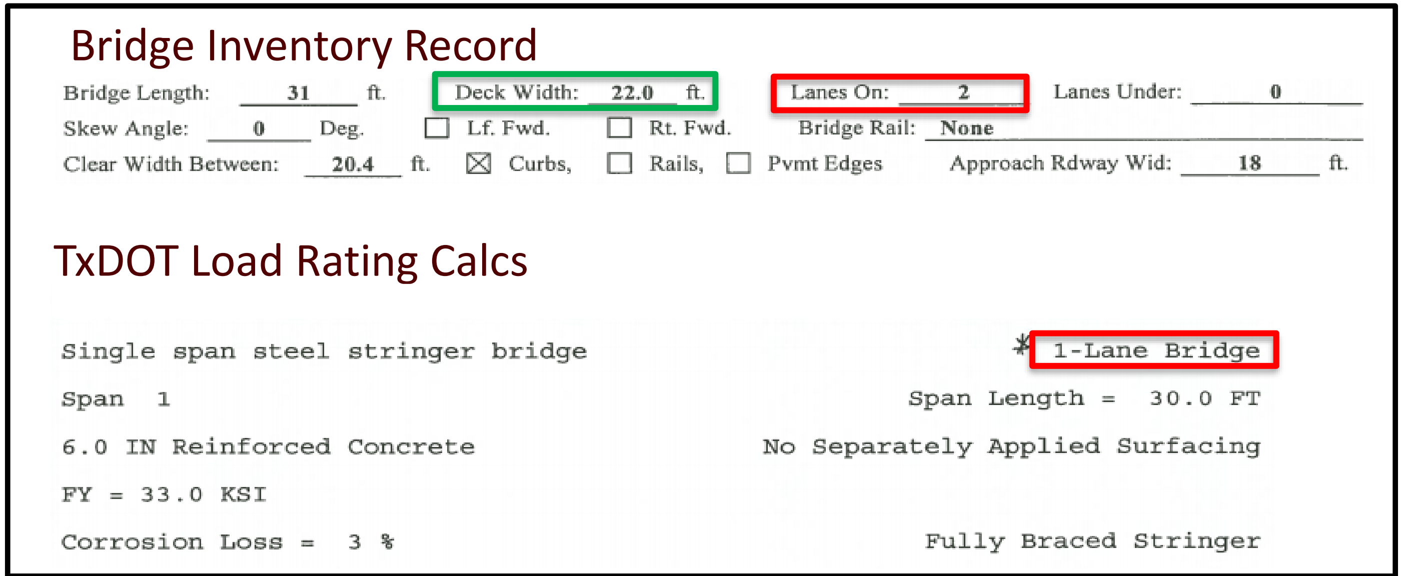
RECOMMENDATION	COMMENTARY
2.1 INSPECTION The following should be performed during routine inspection of the bridge. Observations made will be relevant to the methods used to determine refined load ratings.	
2.1.1 Geometry and Traffic Examine and note the bridge geometry with respect to the roadway width, lane widths, and number of lanes.	**C2.1.1 Geometry and Traffic** Refer to the NBI records for ADT and ADTT information.
2.1.2 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.	**C2.1.2 Girder Flange Embedment** 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 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.	**C2.1.3 End Conditions** 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

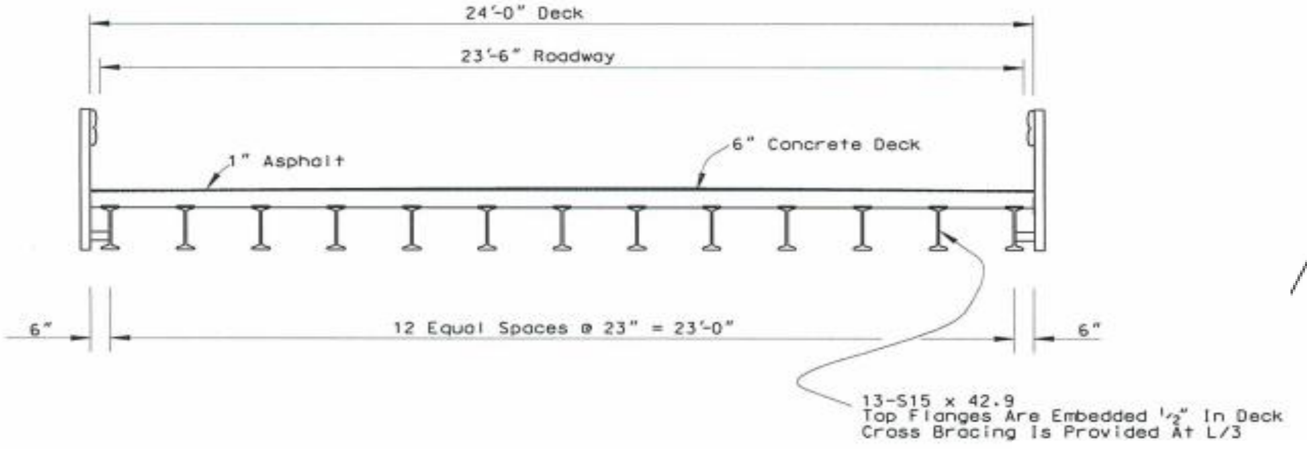
Concrete Slab with Integral Curbs (FS) Bridge Considerations

- 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

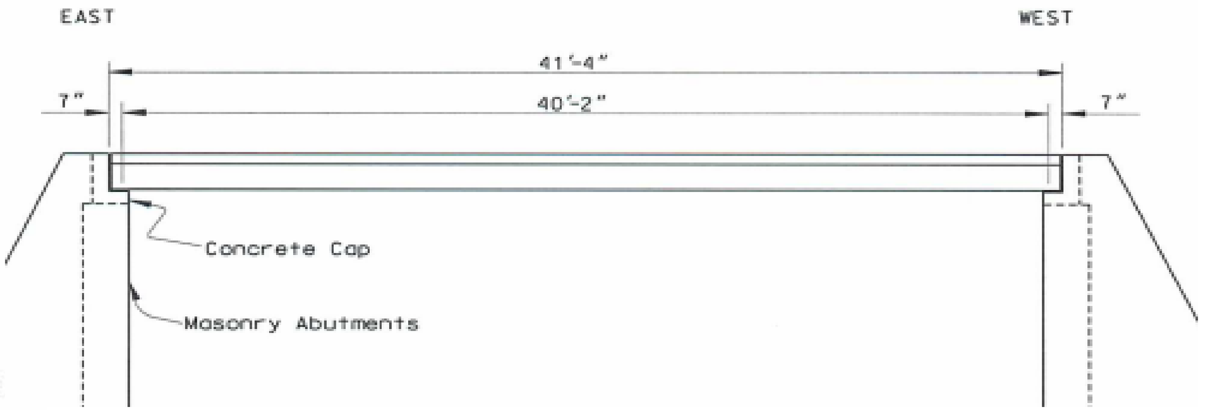
Load Rating Examples

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


24'-0" Deck
23'-6" Roadway
1" Asphalt
6" Concrete Deck
6"
12 Equal Spaces @ 23" = 23'-0"
6"
13-S15 x 42.9
Top Flanges Are Embedded ½" In Deck
Cross Bracing Is Provided At L/3

TYPICAL SECTION


EAST
WEST
41'-4"
7"
40'-2"
7"
Concrete Cap
Masonry Abutments

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

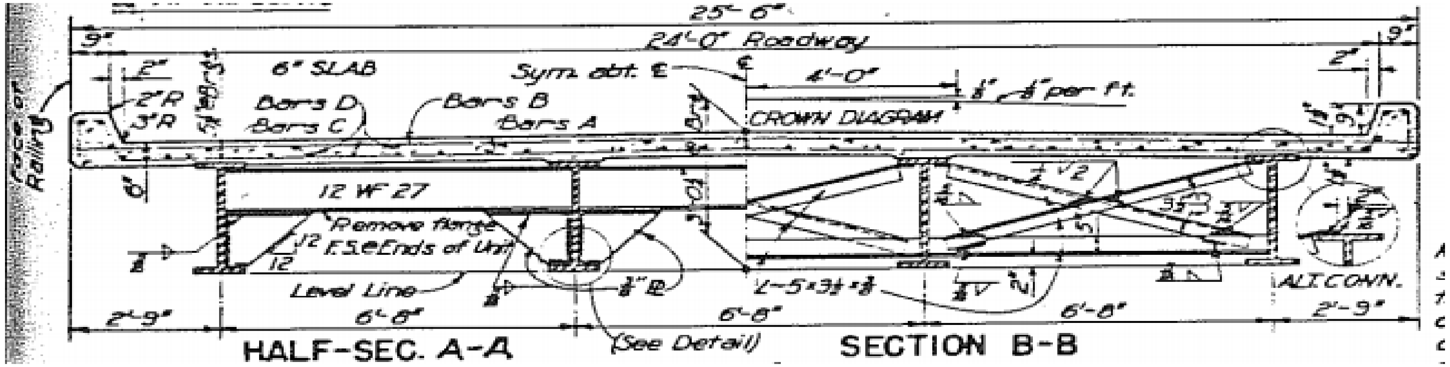
Bridge SM-5 Summary

- 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


25'-6"
9"
24'-0" Roadway
9"
2"
6" SLAB
Sym. abt. ℄
℄
4'-0"
⅛" - ¼" per ft.
2"
2"R
3"R
Bars D
Bars C
Bars B
Bars A
CROWN DIAGRAM
Face of Railing
6"
12 WF 27
Remove flange
F.S. @ Ends of Unit
12
Level Line
⅜" ℞
L-5×3½×⅜
ALT. CONN.
2'-9"
6'-8"
6'-8"
6'-8"
2'-9"
HALF-SEC. A-A
(See Detail)
SECTION B-B

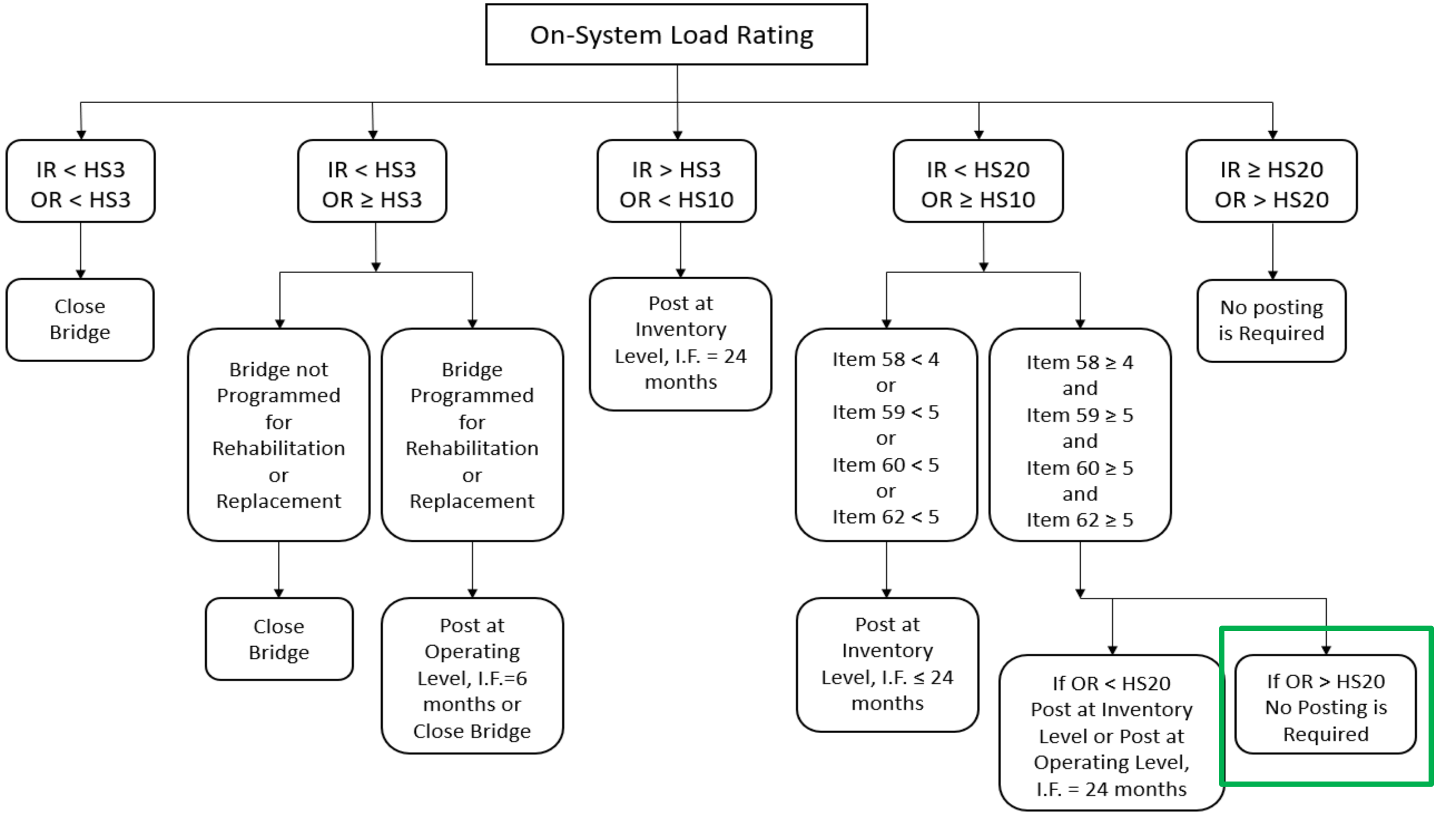
Partial Composite Action – Level II

- 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



On-System Load Rating

IR < HS3
OR < HS3

Close
Bridge

IR < HS3
OR ≥ HS3

Bridge not Programmed for Rehabilitation or Replacement

Close
Bridge

Bridge Programmed for Rehabilitation or Replacement

Post at Operating Level, I.F.=6 months or Close Bridge

IR > HS3
OR < HS10

Post at Inventory Level, I.F. = 24 months

IR < HS20
OR ≥ HS10

Item 58 < 4
or
Item 59 < 5
or
Item 60 < 5
or
Item 62 < 5

Post at Inventory Level, I.F. ≤ 24 months

Item 58 ≥ 4
and
Item 59 ≥ 5
and
Item 60 ≥ 5
and
Item 62 ≥ 5

If OR < HS20
Post at Inventory Level or Post at Operating Level, I.F. = 24 months

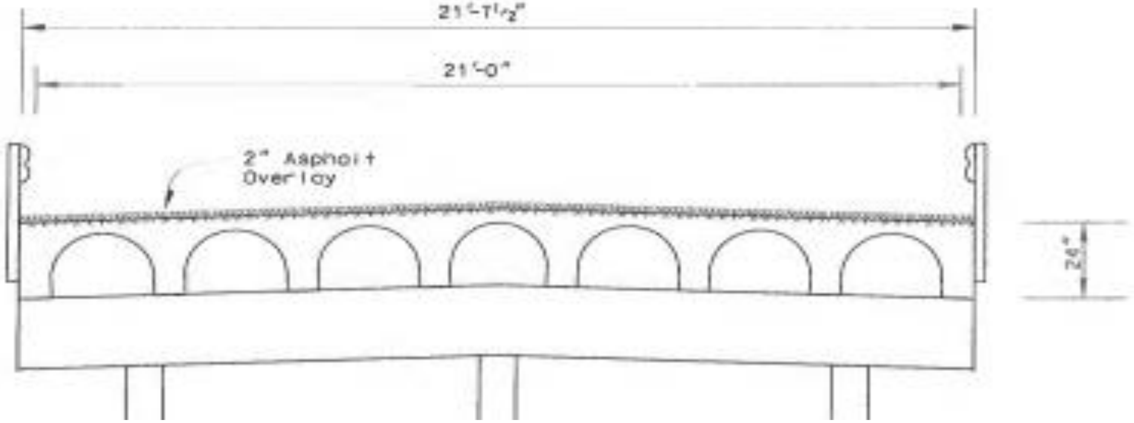
If OR > HS20
No Posting is Required

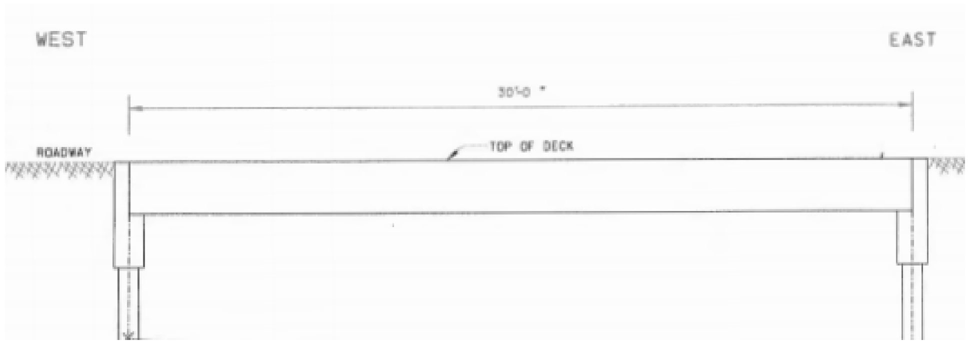
IR ≥ HS20
OR > HS20

No posting is Required

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.


21'-7½"
21'-0"
2" Asphalt Overlay
24"


WEST
EAST
30'-0"
ROADWAY
TOP OF DECK

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

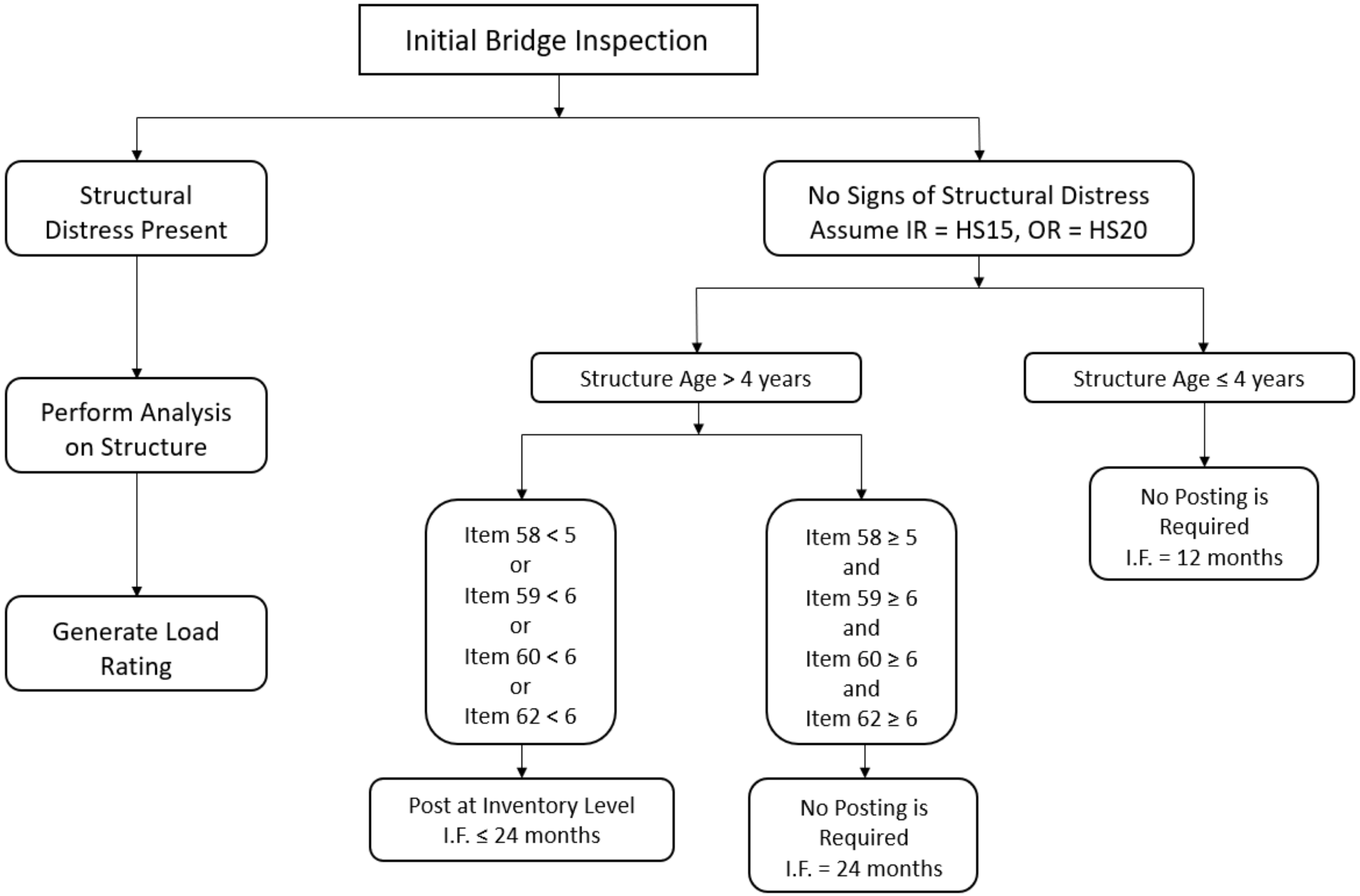
Note: Basic load rating considers simply supported boundary conditions

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


Initial Bridge Inspection
Structural Distress Present
Perform Analysis on Structure
Generate Load Rating
No Signs of Structural Distress
Assume IR = HS15, OR = HS20
Structure Age > 4 years
Structure Age ≤ 4 years
Item 58 < 5 or Item 59 < 6 or Item 60 < 6 or Item 62 < 6
Item 58 ≥ 5 and Item 59 ≥ 6 and Item 60 ≥ 6 and Item 62 ≥ 6
Post at Inventory Level
I.F. ≤ 24 months
No Posting is Required
I.F. = 24 months
No Posting is Required
I.F. = 12 months

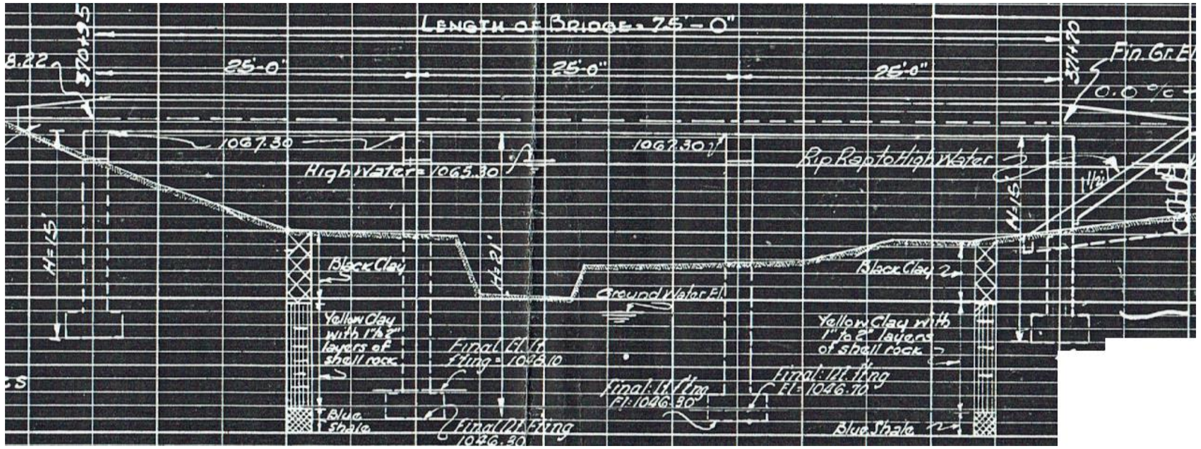
9: Excellent Condition
8: Very Good Condition
7: Good Condition
6: Satisfactory Condition
5: Fair Condition
4: Poor Condition
3: Serious Condition
2: Critical Condition
1: "Imminent" Failure Condition
0: Failed Condition

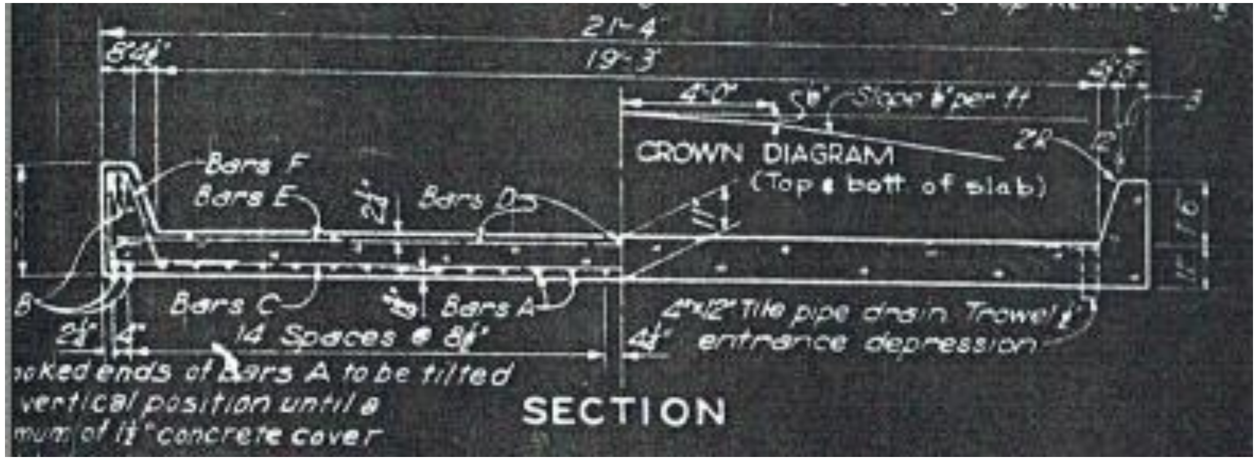
Item 58: Deck condition rating
Item 59: Superstructure condition rating
Item 60: Substructure condition rating
Item 62: Culvert condition rating

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


LENGTH OF BRIDGE = 75'-0"
8.22
370+95
25'-0"
25'-0"
25'-0"
371+70
Fin. Gr. El
0.0 %
1067.30
1067.30
High Water = 1065.30
Rip Rap to High Water
H=15'
H=21'
H=15'
Black Clay
Black Clay
Ground Water El.
Yellow Clay with 1" to 2" layers of shell rock
Yellow Clay with 1" to 2" layers of shell rock
Final El. Lt. Ftng = 1048.10
Final: Lt. Ftng El: 1046.30
Final: Rt. Ftng El: 1046.70
Final Rt. Ftng 1046.30
Blue Shale
Blue Shale


21'-4"
19'-3"
8¼"
4'-0"
Slope ⅛" per ft
CROWN DIAGRAM
(Top & bott. of slab)
Bars F
Bars E
Bars D
Bars C
Bars A
14 Spaces @ 8¼"
4'½" Tile pipe drain. Trowel entrance depression
4¼"
1'-6"
oked ends of Bars A to be tilted
vertical position until a
mum of 1½" concrete cover
SECTION

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

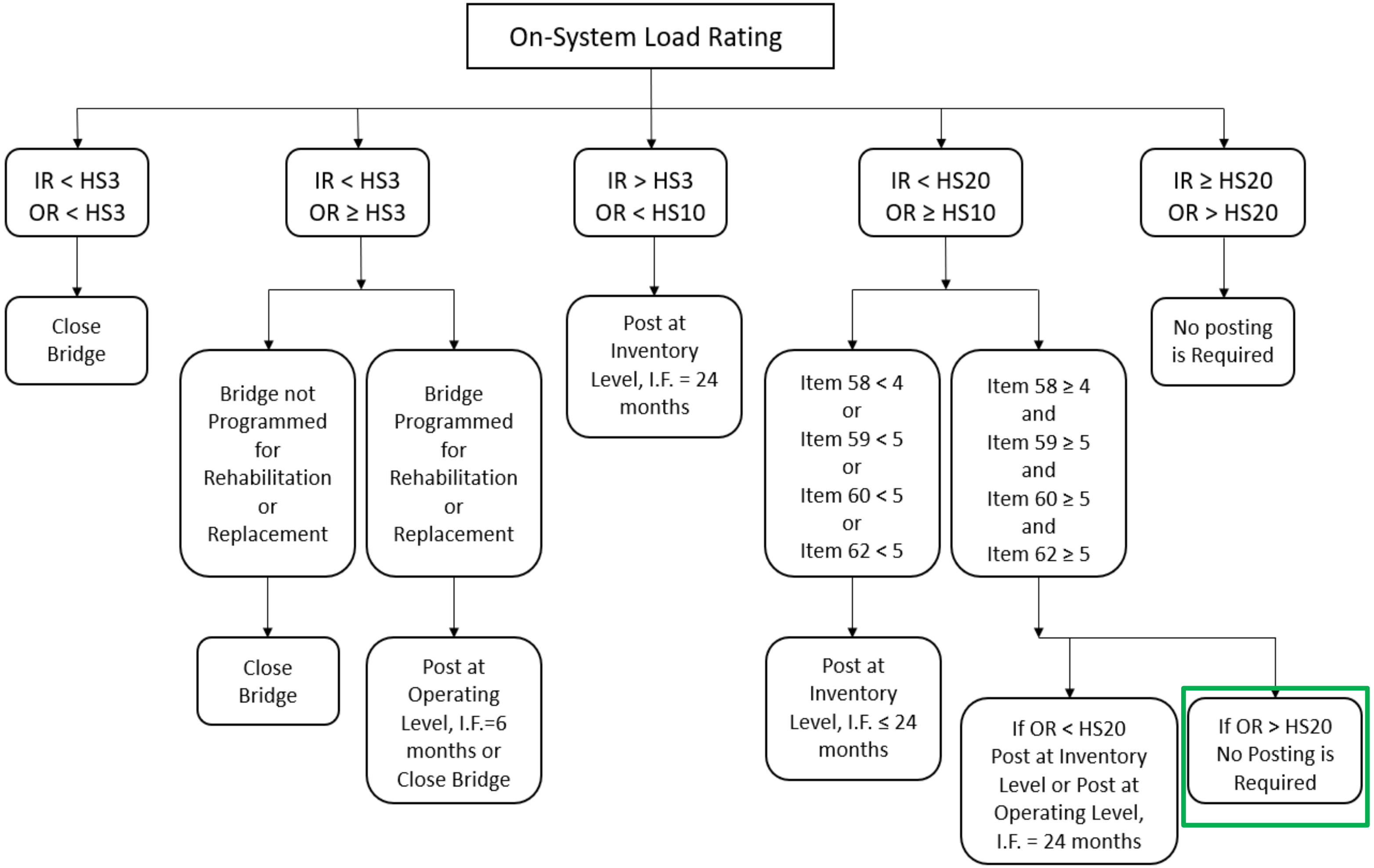
Note: Basic load rating considers simply supported boundary conditions

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



On-System Load Rating

IR < HS3 OR < HS3 → Close Bridge

IR < HS3 OR ≥ HS3
- Bridge not Programmed for Rehabilitation or Replacement → Close Bridge
- Bridge Programmed for Rehabilitation or Replacement → Post at Operating Level, I.F.=6 months or Close Bridge

IR > HS3 OR < HS10 → Post at Inventory Level, I.F. = 24 months

IR < HS20 OR ≥ HS10
- Item 58 < 4 or Item 59 < 5 or Item 60 < 5 or Item 62 < 5 → Post at Inventory Level, I.F. ≤ 24 months
- Item 58 ≥ 4 and Item 59 ≥ 5 and Item 60 ≥ 5 and Item 62 ≥ 5
  - If OR < HS20 Post at Inventory Level or Post at Operating Level, I.F. = 24 months
  - If OR > HS20 No Posting is Required

IR ≥ HS20 OR > HS20 → No posting is Required

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