TRANSPORTATION RESEARCH BOARD

Evaluating Load Testing for Bridges

Tuesday, February 11, 2020
1:00-3:00 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

Purpose

Provide an overview of how the overall structural behavior of a bridge can be determined through load testing

Learning Objectives

At the end of this webinar, you will be able to:

- Identify if a load test can meet desired objectives
- Select the appropriate type of load test
- Use the outcome to evaluate bridge structural behavior
- Determine the structural safety of a bridge, quantified by the probability of failure

Load Testing for Evaluating Bridges

W E B I N A R

INTRODUCTION TO WEBINAR AND BRIDGE LOAD TESTING

Sponsored by:

TRB Standing Committee on Testing and Evaluation of Transportation Structures

Eva Lantsoght, Ph.D.

WEBINAR SCHEDULE

- Introduction to webinar and e-circular – Dr. Eva Lantsoght, USFQ & Delft University of Technology

- General considerations and preparation for load testing – Dr. Eva Lantsoght

- Diagnostic load tests – Jesse Grimson, BDI

- Proof load tests – Dr. Ed Zhou, AECOM

- Estimating the reliability index and remaining service life after load testing – Dr. David Yang, Lehigh University

- Questions and answers - Moderator: Dr. Sreenivas Alampalli, New York State Department of Transportation, Chair AFF40, TRB Standing Committee on Testing and Evaluation of Transportation Structures

LEARNING OBJECTIVES

1. Identify whether a load test can meet desired objectives (e.g., improved load ratings)

2. Select the type of load test to meet the test objectives

3. Understand the outcome of a load test, learn how to use this outcome to meet the test objectives, as well as to evaluate bridge structural behavior

4. Determine the structural safety of a bridge, quantified by the probability of failure, updated with the information from the load test

WHY AN E-CIRCULAR ON LOAD TESTING?

- 1998 Manual for Bridge Rating through Load Testing

- Basis for AASHTO Manual for Bridge Evaluation (MBE)

- Need to include current state-of-the-practice
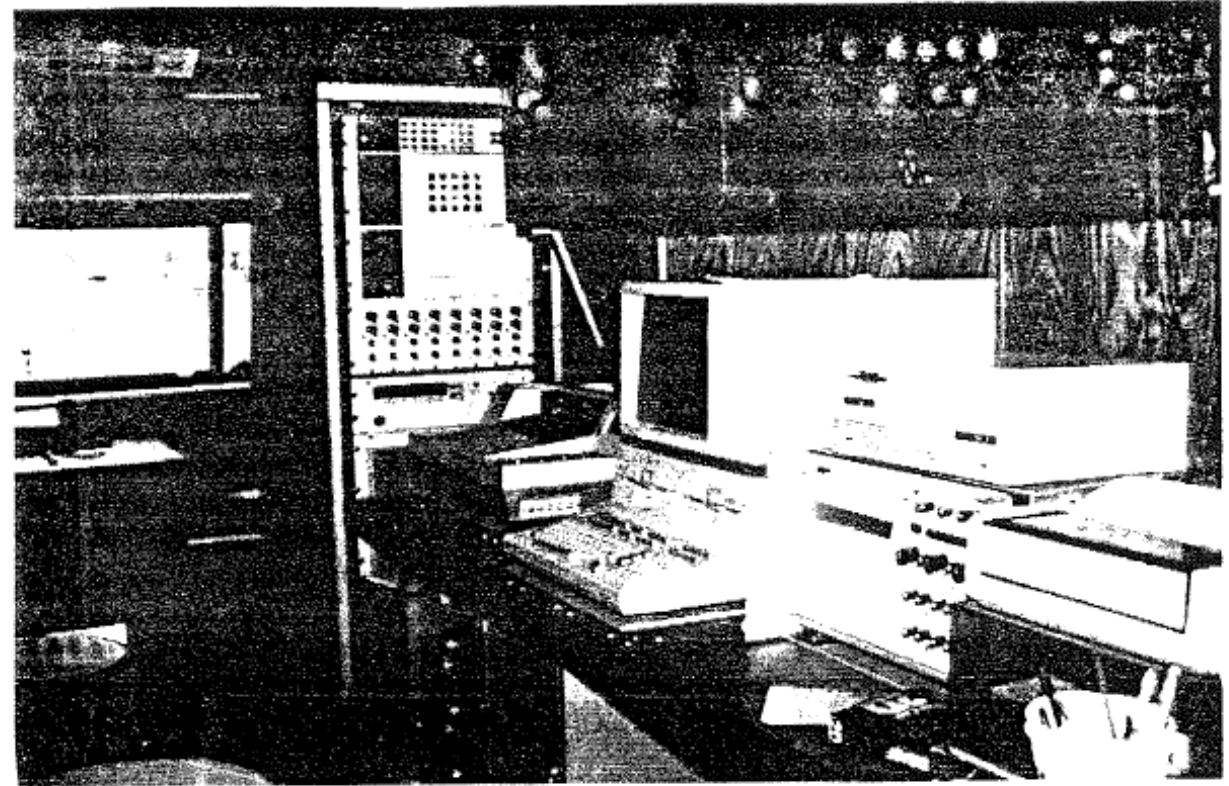
FIGURE 5-9: Computer equipment and automatic data acquisition system used by Florida DOT for load testing of bridges.

NCHRP, *Manual for Bridge Rating through Load Testing*. 1998: Washington, DC. p. 152.

CONTENTS OF E-CIRCULAR

Chapter	Title
1	Introduction
2	General Considerations
3	General load test preparation
4	Diagnostic load tests
5	Proof load tests
6	Estimating the reliability index and remaining service life
7	Illustrative examples

TRANSPORTATION RESEARCH
CIRCULAR
Number E-C257   November 2019

Primer on Bridge
Load Testing

The National Academies of
SCIENCES · ENGINEERING · MEDICINE
TRB
TRANSPORTATION RESEARCH BOARD

Download link: http://onlinepubs.trb.org/onlinepubs/circulars/ec257.pdf
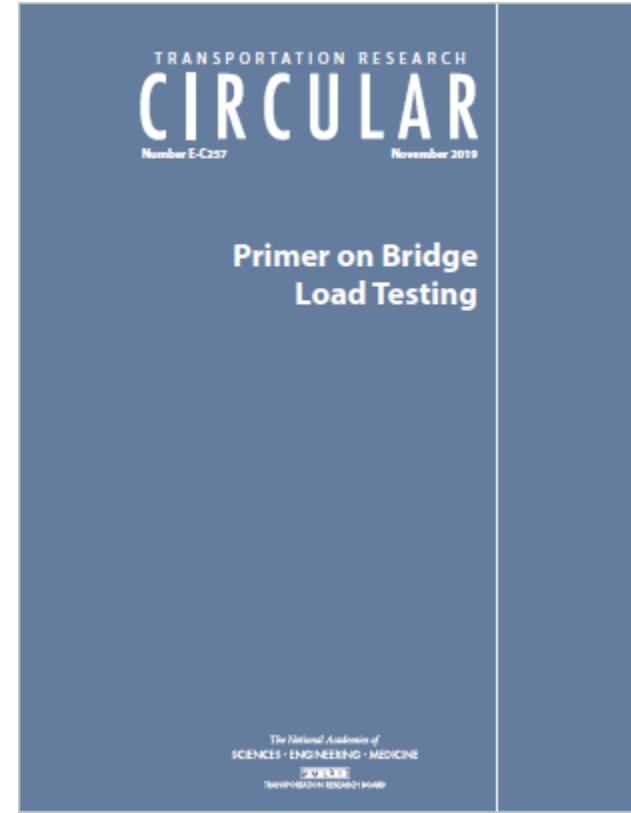
APPLICATION OF LOAD TESTS

Learning objective: Identify whether a load test can meet desired objectives

- Current load rating close to 1
- Multi-girder bridges
- Slab bridges
- Bridges with deterioration or damage
- Bridges with no plans
- Arch bridges
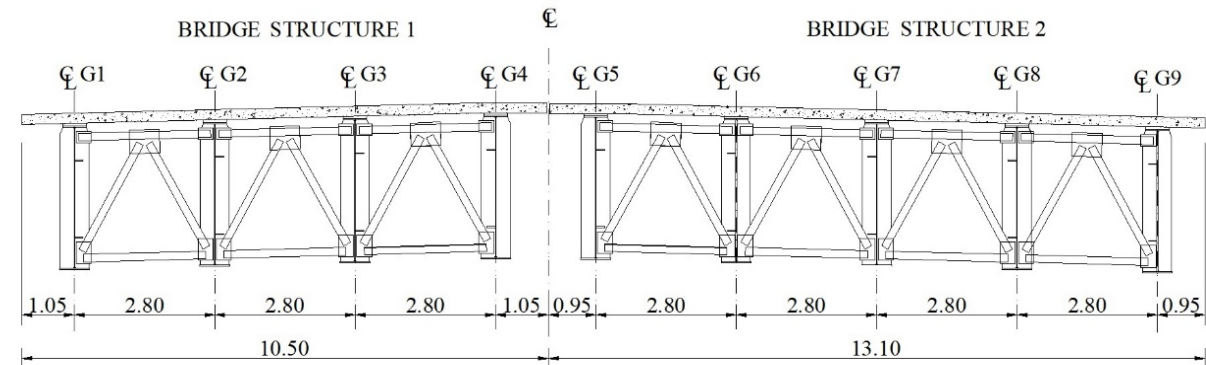
Lantsoght, E. O. L., Bonifaz, J., Sanchez, T. A. and Harris, D. K., 2019, "Chapter 8: Methodology for diagnostic load testing," *Load Testing of Bridges: Current practice and Diagnostic Load Testing*, Lantsoght, E. O. L., ed., Taylor & Francis, Structures and Infrastructures, Series Editor: D.M. Frangopol.

SCOPE OF E-CIRCULAR

Scope:

- Preparation

- Execution

- Analysis of load tests

- Long-span bridges outside the scope, but elements can be tested according to e-circular

Lantsoght, E.O.L., et al., *Proof load testing of reinforced concrete slab bridges in the Netherlands.* Structural Concrete, 2017. **18**(4): p. 597-606.

Load Testing for Evaluating Bridges

WEBINAR

GENERAL CONSIDERATIONS AND PREPARATION

Sponsored by:

TRB Standing Committee on Testing and Evaluation of Transportation Structures

Eva Lantsoght, Ph.D.

OBJECTIVES OF A LOAD TEST (1)

Learning objective: Select the type of load test to meet the test objectives

Diagnostic load testing

Proof load testing

Lantsoght, E. O. L., Bonifaz, J., Sanchez, T. A. and Harris, D. K., 2019, "Chapter 8: Methodology for diagnostic load testing," *Load Testing of Bridges: Current practice and Diagnostic Load Testing*, Lantsoght, E. O. L., ed., Taylor & Francis, Structures and Infrastructures, Series Editor: D.M. Frangopol.

Lantsoght, E. O. L., Koekkoek, R. T., Hordijk, D. A. and De Boer, A., 2017, "Towards standardization of proof load testing: pilot test on viaduct Zijlweg," *Structure and Infrastructure Engineering*, pp. 16.

OBJECTIVES OF A LOAD TEST (2)

Learning objective: Select the type of load test to meet the test objectives

Diagnostic load testing

- Known load, fraction of design live load

- Compare analytical response to experimental response

- Develop field-validated model

- Load rating based on improved model

Proof load testing

- Apply factored live load

- Direct proof that bridge can carry loads

- Evaluate long-term reliability of load-carrying mechanisms

- Careful execution

LOAD TESTING FOR LOAD RATING

Learning objective: Identify whether a load test can meet desired objectives

- Rating factor according to MBE

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

- Diagnostic load test: identify Live Load effect (LL) more accurately

- Proof load test: Rating Factor (RF)

- Load rating:
- Diagnostic load test: with field-validated model, adjusted for rating
- Proof load test: based on rating vehicle weight L_R and maximum proof load L_P

$$RF_o = \frac{OP}{L_R(1 + IM)}$$

$$OP = \frac{k_0 L_p}{X_{pA}}$$

PREPARATION FOR LOAD TESTING

Learning objective: Identify whether a load test can meet desired objectives
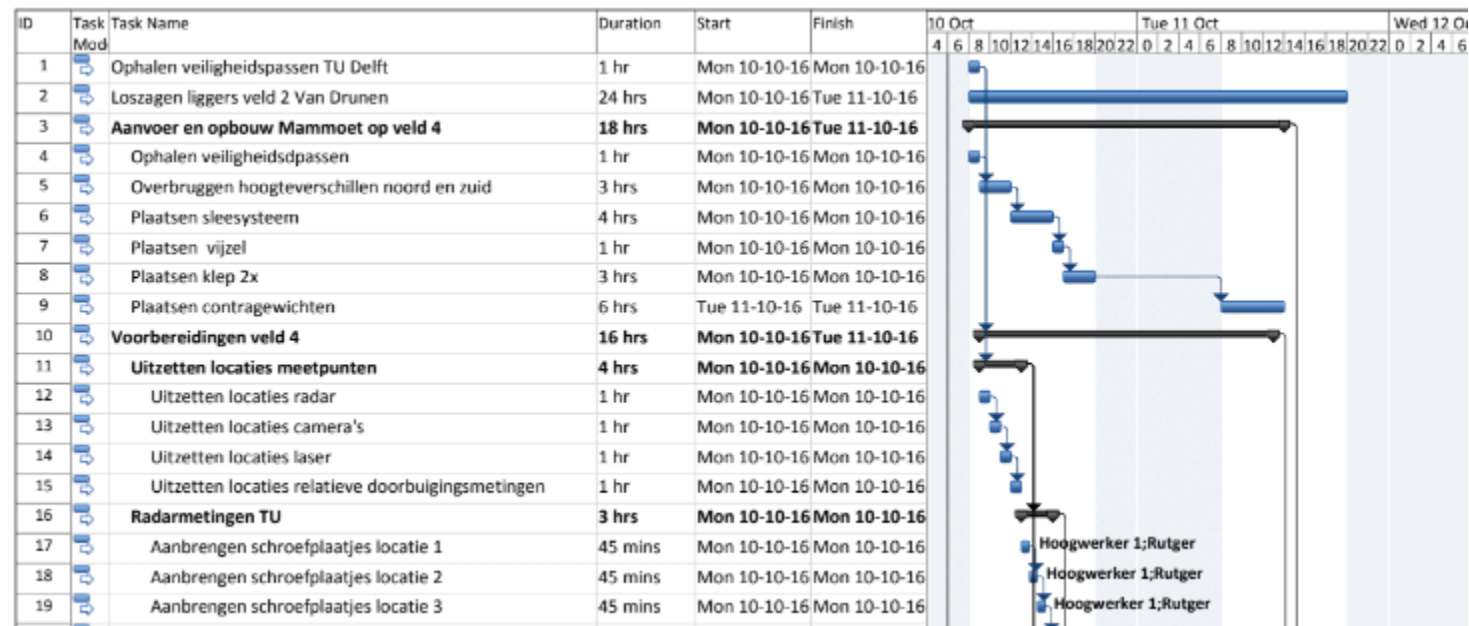
- Gather available documentation
- Field inspection according to MBE
  - Section losses
  - Deterioration
- Preliminary calculations
  - Load rating
  - Expected capacity
- Material parameters
- Analytical model
- Available nondestructive evaluation (NDE) data
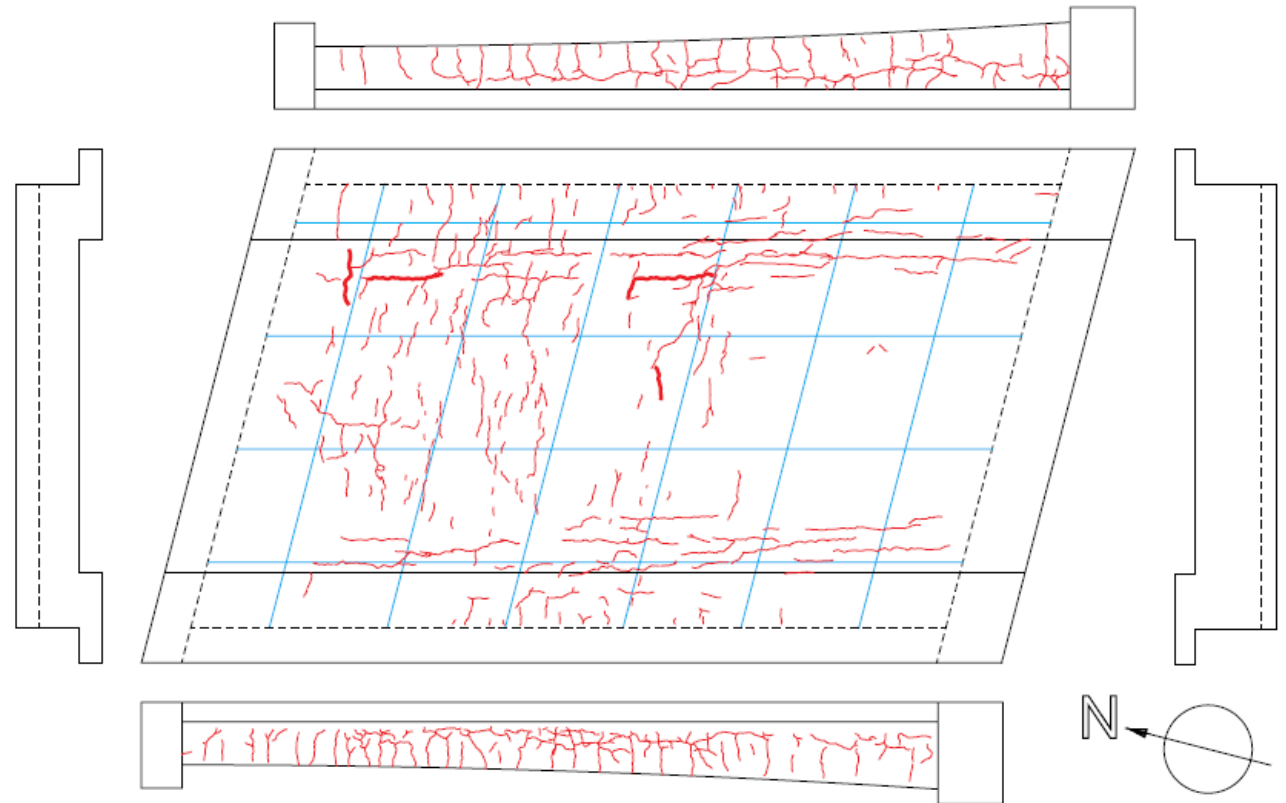
Lantsoght, E.O.L., et al., *Towards standardization of proof load testing: pilot test on viaduct Zijlweg.* Structure and Infrastructure Engineering, 2017: p. 16.

PLANNING AND PREPARATION OF LOAD TESTS

- Site-specific limitations ⇔ inspection
  - Instrumentation plan
  - Load application
  - Site-specific safety concerns
- Preparation ⇔ test objectives
- Include interpretation of responses + define stop criteria
- Safety and risk analysis plan
- Planning of on-site activities

ID	Task Mod	Task Name	Duration	Start	Finish
1		Ophalen veiligheidspassen TU Delft	1 hr	Mon 10-10-16	Mon 10-10-16
2		Loszagen liggers veld 2 Van Drunen	24 hrs	Mon 10-10-16	Tue 11-10-16
3		**Aanvoer en opbouw Mammoet op veld 4**	**18 hrs**	**Mon 10-10-16**	**Tue 11-10-16**
4		Ophalen veiligheidsdpassen	1 hr	Mon 10-10-16	Mon 10-10-16
5		Overbruggen hoogteverschillen noord en zuid	3 hrs	Mon 10-10-16	Mon 10-10-16
6		Plaatsen sleesysteem	4 hrs	Mon 10-10-16	Mon 10-10-16
7		Plaatsen vijzel	1 hr	Mon 10-10-16	Mon 10-10-16
8		Plaatsen klep 2x	3 hrs	Mon 10-10-16	Mon 10-10-16
9		Plaatsen contragewichten	6 hrs	Tue 11-10-16	Tue 11-10-16
10		**Voorbereidingen veld 4**	**16 hrs**	**Mon 10-10-16**	**Tue 11-10-16**
11		**Uitzetten locaties meetpunten**	**4 hrs**	**Mon 10-10-16**	**Mon 10-10-16**
12		Uitzetten locaties radar	1 hr	Mon 10-10-16	Mon 10-10-16
13		Uitzetten locaties camera's	1 hr	Mon 10-10-16	Mon 10-10-16
14		Uitzetten locaties laser	1 hr	Mon 10-10-16	Mon 10-10-16
15		Uitzetten locaties relatieve doorbuigingsmetingen	1 hr	Mon 10-10-16	Mon 10-10-16
16		**Radarmetingen TU**	**3 hrs**	**Mon 10-10-16**	**Mon 10-10-16**
17		Aanbrengen schroefplaatjes locatie 1	45 mins	Mon 10-10-16	Mon 10-10-16
18		Aanbrengen schroefplaatjes locatie 2	45 mins	Mon 10-10-16	Mon 10-10-16
19		Aanbrengen schroefplaatjes locatie 3	45 mins	Mon 10-10-16	Mon 10-10-16

Planning of on-site activities

INSTRUMENTATION

- Instrumentation plan:
  - Sensor layout
  - Data collection plan
  - Mounting & wiring details
- + Parameters to measure
- Include redundancy
- Examples:
 - Displacement
  - Strain
  - Crack opening
  - T, RH
  - …
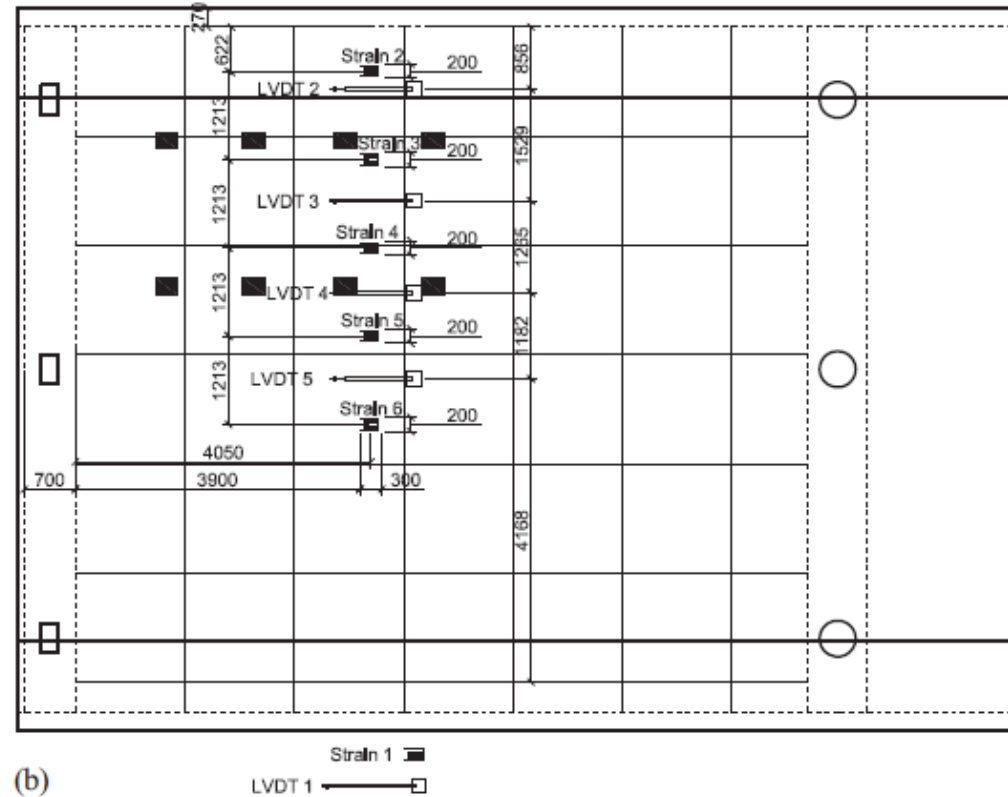
Lantsoght, E.O.L., et al., *Pilot Proof-Load Test on Viaduct De Beek: Case Study.* Journal of Bridge Engineering, 2017. **22**(12): p. 05017014.

PREPARATION OF LOAD TEST

- Data acquisition and visualization
  - Sampling rate
  - Real-time output of measurements
  - Calibration before test

- Personnel requirements
  - Responsibility: qualified bridge engineer
  - Adequate staff for test and traffic control
  - Local agencies' requirements

ENVIRONMENTAL EFFECTS

- Effect of temperature and humidity
  - On structural response
  - On sensor

- Structural response
  - Reference (dummy) sensor
  - "No load" cases

- Sensor
  - Sensor selection, small sensitivity
  - Corrections provided by manufacturer
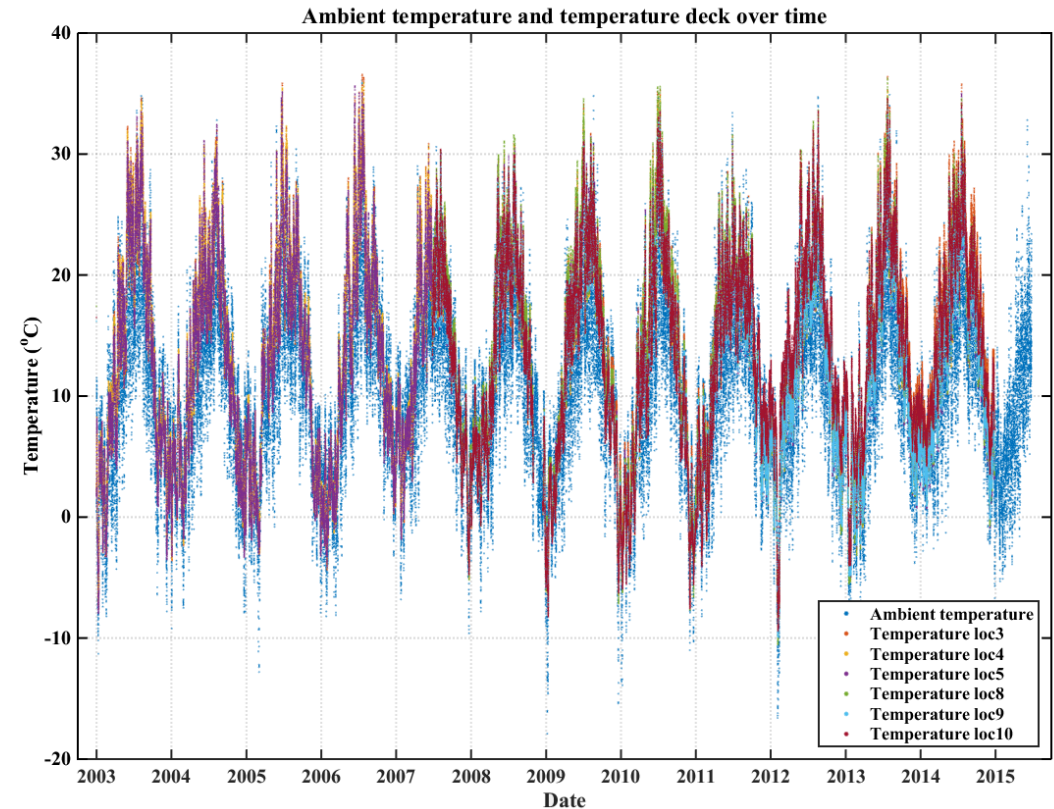
Koekkoek, R.T., E.O.L. Lantsoght, and D.A. Hordijk, *Proof loading of the ASR-affected viaduct Zijlweg over highway A59*. 2015, Delft University of Technology: Delft, The Netherlands. p. 180.

SUMMARY

- Identify objectives

- Can load test address these objectives?

- Required type of load test

$\Rightarrow$ Preparation of load test

  - Planning
  - Loading
  - Instrumentation

- Next: execution and interpretation of diagnostic load test and proof load tests

Thank You

Next: Diagnostic Load Testing

Load Testing for Evaluating Bridges

W E B I N A R

DIAGNOSTIC LOAD TESTING

Sponsored by:

TRB Standing Committee on Testing and Evaluation of Transportation Structures

Jesse Grimson - BDI

DIAGNOSTIC LOAD TESTING

LEARNING OBJECTIVE

1. Identify whether a load test can meet desired objectives
2. Select the type of load test to meet the test objectives
3. Understand the outcome of a load test, learn how to use this outcome to meet the test objectives, as well as to evaluate bridge structural behavior
4. Determine the structural safety of a bridge, quantified by the probability of failure, updated with the information from the load test

INTRODUCTION

- Measure the actual response of the structure against known loads so that realistic analytical models can be established.

- Often used to reduce uncertainties with respect to as-built condition that cannot be analyzed through traditional methods.
  - Boundary conditions, transverse distribution, secondary non-structural elements, etc.

- Typically use maximum service load for load test and can be performed in a very short time frame with low impact on traffic.

- Data is used to refine and validate analytical approach.

- Final result is typically an updated load rating for the bridge with critical load rating locations.

Typical load test being conducted on a short span structure that has been posted with a load limit.

DIAGNOSTIC LOAD TESTING
KEY CONSIDERATIONS

- field verification of design assumptions;

- distribution of live load effects;

- measurement of stress response in certain members;

- determining actual performance of bridge appurtenances that affect structural boundary conditions (i.e., expansion joints or pinned connections);

- measuring the maximum unexpected stresses in members connected to a "frozen" pin or other malfunctioning appurtenance; and

- development of load ratings for particular vehicle configurations.

COST BENEFIT ANALYSIS

<u>Before undertaking a load test, it is important to evaluate the cost benefit</u>

Typical Load Rating:

- $1,500 - $5,500

Typical Diagnostic Load Test and Load Rating:

- $25,000 - $35,000

- MPT and access not included

Alternative:

- Replacement

- Strengthening/Repairs

- Load Posting

<u>Must be able to calculate the alternative!</u>

More to come on cost benefit analysis

CASE STUDY – KEY CONSIDERATIONS

About the Structure:

- Four span, cast-in-place reinforced concrete slab single lane bridge

- Current load rating below acceptable limit for the service loads

- Condition of the bridge was good, no signs of degradation

Objective:

- Provide a more accurate load rating through a diagnostic load test

Cost-Benefit Analysis:

- Simplified approach, comparing the cost of strengthening to load testing

- Estimated strengthening cost ~ $250,000

- Diagnostic Load Test ~ $30,000

PLANNING & EXECUTION

1. **Develop instrumentation plans**

2. **Project site planning**

   a. Bridge access, traffic control plan, and loading vehicle

3. **Execute diagnostic load test**

4. **Validate data on-site**
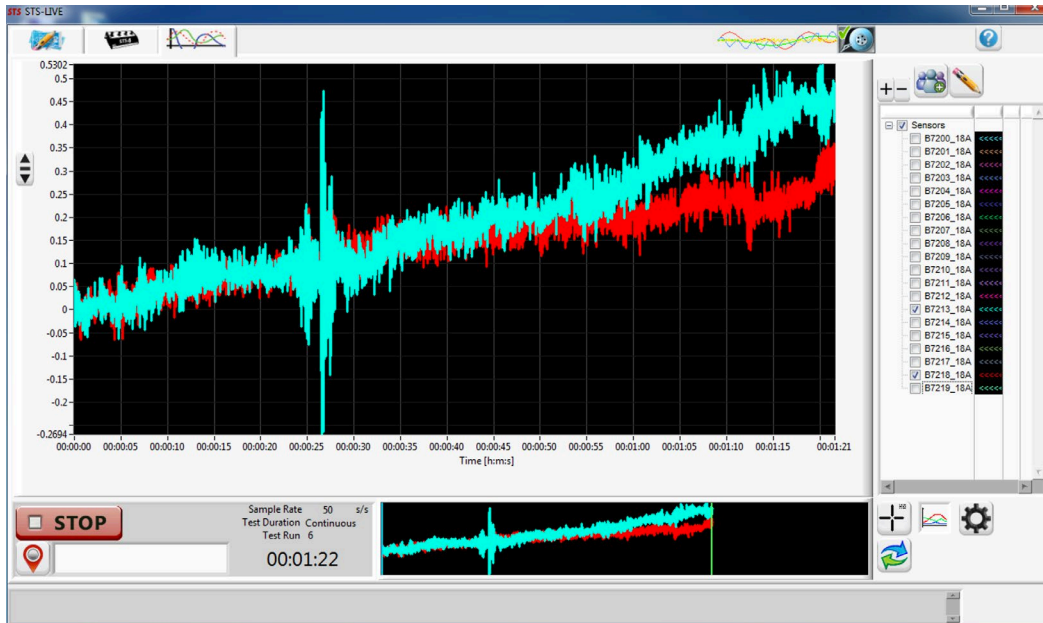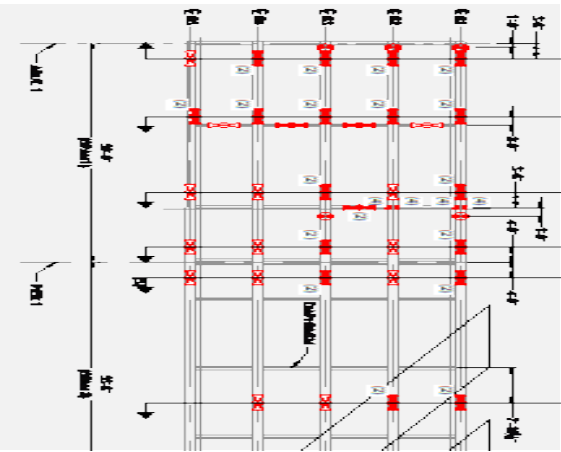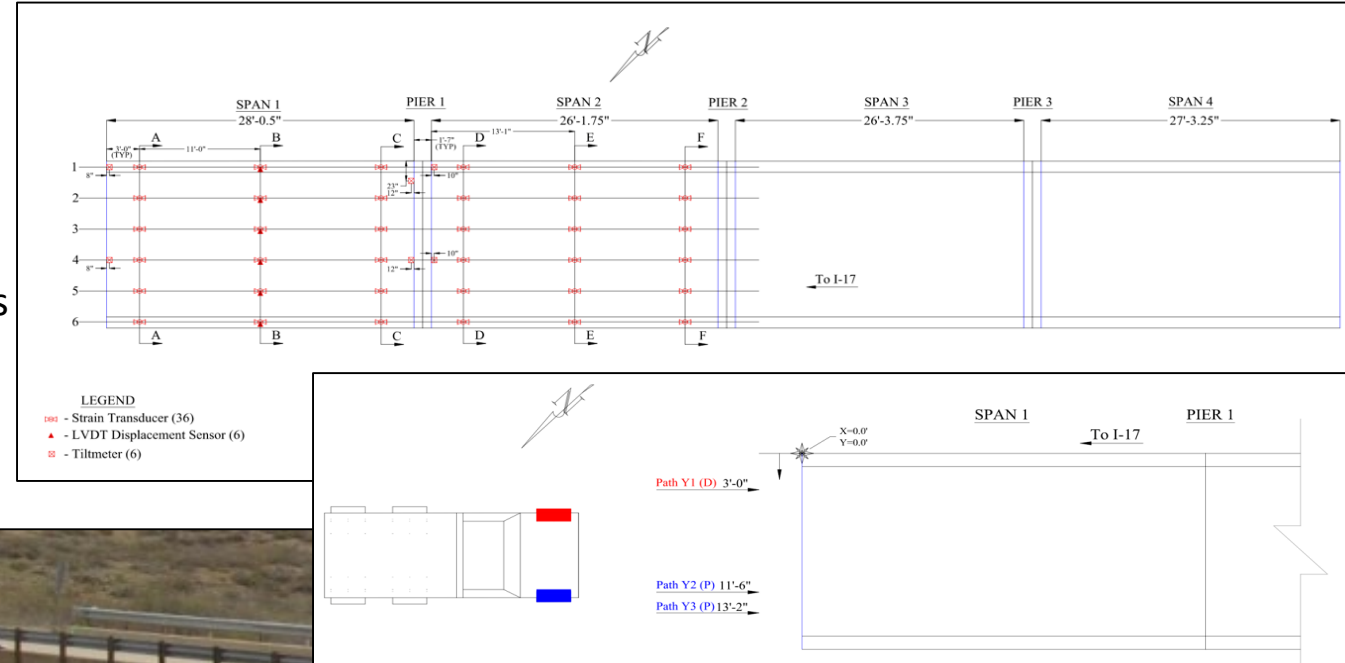
CASE STUDY – PLANNING & EXECUTION

Instrumentation Plans:

- Focus on 2 of 4 spans with 6 cross sections on sensors

- Strain, displacement, and rotation as primary measurements

- 3 lateral load paths defined

Site Planning:

- Access via scaffolding and step ladders

- Traffic control was performed by load testing crew (low volume road)

- Tandem dump truck loaded to the legal limit used as test vehicle

DATA INTERPRETATION

1. **Qualitative data review**
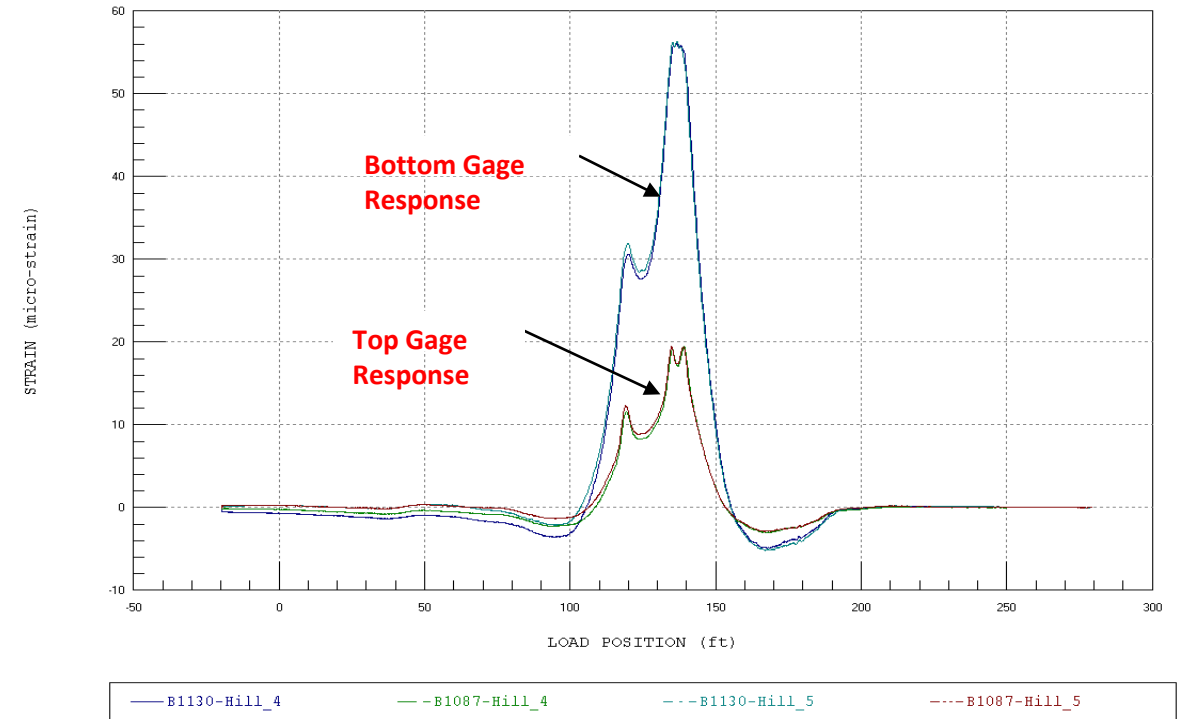
2. **Develop analytical model**
   a. Identify and assign initial model parameters

3. **Validate and refine analytical model**
   a. Adjust model parameters to match field responses

4. **Final field-verified model**
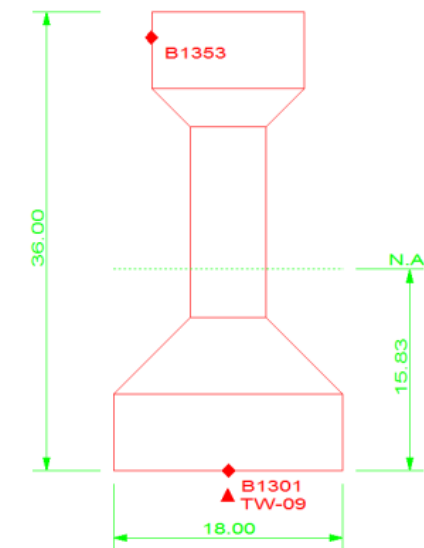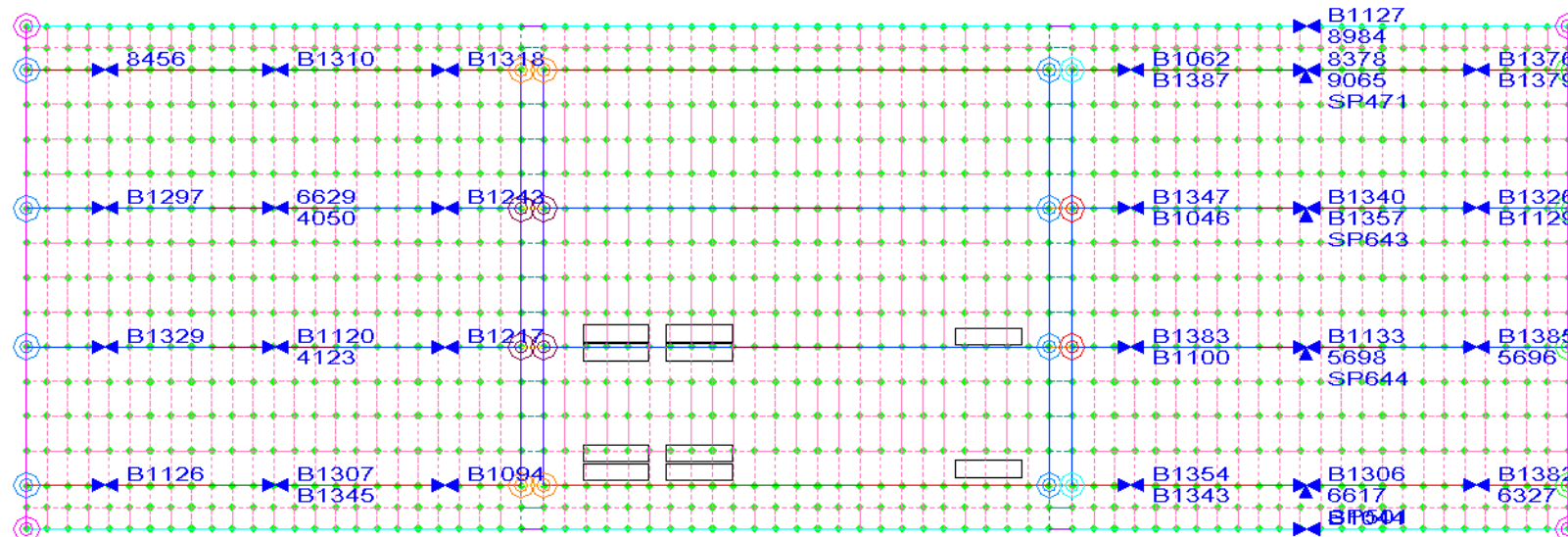
CASE STUDY – DATA QUALITY REVIEW

Key Points:

- **Reproducibility and linearity of responses**

- **Thermal drift not an issue**

PARAMETER REFINEMENT

Element Type and Mesh Size	Strain or stress output, depending on the element type and mesh size at sensor locations, must be comparable to the gage length and orientation of strain sensors used in load test.
Secondary Members	Secondary members such as barriers, sidewalks, diaphragms, etc., need to be properly included for their geometrical, material, and stiffness properties.
Bearing Support Conditions	Typical bridge bearings, of fixed or expansion, provide a rectangular patch support to the superstructure. Expansion bearings usually have frictional resistance. Use of idealized fixed or roller point or line supports in the analytical model may cause discrepancies with load test measurements due to simplifications.
Elastic Modulus of Concrete (E_c)	E_c is usually estimated from the specified concrete compressive strength (f_c') using an empirical formula. In reality, most concrete mixes are placed at a higher strength than design requirements, and concrete continues to gain strength over time. When modelling the sectional stiffness, both the effect of the concrete strength and the provided reinforcement are considered. If test data is available, using the actual material properties instead of nominal values will improve the fidelity of results from the model.
Link Members for Eccentricities	Use of line or planar elements in a FEM requires the use of link members to address the eccentricities between intersecting or connecting bridge members. Proper definitions of the stiffness properties of the link members are important to simulate the overall behavior of the structural system, including intended or unintended composite actions between adjacent members.
Member End Connection Stiffness	For steel members of I-shaped or other types that do not have a full moment connection at the end in the framing system, e.g., the commonly used partial web height double-angle bolted connection, the actual rotational stiffness of the connection falls between those of a fixed and a pinned connection. Depending on the type of elements used in the model, adjustments can be made to the rotational stiffness for better agreement with field measurements. For example, a rotational stiffness constant can be defined at the connection when beam members are used in the model.

CASE STUDY – PARAMETER REFINEMENT
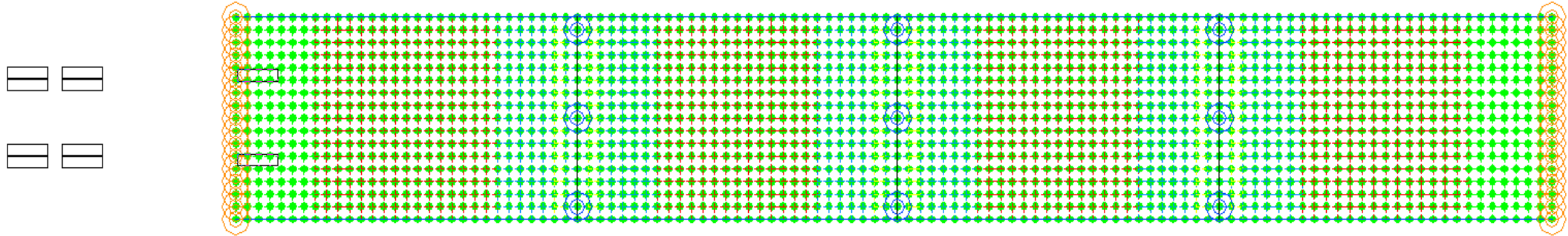
Finite Element Model Stats:

- 2D composed of shell elements, frame elements, and springs

- 2-D footprint of test truck consisting of 10 vertical point loads

- Loading increments every 2ft. (204 load cases)

- 9,792 measurement comparisons (36 strain, 6 disp., 6 rotation)

Finite Element Model Adjustments:
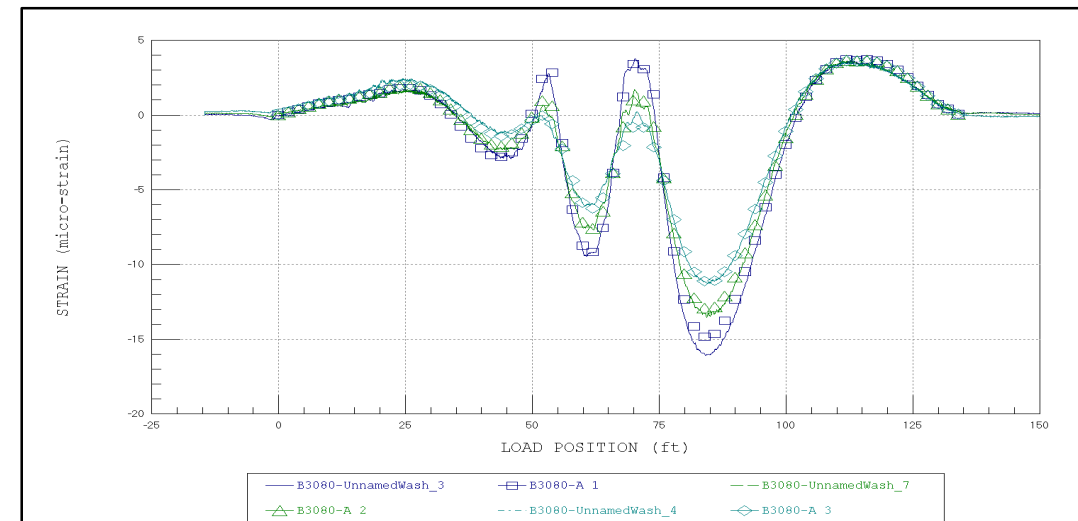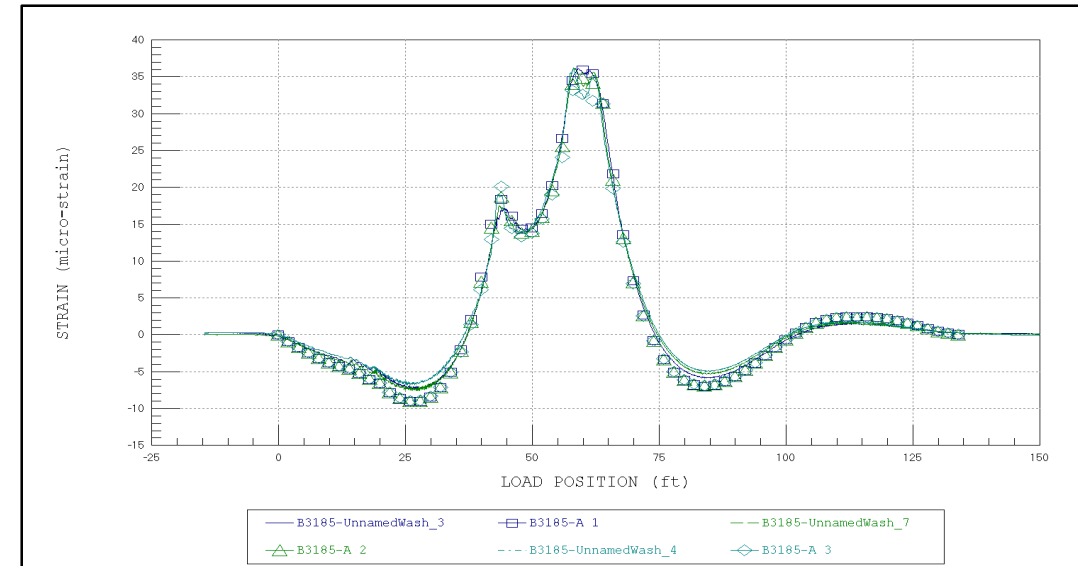
- Friction-Based Rotational Resistance: Bottom of the slab at piers (Fx)

- Slab Stiffness: Midspan Slab (E)

- Slab Stiffness: Slab near abutments (E)

- Slab Stiffness: Slab near piers (E)

- Slab Stiffness: Slab adjacent to piers (E)

CASE STUDY – PARAMETER REFINEMENT

Final Model:

- **Excellent correlation with measured response**

MODELING PARAMETER	INITIAL MODEL VALUE	FINAL MODEL VALUE
Slab Stiffness		
- Slab at midspan (E)	3,200 ksi (22.06 GPa)	2,600 ksi (17.93 GPa)
- Slab near abutments (E)	3,200 ksi (22.06 GPa)	3,300 ksi (22.75 GPa)
- Slab near pier (E)	3,200 ksi (22.06 GPa)	3,300 ksi (22.75 GPa)
- Slab directly adjacent to piers (E)	3,200 ksi (22.06 GPa)	2,150 ksi (14.82 GPa)
- Spring Resistance at Piers (F_x)	0	400 kip/in (70.1 kN/mm)
MODEL CORRELATION	INITIAL MODEL VALUE	FINAL MODEL VALUE
Correlation Coefficient	0.9782	**0.9856**

LOAD RATING

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

1. **Model adjustments for load rating**
   a. Remove/reduce parameters that may not be counted on reliably.

2. **Calculate member capacities**
   a. Member capacities are calculated using the applicable code [MBE].

3. **Apply dead and live load**
   a. Dead load may have to be applied separately (non-composite)
   b. Apply design live loads according to applicable code [MBE].

4. **Extracting results**
   a. Typically rating factors should be produced for all elements where capacities were assigned.

REPORTING

FOCUSED REPORT OUTLINING THE RESULTS AND RECOMMENDATIONS. NOT A RESEARCH REPORT!

1. **Executive summary with load rating results**

2. **Summary of load test procedure and instrumentation plans**

3. **Analysis approach**
   a. Data quality, notable observed behavior
   b. Modeling approach (2D/3D) and comparison between analytical model and field measurements
   c. Summary of parameters refinement results and justification

4. **Final load rating and recommendations/advice**
   a. Summary of final modeling parameters used for load rating
   b. Load rating parameters: load factors and capacities used for load rating along with assumptions made
   c. Detailed load ratings for requested vehicle configurations
   d. Recommendations, if any

Thank You

Next: Proof Load Testing

Load Testing for Evaluating Bridges

WEBINAR

# PROOF LOAD TESTING

Sponsored by:
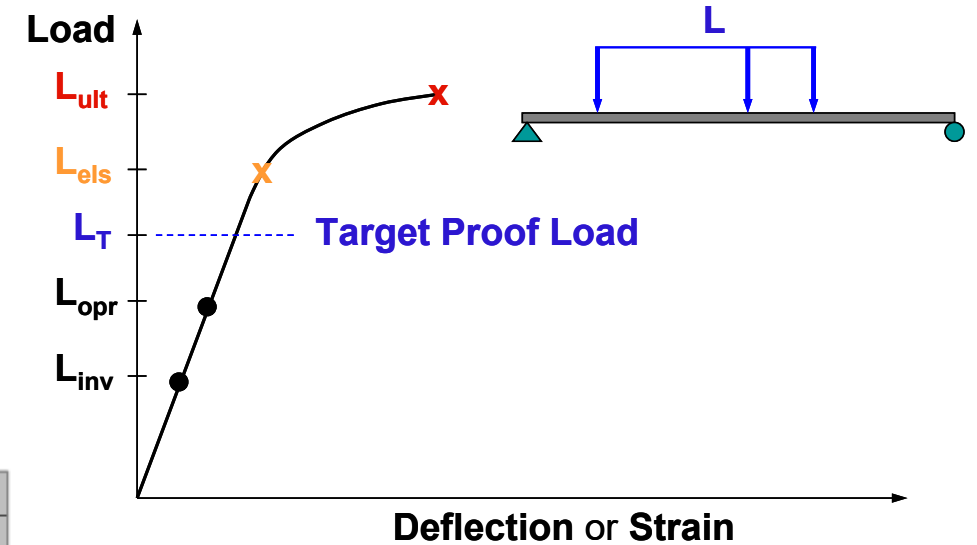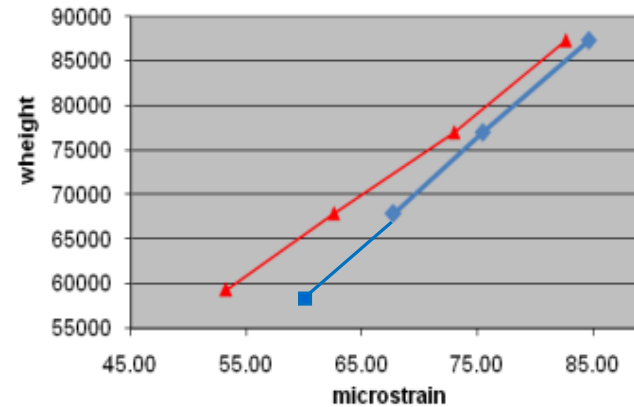
TRB Standing Committee on Testing and Evaluation of Transportation Structures

Y. Edward Zhou, PhD, PE

PROOF LOAD TESTING

INTRODUCTION

- For bridges lacking info for calculating capacities

- Less need for structural analysis or rating calcs

- Incrementally loading/unloading to a target load

- Physically proving a lower-bound load capacity at full DL + a magnified LL

PROOF LOAD TESTING

COMPARISONS BETWEEN DIAGNOSTIC AND PROOF LOAD TESTS

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

Diagnostic Load Tests

♦ Investigate structural behavior through determining actual effects of *LL* &/or impact

♦ Compare measured strains and deflections under test loads with analytical predictions

♦ Generally require structural analysis, e.g., finite element modeling (FEM)

♦ Test loads typically at service load level

♦ Simpler field testing operation, with low levels of risks

♦ Calculate load ratings using any method at all levels for any rating vehicles

♦ Uncertainties in capacities (*C*) remain

Proof Load Tests

♦ Physically prove a lower-bound load capacity with full *DC+DW+P* plus magnified *LL* &/or *IM*

♦ Monitor and assess key response measurements to increasing test load

♦ Less analysis or rating calculation needs

♦ Test loads at 130 ~ 220% service load in multiple loading/unloading steps

♦ More complex field testing operation, with a higher level of risks

♦ Conclude if *RF* ≥ 1.0 for specific vehicles at Design Operating, Legal, or Permit levels

♦ A higher level of overall reliability

PROOF LOAD TESTING

AASHTO BRIDGE LOAD RATING METHODS & CRITERIA – LL FACTORS

LRFR: $RF = \dfrac{C - (\gamma_{DC})(DC) - (\gamma_{DW})(DW) \pm (\gamma_P)(P)}{(\gamma_{LL})(LL + IM)}$ ASR/LFR: $RF = \dfrac{C - A_1 D}{A_2 L(1+I)}$

- Allowable Stress Rating (ASR), rating levels & factors of safety (F.S.)
    - Inventory Rating (INV), design F.S.; Operating Rating (OPR), reduced F.S.
    - $A_1 = A_2 = 1.0$; C_{INV} and C_{OPR} vary with failure mode, $RF_{OPR}/RF_{INV} \approx 1.36$
- Load Factor Rating (LFR), rating levels & safety margins (S.M.)
    - Inventory Rating (INV), design S.M.; Operating Rating (OPR), reduced S.M.
    - $A_1 = 1.3$ for INV & OPR; $A_2 = 2.17$ for INV = 1.3 for OPR; $RF_{OPR}/RF_{INV} = 1.67$
- Load and Resistance Factor Rating (LRFR), rating levels & reliability index (β)
    - Design Load Rating (Strength I): $\gamma_{LL} = 1.75$ for INV (β ≈ 3.5) = 1.35 for OPR (β ≈ 2.5)
    - Legal Load Rating (Strength I): $\gamma_{LL} = 1.30$ or 1.45 (β ≈ 2.5) per ADTT, $\gamma_{DC} = 1.25$, $\gamma_{DW} = 1.50$
    - Permit Load Rating (Strength II): $\gamma_{LL} = 1.10 \sim 1.40$ (β ≈ 2.5) per permit type

PROOF LOAD TESTING

CASE STUDY: I-195 WB OVER SEEKONK RIVER, PROVIDENCE, RI
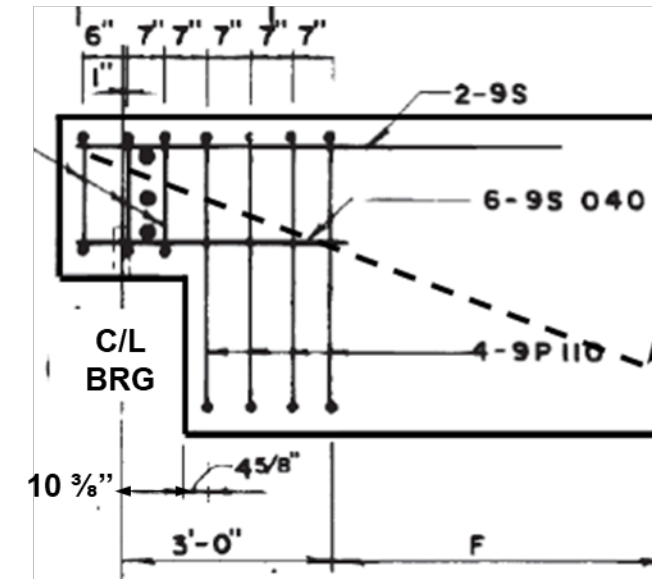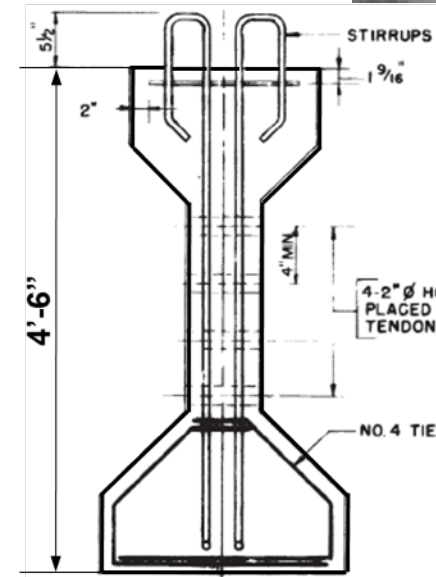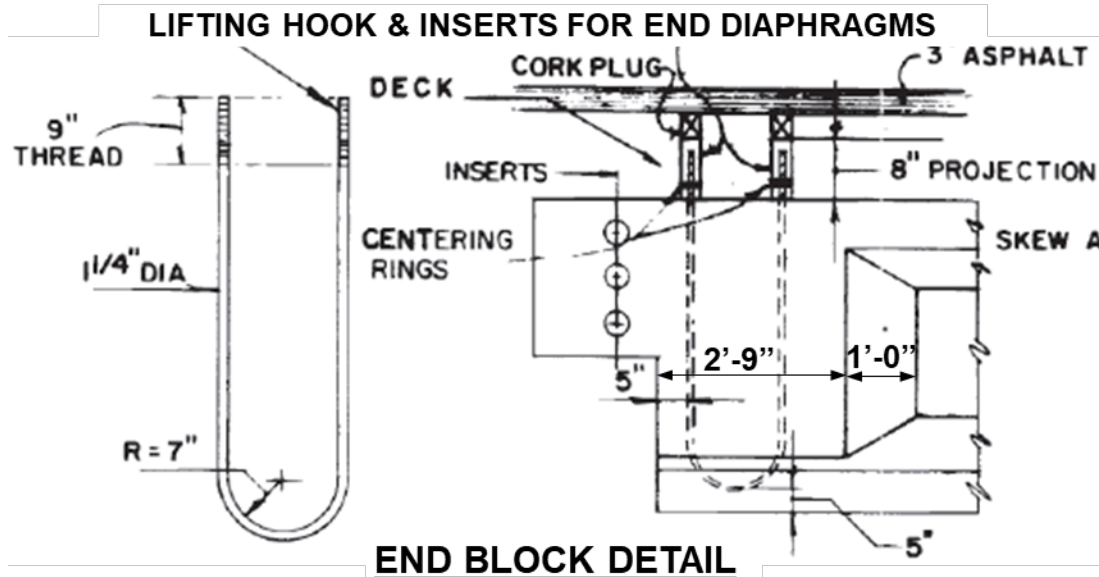
- 1967 PSC cantilevered & drop-in girders
- Insufficient analytical bridge load ratings
- Serving interstate without restrictions
- Governed by shear at girder dapped ends
- One span selected for load testing

PROOF LOAD TESTING

CASE STUDY: SELECTION OF PROOF TESTING OVER DIAGNOSTIC TESTING

- Uncertainties in calculating shear resistance at dapped end
  - Failure section/plane
  - Stirrup and longitudinal/horizontal reinforcement
  - Prestressing
  - Concrete with existing cracks
  - Participations of deck and end diaphragms

LIFTING HOOK & INSERTS FOR END DIAPHRAGMS

END BLOCK DETAIL

PROOF LOAD TESTING

AASHTO MBE, 3RD EDITION, 2018 – TARGET PROOF LOAD

- Target proof load L_T (governing force effect)
    - Enveloping rating vehicle LL plus IM
    - Target LL factor base value X_p = 1.40
    - Target adjusted LL factor $1.3 \leq X_{pA} \leq 2.2$

- Placed on bridge in multiple stages
    - First-stage loading $\leq 0.25 L_T$
    - Second-stage loading $\leq 0.5 L_T$

Table 8.8.3.3.1-1—Adjustments to X_p

Consideration	Adjustment
One-Lane Load Controls	+15%
Nonredundant Structure	+10%
Fracture-Critical Details Present	+10%
Bridges in Poor Condition	+10%
In-Depth Inspection Performed	−5%
Rateable, Existing $RF \geq 1.0$	−5%
$ADTT \leq 1,000$	−10%
$ADTT \leq 100$	−15%

8.8.3.3—Target Proof Loads

8.8.3.3.1—Selection of Target Live-Load Factor

8.8.3.3.2—Application of Target Live-Load Factor, X_{pA}

$$X_{pA} = X_p \left(1 + \frac{\sum\%}{100} \right) \qquad (8.8.3.3.2\text{-}1)$$

The target proof load L_T is then:

$$L_T = X_{pA} L_R (1 + IM) \qquad (8.8.3.3.2\text{-}2)$$

where:

L_R = comparable unfactored live load due to the rating vehicle for the lanes loaded

IM = dynamic load allowance

X_{pA} = target adjusted live-load factor

PROOF LOAD TESTING

CASE STUDY: ESTABLISHMENT OF TARGET PROOF LOAD (L_T)

- Bridge load ratings governed by maximum shear force (V_{max}) at dapped end

- V_{max} used as key parameter to establish target proof load L_T

- A simple beam analysis for HL93 design truck and 8 different legal vehicles

- SU7 producing highest V_{max} among all legal vehicles, 99% of design truck V_{max}

V_{max} in a 53'-7½" Simple Span due to Different Rating Vehicles

Vehicle	Type	GVW	Axle Configuration (Weight in K = kips & Spacing in ' = ft)	V_{max} (K)
HL93 (Truck)	Design	72K	8K (14.0') 32K (14.0') 32K	59.47
H20	Legal	40K	8K (14.0') 32K	37.91
Type 3	Legal	50K	16K (15.0') 17K (4.0') 17K	43.06
Type 3S2	Legal	72K	10K (11.0') 15.5K (4.0') 15.5K (22.0') 15.5K (4.0') 15.5K	47.01
Type 3-3	Legal	80K	12K (15.0') 12K (4.0') 12K (15.0') 16K (16.0') 14K (4.0') 14K	44.43
SU4	Legal	54K	12K (10.0') 8K (4.0') 17K (4.0') 17K	47.51
SU5	Legal	62K	12K (10.0') 8K (4.0') 8K (4.0') 17K (4.0') 17K	52.83
SU6	Legal	69.5K	11.5K (10.0') 8K (4.0') 8K (4.0') 17K (4.0') 17K (4.0') 8K	55.94
SU7	Legal	77.5K	11.5K (10.0') 8K (4.0') 8K (4.0') 17K (4.0') 17K (4.0') 8K (4.0') 8K	58.76

PROOF LOAD TESTING

CASE STUDY: TARGET PROOF LOAD IN TEST TRUCK WEIGHTS

- Two 3-axle dump trucks similar to Type 3

- Type 3 GVW for equivalent SU7 V_{max}: (58.76K/43.06K)(50K) = 68.23K

- Using target live load factor (X_p) base value = 1.40, without dynamic impact (IM)

- Test trucks GVW (W): $W_{Initial}$ = 68.23K; W_{Target} = (1.40)(68.23) = 95.52K

- Trucks loaded with gravels near bridge; wheel weights obtained by portable scales

PROOF LOAD TESTING

CASE STUDY: 44 TEST RUNS (13 @ WL#1 & WL#2, 9 @ WL#3 & SWL#4)

- Direct and similar loading to each girder
- Different single & side-by-side runs at each level
- Pairs of slow and speed runs for dynamic impact

Test Run No.	Weight Level	Test Truck Position and Combination					Speed	Travel Direction
		Lane 1	Lane 2	Lane 3	Lane 4	R. Shldr		
14	WL#2	Truck A					Crawl (5 MPH)	Forward WB
15			Truck B					
16				Truck A				
17					Truck B			
18						Truck A		
19		Truck A	Truck B					
20			Truck A	Truck B				
21				Truck A	Truck B			
22					Truck A	Truck B		
23		Truck A					Speed Limit (55 MPH)	
24			Truck B					
25				Truck A				
26					Truck B			
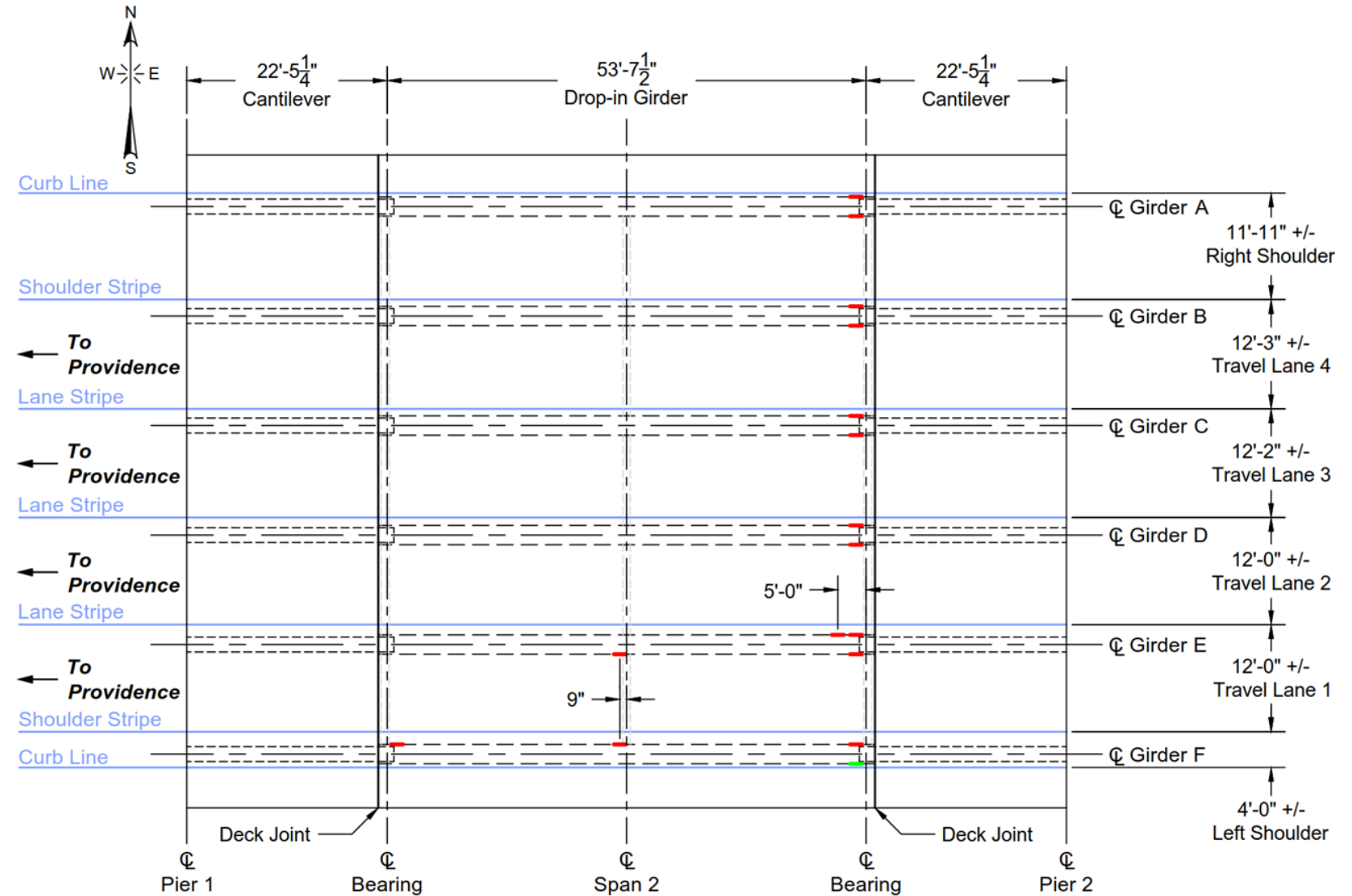
Test Truck 'A' Weights

No.	Axle (lbs)			Vehicle (K)
1	18,760	25,020	25,060	68.84
2	21,960	28,460	28,600	79.02
3	24,180	31,640	32,420	88.24
4	27,100	38,440	36,180	101.72

19'-6" 4'-6"

Test Truck 'B' Weights

| No.	Axle (lbs)			Vehicle (K)
1	22,630	23,800	21,860	68.29
2	24,640	27,960	26,840	79.44
3	23,160	33,540	31,660	88.36
4	25,140	43,060	32,180	100.38

20'-8" 4'-4"

PROOF LOAD TESTING
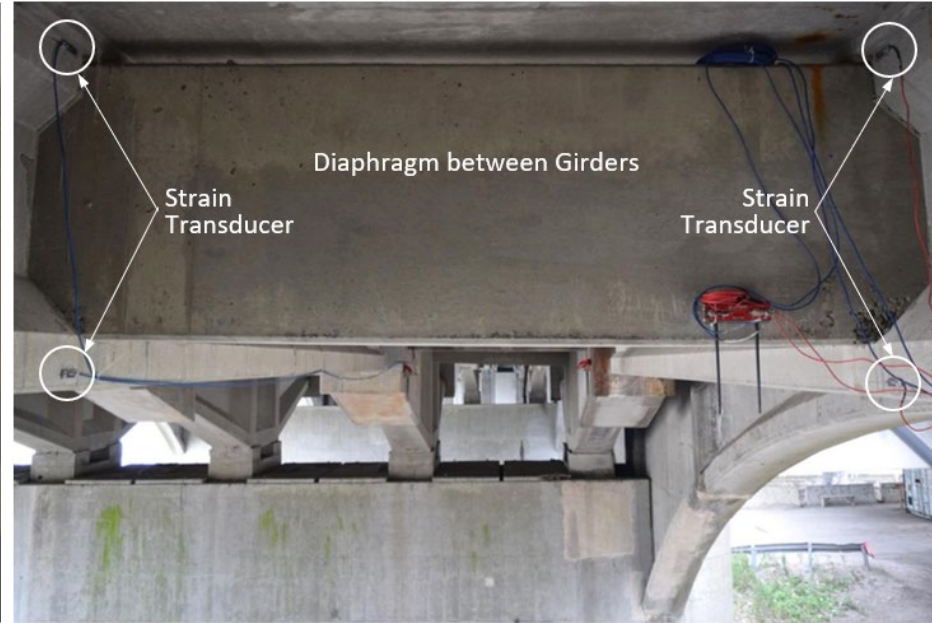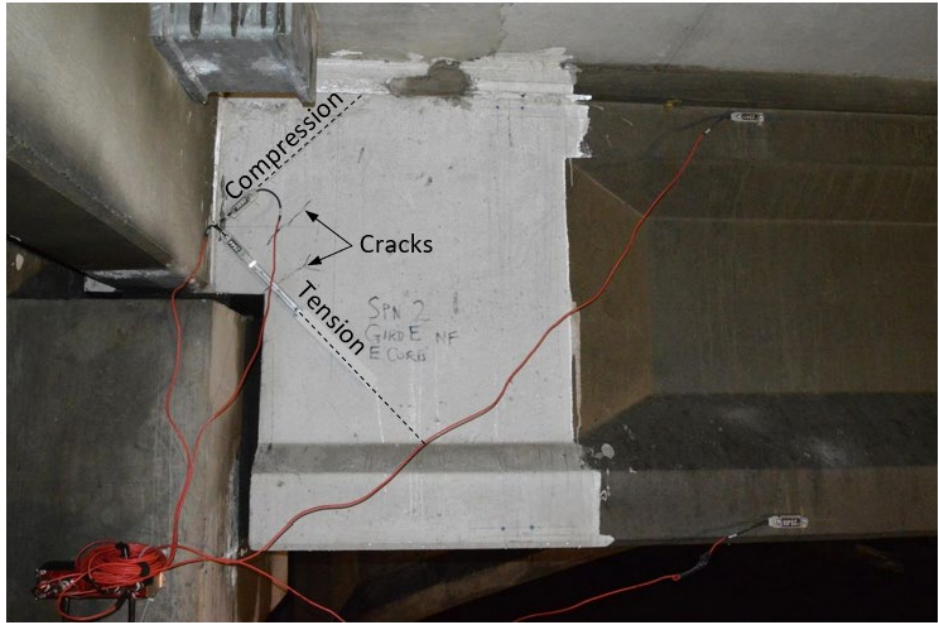
CASE STUDY: SENSOR LAYOUT PLAN VIEW

- 32 strain sensors total

- Concrete shear in dapped end (DE) on both webs of all six girders east end (22)

- Exposed stirrups (2)

- Concrete shear in DE on one web of one girder west end (2)

- Flexure at mid-span of two girders (4)

- Deck-girder composite action near end (2)

- Varying gage length
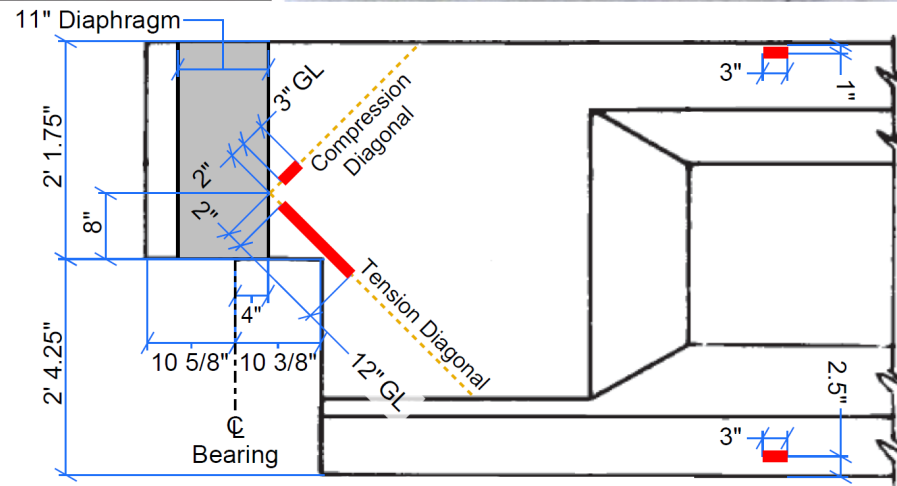
CASE STUDY: SENSOR PLACEMENT DETAILS

Compression
Cracks
Tension
SPN 2
GIRD E NF
E CORB

Diaphragm between Girders

Strain Transducer

Strain Transducer

SPN 2
GIRD F SF
E CORB

Drop-in Girder Dapped End

Cantilevered Girder Section from Pier

Objectives:

1) Capture onset of shear failure at dapped ends

2) Investigate deck-girder composite action

11" Diaphragm
2' 1.75"
8"
2"
2"
3" GL
Compression Diagonal
Tension Diagonal
3"
1"
2' 4.25"
4"
10 5/8" 10 3/8"
12" GL
2.5"
3"
℄ Bearing

LEGEND
■ = Strain Transducer;   GL = Gage Length

PROOF LOAD TESTING

CASE STUDY: LOAD TEST IN TWO NIGHT OPERATIONS

- Two left lanes of I-195 WB closed as staging area

- All lanes closed intermittently during test runs only

- Results reviewed after each test run (magnitudes, linearity, zero returns...)
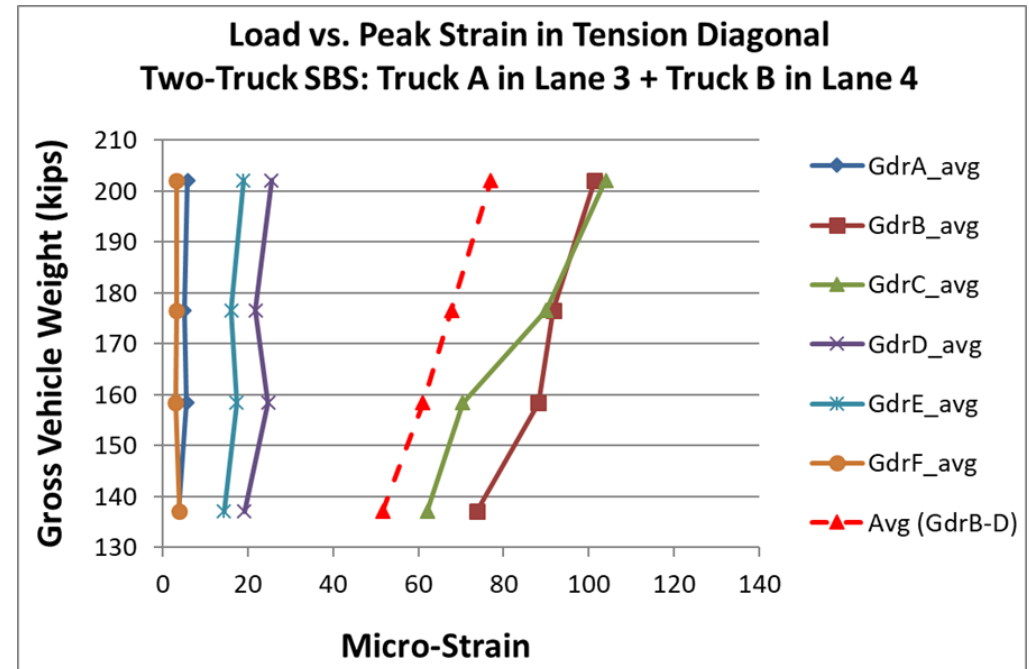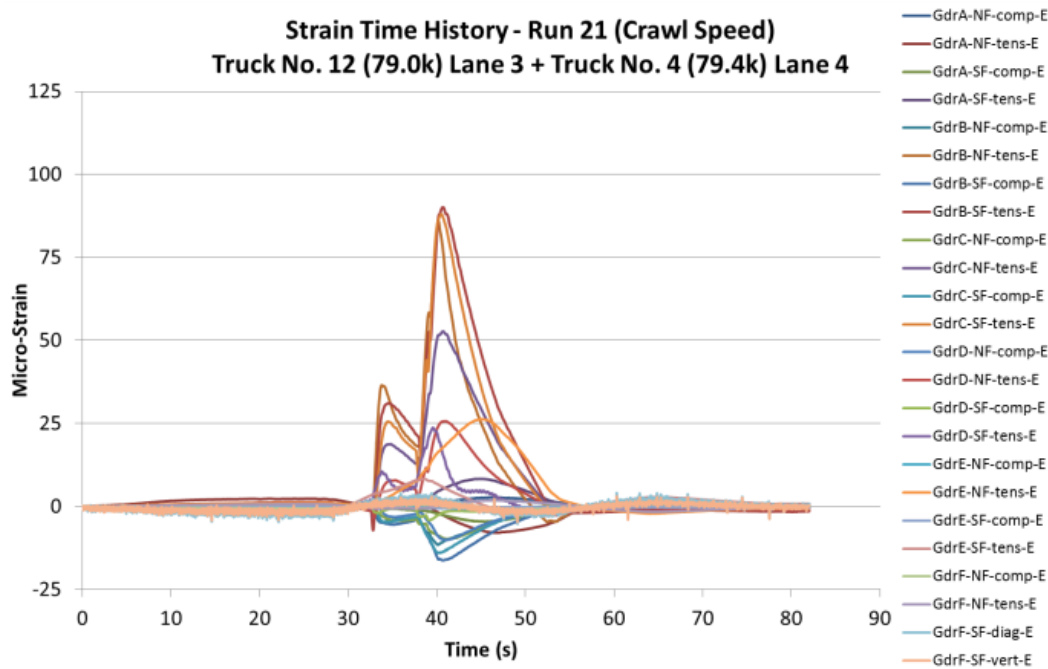
PROOF LOAD TESTING

CASE STUDY: RESPONSE VS. LOAD FOR LINEAR ELASTIC BEHAVIOR

- Examination of magnitudes and zero-return of sensor measurements after each test run
- Identification of possible nonlinear behavior or onset of failure
- Concrete strain in tension diagonal at dapped end as key parameter for load-response plots
- A consistent decrease in slope (stiffness) indication of distress or onset of failure
- Lateral shift of vehicle position between increments causes change of slope for some sensors

PROOF LOAD TESTING

DERIVING LOAD RATINGS FROM PROOF LOAD TEST RESULTS

- A lower-bound rating factor: $RF_P = (k_O)(W_P/W_R)(f_V)/[(\gamma_{LL})(1+IM)]$

  - k_O = proof load test termination factor (1.00 or 0.88)
  - W_R = gross vehicle weight (GVW) of rating vehicle
  - W_P = final GVW of test vehicle from proof load test
  - f_V = vehicle adjustment factor = W_{eq}/W_P, where W_{eq} = equiv. GVW of rating vehicle for the same force effect of test truck
  - IM = dynamic allowance, based on field measurements.
  - γ_{LL} = live load factor for specific load rating levels per MBE

AASHTO MBE, 2018

8.8.3.3.3—Load Capacity and Rating

At the conclusion of the proof load test, the actual maximum proof live load L_p applied to the bridge is known. The Operating level capacity OP is found as follows:

$$OP = \frac{k_O L_p}{X_{pA}} \quad (8.8.3.3.3-1)$$

The rating factor at the operating level RF_o is:

$$RF_o = \frac{OP}{L_R(1+IM)} \quad (8.8.3.3.3-2)$$

Load Rating Method	Load Rating Level	Live Load Factor γ_{LL}	AASHTO MBE Source
Load and Resistance Factor Rating (LRFR)	Design Inventory	1.75	Table 6A.4.3.2.2-1
	Design Operating	1.35	
	Legal	1.45 (ADTT ≥ 5,000)	Table 6A.4.4.2.3a-1
		1.30 (ADTT ≤ 1,000)	(linear interpolation)
	Permit	1.10 to 1.40	Table 6A.4.5.4.2a-1
Load Factor Rating (LFR)	Inventory	2.17	Article 6B.4.3
	Operating	1.3	

Note: Proof load tests should be used to derive bridge load ratings at the Design Operating, Legal, or Permit levels, but not at the Design Inventory level.

PROOF LOAD TESTING
CASE STUDY: LOWER-BOUND RATINGS DERIVED FROM TEST RESULTS

$$RF_P = (k_O)(W_P/W_R)(f_V)/[(\gamma_{LL})(1+IM)]$$

Load Ratings of LRFR Legal ADTT ≤ 1,000:

$k_O = 1.00 \qquad \gamma_{LL} = 1.30$

Rating Vehicle	Type	W_R (kips)	$RF_P = (RF_P)_V$	Flexure					Shear				
				M_{max} (k-ft)	W_{eq} (kips)	f_V	IM	$(RF_P)_M$	V_{max} (kips)	W_{eq} (kips)	f_V	IM	$(RF_P)_V$
'Truck A'	Testing	101.7		1019.8	101.7	1.00			86.1	101.7	1.00		
H-15	Legal	30	**2.14**	361.0	84.7	0.83	20%	1.81	28.2	91.7	0.90	10%	2.14
Type 3		50	**1.41**	518.8	98.3	0.97	20%	1.26	42.8	100.7	0.99	10%	1.41
HS-20		72	**1.02**	689.6	106.5	1.05	20%	0.95	58.9	105.3	1.04	10%	1.02
SU7		77.5	**1.02**	774.8	102.0	1.00	20%	0.84	58.9	113.2	1.11	10%	1.02

M_{max} and V_{max} based on simple beam of 53.625 ft span length

Load Ratings of LRFR Legal ADTT ≥ 5,000:

$k_O = 1.00 \qquad \gamma_{LL} = 1.45$

Rating Vehicle	Type	W_R (kips)	$RF_P = (RF_P)_V$	Flexure					Shear				
				M_{max} (k-ft)	W_{eq} (kips)	f_V	IM	$(RF_P)_M$	V_{max} (kips)	W_{eq} (kips)	f_V	IM	$(RF_P)_V$
'Truck A'	Testing	101.7		1019.8	101.7	1.00			86.1	101.7	1.00		
H-15	Legal	30	**1.92**	361.0	84.7	0.83	20%	1.62	28.2	91.7	0.90	10%	1.92
Type 3		50	**1.26**	518.8	98.3	0.97	20%	1.13	42.8	100.7	0.99	10%	1.26
HS-20		72	**0.92**	689.6	106.5	1.05	20%	0.85	58.9	105.3	1.04	10%	0.92
SU7		77.5	**0.92**	774.8	102.0	1.00	20%	0.76	58.9	113.2	1.11	10%	0.92

PROOF LOAD TESTING

OTHER BRIDGE TYPES FOR PROOF LOAD TESTING

- Prestressed concrete (PSC) structures:
  - Adjacent box/channel/slab beams

- Concrete encased steel beams

- Reinforced concrete (RC) structures:
  - Rigid frames
  - Box culverts
  - Arches
  - Slabs

Important Notes:

a) Loading history and signs of distress

b) Evidences for supporting target proof load

PROOF LOAD TESTING

COST-BENEFIT EVALUATION

- Benefits ($$$)
  - A physically proven load carrying capacity (full DL + magnified LL)
  - Eliminating unnecessary bridge replacement/rehabilitation/repairs
  - Reducing economical impacts due to unnecessary weight restrictions
- Costs ($30K–$80K)
  - Sensors and test equipment – depending on type and scale of structure
  - Test vehicles – typically two dump trucks capable of being loaded to 100K GVW each
  - Loading material and equipment – hauling and loading vehicles, etc.
  - Maintenance of traffic – depending on site condition
  - Engineering – depending on structure type and load rating needs
- Cost-benefit ratio varies depending on case specific situation

Thank You

Next: Reliability and Cost-Benefit

Load Testing for Evaluating Bridges

WEBINAR

RELIABILITY AND COST-BENEFIT

Sponsored by:

TRB Standing Committee on Testing and Evaluation of Transportation Structures

David Y. Yang, Ph.D., Dan M. Frangopol, Ph.D.

LEARNING OBJECTIVES

- **Determine the structural safety of a bridge, quantified by the probability of failure, updated with the information from the load test**
  - ✓ Quantify the cost and benefit of a bridge load test
  - ✓ Incorporate bridge load tests in the life-cycle management of deteriorating bridges

UNCERTAINTIES IN STRUCTURAL ANALYSIS

- Aleatory uncertainty
  - ✓ Inherent randomness that cannot be reduced or eliminated (e.g., material properties and traffic loads)

Data from: Nowak and Collins (2000)

UNCERTAINTIES IN STRUCTURAL ANALYSIS

- Epistemic uncertainty
  - ✓ Due to a lack of complete knowledge
  - ✓ Can be reduced

Adapted from: Wang et al. (2011)

RELIABILITY AND RISK ASSESSMENT

Structural Reliability Analysis

$$g = R - S < 0$$

Structural failure

Structural capacity (resistance)

Structural demand (load effects)

Quantitative risk assessment

$$R = p_f \cdot C_f$$

Probability of failure (PoF)
$$p_f = \Pr[R - S \leq 0]$$

Cost of failure (CoF)

Sustainable infrastructure

COST-BENEFIT ANALYSIS FOR LOAD TESTS

- What is the benefit of a load test?
  - ✓ How to quantify it?
- What is the TOTAL cost of a load test?
  - ✓ Is it really just what I paid out of pocket?
- Decisions on load tests:
  - ✓ What load level?
  - ✓ When should one use a load test?

BENEFIT OF A LOAD TEST

After a load test …

$$g = R - S < 0$$

Structural failure

Structural capacity (resistance)

Structural demand (load effects)

PDF

R' R

S

Load effect in a load test

Quantitative risk assessment

$$R = p_f \cdot C_f$$

Probability of failure (PoF)
$$p_f = \Pr[R - S \leq 0]$$

Cost of failure (CoF)

$$R'_L = p_{f|LT}(t) \cdot C_f$$

$$\text{VoI} = \left[p_f - p_{f|LT}(t) \right] \cdot C_f$$

Value of information

COST OF A LOAD TEST

- Apart from testing cost, there is failure risk during a load test

Structural resistance
(*Structural capacity*)

R

Load effect
(*Structural demand*)

S

G

PDF

Failure probability
during a load test

Probability
of failure

Load effect in a
load test

$$R_d = \underbrace{p_{fd}} \cdot \underbrace{C_{fd}}$$

Probability of
failure during a load test

Cost of failure
in a load test

$$C_{PLT} = C_{test} + p_{fd} \cdot C_{fd}$$
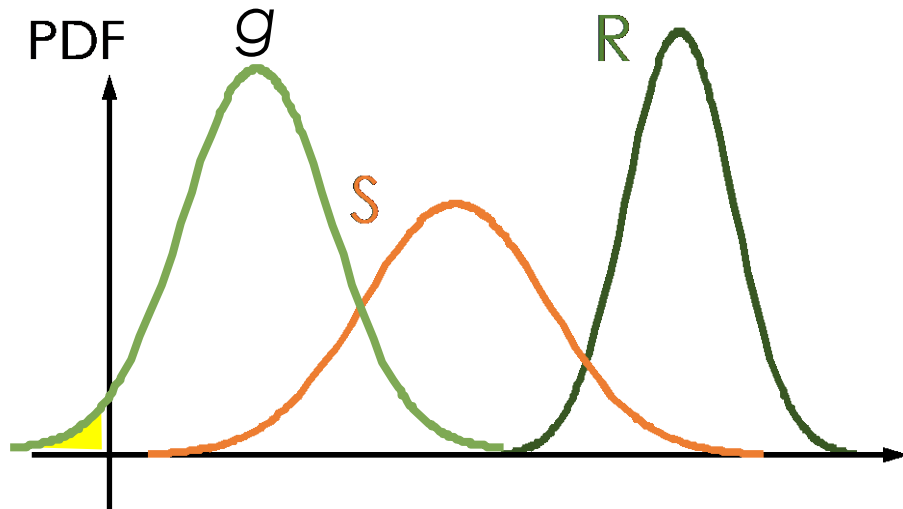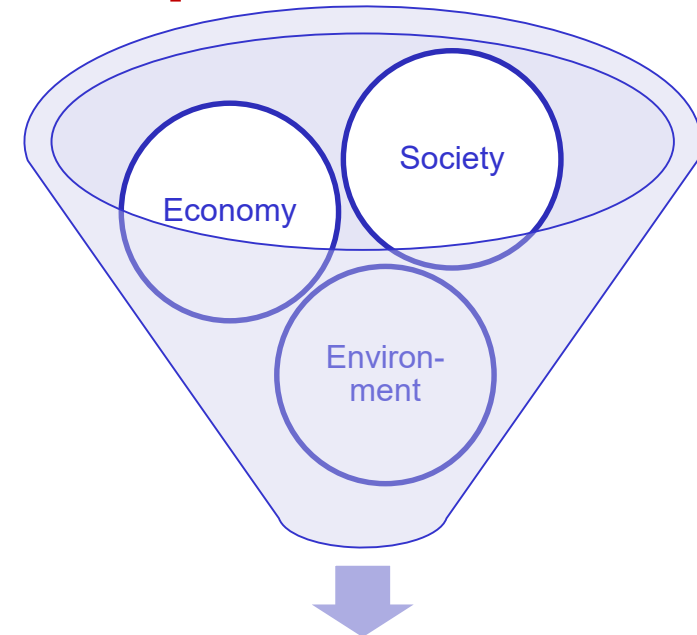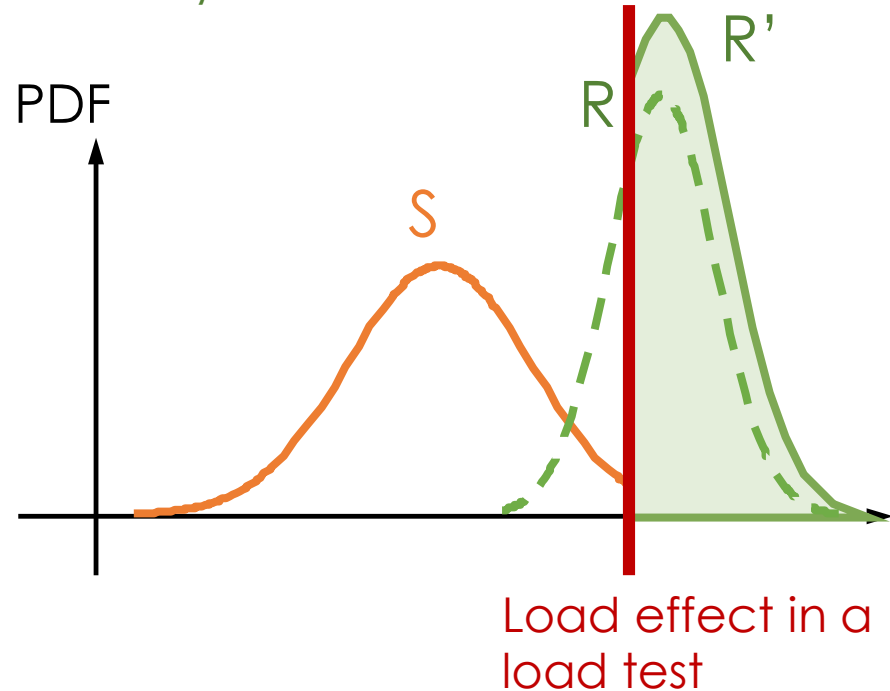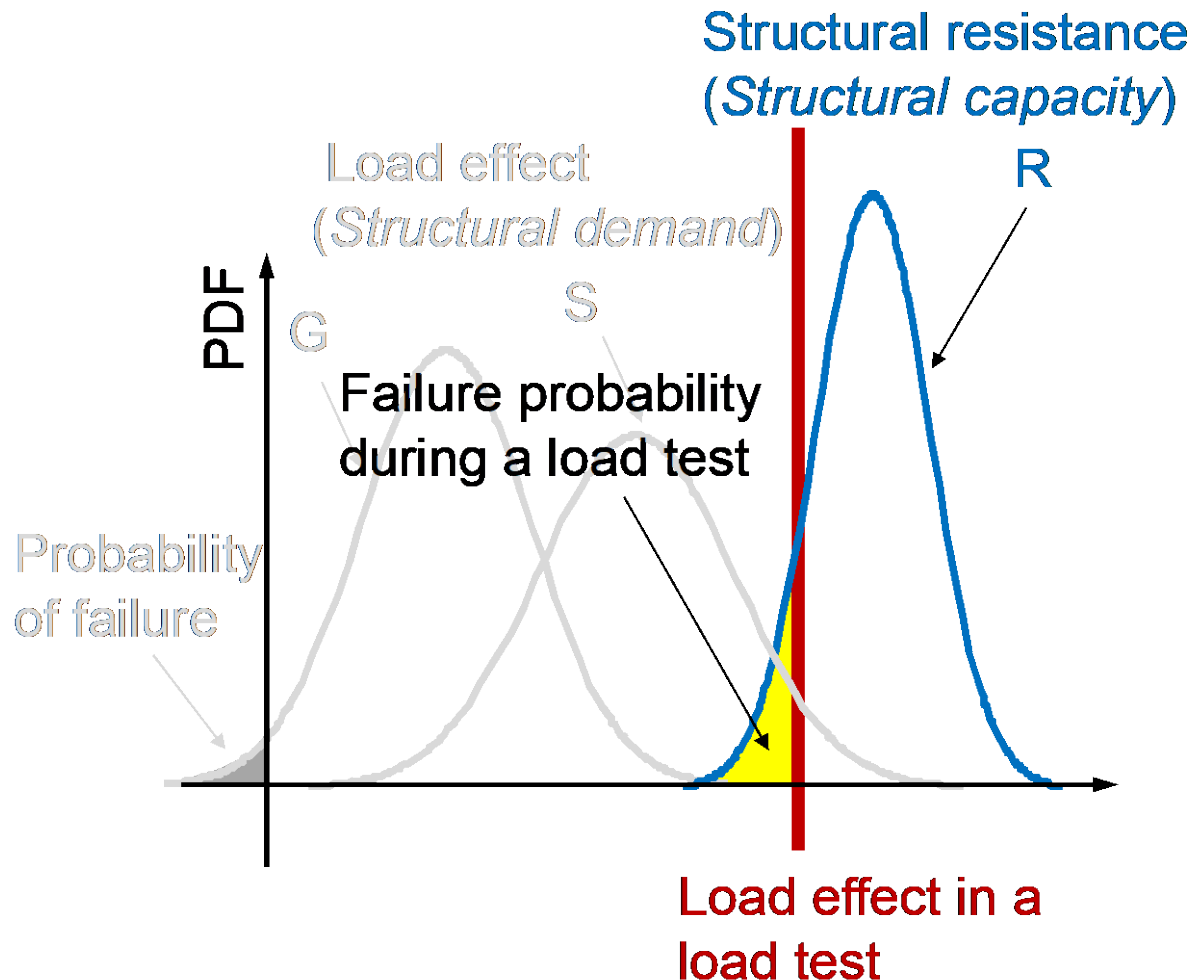
Cost-Benefit Analysis

C_{PLT}

VoI
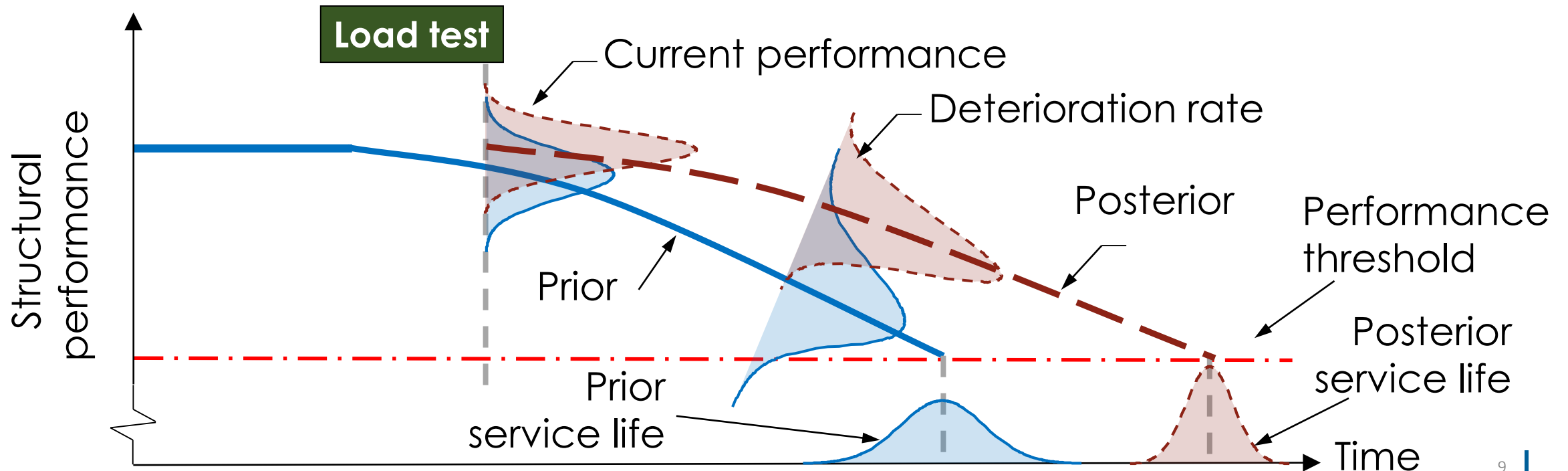
LOAD TESTING IN A LIFE-CYCLE CONTEXT

- Life-cycle performance considering information from load tests
  - Reduce uncertainty
  - Update deterioration processes
 - Guide maintenance decisions
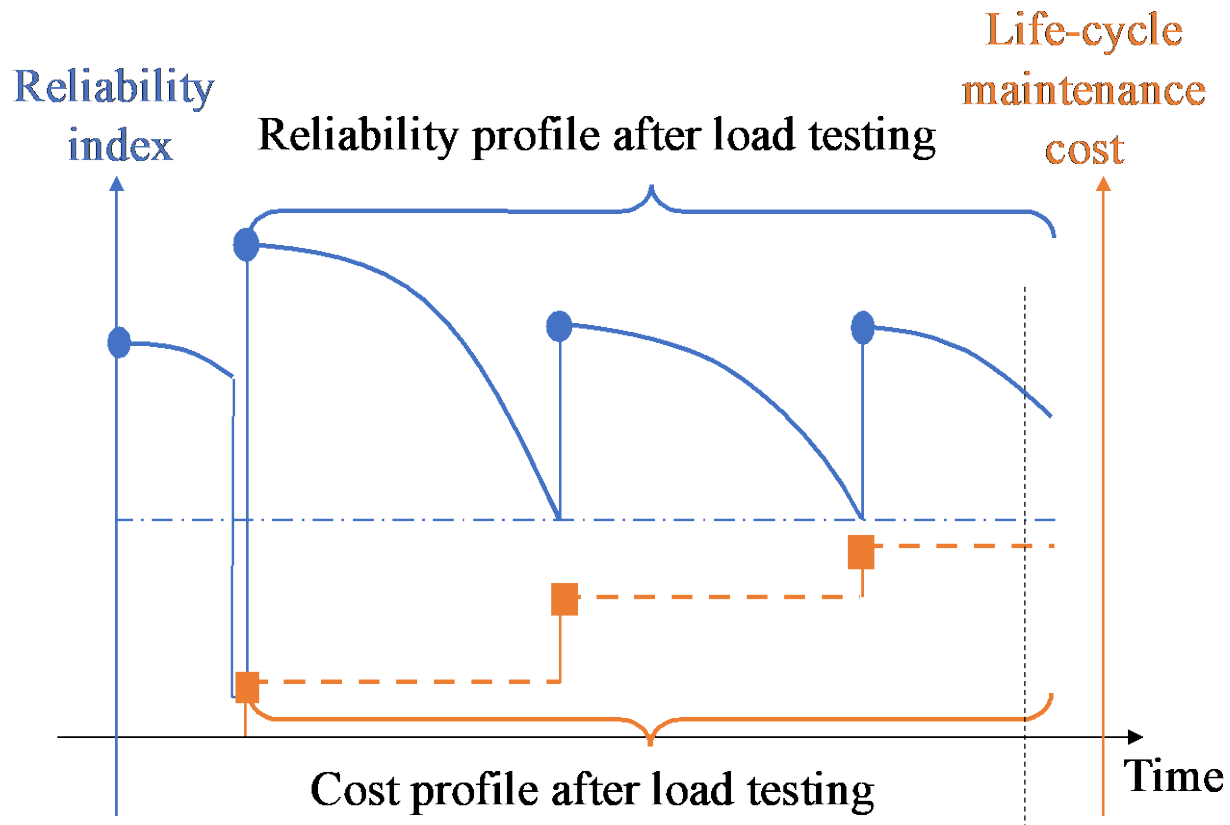
Provide Value of Information (VoI)
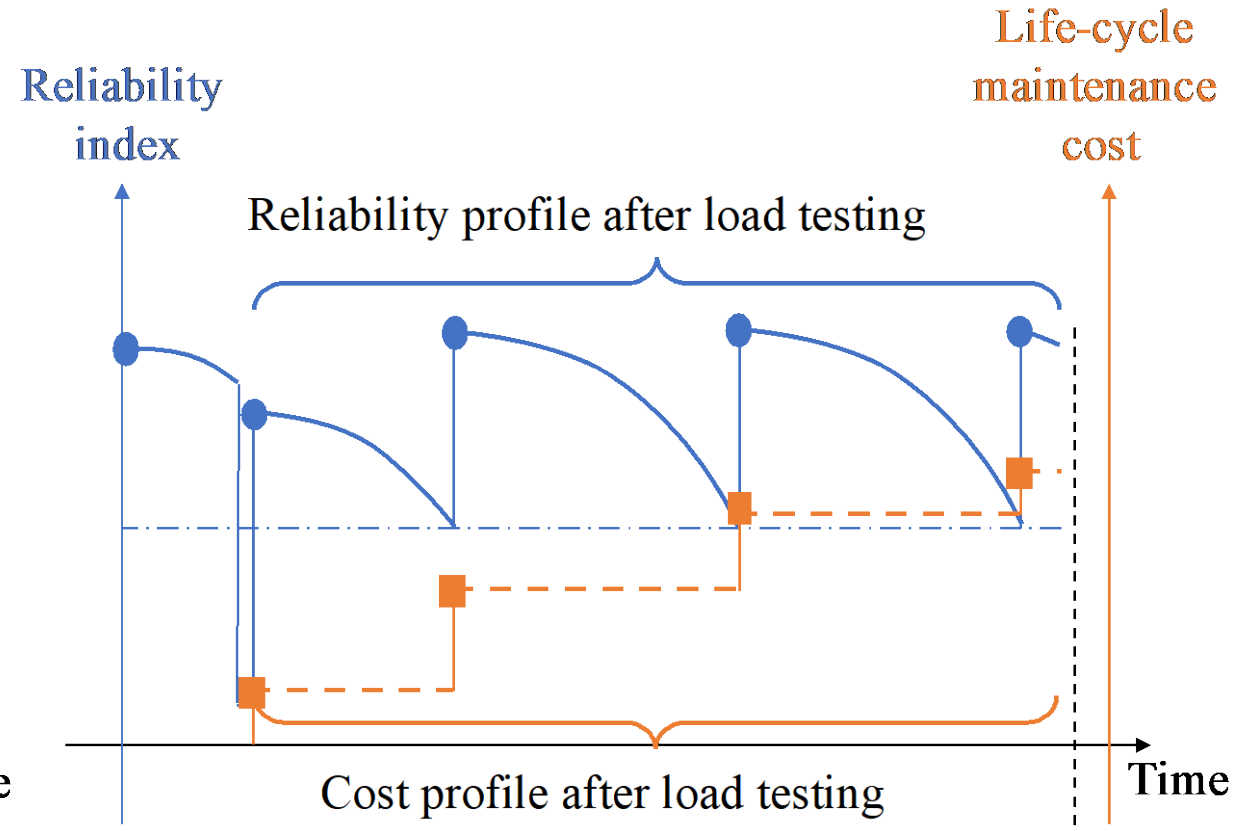
LOAD TESTING IN A LIFE-CYCLE CONTEXT

- Life-cycle reliability and cost considering load tests
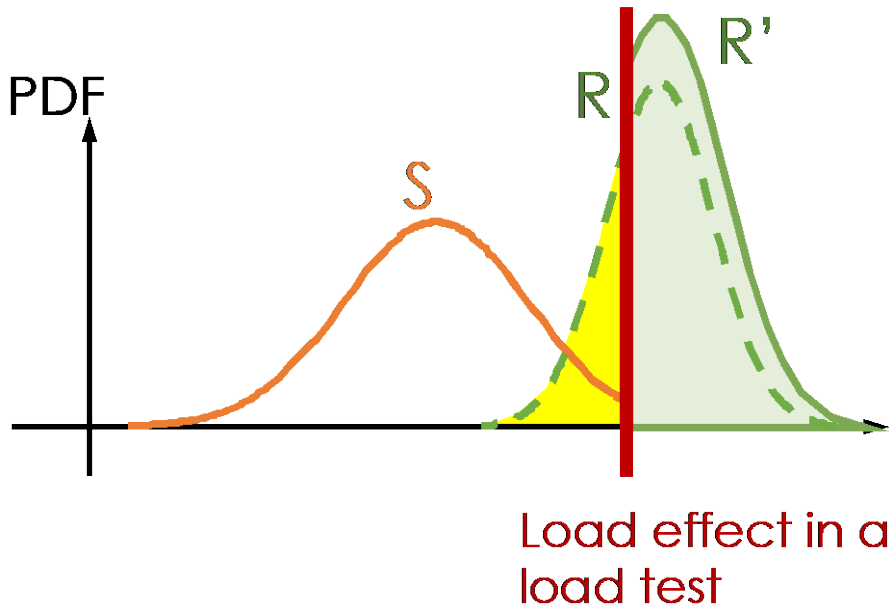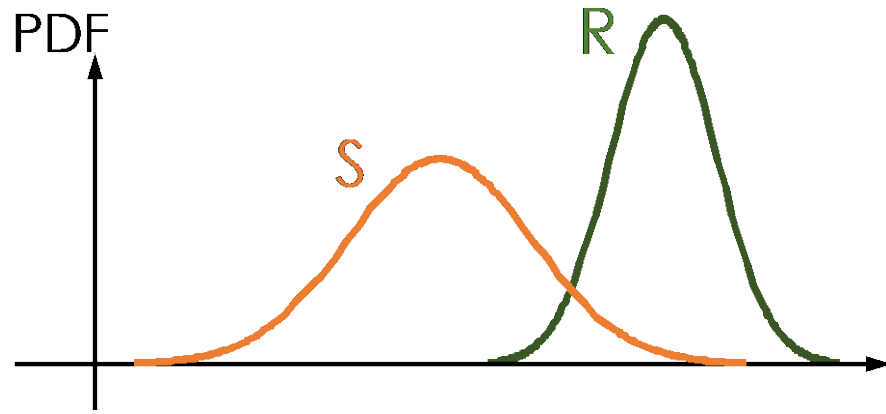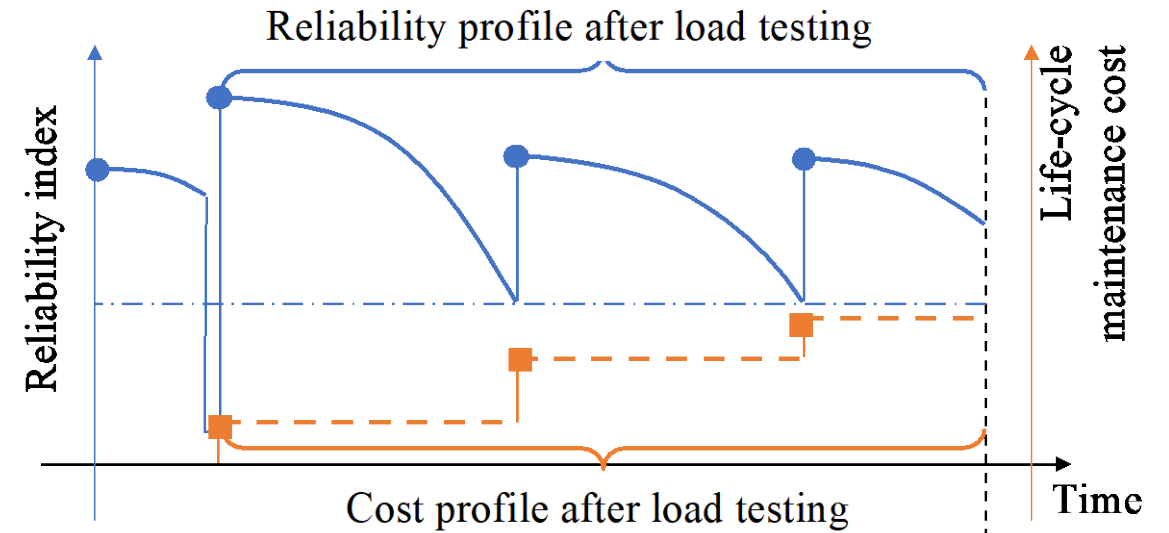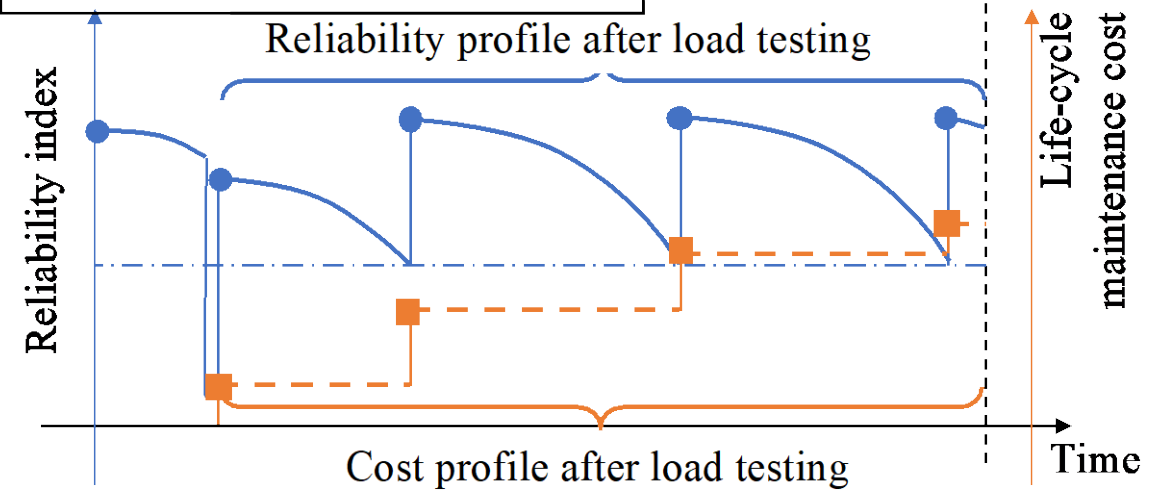
RECAP
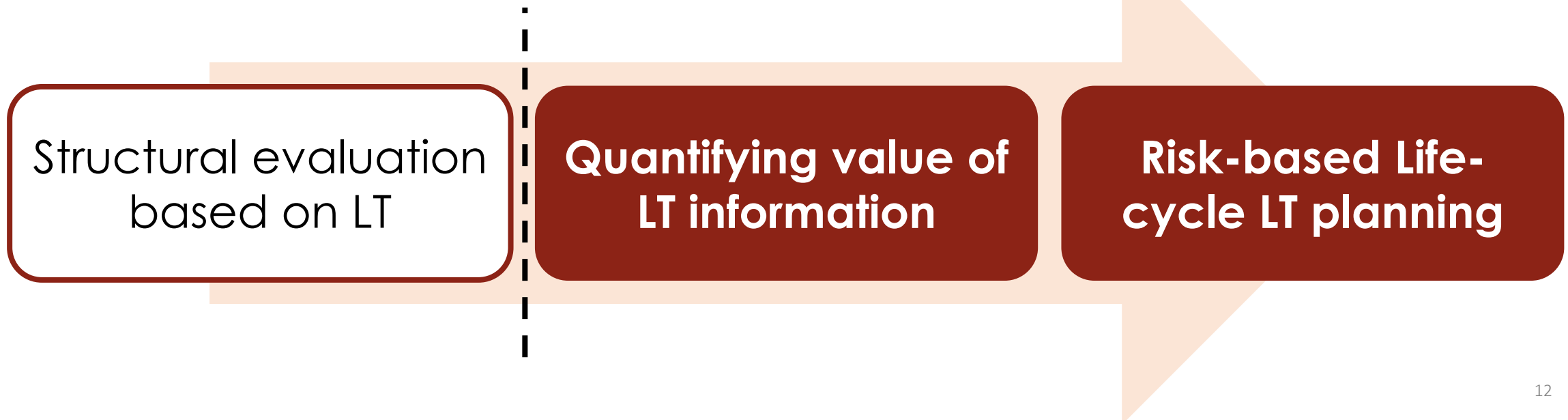
# LOOKING FORWARD ...

- Merging bridge load testing (LT) and risk-based life-cycle management (LCM) of bridges

- To extend structural service life and achieve sustainable built environments through optimal planning and execution of bridge load testing, inspection/monitoring, and maintenance actions

Structural evaluation based on LT

Quantifying value of LT information

Risk-based Life-cycle LT planning

REFERENCES

[1] Alampalli S, Frangopol DM, Grimson J, Kosnik D, Halling M, Lantsoght EOL, Weidner JS, Yang DY, Zhou YE. Primer on Bridge Load Testing. Transportation Research Circular. 2019

[2] Frangopol DM., Yang DY., Lantsoght EOL, Steenbergen R. Reliability-based analysis and life-cycle management of load tests. Chapter 21 In Lantsoght, EOL ed(s). Load Testing of Bridges (Structures and Infrastructures), CRC Press; 2019.

[3] Ayyub BM, McCuen RH. Probability, Statistics, and Reliability for Engineers and Scientists. 3rd ed. CRC Press; 2011.

[4] Ghosn M., Moses F. Redundancy in Highway Bridge Superstructures. NCHRP Report 406. National Academy Press; 1998.

[5] Moses F. Calibration of Load Factors for LRFR Bridge Evaluation. NCHRP Report 454. National Academy Press; 2001.

[6] Nowak AS, Collins KR. Reliability of Structures. McGraw-Hill; 2000.

[7] Wang N, Ellingwood BR, Zureick A-H. Bridge rating using system reliability assessment. II: Improvements to bridge rating practices. Journal of Bridge Engineering, ASCE 2011;16:863–71.

[8] Yang DY, Frangopol DM. Evidence-based framework for real-time life-cycle management of fatigue-critical details of structures. Structure and Infrastructure Engineering 2018;14:509–22.

[9] Yang DY, Frangopol DM. Probabilistic optimization framework for inspection/repair planning of fatigue-critical details using dynamic Bayesian networks. Computers & Structures 2018;198:40–50.

Thank You

Next: Q & A

TRB WEBINAR: Load Testing for Evaluating Bridges

Today's Participants

- Eva Lantsoght, *Universidad San Francisco de Quito*, elantsoght@usfq.edu.ec

- Jesse Grimson, *BDI*, jesseg@bditest.com

- David Yang, *Lehigh University*, yiy414@lehigh.edu

- Ed Zhou, *AECOM*, ed.zhou@aecom.com

- Sreenivas Alampalli, *New York State Department of Transportation*, sreenivas.alampalli@dot.ny.gov

Panelists Presentations

http://onlinepubs.trb.org/onlinepubs/webinars/200211.pdf

After the webinar, you will receive a follow-up email containing a link to the recording

Get Involved with TRB

- Getting involved is free!
- Join a Standing Committee (http://bit.ly/2jYRrF6)
- Become a Friend of a Committee (http://bit.ly/TRBcommittees)
    - Networking opportunities
    - May provide a path to become a Standing Committee member
- ***Sponsoring Committee: AFF40***
- For more information: www.mytrb.org
    - Create your account
    - Update your profile

TRB turns 100 on November 11, 2020

100 YEARS 2020 TRB

Help TRB:

· Promote the value of transportation research;

· Recognize, honor, and celebrate the TRB community; and

· Highlight 100 years of accomplishments.

Learn more at

www.TRB.org/Centennial

MOVING IDEAS: ADVANCING SOCIETY—100 YEARS OF TRANSPORTATION RESEARCH

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRB
TRANSPORTATION RESEARCH BOARD