FAST Act Emergency Vehicle (EV3) Truck Loading & its Impact on Oklahoma DOT Bridge Inventory

Oklahoma Department of Transportation

OKLAHOMA STATE UNIVERSITY COOPERLAB COLLEGE OF ENGINEERING, ARCHITECTURE AND TECHNOLOGY

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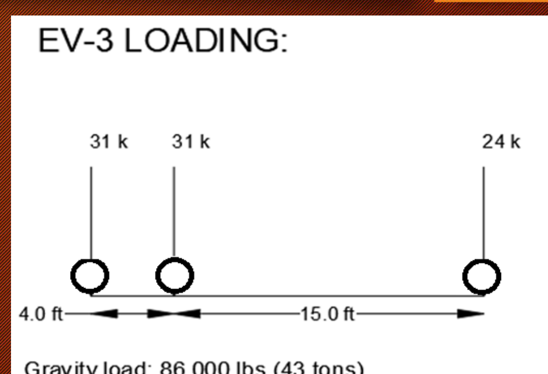
Emergency Vehicle (EV3):

Oklahoma is using EV3 for Load Rating

Aerial Ladder Truck (Photo Credit: Joe Mabel)

RB3



Gross Weight = 86,00 lbs over 19 ft.

2

Slide 2

RB3 Make the "roadway" a rectangle with a patterned fill in the "roadway". Then Draw Three Circles underneath the Loads so that they circles look like wheels or axles.

Russell, Bruce, 7/28/2021

FAST ACT (2015) and Emergency Vehicles (EV's).

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- The FAST ACT (2015).
  - Mandated that some specific Emergency Vehicles (EV's) are made LEGAL on the Interstate Highway System (IHS).
  - Included roadways and bridges "within reasonable access" to the Interstate Highway
- EV's Loads (86,000 lbs) are HEAVIER with tighter axle spacing when compared to:
  - LEGAL TRUCKS (typically 80,000 lb. with 51 ft. axle spacings that conform to the Bridge Formula), and
  - Design Trucks (H-20, HS-20, or HL-93)

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Impact of EV3 Loading on Bridge Rating. SH 14 Bridge "A" over Eagle Chief Creek, Woods Co., Oklahoma (NBI 13088)

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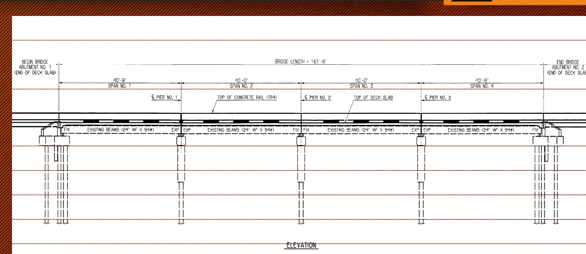
The Eagle Chief Creek Bridge "A" – SH 14 Woods Co., OK.



Four Spans Total = 161 ft. 6 in.
Nominal Span Length = 40 ft.
c/c Bearings = 38 ft. 10 in.
Clear roadway width = 28 ft. 6 in.
Original Construction = 1954 (Fy = 33 ksi)
Rehabilitation (Re-decking) = 2011

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EV3 Load Testing – Prototype Bridge at the Cooper Lab

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- Two W24x94 steel girders supporting a composite concrete deck.
- Bridge Span = 38 ft 10 in. center to center (c/c) of the bearings.
- Steel Bearings match those found in the Eagle Chief Creek Bridge "A" in Woods Co. OK on SH 14.
- Composite concrete deck 8 in. thick and 14 ft wide.
- Concrete Deck is ODOT AA concrete mixture with ODOT Curing

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Older Bridges were designed under different and less stringent criteria, and smaller design loads.

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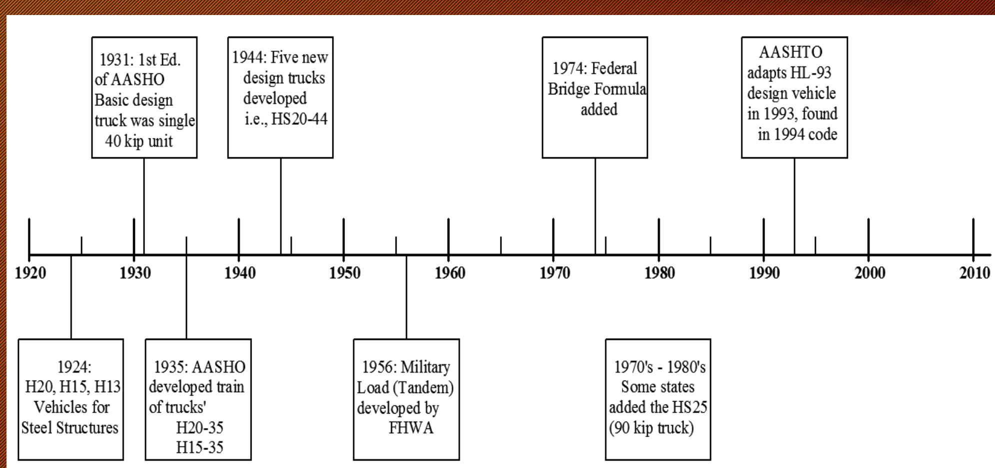

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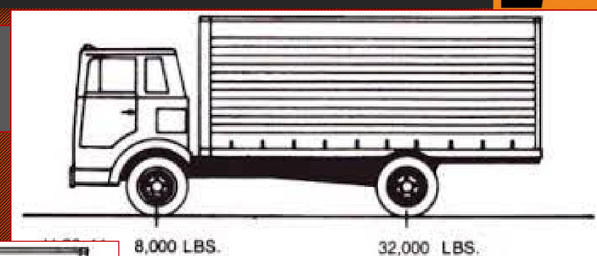
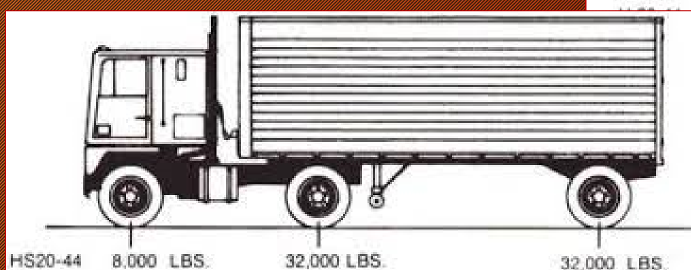
AASHTO Design Trucks (Standard Specifications):

H 20-44 Truck Loading.
GVW = 20 Tons (40,000 lbs.)
Axle Spacing = 14 ft. to 30 ft.





HS 20-44 Truck Loading
GVW = 36 Tons (72,000 lbs.)
(Axle Spacing = 14 ft. to 30 ft.)

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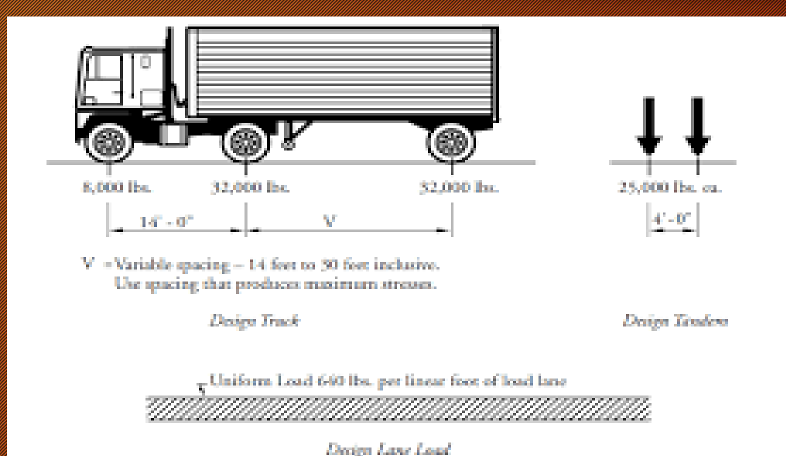
AASHTO Design Trucks (LRFD): HL-93 for Bridge Design



HL-93
Combines the HS 20-44 Design Truck plus the 640 lb/ft Lane Live Load

*** Current AASHTO LRFD**

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Legal Trucks for Interstate Highways Defined by the Interstate Highway Act of 1956 and the U.S. Code

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§23 of U.S. Code (1956)

- **GVW < 80,000 lbs.**
- **Single Axle < 20,000 lbs.**
- **Tandem Axles < 34,000 lbs.**
- **1974 Act invested the BRIDGE FORMULA**
- **State Laws are not uniform, and some exceptions are allowed by U.S. Code based on grandfathering provisions.**
- **States allow permit loads**

Russell et al (2017), "Comparative Assessment of Current Gross and Axle Truck Weight… Laws" ODOT SP&R Item No. 2271. February 2017

The Bridge Formula (1974)

$$W = 500 \cdot \left\{ \left[\frac{LN}{(N-1)} \right] + 12 \cdot N + 36 \right\}$$

Where:

- **W = Maximum Weight (lbs) that can be carried by two or more adjacent axles**
- **L = Spacing in feet between the outer axles being considered**
- **N = The number of axles considered**

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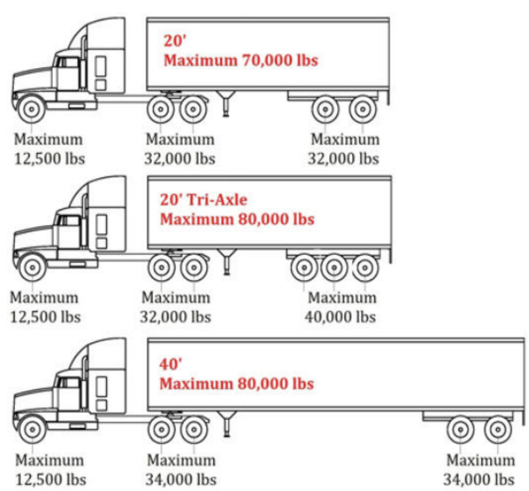
Legal Trucks by the U.S. Code §23 and the Bridge Formula

Trucks conforming to the Bridge Formula, a.k.a. "FORMULA B."

- The Truck Configuration at the lower right with five axles and 80,000 GVW is typical.
- The Bridge Formula allows rounding of 500 lbs., so the configuration shown at lower right is 80,500 lbs.
- Axle Tandems are spaced at 4 ft. with maximum tandem weight of 34,000 lbs.



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FAST Mandate for Legal Emergency Vehicles requires Examination and impetus for Load Testing.

- FHWA: 614,387 bridges in the National Highway System (NHS) and the National Bridge Inventory (NBI).
- In 2016 about 56,000 bridges were described as structurally deficient in the NBI (ASCE 2017, Russell et al, 2015).
- ODOT: 1600+ Steel Span Bridges
- ODOT: 1400+ Span Bridges 80 years old or older
- EV3 Loading creates higher moments and shears than Notional Design Loads or other Legal Truck Configurations
- ODOT Steel Bridge Inventory Replacement costs approach $6 billion.

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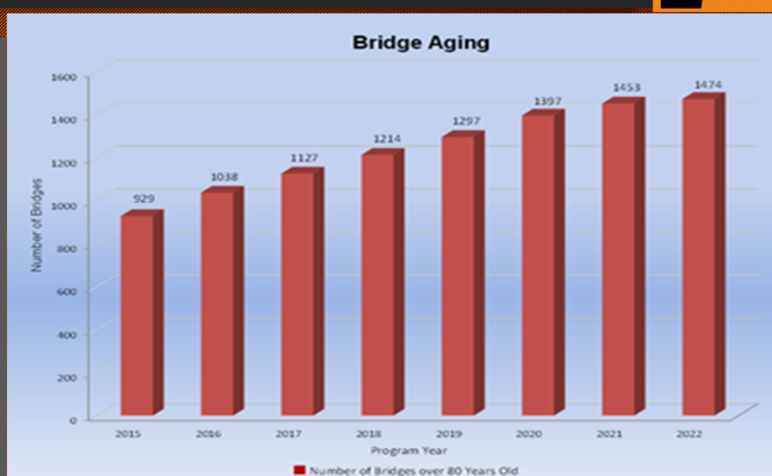
Oklahoma's Aging Bridges
Number of ODOT Bridges 80 Years Old or Older

- **With every passing year the Bridge Inventory AGES**
- **1453 Span Bridges in the ODOT Bridge Inventory is 80 years old or older**
- **The Interstate Highway build-out is about 60 years old**
- **600+ Steel Girder Bridges built in 1960's**



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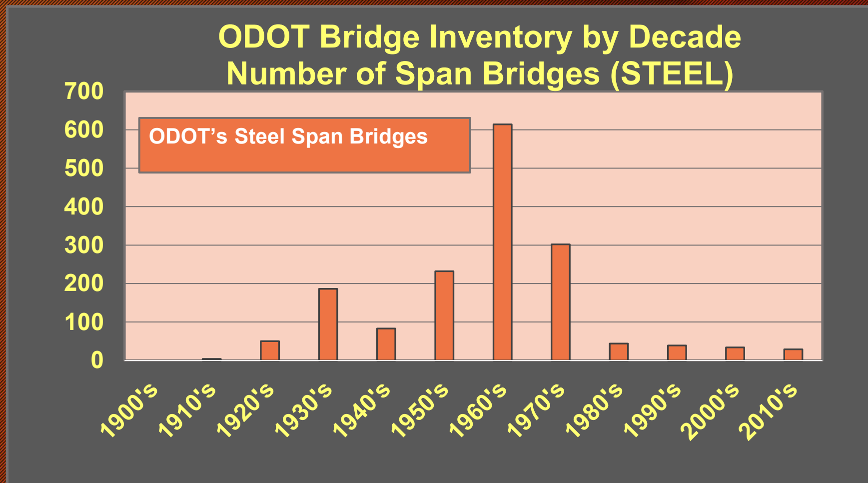
ODOT STEEL BRIDGE INVENTORY BY DECADE

- ODOT Bridge Inventory contains 1618 Steel Girder Bridges
- Peak Construction in the 1960’s with the Interstate Highway Build-Out
- This chart reflects ORIGINAL construction date for bridges, even if rehabilitated.



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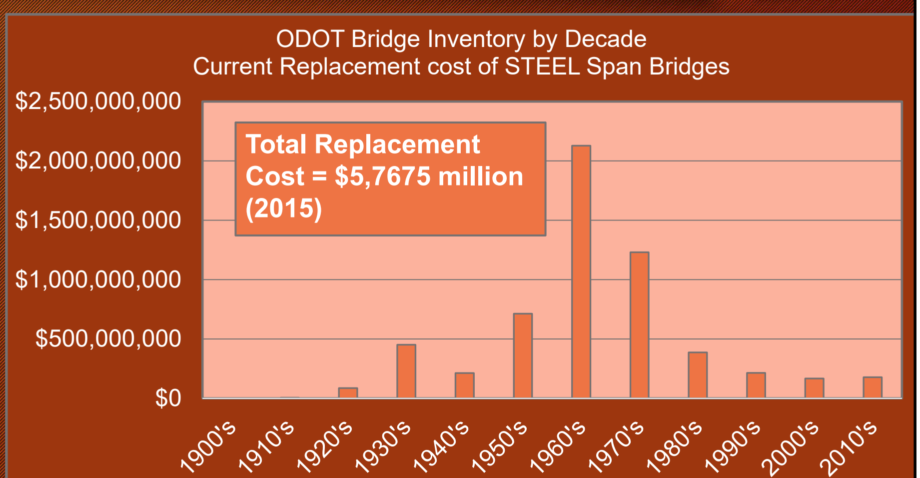
ODOT STEEL BRIDGE INVENTORY REPLACEMENT COSTS

- Replacement Costs are in 2015 dollars. (Russell et al, 2015).



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EV3 Loads produce greater Moments and Shears than H 20, HS 20 or HL-93 Loadings

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Moments and Shears Produced by various Design and Rating Vehicles for Eagle Chief Creek Bridge (A)

- Span Length = 38.83 ft.:
  - H 20-44 M = 334 k-ft V = 35 kips
  - HS 20-44 M = 429 k-ft V = 51 kips
  - HL-93 M = 549.7 k-ft V = 63 kips
  - Legal Truck: 5 axle (80k) M = 324 k-ft V = 37 kips
  - **EV3 M = 597 k-ft V = 66.8 kips**

The EV3 Emergency Vehicle increases the Load Effects beyond that of common design loads.

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EV3 Loads compared to current and historical design loads (Factored and un-factored).

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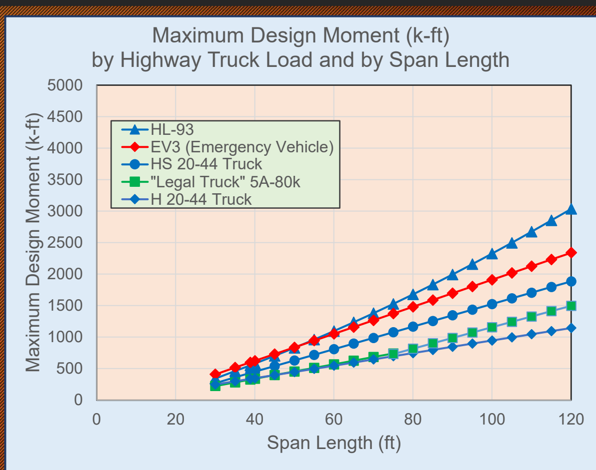

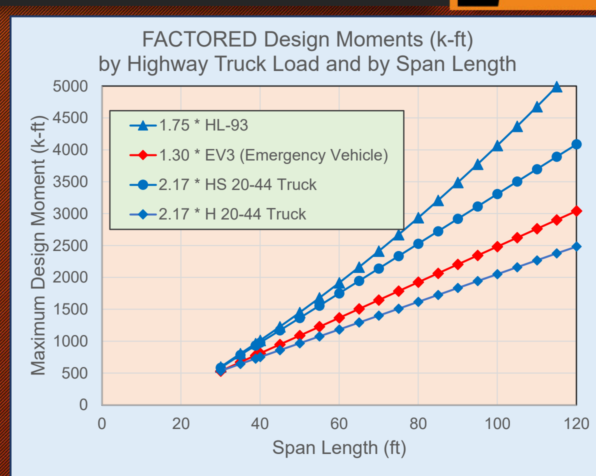

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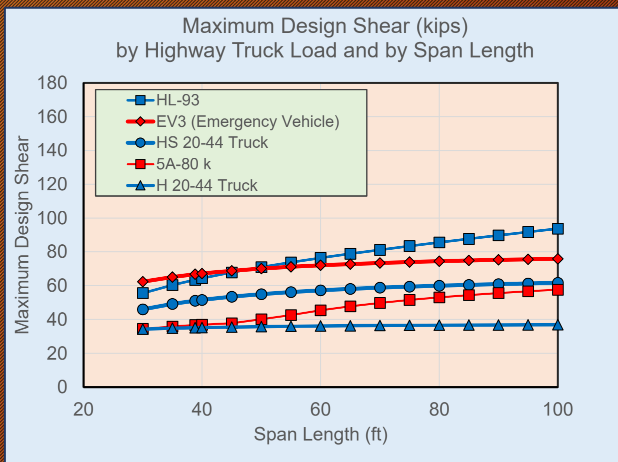
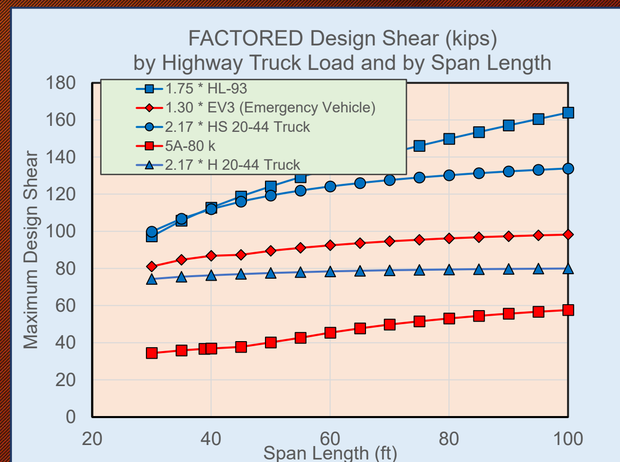
EV3 Loads Compared to Current and Historical Design Loads (Un-Factored and Factored)





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Load Rating Calculation:

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

In English:

$$RF = \frac{\textit{Capacity for Live Load beyond the existing DL's}}{\textit{Factored Live Loads including Impact}}$$

- $DW = 0$
- $IM = 0.33$
- $\gamma_{LL} = 1.30$
- C = Nominal Capacity (C = 522 k for shear; C = 3392 $k - ft$ for moment)
  - These numbers are based on ***Fy = 36 ksi.*** Note that the original W sections were re-used during the bridge rehabilitation in 2011.
- γ_{DC} = 1.25
- DC: Dead Loads (DC = 29.4 kips for shear or DC = 304.55 k-ft)
- LL: Live Load (LL = 67 kips for shear and LL = 597 kip-ft for moment)

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Load Rating: Calculating RF – Rating Factor

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Load Rating for Bending

$$RF = \frac{3{,}392\ k \cdot ft - (1.25)\ 304.5\ k \cdot ft}{(1.30)(597k \cdot ft)(1 + 0.33)} = \mathbf{2.92}$$

Load Rating for Shear

$$RF = \frac{522\ k - (1.25)\ 29.4kips}{(1.30)(67k)(1 + 0.33)} = \mathbf{4.20}$$

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Load Rating: Calculating RF
RF for varying Steel Grades (F_y)

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Moment and Shear Capacity per Girder			
Fy (Steel Beam) in ksi	33	36	50
Moment Capacity in kip-ft	1566	1696	2335
Shear Capacity in Kip	240	261	363

Rating Factors			
Fy (Steel Beam) in ksi	33	36	50
RF for Moment	2.66	2.92	4.16
RF for Shear	3.82	4.20	5.95

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EV3 Load Testing - SCOPE

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Four Load Configurations:

Type of Test	Loading @	Symmetric or Eccentric
1) Flexure	Midspan	Symmetric
2) Flexure	Midspan	Eccentric
3) Shear	Near East End	Symmetric
4) Shear	Near Near End	Eccentric

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Test Setup: Tests for Flexural Response

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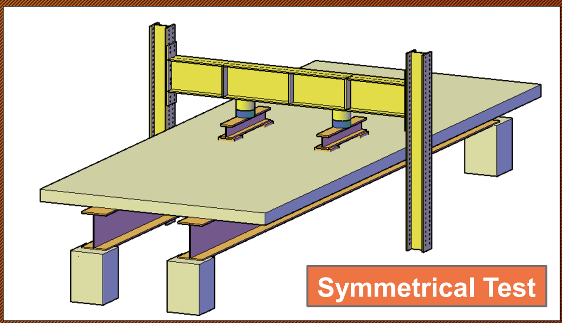

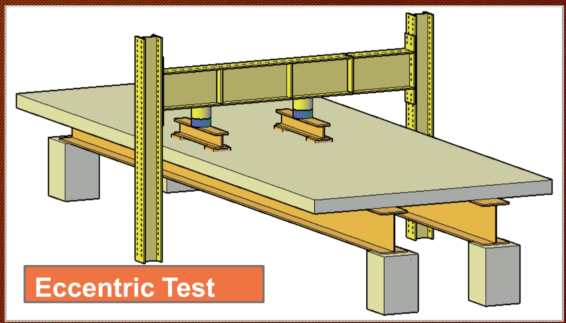

- Symmetric Flexure Test @ Midspan with point loads **In-line** with W24's
- Eccentric Flexural Test @ Midspan with Points Loads **Offset 2 ft.** from Girder CL's.

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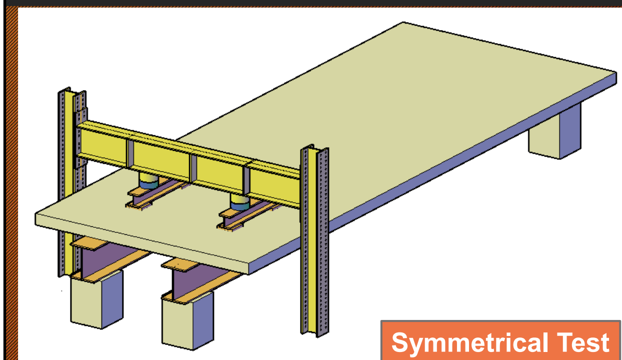
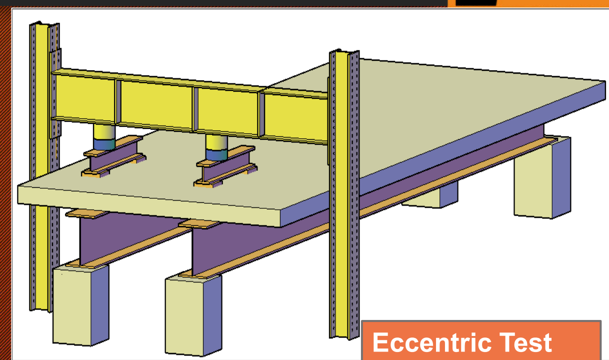
Shear Tests:





- Symmetric Shear Test @ E. End with point loads **In-Line** with W24's
- Eccentric Shear Test @ E. End with Points Loads Offset 2 ft. from Girder CL's.

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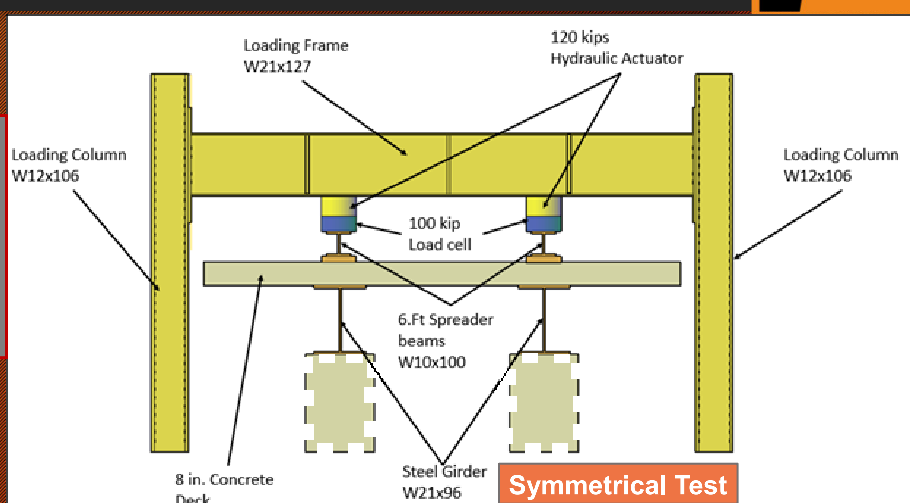
Test Setup: Flexural Test

Cross Section Details:
- (2) W24x94
- Girder Spacing = 6'-0
- Slab Width = 14'-0
- Slab Thickness = 8 in.
- Fy = 36 ksi
- f'c = 4 ksi



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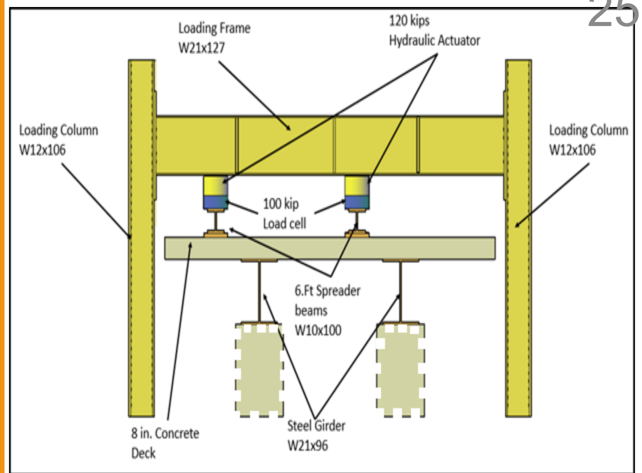
Eccentric Loading

Cross Section Details:
- (2) W24x94
- Girder Spacing = 6'-0
- Slab Width = 14'-0
- Slab Thickness = 8 in.
- Fy = 36 ksi
- f'c = 4 ksi

- Load Offset (Eccentricity): 2'-0"



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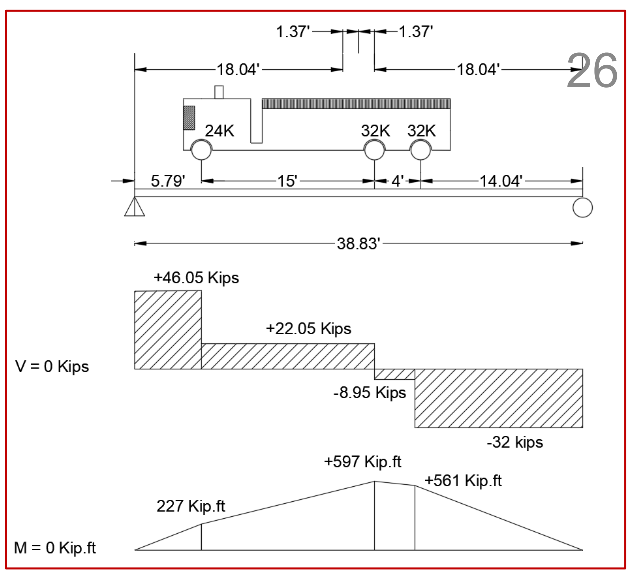
Flexural loading: @ Midspan

Axle Configuration for Maximum Moment
- $M_L = 597.1\ kip.ft$
- $Vmax = 40.6\ \ kip$

The Test Loading is a different configuration but produces Moment to Shear ratio of 19.2 ft.



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Prototype SH 14 Bridge built in the Cooper Lab w/ 38 ft. 10 in. span supported by (2) W24x94's with 14 ft. wide composite concrete deck.

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Instrumentations on the south girder (South Elevation) :

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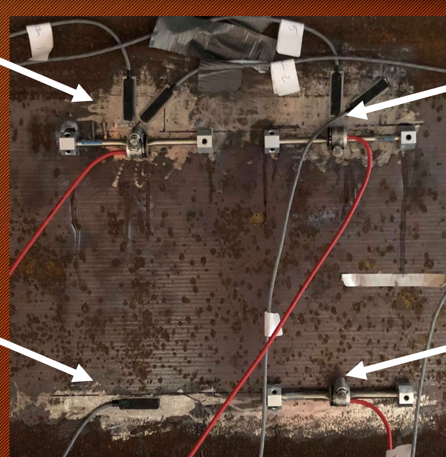
Strain gage at 6in. from the top of the steel girder Rosette at 45 in.

Strain gage at 18 in. from the top of the steel girder At 45 in. from the support



Strain gage at 6 in. from the top of the steel girder Rosette at 36 in.

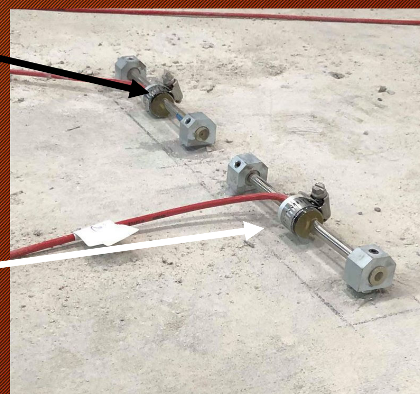
Strain gage at 18 in. from the top of the steel girder At 36 in. from the support

28

Instrumentation:

29

Strain gage at 45 in from the support



Strain gage at 36 in from the support

29

Instrumentation:

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- **Shear Strain**:

The shear strain is the ratio of the change in deformation to its original length perpendicular to the axes of the member due to shear stress.

- **Strain gage rosettes:**

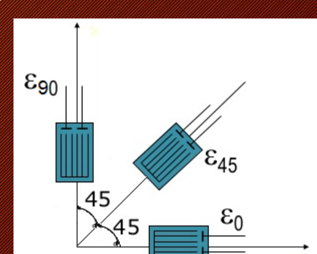
We set up our gages in position where we can capture the three gages measurements with a known angular position so we can compute the shear strain.

ε_0: *Measured horizontal strain*

ε_{90}: *Measured vertical strain*

ε_{45}: *Measured inclined strain*

$$\gamma = 2 \times \varepsilon_{45} - (\varepsilon_{90} + \varepsilon_0)$$



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Results: Symmetric Flexural Test

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Load vs Displacement of the Steel Girders (Symmetric Flexural Test)

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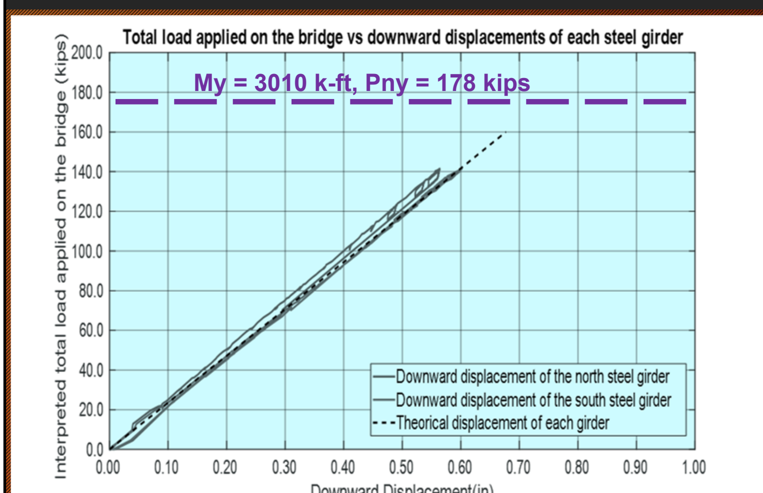

Take-Aways:

- P_{test} > 140 kips
- P_{ny} = 178 kips
- P_{EV3} = 35.3 kips
- P_{test} exceeds P_{EV3} by 4x
- P_{test} exceeds 1.30 P_{EV3} by 3X
- P vs. Δ from test matches that from "Theory"
- P vs. Δ is linear-elastic – The Bridge is "undamaged" by the test load.

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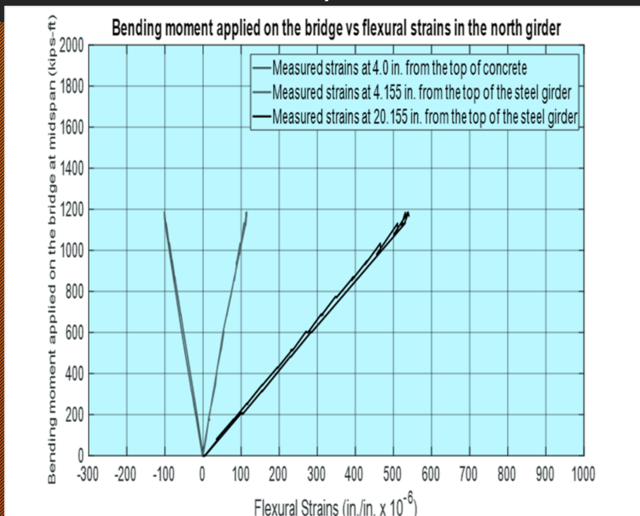
Flexural Test, Symmetric (Load vs Strains North Girder)



Take-Aways:

- Tensile strains are measured at the bottom of the cross section. Maximum tensile strain of 535 microstrains corresponds to 15.5 ksi. Note that 0.6 Fy = 21.6 ksi.
- Tensile strains also exist near the TOP of the steel girder. Designers can ensure this condition by choosing girder sections, spacings and slab depths to produce a N.A. at or near the top flange.
- Compression strains are measured at mid-depth of the concrete deck slab. Concrete Strains ≈ - 100 microstrains. The Concrete Compression strain of 100 microstrains corresponds to a concrete compressive stress of 450 psi.
- Linear Load vs. Strains demonstrates that both steel and concrete materials remain linear-elastic and are not likely to suffer damage with repeated EV3 Loadings.

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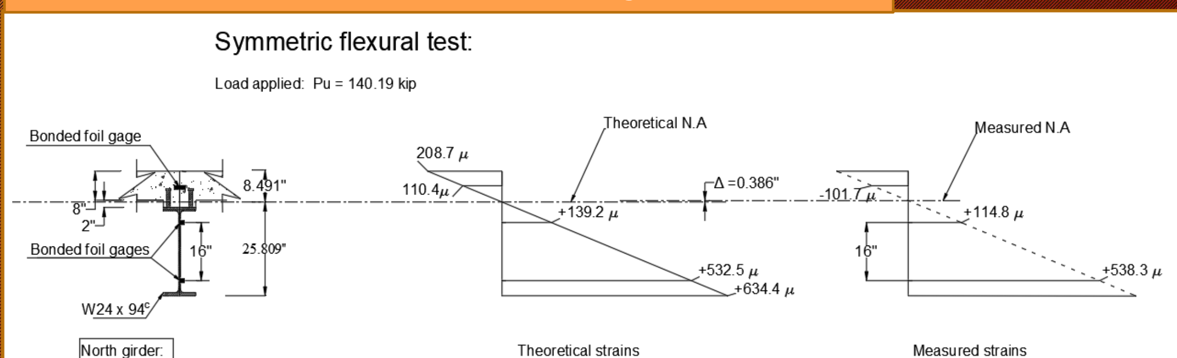
Midspan Strain Diagram for the North Girder (Symmetric Flexural Test)

Take-away: Beam Behavior Governs
And Beam Theory can be used to predict behavior and perform Load Rating Calculations



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Results: Eccentric Flexural Test

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Flexural Load Test (Asymmetric Loading)

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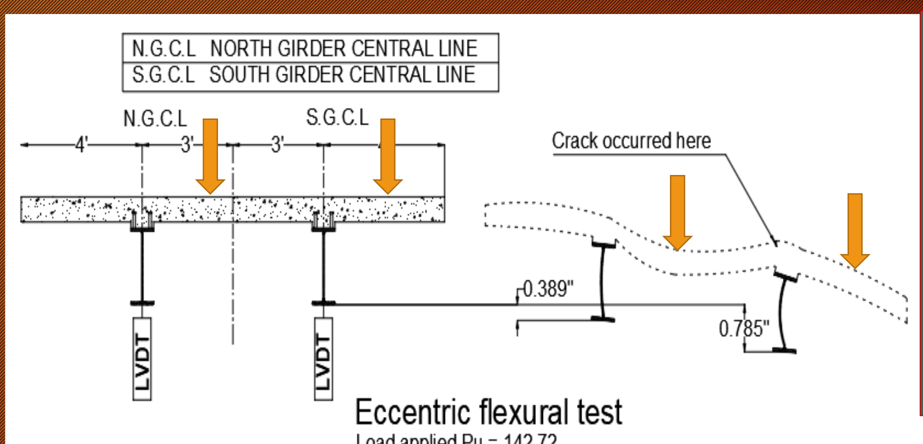

From the Assymmetric Flexural Load Test:

- $\Delta_{South} \approx 0.785$ in.↓
- $\Delta_{North} \approx 0.389$ in.↓
- The relative Δ's suggest that the Test DF = 2/3 or 0.67 (or that the South girder supported 2/3 of the loading and the North girder supported 1/3 of the load.
- Total applied load Pu = 142.7 kips

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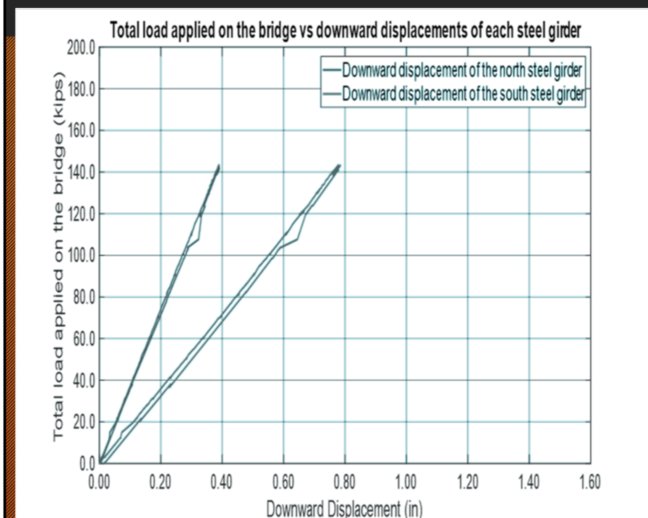
Flexural Load Tests: Eccentric Test



Take-Aways – Comments about Distribution Factors

- Load was applied Asymmetrically, with the CG of the Load offset 2'-0 from the CG of the bridge.
- Girder Spacing is 6'-0, so the Lever Rule gives the DF = 5/6 or 0.83.
- AASHTO Appendix F - LL Distribution, Rigid Method gives a DF = 0.83

From the Assymmetric Flexural Load Test:

- $\Delta_{South} \approx 0.80$ in.↓
- $\Delta_{North} \approx 0.40$ in.↓
- The relative Δ's suggest that the Test DF = 2/3 or 0.67 (or that the South girder supported 2/3 of the loading and the North girder supported 1/3 of the load.
- These measurements are made on the FLEXURAL tests and do not necessarily apply to the Shear Tests; however, we found that similar behavior in the Shear tests.

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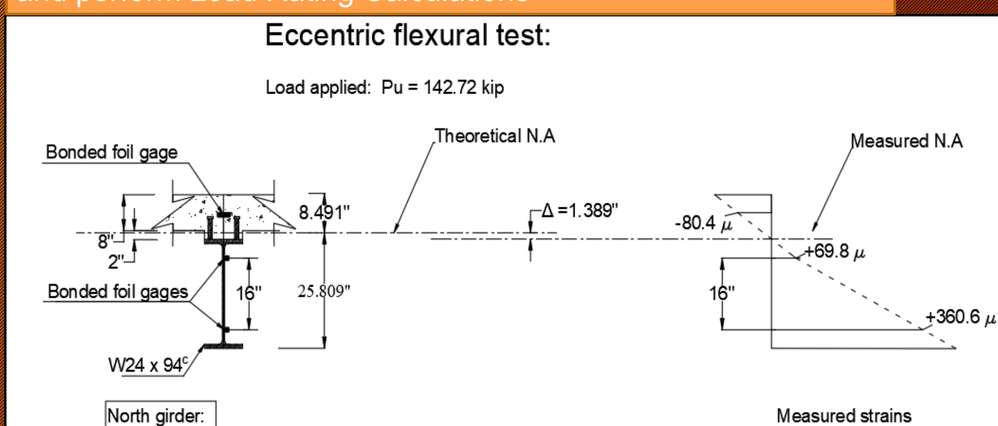
Bending Strains at Midspan - North Girder Asymmetric Flexural Test

Take-away: Beam Behavior Governs
And Beam Mechanics can be used to predict bridge behavior and perform Load Rating Calculations



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Results: Symmetric Shear Test

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Shear Load Tests: Symmetric Test

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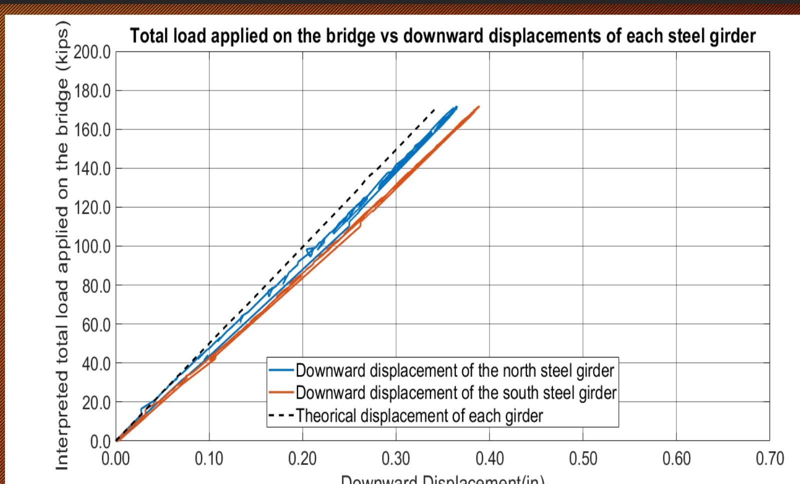

Take-Aways:

- P_{test} > 170 kips
- V_n = 722 kips
- P_{EV3} = 66.7 kips
- P_{test} exceeds P_{EV3} by 2.5X
- P_{test} exceeds 1.30 P_{EV3} by 2.0X
- P vs. Δ from test matches that from "Theory"
- P vs. Δ is linear-elastic – The Bridge is "undamaged" by the test load.

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Load vs Shear Strain @ 45in. From the End (Symmetric Shear Test).

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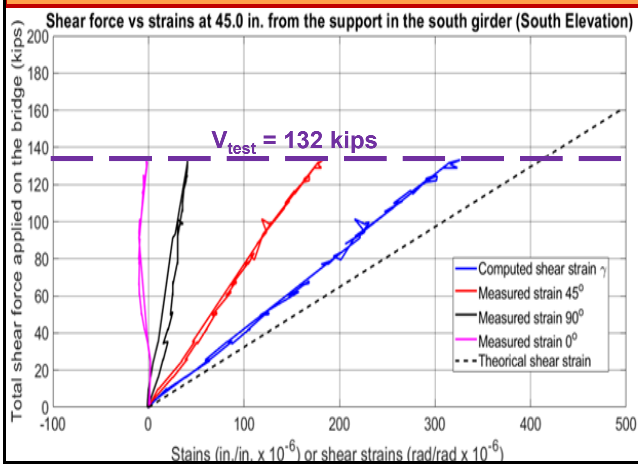
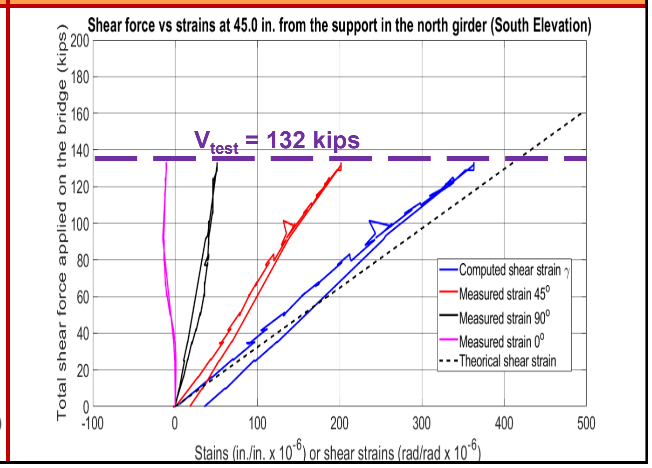
South Girder: γ ≈ 325 e-6 radians



North Girder: γ ≈ 350 e-6 radians



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Strain Diagrams South Girder @ 45in. From the End (Symmetric Shear Test)

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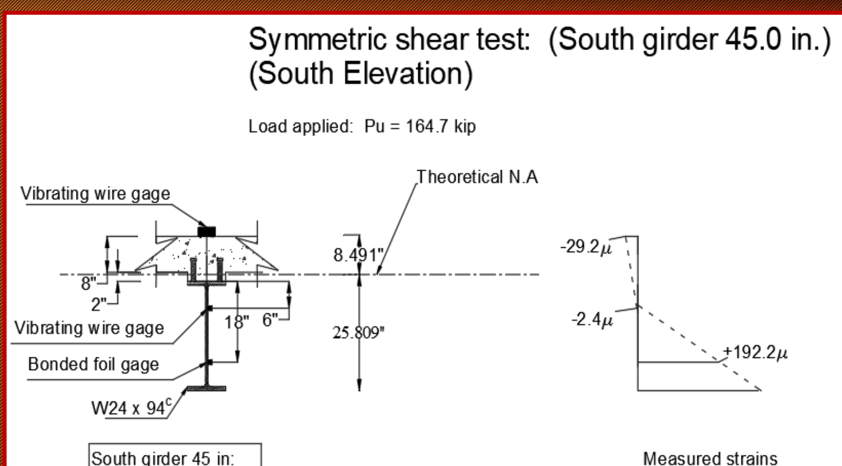

Take-Aways:

- The two girders share loads equally (symmetric load test)
- Shearing strains remain linear elastic through test load that exceeds the EV3 load by 2.5X
- Shear Stress (Test) = *Gγ ≈ 4.0 ksi.*
- Shear Stress (Calculation):

$$\tau = \frac{V_{test}}{D \cdot t_w} = \frac{66\ kips/girder}{32\ in. \cdot 0.515\ in.} = 4.0\ ksi$$

- Non-Linear bending strains indicate that shear distortion between composite slab and steel girder is significant.

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Results: Eccentric Shear Test

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Eccentric Shear Load Test:

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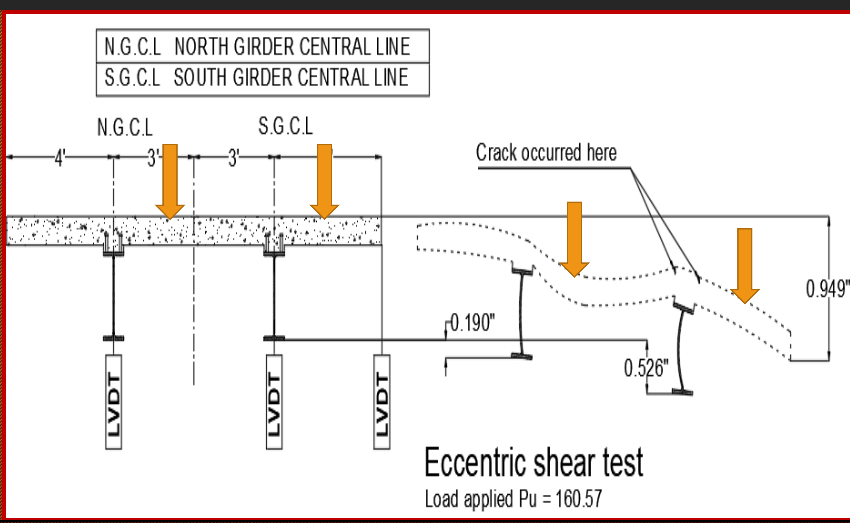

From the Assymmetric Flexural Load Test:

- $\Delta_{slab\ edge}$ = 0.949 in.↓
- Δ_{South} = 0.526 in.↓
- Δ_{North} = 0.190 in.↓
- The relative deflections were measured near the end regions where shear was applied.
- The deflections suggest that the DF for the "Exterior" (South) girder was 0.73.
- Lever Rule gives a DF = 0.83, so the lever rule would provide conservative results for RF purposes.
- Longitudinal cracking formed above the "exterior" girder. Crack widths remained proportional to the load applied.

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Shear Load Tests: Eccentric Test

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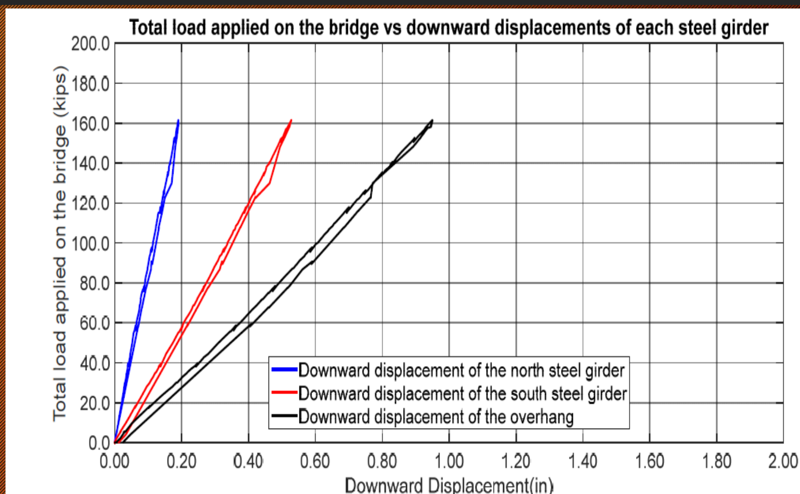

Take-Aways:

- P_{test} > 160 kips
- P vs. Δ is linear-elastic at both girders and at the outside edge of the deck slab. This shows that the bridge and its materials remain "undamaged" by the test load.

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Eccentric Shear Test: Crack Growth

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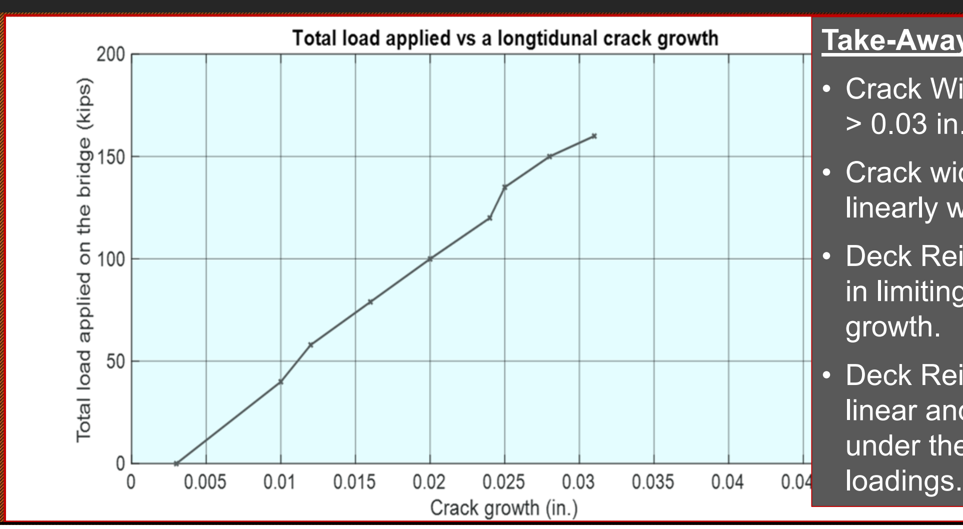

Take-Aways:

- Crack Width grows to a width > 0.03 in.
- Crack width progresses linearly with increasing load
- Deck Reinforcement is active in limiting crack width and growth.
- Deck Reinforcement remains linear and does not yield under the asymmetric loadings.

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Conclusions: Flexural Testing

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- Applied Loading exceeded the EV3 Loads by 4X .
- Despite large loads, P vs. Δ remains LINEAR.
- With Unloading, P vs. Δ remains elastic and rebounds to original deflection.
- The Bridge Response is Linear-Elastic and is NOT damaged during symmetric loading.
- Material Response (both Steel Girder and Concrete Deck) Remain Elastic under symmetric loading.
- Composite Bridge System is capable of supporting the EV3 Loading without Posting.
- Asymmetric Loading caused minor cracking in the deck slab but did not adversely affect Bridge Performance.

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Conclusions: (Flexural Testing Continued)

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- Overall, a rigorous factored load (140,000 lbs) was applied to the prototype bridge, both in symmetric loading pattern and in an asymmetric load pattern. In both sets of load tests, the bridge behaved linearly, elastically, and without yielding or significant cracking. Furthermore, the bridge demonstrated its ability to resist the EV-3 loading without compromise and demonstrates that the steel girder bridges in Oklahoma are capable, in general, of supporting the EV-3 loading as required by the federal FAST ACT.

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Conclusions: Shear Testing

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- Applied Loading approximately EXCEEDED the EV3 Loading.
- P vs. Δ remains LINEAR.
- With Unloading, P vs. Δ remains elastic and rebounds to original deflection.
- The Bridge Response is Linear-Elastic and is NOT damaged during symmetric loading.
- Material Response (both Steel Girder and Concrete Deck) Remain Elastic under symmetric loading.
- Composite Bridge System is capable of supporting the EV3 Loading without Posting.

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Conclusions: (Shear Testing Continued)

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- The asymmetric shear loading tests caused cracks in the slabs that resulted from tension in the top fiber of the slab as the point loads were applied at a location that caused cantilever action (tension on the top fiber) of the slab. The crack development did not affect the load distribution ratio in the two girders.
- During asymmetric shear loading, crack size increased linearly as loads were applied. This demonstrates that the reinforcement that bridged the cracks remained linear elastic and did not yield.
- This indicates that the steel and the rebar and the concrete materials remained elastic throughout the loading range and that the bridge did not suffer any yielding or inelastic behavior due to the factored loading from the notional EV-3 loads.

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Conclusions: (Shear Testing Continued)

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- Overall, a rigorous factored load (160,000 lbs) was applied to the prototype bridge, both in symmetric loading pattern and in an asymmetric load pattern. In both sets of load tests, the bridge behaved linearly, elastically, and without yielding or significant cracking. Furthermore, the bridge demonstrated its ability to resist the EV-3 loading without compromise and demonstrates that the steel girder bridges in Oklahoma are capable, in general, of supporting the EV-3 loading as required by the federal FAST ACT.

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- Organize alphabetically

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Thank you

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