Load Rating of Bridges without Plans

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106th Purdue Road School
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Study Advisory Committee

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Outline

- Problem Definition
- Proposed Load Rating Procedure
- Field Assessment
- Case Study: Doan’s Creek Bridge
- Conclusions

PROBLEM DEFINITION

Introduction

- Typically performed using relevant bridge information available on bridge plans
- Common practice for load rating bridges without plans
  - Load testing
  - Prescribed rating value based on NBI condition rating

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Problem Statement

- Challenging to adequately complete for bridges without plans
- Research conducted to evaluated old, poorly-documented bridges is limited
- The MBE and load rating methodologies do not provide a straightforward load rating process for bridges without plans

Objective

- Propose a general load rating procedure for bridges in Indiana with unknown details
- Procedure in compliance with the MBE and INDOT standards

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Methodology

- Literature review
  - Includes the study of load rating techniques and processes for the assessment of existing bridge structures
- Formulation of the general procedure
- Proof of concept of procedure using two case study bridges

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PROPOSED LOAD RATING PROCEDURE

General Procedure

- Four-step process:
  - Bridge Characterization
  - Bridge Database
  - Field Survey and Inspection
  - Load Rating Evaluation

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Bridge Characterization

- Identification of critical bridge information needed for the load rating and assessment of the bridge structure
  - Material properties, geometric feature, limit states
  - Create a list of variables

Bridge Database

- Collection of historical and representative information complied of similar bridge structures
  - Historical inspection reports
  - AASHO/AASHTO/ASTM standards
  - Survey of comparable bridge plans

Field Survey and Inspection

- Measurements of actual bridge geometric features and collection of information of the structural condition
  - Corroborate information detailed in inspection reports
  - Supplement unknown bridge information
  - Create as-built drawings (layout for structural modeling)

Load Rating Evaluation

- Measure of the safe live load capacity
- Load rating options:
  - Simplified structural analysis
  - Refined structural analysis
  - Load testing

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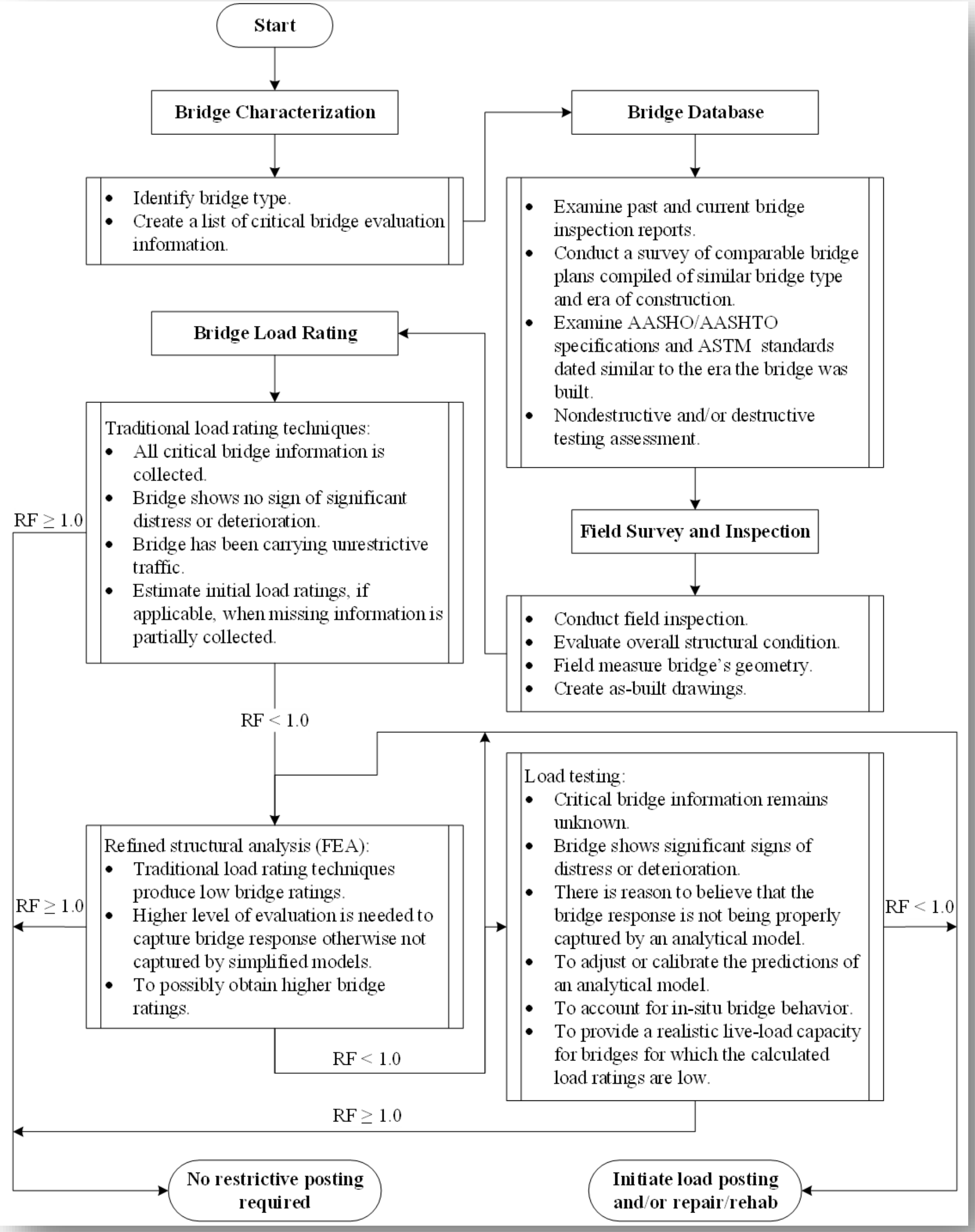
Flowchart



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FIELD ASSESSMENT

Indiana Bridge Inventory

- Stated-owned without plans
- Total of 53 bridges
  - 29 with soil cover
  - 2 case study bridges selected

Type of Bridge	Abbreviation	Qty.
Multi-Plate Arch Under Fill	MPA-UF	14
Reinforced Concrete Arch	RCA	11
Reinforced Concrete Arch Under Fill	RCA-UF	5
Reinforced Concrete Box Under Fill	RCB-UF	5
Precast Concrete Slab Under Fill	PCS-UF	2
Precast Concrete Arch Under Fill	PCA-UF	2
Steel Thru Truss	STT	2
Riveted Plate Girder	RPG	2
Prestressed Concrete Box Beam	PCBB	1
Steel Box Girder	SBG	1
Continuous Steel Girder	CSG	1
Prestressed Concrete I-Beam	PCIB	1
Reinforced Concrete Slab	RCS	1
Precast Concrete Beam	PCB	1
Welded Girder Rigid Frame	WGRF	1
Reinforced Concrete Slab Under Fill	RCS-UF	1
Bailey Truss	BT	1
Metal Pipe Arch	MPA	1

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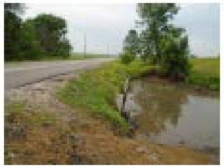
Field Assessments

Field Assessment 1

I65-200-08009 ADJ



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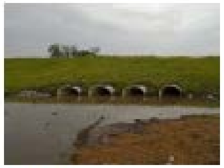

024-52-07576

024-52-07577

024-52-07579

035-09-01948 A

017-09-04177 B

025-09-03841

Field Assessment 2

150-84-02520 A

046-84-06241

045-28-06236

046-53-08789 WBL

231-67-07504

P000-49-07961

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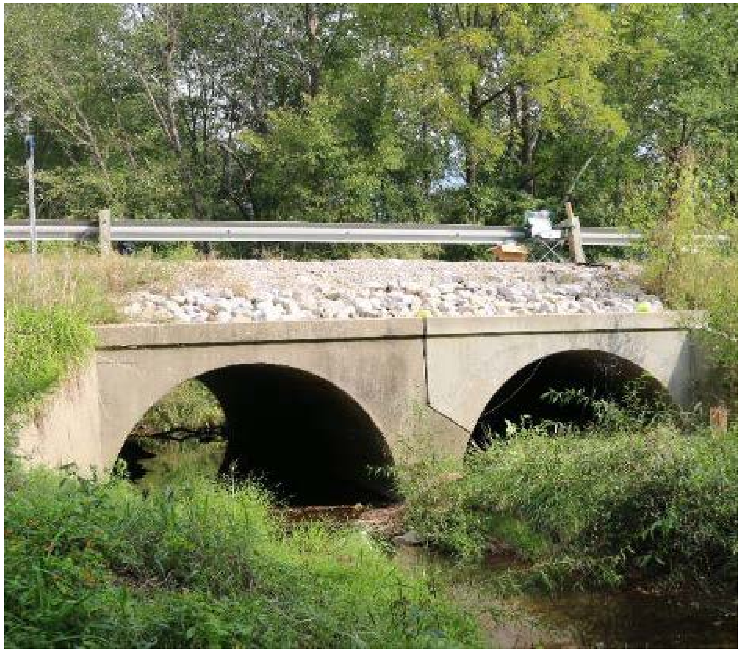
CASE STUDY:
DOAN'S CREEK BRIDGE

Bridge Description

- Two-span earthen-filled RC arch
- Built in 1942
- Rigid buried structure



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Rigid Buried Structures

- Major components:
  - Backfill material
  - Structural member
- Very stiff and do not deflect appreciably
- Load-carrying capacity mostly provided by structural member
- Works primarily in compression but subjected to some degree of flexure (arch)

Rigid Buried Structures

- Assessment of Doan's Creek using general load rating procedure
  - Bridge characterization
  - Bridge Database
  - Field Survey and Inspection
  - Load rating

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Bridge Characterization

Variable	Description
A	bh
A_s	Area of tension reinforcement
A'_s	Area of compression reinforcement
A_v	Area of transverse reinforcement
$c.c.$	Clear concrete cover
b	Width of arch barrel
d	Distance from extreme tension fiber to centroid of
d'	Distance from extreme compression fiber to centro
E_c	Modulus of elasticity of concrete
E_s	Modulus of elasticity of reinforcement
f	Rise
f'_c	Compressive strength of concrete
f_y	Yield strength of steel reinforcement
h	Height of arch barrel
H	Depth of earth cover over crown
l	Clear span
s	Spacing of principal reinforcement
s_v	Spacing of transverse reinforcement
γ_c	Unit weight of concrete
γ_s	Unit weight of backfill
k	Lateral earth coefficient
ϕ'_f	Effective friction angle of backfill

- A_s, A_s' = Area of steel reinforcement
- f = Rise of arch
- f'_c = Concrete compressive strength
- f_y = Rebar yield strength
- h = Thickness of arch
- H = Depth of earth cover over crown
- l = Clear span

Bridge Database

- Indiana Bridge Inspection Application System (BIAS)
  - Stated-owned bridges
  - From1940 through 1950
  - Bridge type: RCA-UF
- Query results:
  - 45 bridges matched search
  - 22 had comparable plans on file (BIAS)

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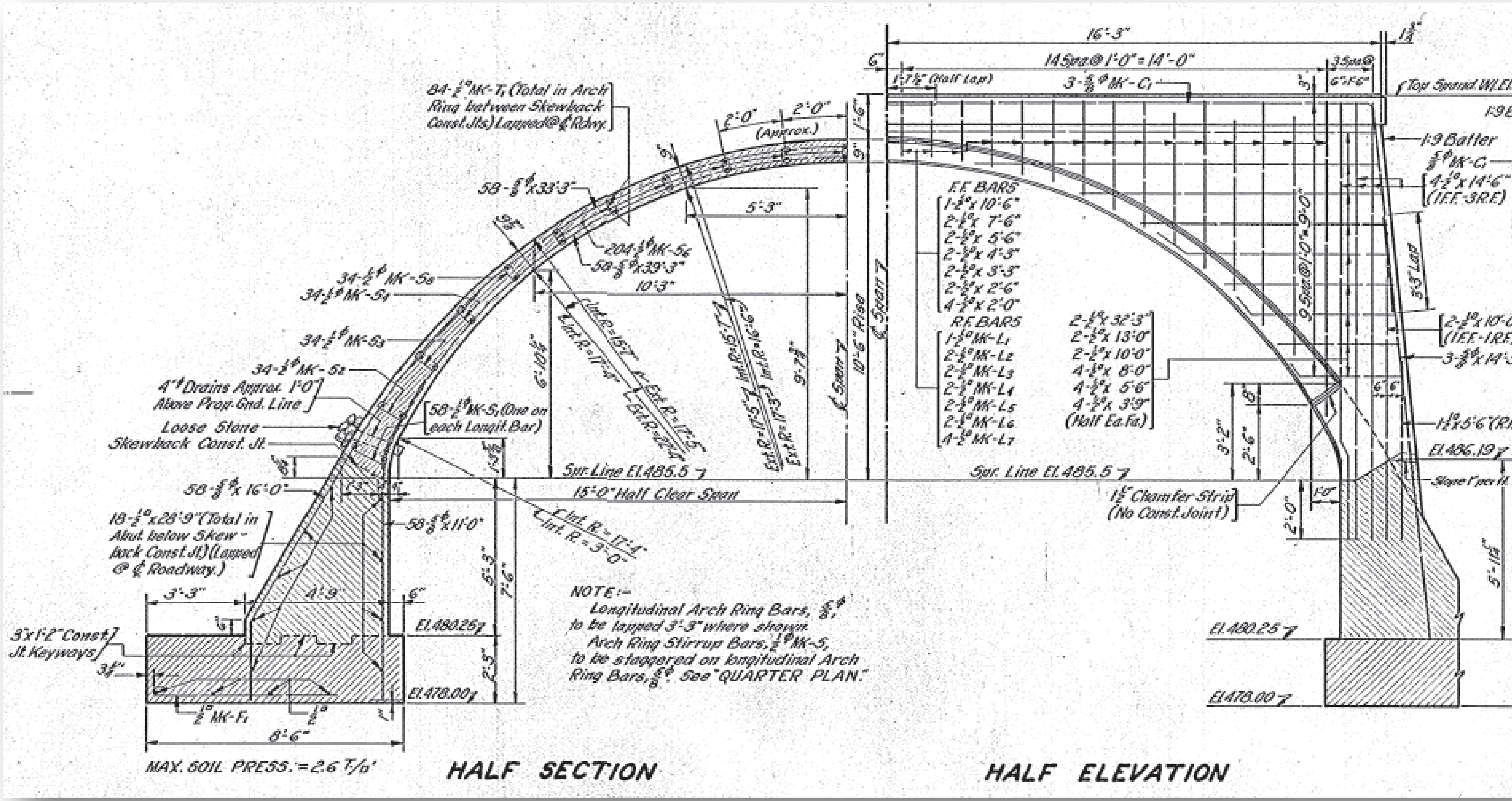
Comparable Plan Example



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List of Comparable Plans

Bridge	Year	h (in.)	f (ft.)	l (ft.)	h/l	f/l	A_s (in.^{2})	ρ
BRG-01	1940	8	8	35	0.019	0.229	0.31	0.0045
BRG-02	1940	8	10.5	30	0.022	0.350	0.31	0.0045
BRG-03	1940	8	8	25	0.027	0.320	0.31	0.0045
BRG-04	1941	8	8	25	0.027	0.320	0.31	0.0045
BRG-05	1941	9	10.5	30	0.025	0.350	0.31	0.0039
BRG-06	1941	8	7	30	0.022	0.233	0.31	0.0045
BRG-07	1942	9	10.5	30	0.025	0.350	0.20	0.0025
BRG-08	1946	10	15	35	0.024	0.429	0.31	0.0034
BRG-09	1946	9	7	30	0.025	0.233	0.44	0.0055
BRG-10	1947	9	9	25	0.030	0.360	0.20	0.0025
BRG-11	1947	9	12	30	0.025	0.400	0.20	0.0025
BRG-12	1947	8	8	25	0.027	0.320	0.31	0.0045
BRG-13	1948	9	9	35	0.021	0.257	0.20	0.0025
BRG-14	1948	9	12	30	0.025	0.400	0.20	0.0025
BRG-15	1948	9	11	30	0.025	0.367	0.31	0.0039
BRG-16	1948	9	9	25	0.030	0.360	0.31	0.0039
BRG-17	1948	8	8	25	0.027	0.320	0.31	0.0045
BRG-18	1948	9	12	35	0.021	0.343	0.31	0.0039
BRG-19	1948	9	11	40	0.019	0.275	0.44	0.0055
BRG-20	1950	8	9	30	0.022	0.300	0.31	0.0045
BRG-21	1950	9	9	25	0.030	0.360	0.31	0.0039
BRG-22	1950	10	15	40	0.021	0.375	0.31	0.0034

Note: A_s = area of tension reinforcement, f = rise, h = thickness of arch member, l = clear span, ρ = tension steel reinforcement ratio.

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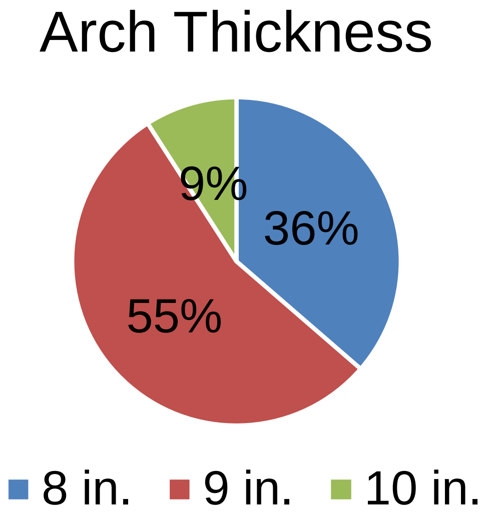
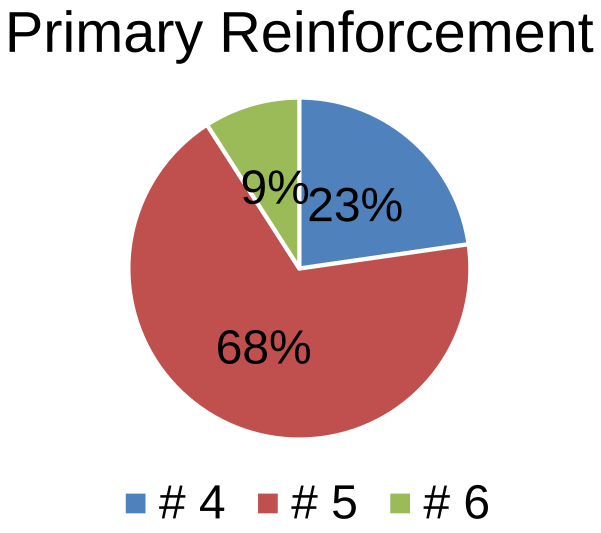
Comparable Plans Findings

- Primary reinf.:
  - 2 layers @ 24 in.
- Secondary reinf.:
  - 2 layers @ 24 in.
- Single leg stirrups:
  - Rebar # 4 @ 24 in.





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Field Survey and Inspection

- Geometric features
  - Clear span: 11.5 ft.
  - Rise: 5.75 ft.
  - Semi-circular arch
  - Soil cover: 3.4 ft.
- No signs of distress

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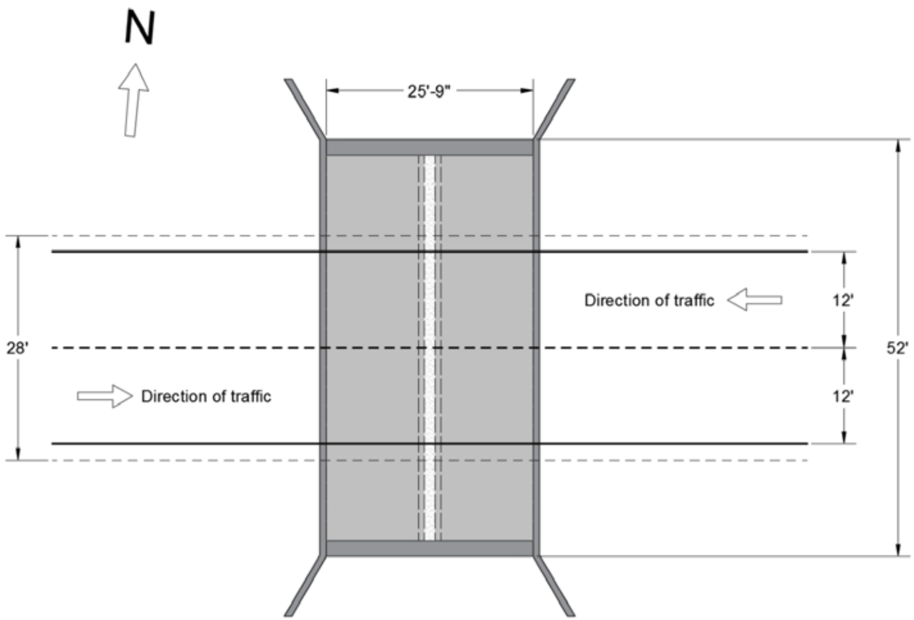
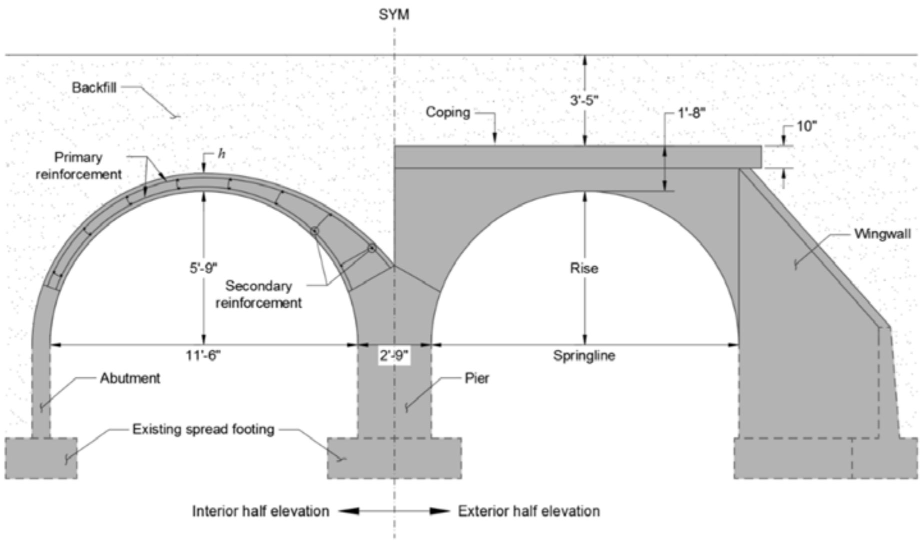
As-Built Drawings

Plan View



Cross-section



Material Properties

- Concrete
  - Unit working stress of 1,000 psi based on f'c = 3,000 psi (AASHO, 1941)
  - f'c = 2,500 psi if built prior 1959 (MBE, 2018)
- Steel reinforcement
  - Unit working stress of 18,000 psi, assumed as 0.545 of yield point (AASHO, 1941)
  - fy = 33,000 psi (AASHO, 1941 & MBE ,2018)

Idealized Cross-Section

- Most common cross-section
  - Arch thickness 9 in.
  - Primary rebar # 5 (A_b = 0.31in.^{2})
- Minimum cross-section
  - Arch thickness 8 in.
  - Primary rebar # 4 (A_b = 0.20 in.^{2})
  - Conservatively used for load rating calculations

Load Rating Evaluation

- Simplified model
  - Loads calculated on a 1-ft. wide section
  - Arch divided into portions approximated by straight members of equal lengths
  - Frame element (beam-column formulation)
  - Forces along arch: axial, shear, & moment
  - Two BCs: two-hinged (pinned) & hingeless (fixed)

Interaction Diagram

- Combined action of axial compression and flexure controlled
- Useful for design but limitation for load rating
- Load-carrying capacity depends upon unknown load
- Rating Factor (RF) is a function of load-carrying capacity

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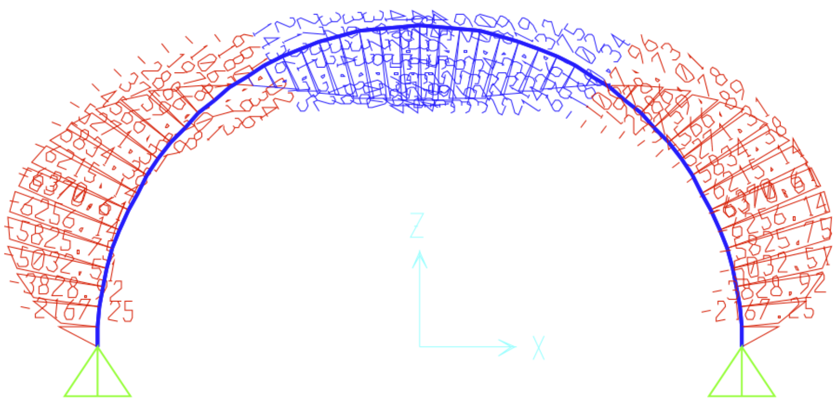
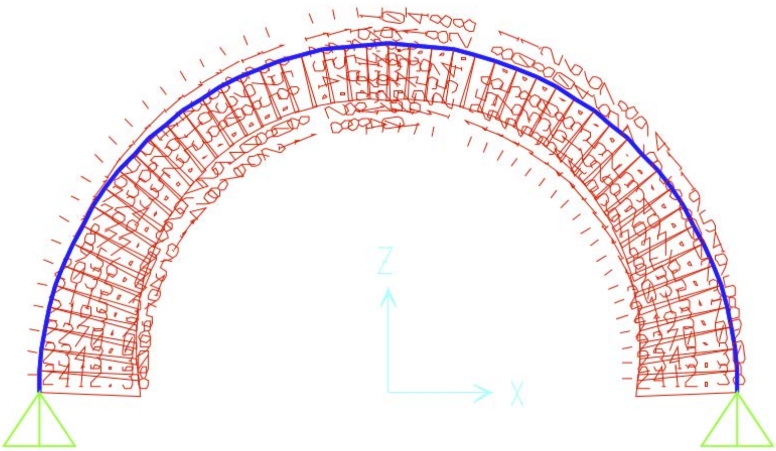
Example of Simplified Analysis

Moment Diagram



Axial Force Diagram



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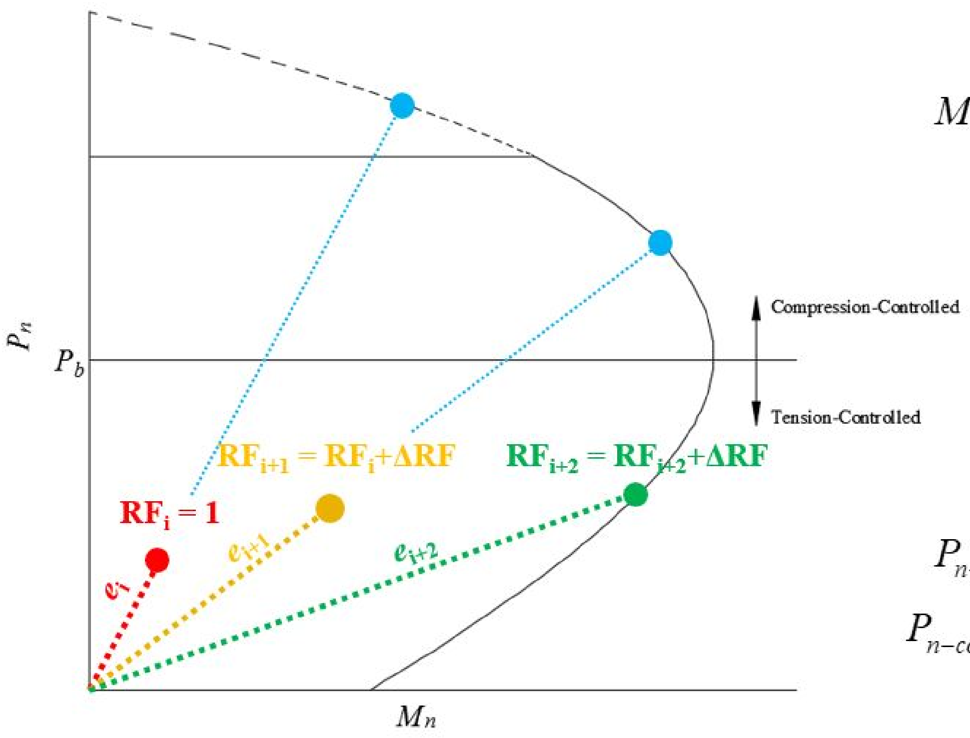
Load Rating - Interaction Diagram



$$P_u = \gamma_{DL} P_{DL} + \gamma_{SDL} P_{SDL} + (RF)\gamma_{LL} P_{LL}$$

$$M_u = \gamma_{DL} M_{DL} + \gamma_{SDL} M_{SDL} + (RF)\gamma_{LL} M_{LL}$$

$$e = \frac{M_u}{P_u}$$

$$P_{n-tension} = \text{Wang and Salmon Equation}$$

$$P_{n-compression} = \text{Wang and Salmon Equation}$$

Equations for tension- and compression-controlled derived by Wang and Salmon (Reinforced Concrete Design, 4th Ed., 1985)

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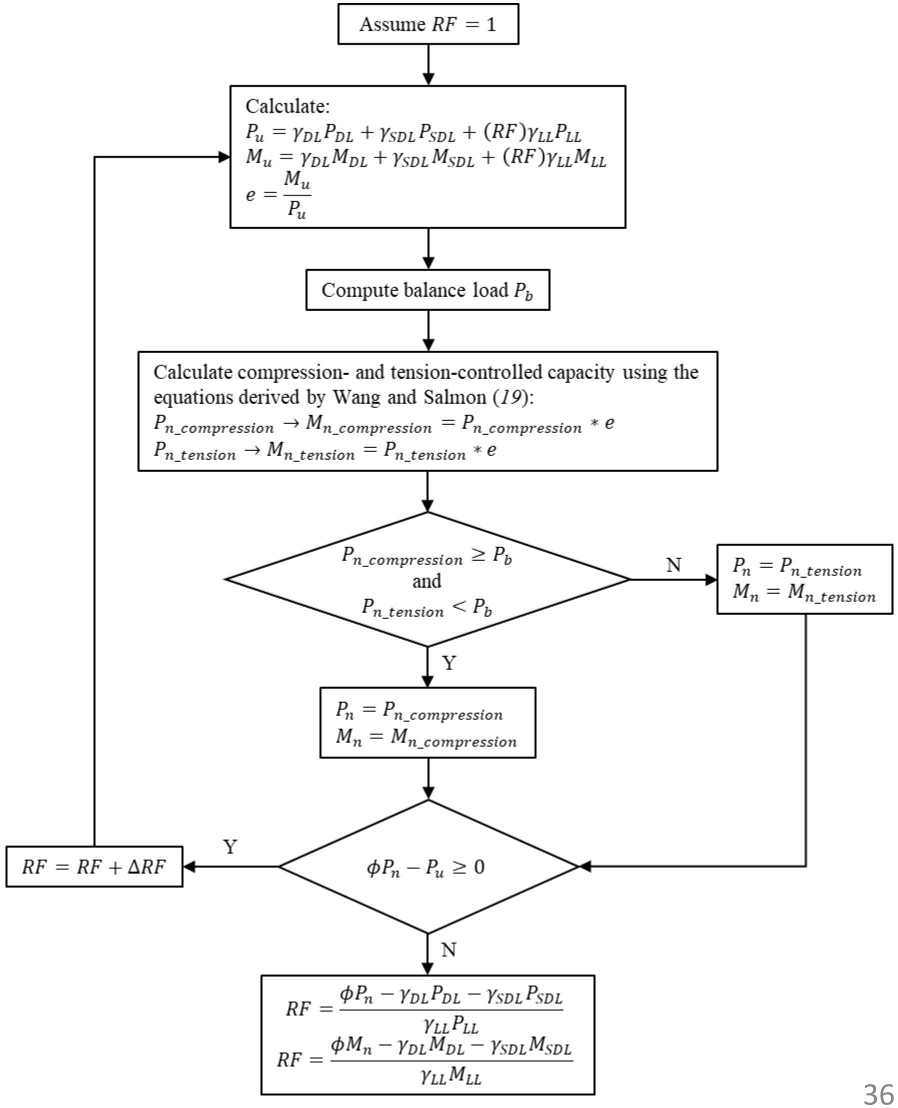
Numerical Load Rating Flowchart

e = eccentricity
P_b = balanced load
P_{DL} = axial force effect due to dead load
$P_{n\_compression}$ = compression-controlled axial capacity
$P_{n\_tension}$ = tension-controlled axial capacity
P_{LL} = axial force effect due to live load
P_{SDL} = axial force effect due to superimposed load
P_u = factored axial force
M_{DL} = bending moment effect due to dead load

$M_{n\_compression}$ = compression-controlled moment capacity
$M_{n\_tension}$ = tension-controlled moment capacity
M_{SDL} = bending moment effect due superimposed load
RF = rating factor
ΔRF = rating factor increment
γ_{DL} = load factor for dead load
γ_{SDL} = load factor for superimposed load
γ_{LL} = load factor for live load
ϕ = reduction factor



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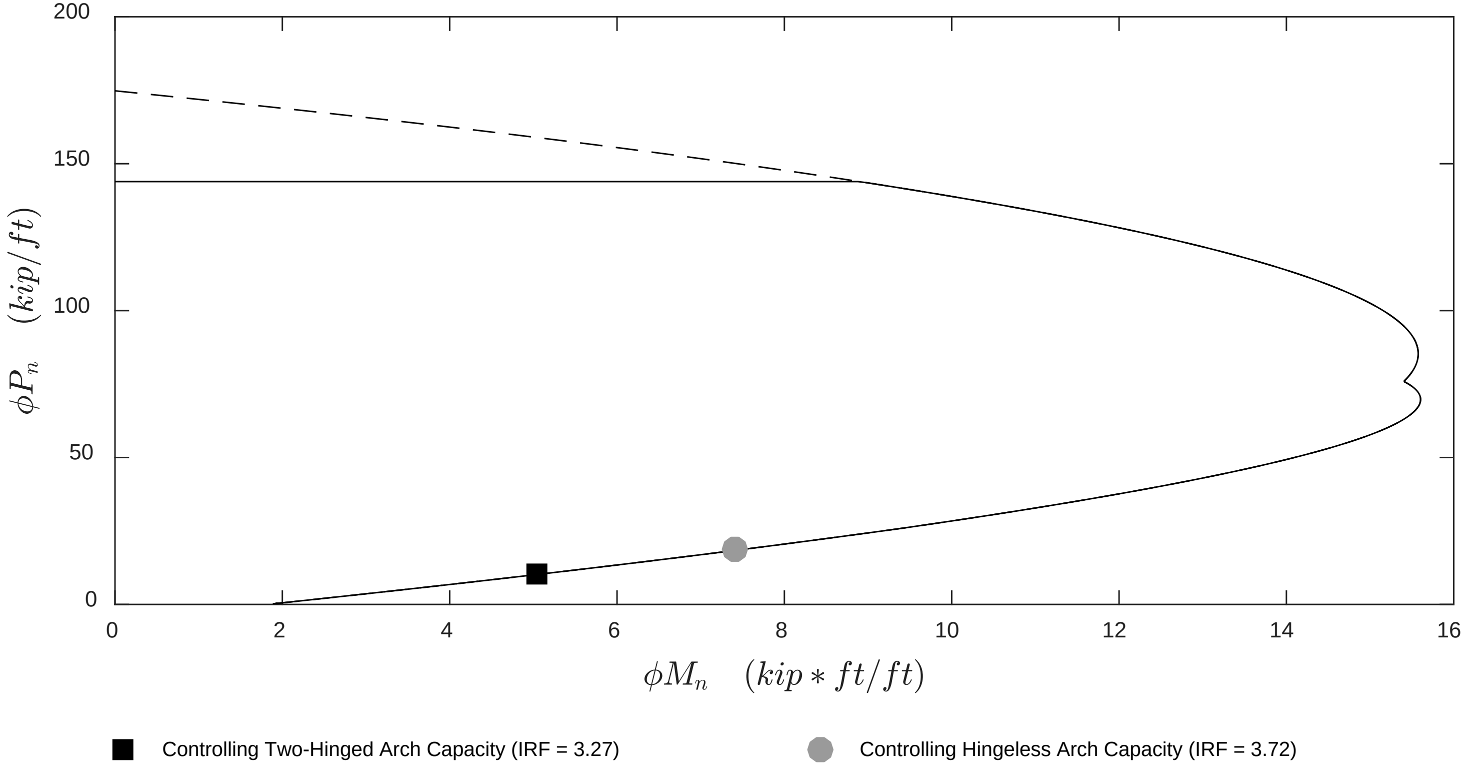
Load Rating Results

- Automated load rating using Matlab
- Inventory level (LFR)
  - RF = 3.27 at crown (two-hinged)
  - RF = 3.72 at end supports (hingeless)
- Operating level (LFR)
  - RF = 5.45 at crown (two-hinged)
  - RF = 6.20 at end supports (hingeless)

Load Rating Validation



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Concrete Compressive Strength

- f'c = 2,500 psi (minimum value per MBE)
- Inventory Level (LFR)
  – RF = 3.22 (two-hinged)
  – RF = 3.62 (hingeless)

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Field Load Testing

- Bridge instrumented
- Conducted to complement calculations
- Two fully loaded trucks used
- One lane and two lane loadings
- Static and dynamic loadings

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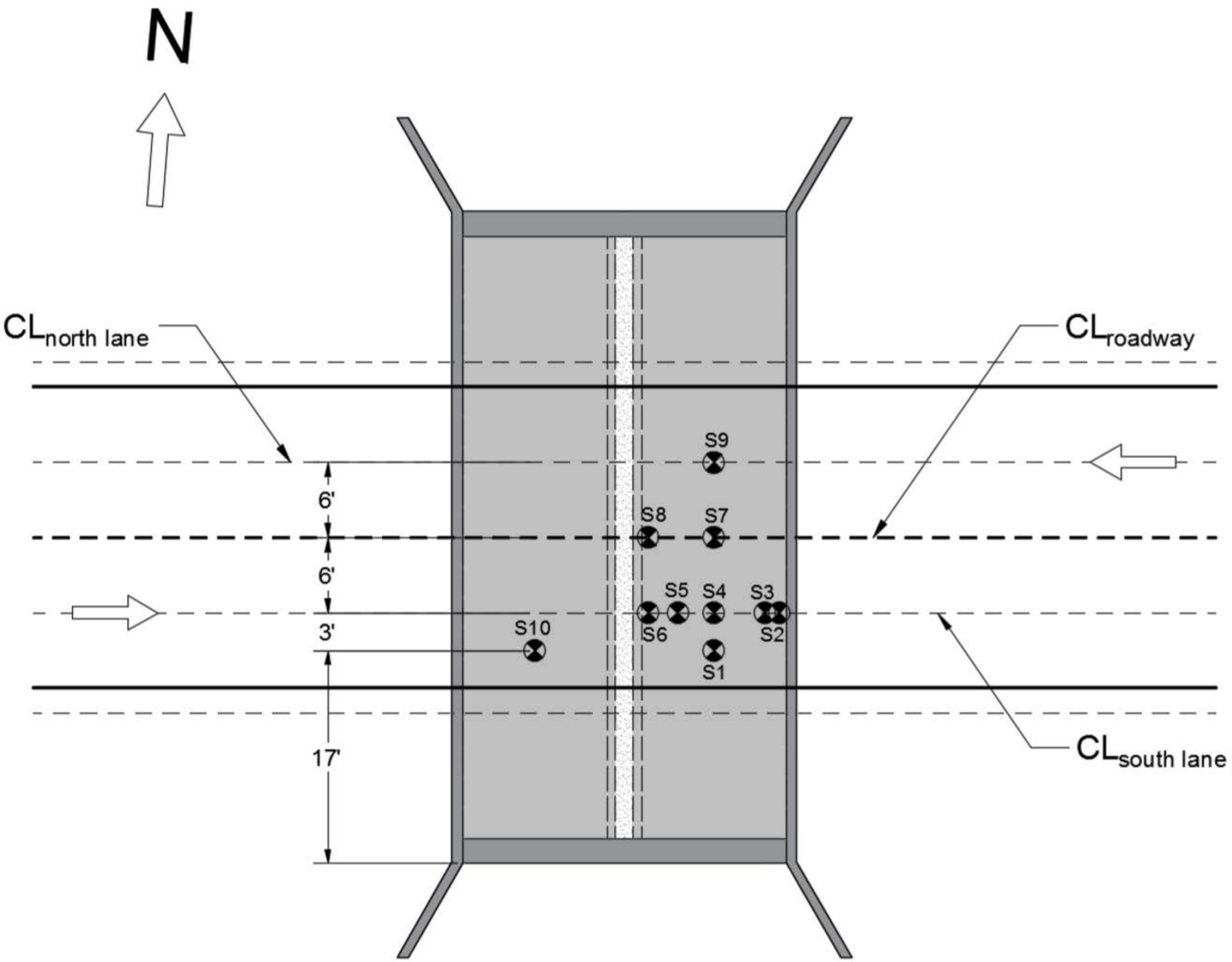
Description

- Concrete strain gages (10)
- String potentiometers (2)
- Campbell Scientific Datalogger (1)
- Two tandem dump trucks (60-Tons total)

Sensor Layout (Plan View)



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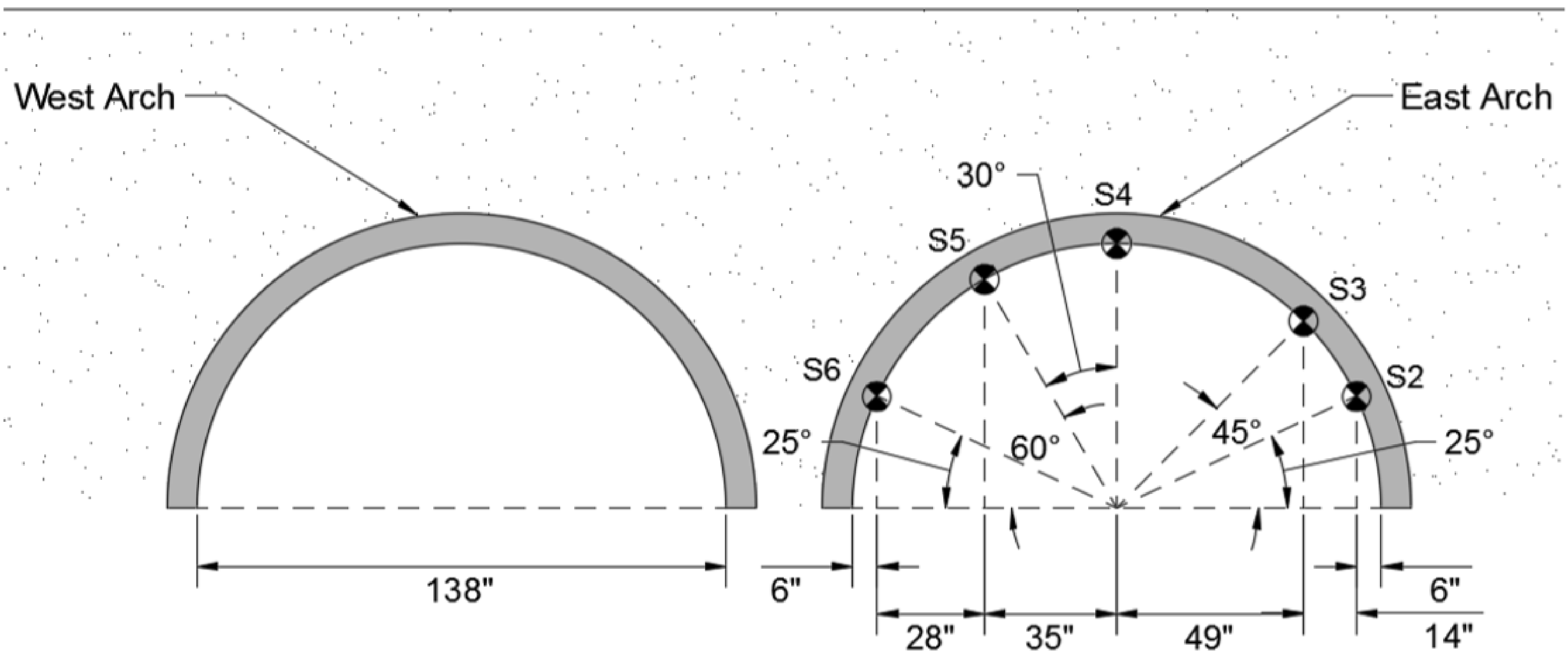
Sensor Layout (Cross-Section)



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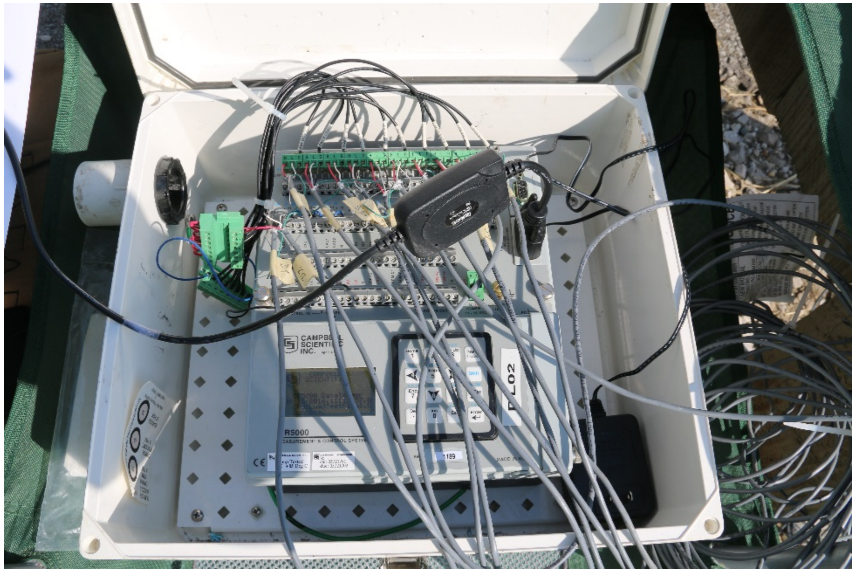
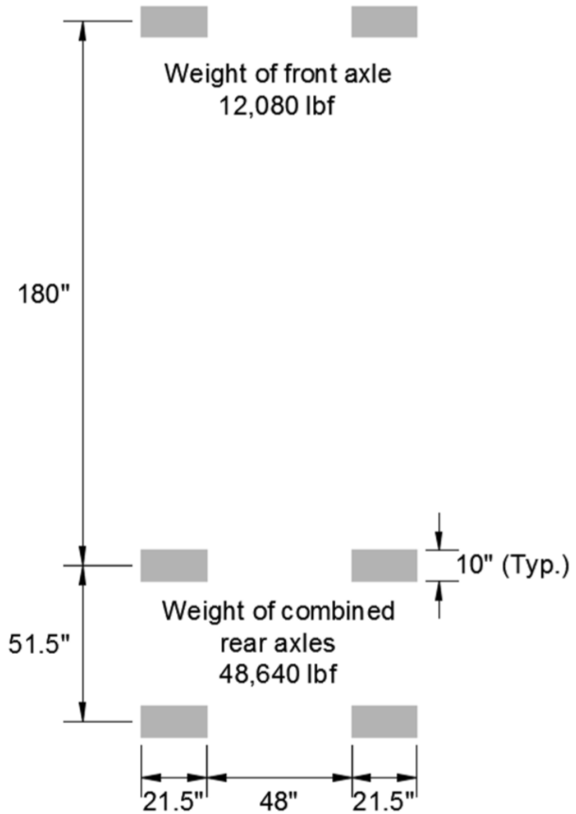
Sensor Installation

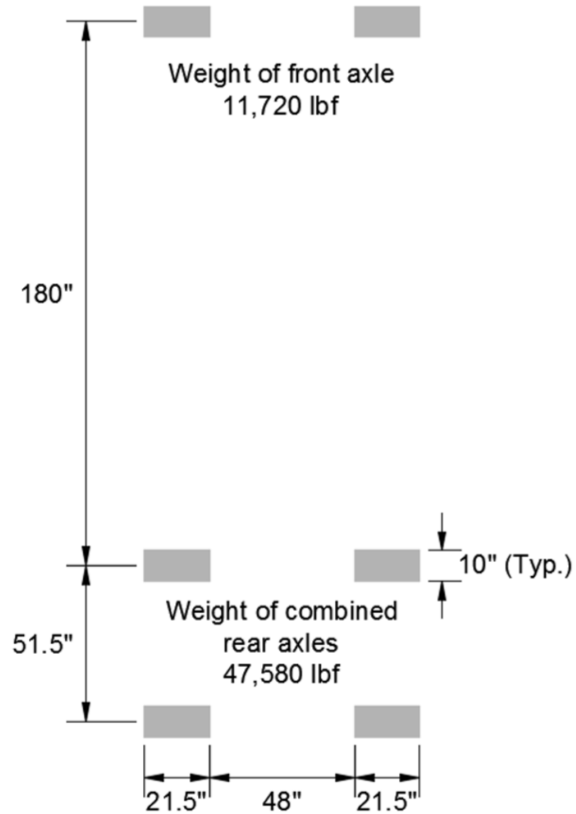


Tandem Dump Truck

Truck Dimensions



Truck A
Gross Weight
60,720 lbf



Truck B
Gross Weight
59,300 lbf

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Load Cases

- Load cases designed to record the peak values of strain in the arch
- Load cases (10)
  - Static (7)
  - Crawl speed, approx. 5 mph (2)
  - Dynamic (1)

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Wheels Placement (Both Trucks)

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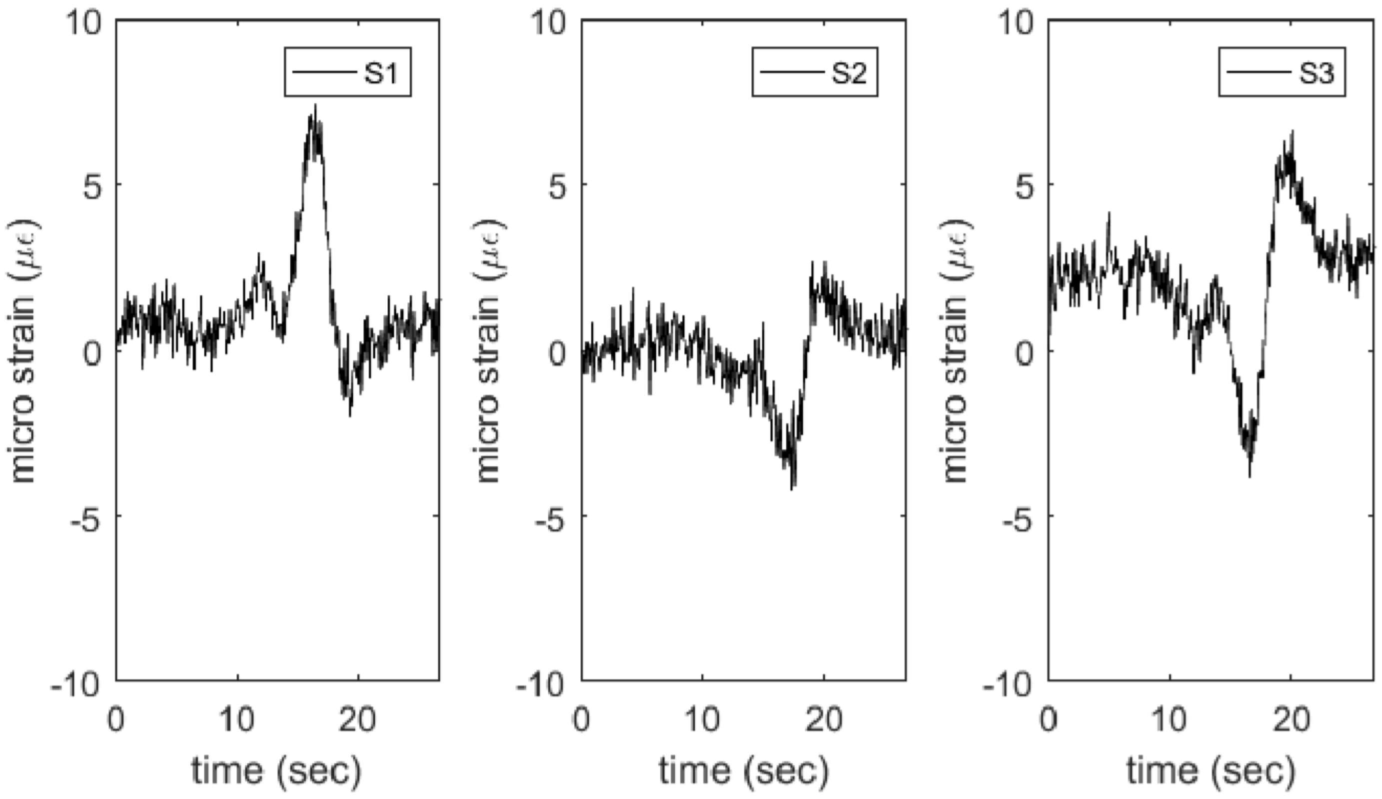
Data Results (Strain)

Load Case 10 (Dynamic)



Load Testing Remarks

- Small magnitudes of strains
- Small magnitudes of deflections
- Earth fill dissipates live load effects
- Have more than enough load-carrying capacity (High RF)

Finite Element Analysis (FEA)

- FE model developed in Abaqus 6.14
- 3D FEA to account for both the in-plane and out-of-plane live load spreading
- Model geometry based on as-built drawings

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Element Modeling

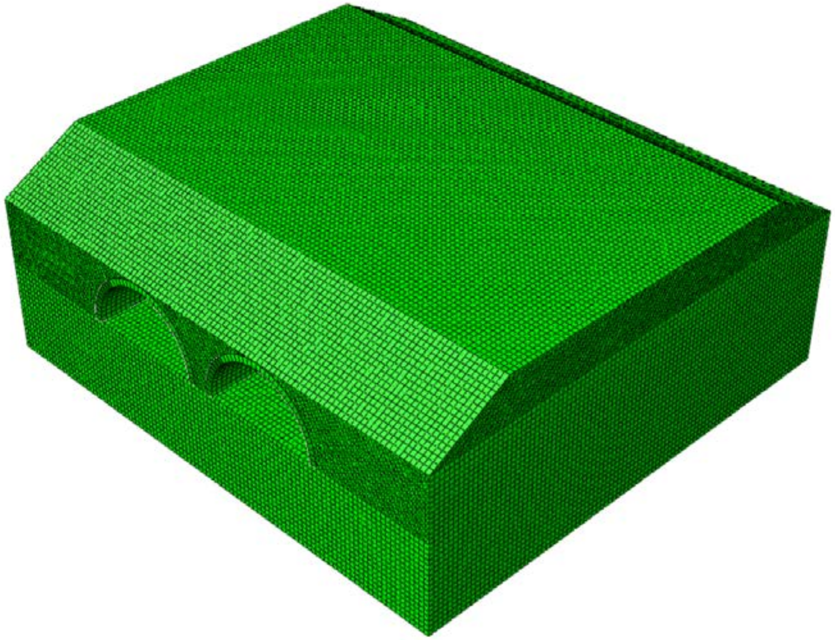
- Arch section
  - S4R (4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains)
- Soil medium
  - C3D6 (6-node triangular prism)
  - C3D8R (8-node linear brick, reduced integration, hourglass control)

Model Considerations

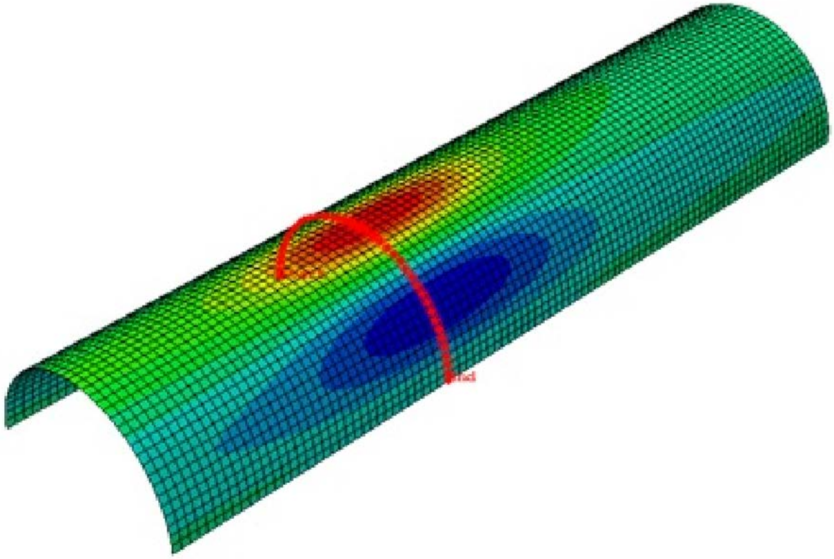
- Soil medium
  - Divided into four layers (SW95 & SW85) (Petersen et. al., 2010 – NCHRP Rep. 473)
  - Uniform soil layer SW-High (TXDOT Culvert Rating Guide, 2009)
- Pavement (Seo et al., 2017)
  - Rigid (concrete)
  - Flexible (asphalt)

FE Model

3D View



Arch Section



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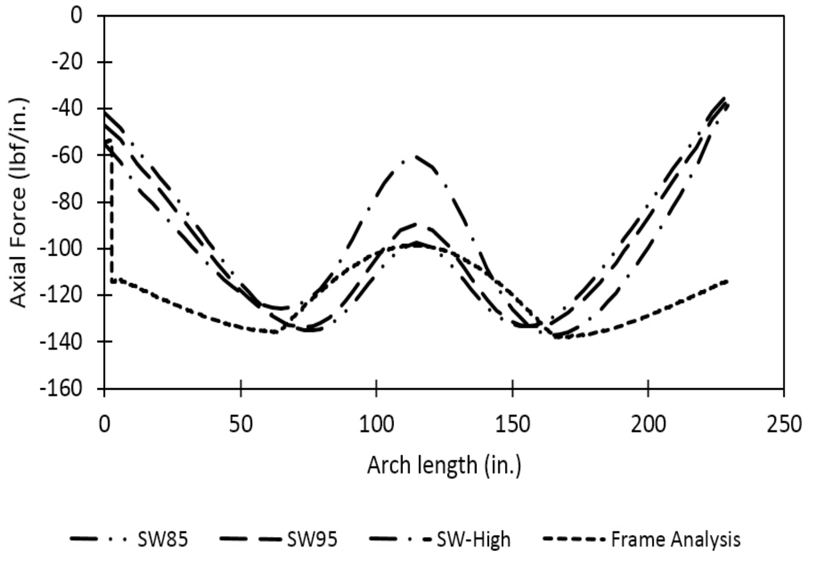
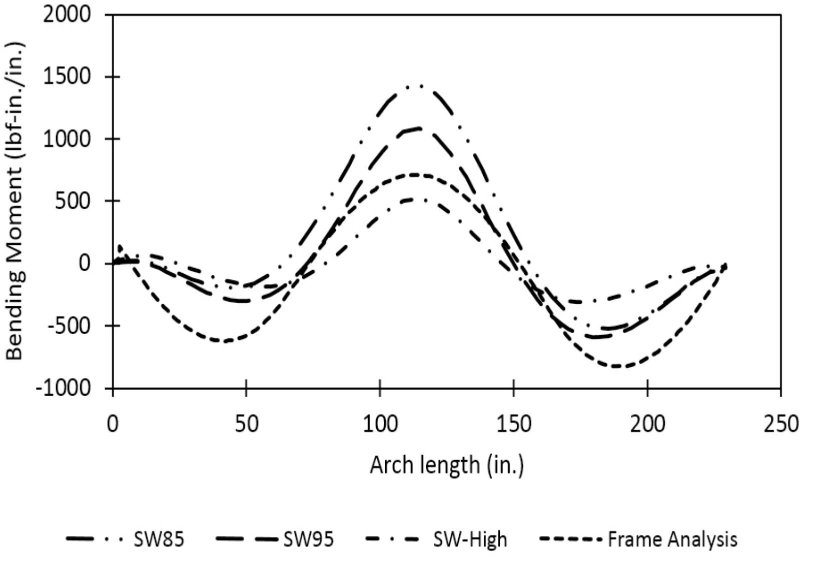
Results

Axial Force



Bending Moment



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Main Findings

- Rigid pavement has greater effect on spreading the live load than flexible pavement
- Four-layered soil model predicted higher strains than load test
- Uniform soil layer results were more consisted with load test measurements

Doan's Creek Bridge Conclusions

- Satisfactory load rating using general procedure and worst-case (conservative) bridge information
- Controlling strength limit state is the combined action of axial compression and flexure
- Automated load rating allows for quick and efficient solution for earthen-filled RCA

CONCLUSIONS

Conclusions

- Systematic methodology for load rating old, poorly-documented bridges
- Implement at the state or county bridge inventory
- Procedure can be customized for a specific bridge type

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SPR-3816 Final Report

- Armendariz, R. R., & Bowman, M. D. (2018). *Bridge load rating* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/07). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316650

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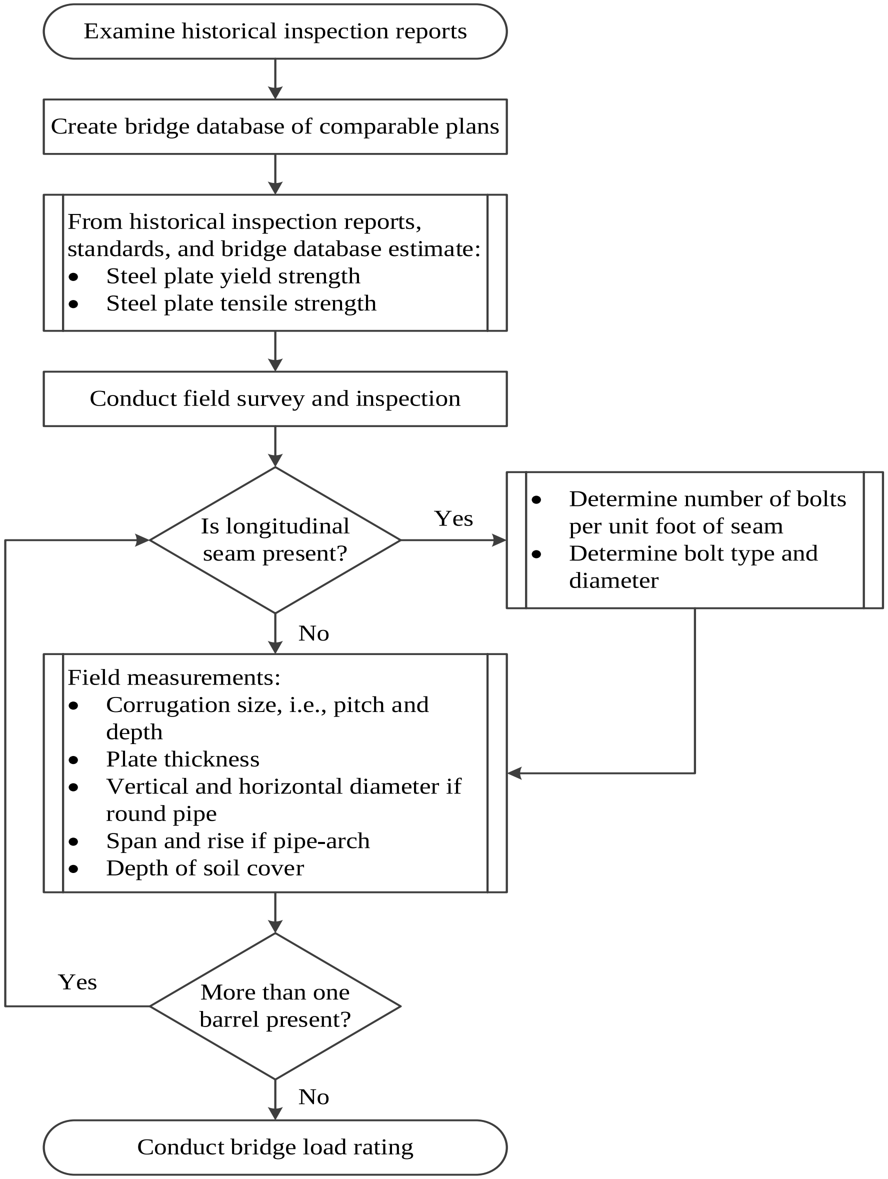
THANK YOU!

Corrugated Steel Pipe Flowchart



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Earthen-Filled RC Arch Flowchart