Liberty Bridge Fire Event: Response Evaluation for Jacking Operations and Ratings

ABCD Susquehanna Chapter

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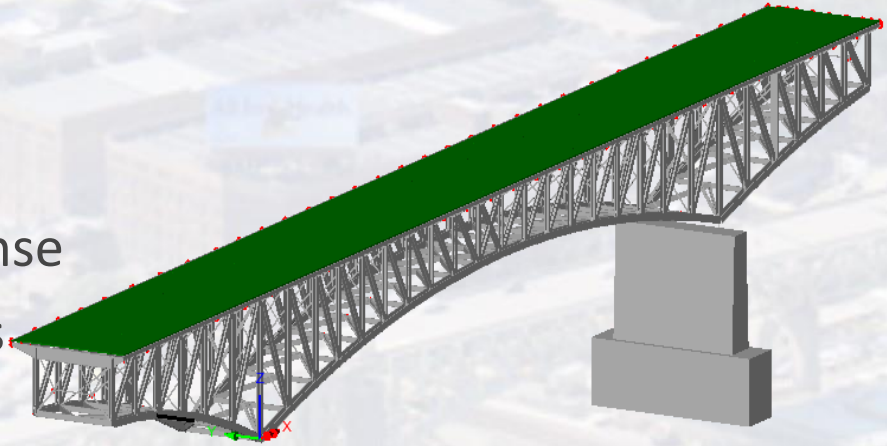
MODJESKI and MASTERS
Experience great bridges.

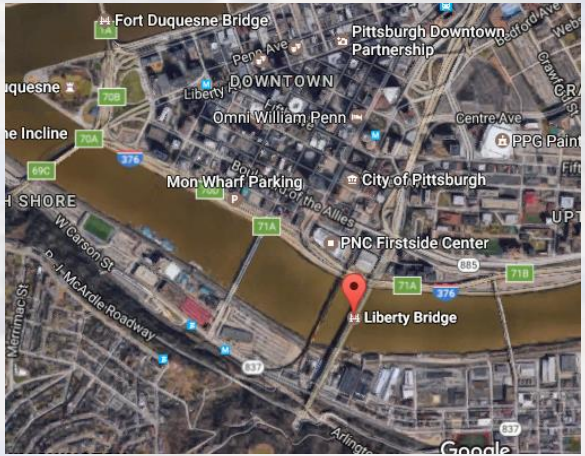
Presentation Outline



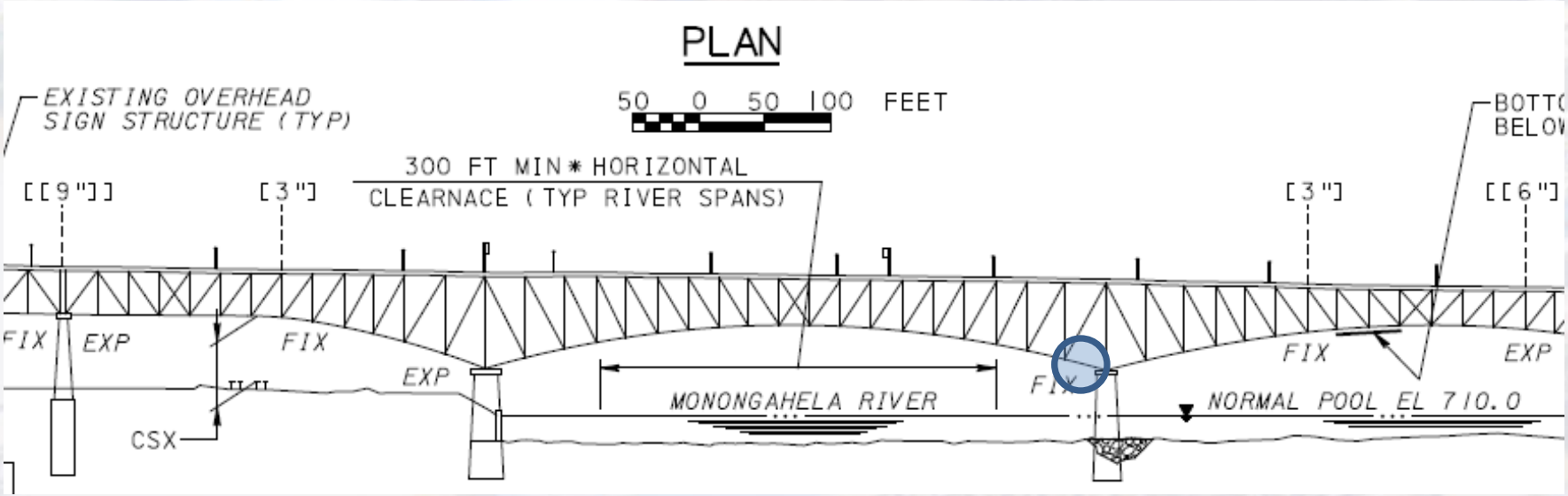
- The Structure
- The Fire and Immediate Response
- Repair Development and Issues
- MM's role
  - 3D Structure Model
  - Rating Scenarios
  - Evaluating Bridge Response during Jacking
  - Evaluation of Final Condition

The Liberty Bridge

- Completed 1928
- Key route into downtown Pittsburgh
- 8-Span steel truss
- 470’-6” main span



The Liberty Bridge



Pier 6

Pier 7

The Liberty Bridge

Rehab Work

- Engineer - HDR
  - Deck Replacement, bridge painting, and miscellaneous structural steel repairs
- Contract Value: ~$80 million
- Prime Contractor: JB Fay
- Contractor's Engineer: SAI
- Let Date: 6/25/15, NTP: 8/19/15
- Completion: 7/27/18

Deck Replacement Operations

Deck Replacement Operations

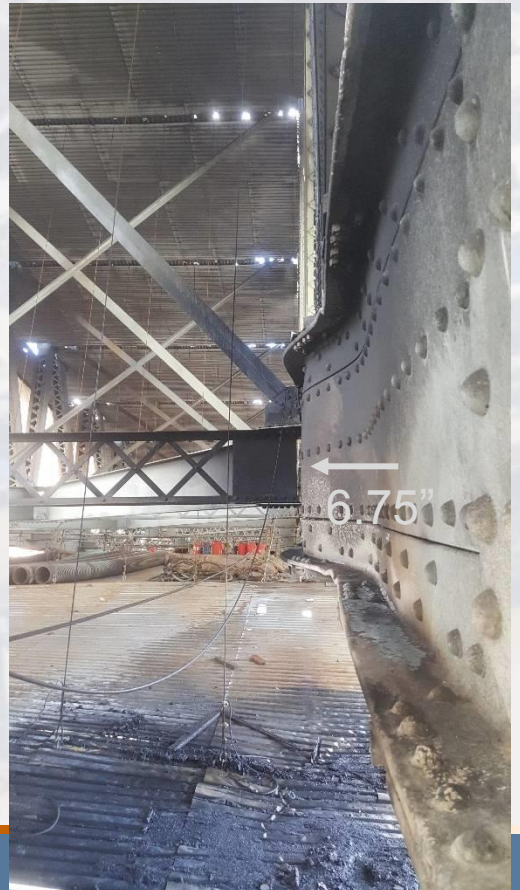
The Fire

- Started Sept. 2, 2016, 1:00pm

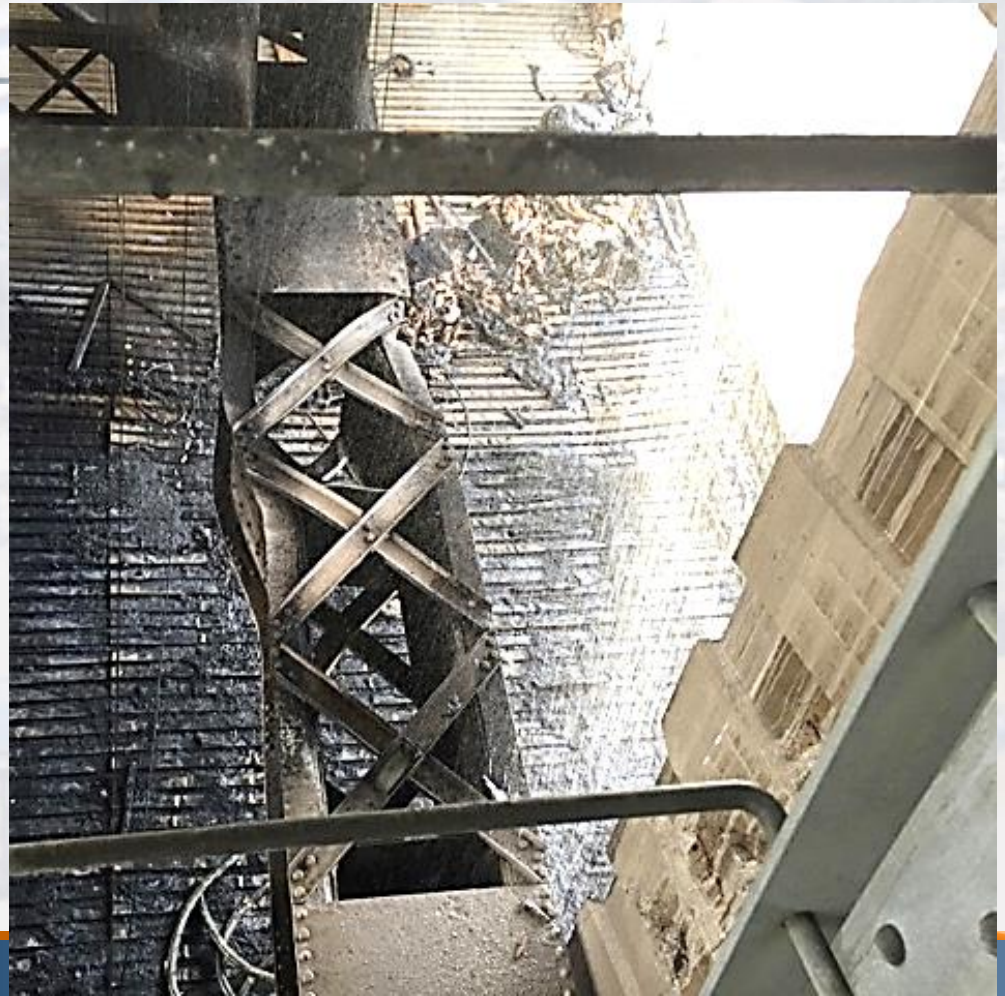
The Fire

- Extinguished ~30 min. after arrival of City of Pittsburgh Fire Dep.

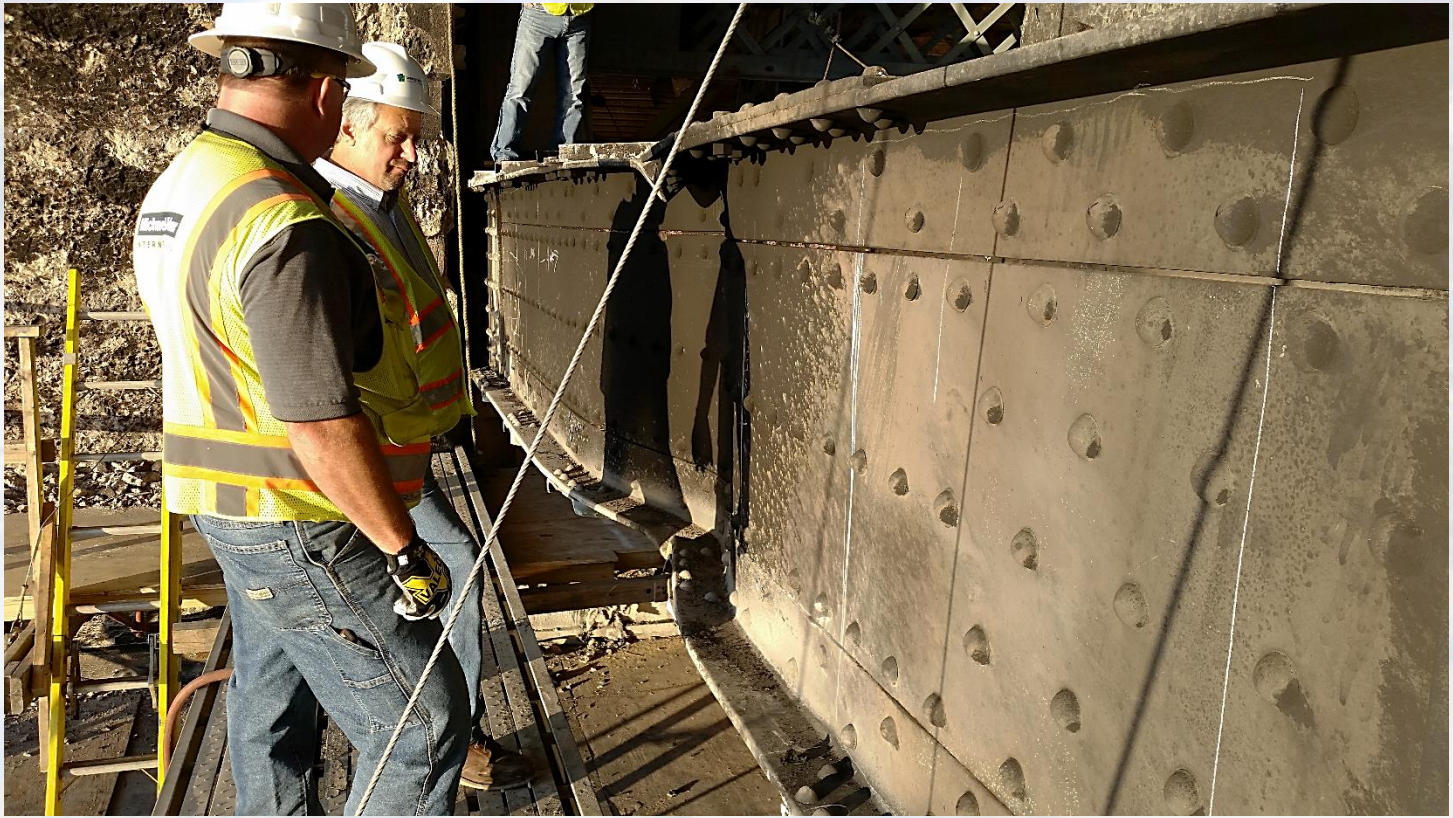
The Fire Damage



The Fire Damage



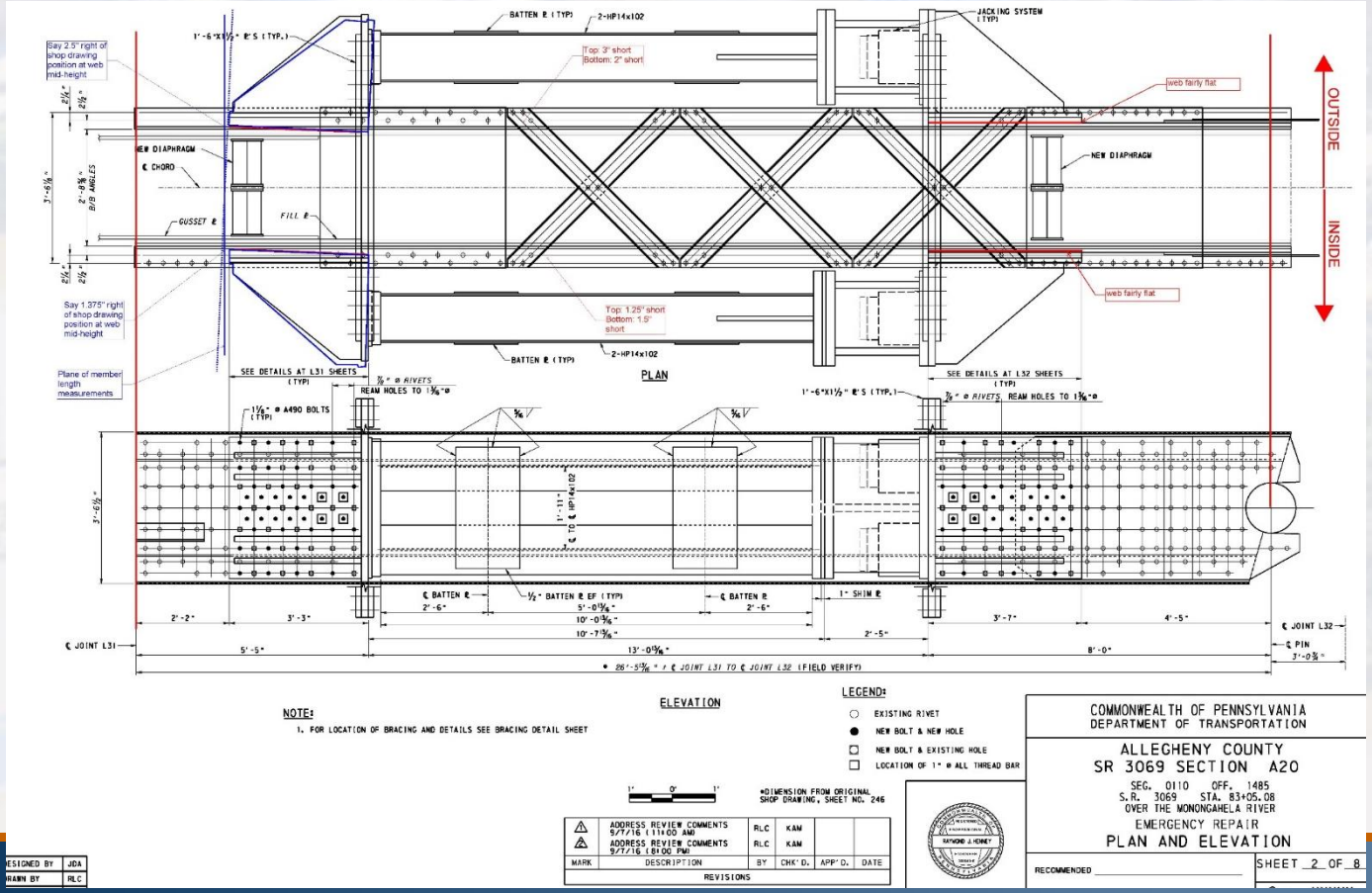
The Fire Damage



Immediate Response

- Night of Sept. 2, 2016
  - Bridge remained closed
  - HDR performed safety assessment of bridge
  - Monitoring of bridge movements (survey)
  - Starting of designs to repair structure (SAI/HDR)

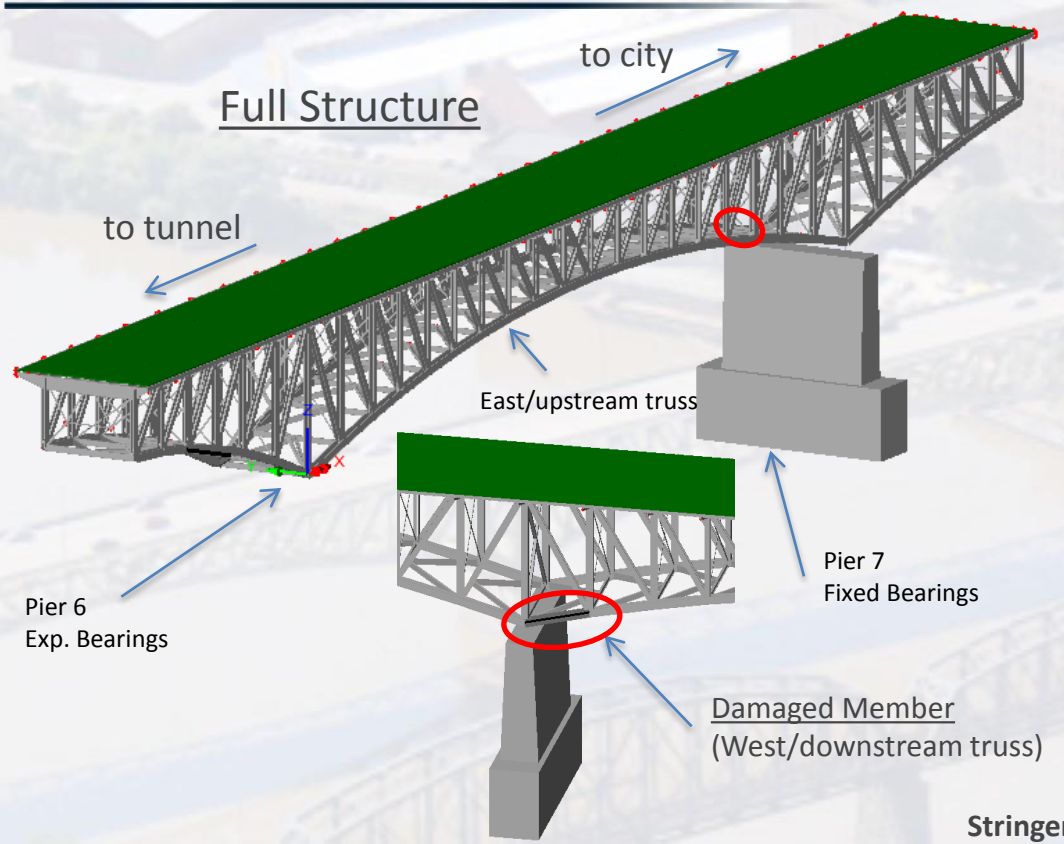
Preliminary Jacking Frame Details



MM's Role

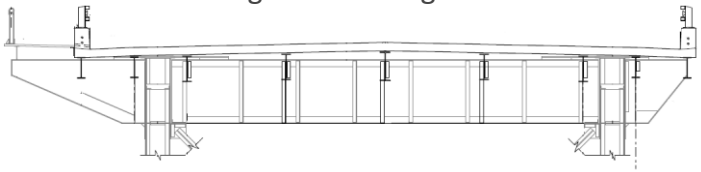
- Tasks focused on examining how the rest of the truss was affected by the fire damage to L31L32W
  - Determine ratings factors for post-fire condition
  - Evaluate effectiveness of jacking operations to restore truss to pre-fire condition
    - If truss geometry not fully restored, is the bridge ok? If not, how many repairs required?
  - Provide updated ratings after jacking
    - Post-process field data to update calculations.
    - Determine if safe to reopen the bridge immediately after jacking.

3D Structure Model



Deck System

Drawing – New Stringers and Deck



Model Stick View

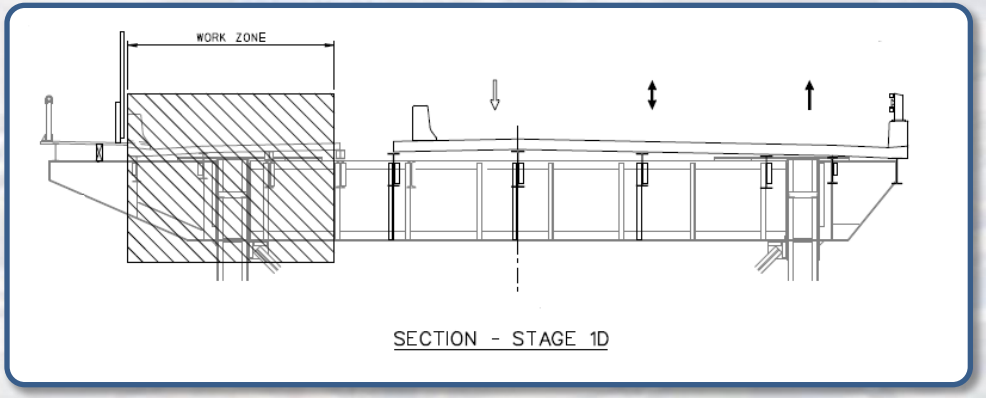
Model Fleshed view

West/downstream truss East/upstream truss

Shell Elements – Deck
Stringers, Floorbeams, Truss Members and Pier – Beam Elements

3D Structure Model

- Modeling of dead load
  - PP7-PP31 – Stage 1D
  - PP31-PP38 – New deck system
  - Results verified by comparison w/HDR model

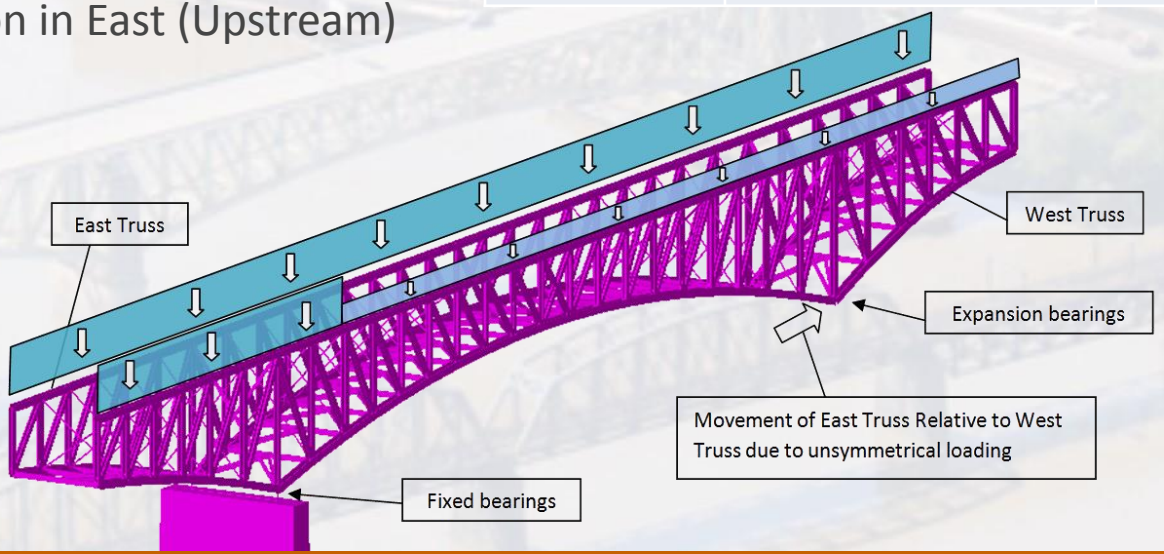


- Modeling effect of fire damage on rest of truss
  - Apply temperature load to L31L32W to achieve desired displacement of L31W
- Variations to consider
  - Deck behavior – composite vs. non-composite action w/ truss
  - Pinned joints vs. fixed joints
  - Boundary conditions at expansion bearings and ends of cantilever span

3D Structure Model

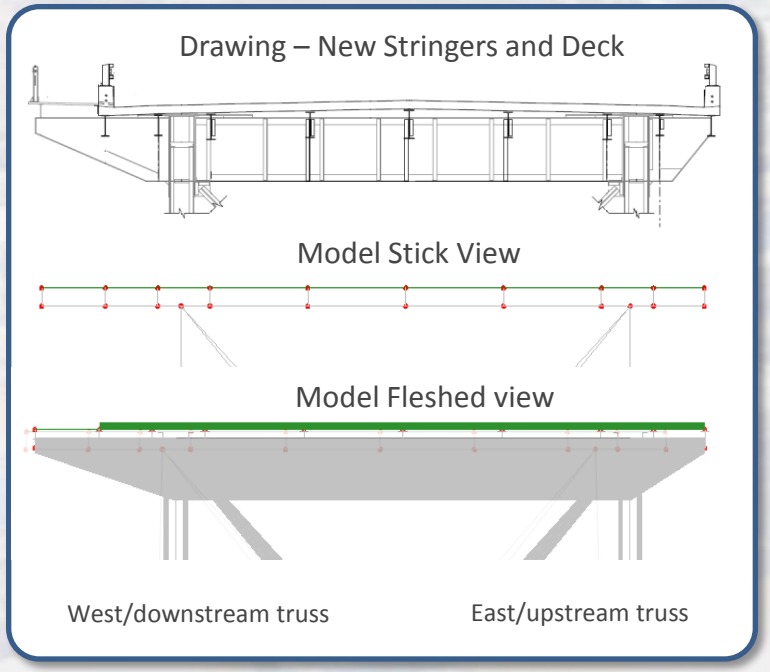
- 3D dead load effects
  - Unequal loading of truss lines causes loads in bottom lateral system and increased compression in East (Upstream) Truss

Member	2D Analysis DL (separate truss lines)	3D Analysis DL
L31L32 East	2353 k	2609 k
L31L32 West	2483 k	2003 k



3D Structure Model – Deck Action

- Deck action significantly changes the behavior of the structure
  - Stiffness Comparison - Movement of L31N along L31L32N
    - w/deck stiffness, ~1100 k/in.
    - w/o deck stiffness, ~460 k/in.
  - Displaced Shape
    - w/ deck stiffness, much smaller lateral movements, more of a localized response
  - Lateral Bracing and Sway Bracing Forces
    - Structure much stiffer w/ deck active, larger forces developed
- So how did the actual structure behave?



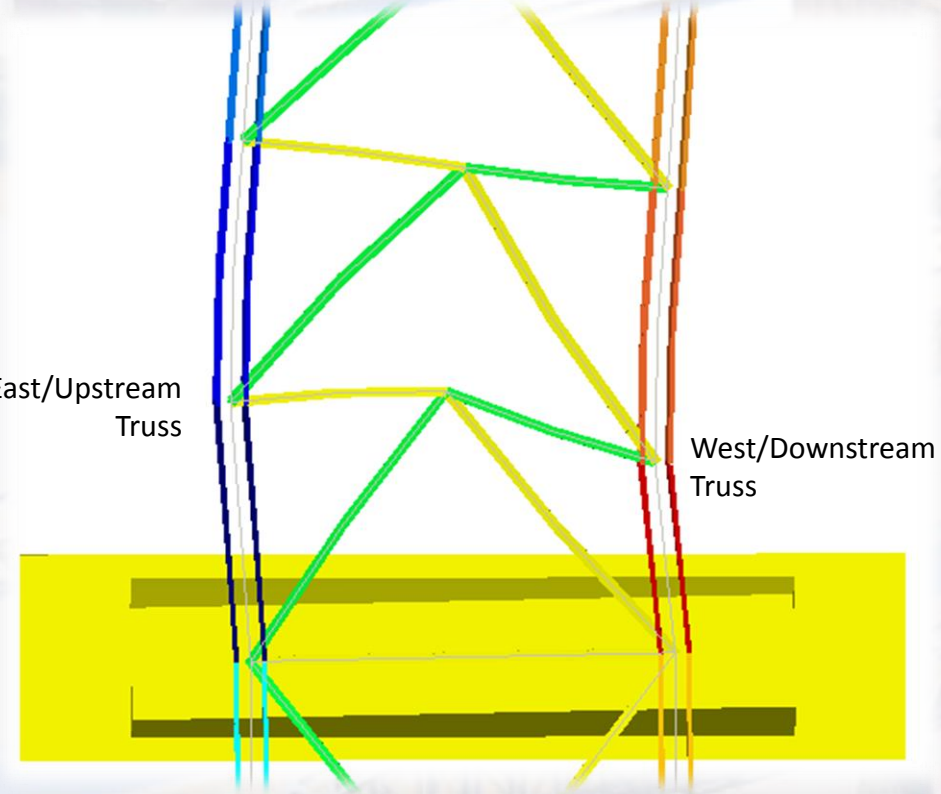
3D Structure Model – Deck Action

- Comparison of sway bracing expected deformations

Location	Composite Deck	Non-Composite Deck	Field Observations of Buckling (Visual)
	P/P_{cr}	P/P_{cr}	
PP26	2.47	0.25	
PP27	3.19	0.31	(moderate)
PP28	4.16	0.44	(moderate)
PP29	4.58	0.61	(severe)
PP30	1.62	0.96	
PP31	3.52	0.39	(severe)
PP32	0.36	0.01	
PP33	0.35	0.05	
PP34	1.12	0.00	(minor)
PP35	1.12	0.00	
PP36	0.74	0.00	(minor)
PP37	0.85	0.00	(minor)

Buckled Sway Bracing near Pier 7

3D Structure Model – Deformations

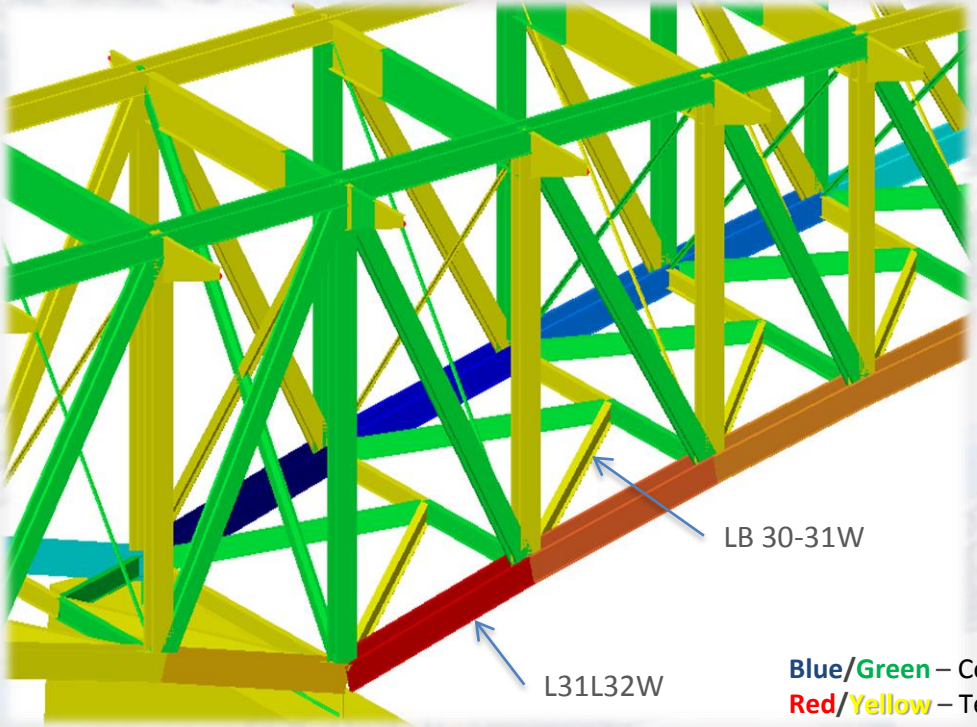


- Exaggerated deformed shape of bottom chords and lower lateral system due to shortening of L31L32W

Blue/**Green** – Compression added
Red/**Yellow** – Tension added

3D Structure Model – Load Shedding

- Change in axial load due to shortening of L31L32W



Member Dead Loads

Member	P (pre-fire)	P (post-fire*)	DL FS (C/DL)
L31L32E	-2609 k	-4565 k	1.22
L31L32W	-2003 k	~0 k	Buckled
LB 30-31E	-9 k	-435 k	-
LB 30-31W	9 k	435k	-
L29L30E	-1468 k	-2730 k	1.07

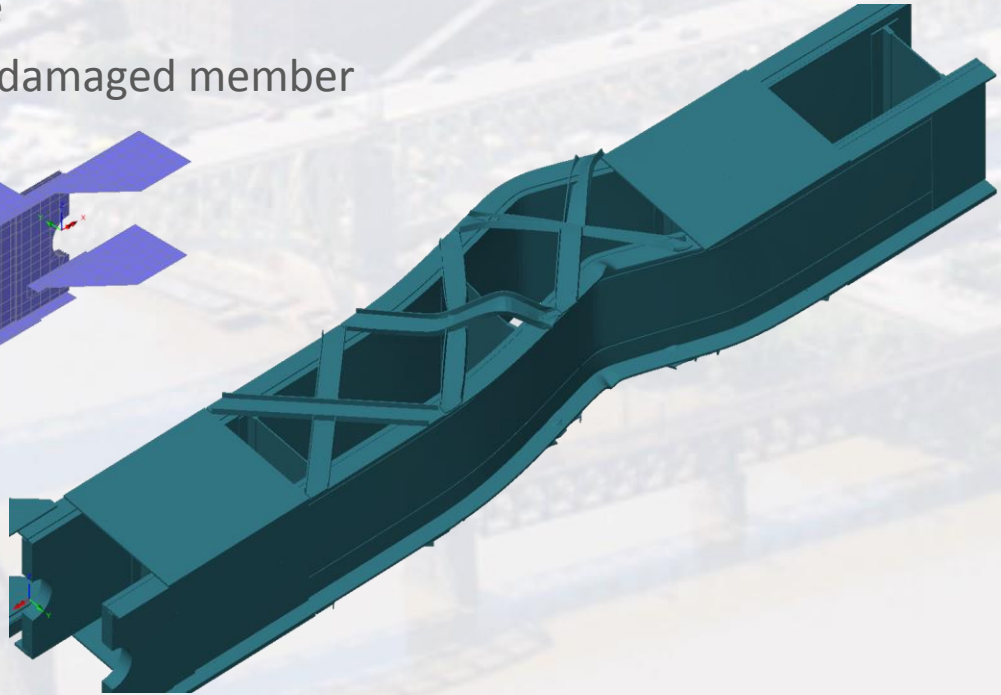
*Post-fire = 1.88” movement of L31W towards L32W

Blue/Green – Compression added
Red/Yellow – Tension added

Estimated Load shift of ~2000 k from West (downstream) truss to East (upstream) truss

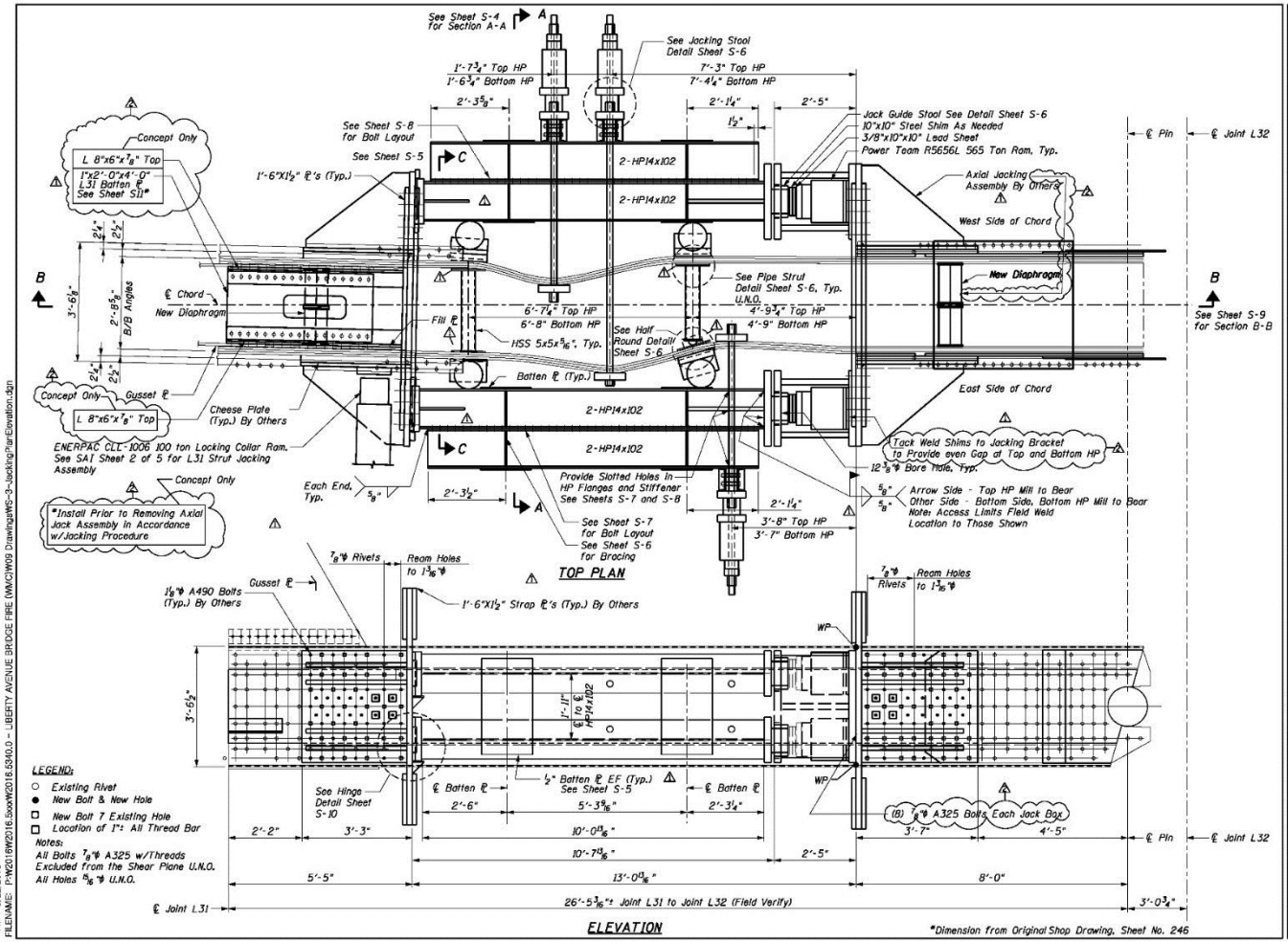
3D Structure Model – Deformations

- Refined Local Analysis of Damaged Member
  - Bound possible behavior during fire
  - Try to estimate forces remaining in damaged member



Can the truss be fully restored to the pre-fire condition?

- Plastic axial strains became a point of discussion
  - Plastic hinges forming under compression result in net axial compressive strains
  - In order to recover all the axial displacement, need to straighten member under significant tension loads
- Would jacking procedure accomplish complete axial recovery?
  - Conclusion (from Lehigh and MM work) – full recovery unlikely
- What effect would an incomplete recovery have on the ability of the structure to carry live loads?
  - Need to determine this and develop approach to rapidly update results based on actual response of bridge



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Seal

WILLIAM J. NUGENT PROFESSIONAL ENGINEER No. PE81402

9/22/16

Consultants

Project

Liberty Bridge
L31-L32 West Truss
Retrofit

Owner

PennDOT District 11-0

Mark	Date	Description
1	9/22/16	Review Comments
2	9/20/16	Review Comments

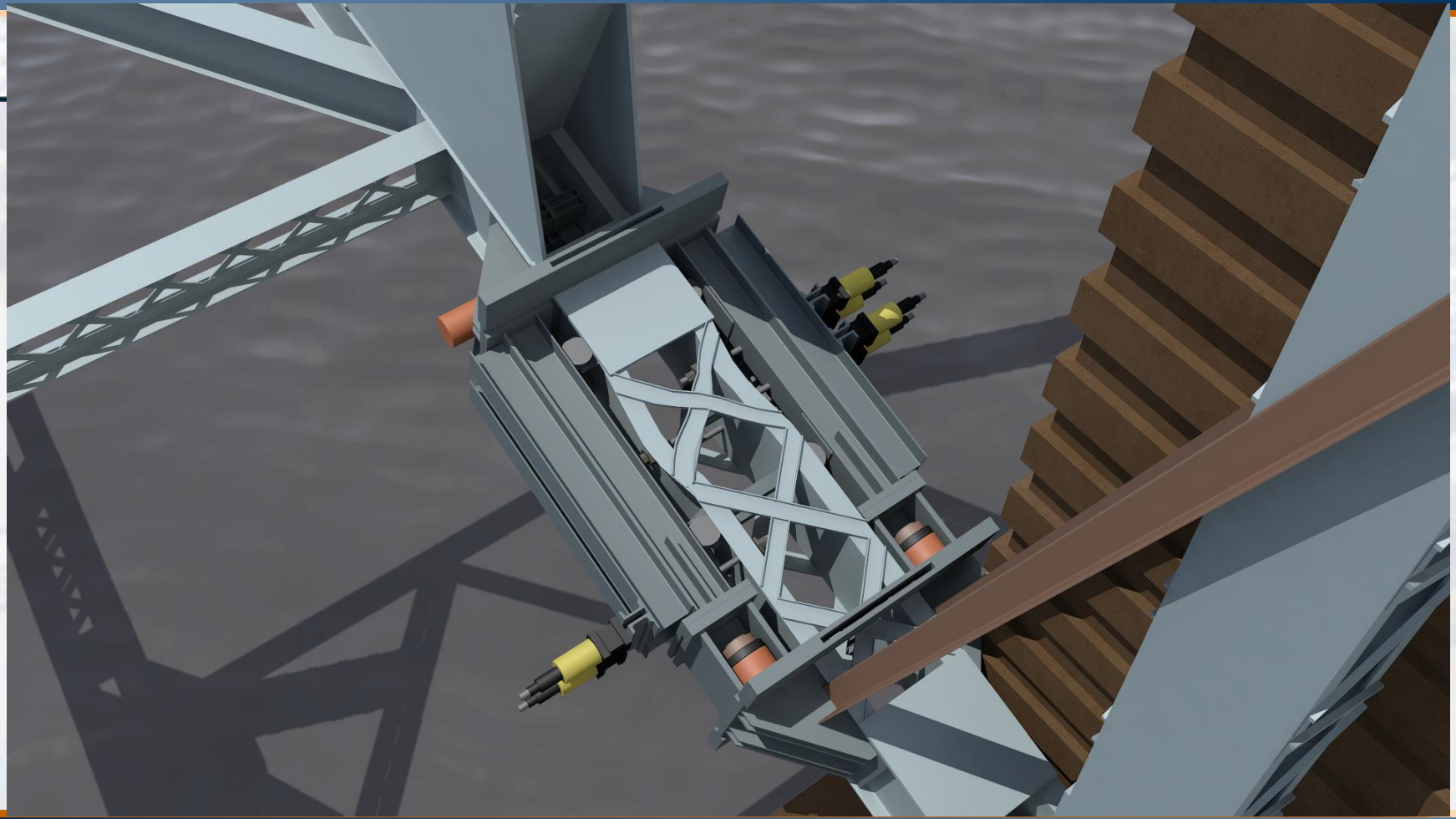
Project No.	2016.5340
Date	9/22/2016
Drawn	IMG
Checked	MWJ
Scale	NTS

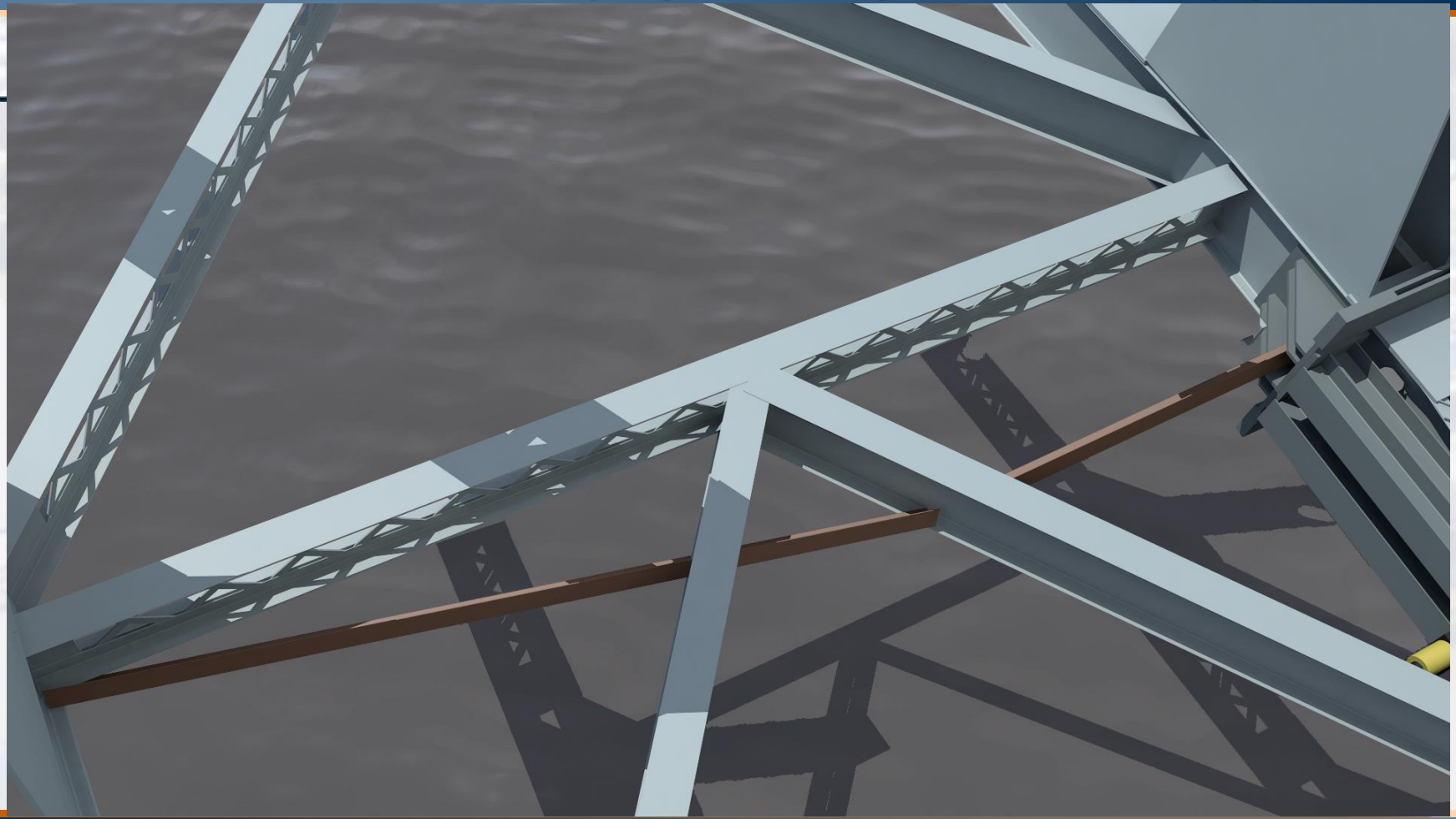
JACKING DETAILS

Sheet Title

Sheet No. S-3

DATE: 9/22/2016
FILENAME: P:\2016\16W2016.5xx\W2016.5340.0 - LIBERTY AVENUE BRIDGE FIRE (WMC\W09 Drawings\WS-3-Jacking\Tar\Elevation.dgn





Initial Ratings (Pre-jacking)

- IR and OR factors:

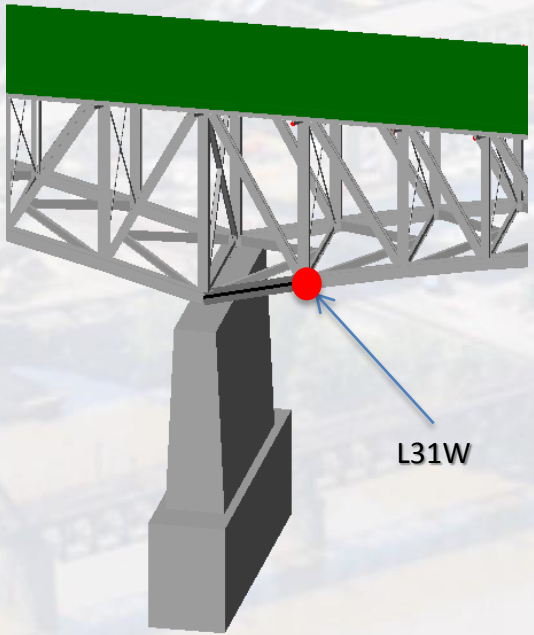
$$RF = \frac{C - 1.3(DL + \mathbf{3D} + \Delta P)}{(1.3 \; or \; 2.17)(LL + IM)}$$

- Fire shift forces (**ΔP**) and construction (**3D**) effects treated as DL
- Loading Conditions:
  - Temporary Construction Stage 1D (asymmetric load → **3D** effects)
  - Final Condition
- Repair Sequence considered:
  - Strengthening plates assumed to resist only loads applied after installation

  ∴ Terms in rating equation normalized with respect to the corresponding effective areas

Initial Ratings (Pre-jacking)

- Restored displacements of 1” to 1.88”, in 0.125” increments:
  - A_s req’d → **30 Ton HS20 OR** in the **Construction** Staging Condition
  - A_s req’d → **1.50 HS20 ORF** in the **Final** Condition
  - Number of members requiring retrofit
- Goal→ get the bridge open to traffic

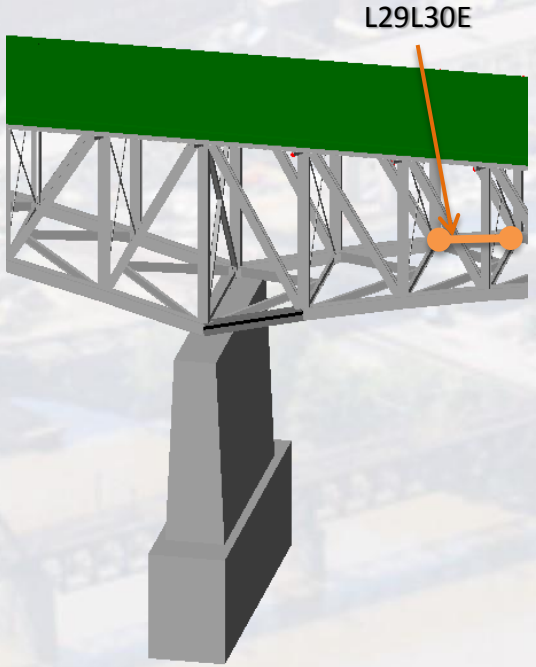


Initial Ratings (Pre-jacking)

- Stage 1D: HS20 OR > 30 Tons
  - Critical Member – L29L30E (upstream)

Joint L31W Restored Displ.	HS20					
	Inventory		Operating		2015 Contract Rehab Steel*	Add'l Steel Req'd for 30Tons
in.	RF	Tons	RF	Tons	in.^{2}	in.^{2}
1.00	0.13	4.8	0.22	8.1	58	258
1.125	0.19	6.9	0.32	11.5		129
1.250	0.25	8.9	0.41	14.9		60
1.375	0.31	11.0	0.51	18.3		16
1.500	0.36	13.0	0.60	21.8		0
1.625	0.42	15.1	0.70	25.2		0
1.750	0.48	17.1	0.79	28.6		0
1.88	0.54	19.3	0.89	32.2		0

*Original design repair area for a minimum HS20 ORF of 1.5 in the final condition

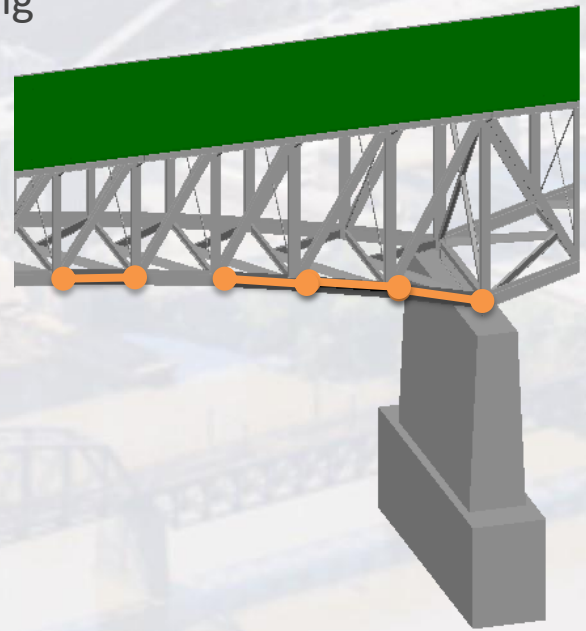


Initial Ratings (Pre-jacking)

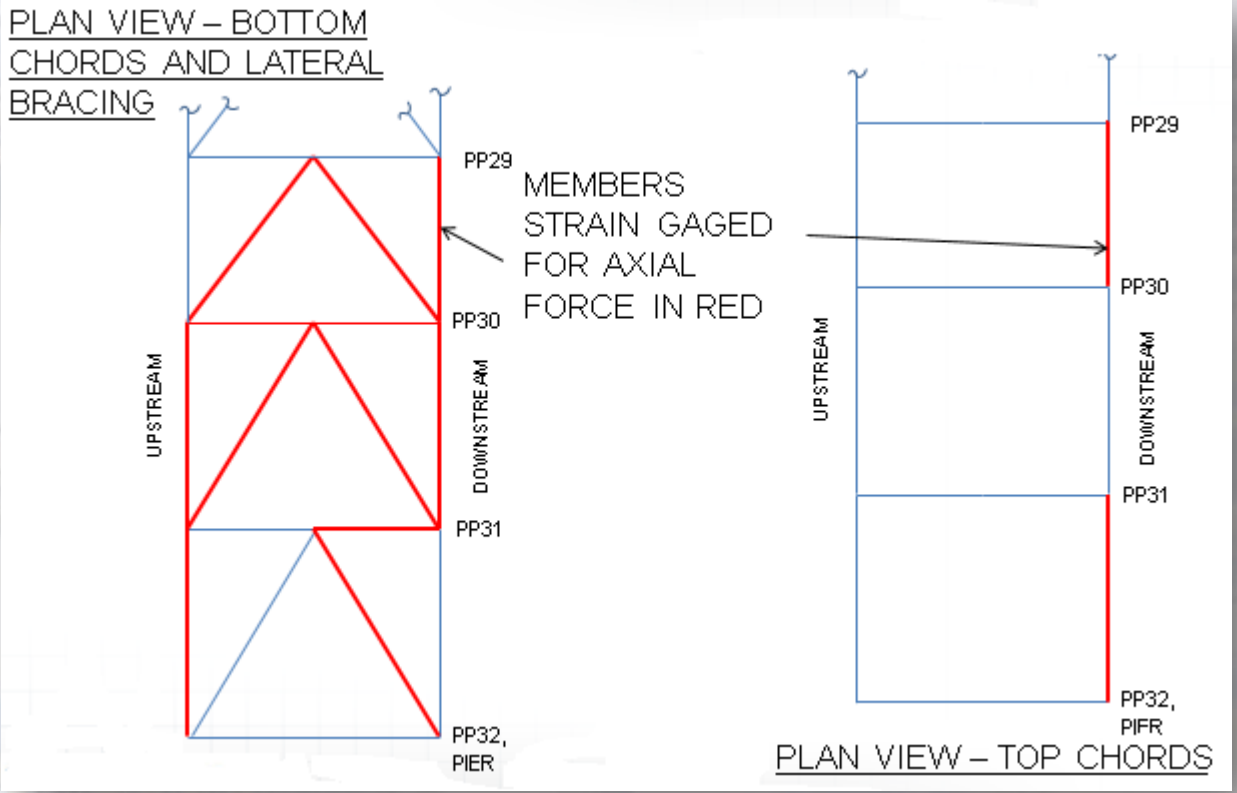
- Final Condition: HS20 ORF > 1.5
  - Four East LC members possibly require strengthening

Joint L31W Restored Displ.	Add'l Retrofit Steel Area			
	L27L28	L29L30*	L30L31	L31L32
in.	$in.^2$	$in.^2$	$in.^2$	$in.^2$
1.00	8	137	41	1
1.125	5	91	19	0
1.250	1	57	1	0
1.375	0	31	0	0
1.500	0	10	0	0
1.625	0	0	0	0
1.750	0	0	0	0
1.88	0	0	0	0

*3D effect relieved from strengthening plates if installed during Stage 1D

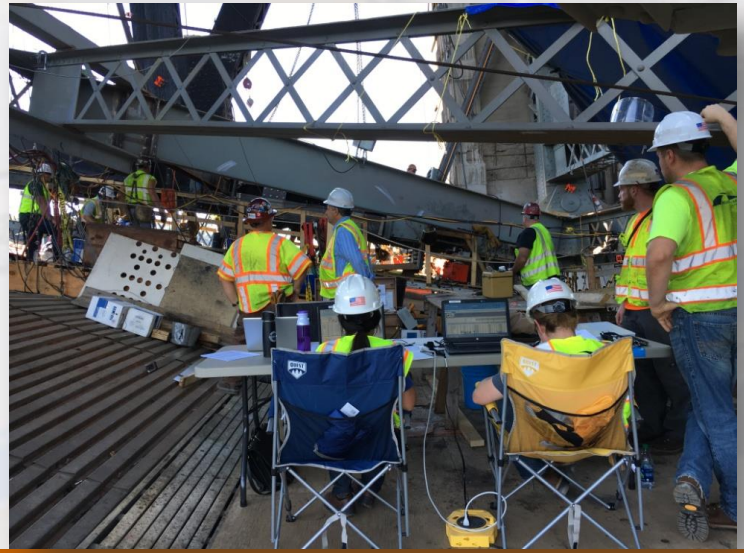


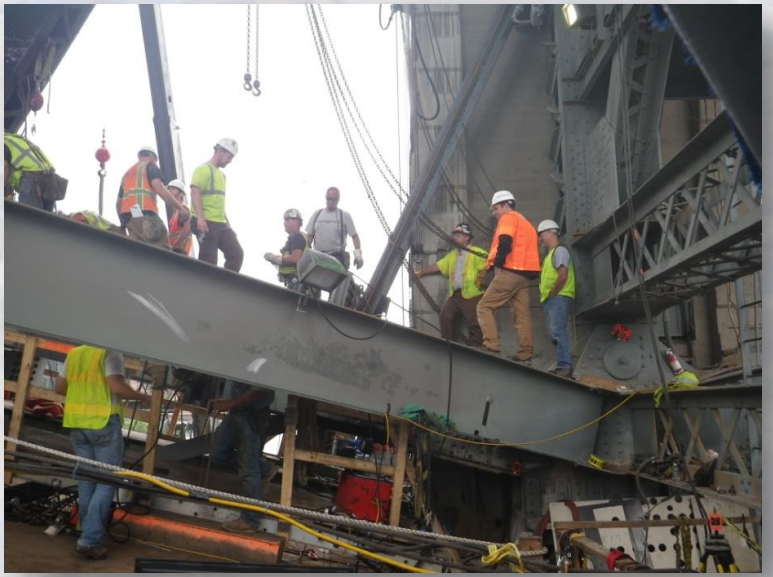
Instrumentation



Evaluating Bridge Response During Jacking

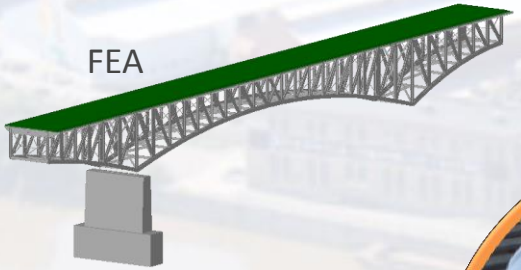
- Goals
  - Compare bridge behavior to analysis model, ensure unexpected behaviors not occurring
  - Give go/no-go for next jacking stage

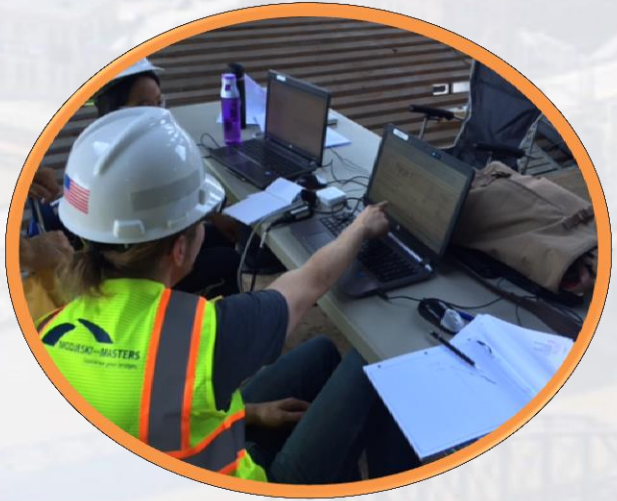




- Determine rating factors for critical bridge members as load is shifted back to pre-fire condition

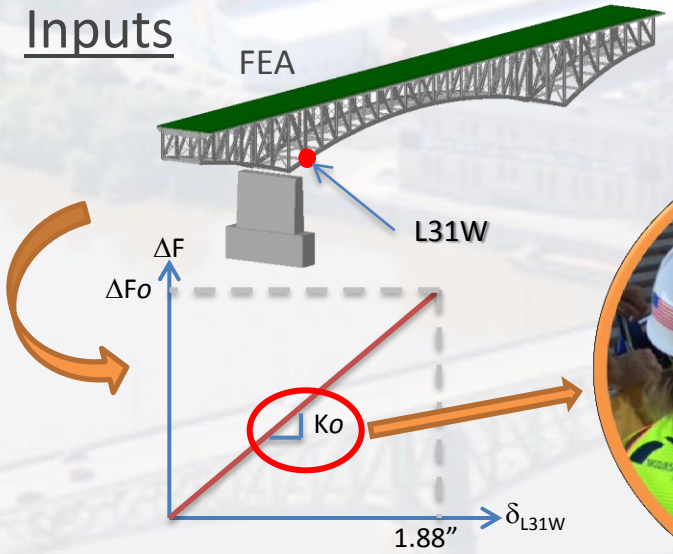
Evaluating Bridge Response During Jacking

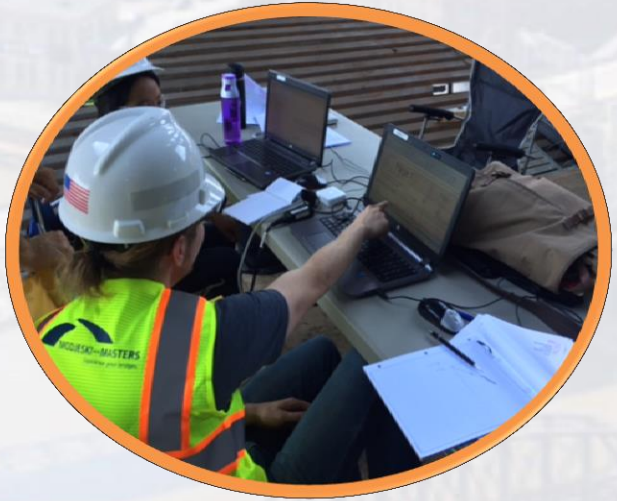




Evaluating Bridge Response During Jacking

- Inputs





Evaluating Bridge Response During Jacking

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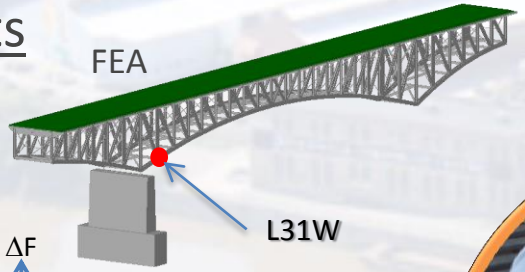
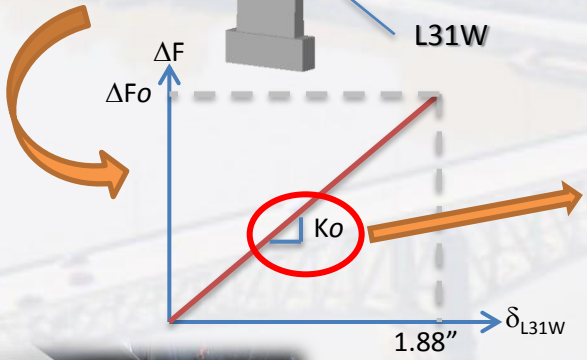


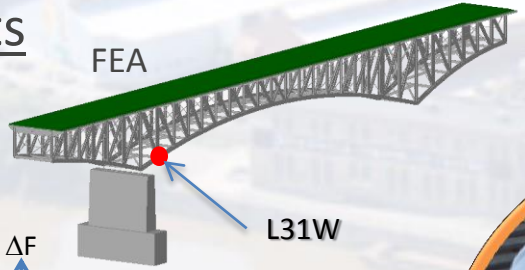


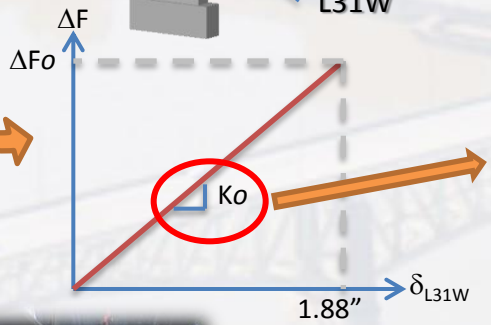
Field

- *Instrumented members:* $\varepsilon, T \rightarrow \Delta F$
- *Restoring displacement:* δ_{L31W}

Evaluating bridge response during jacking

Inputs





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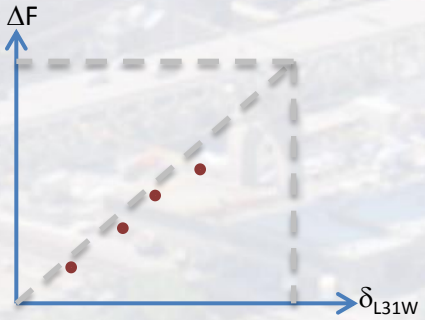
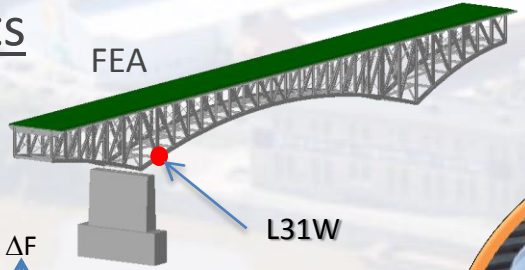
Outputs

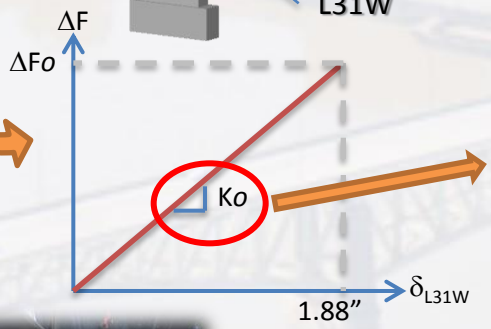


Evaluating bridge response during jacking

Inputs

FEA





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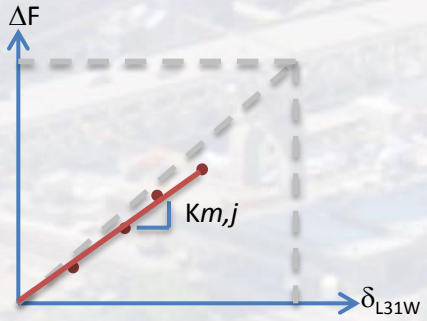
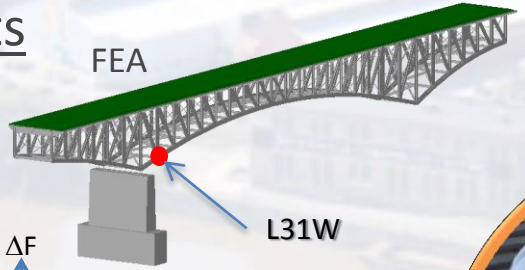
- *Restoring displacement:* δ_{L31W}

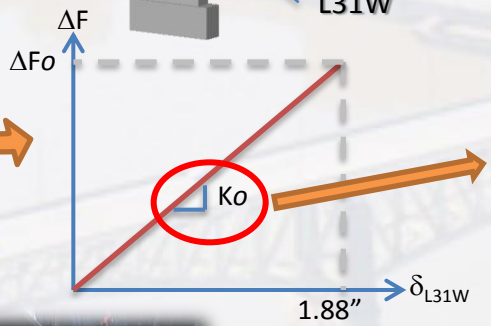
Outputs



Evaluating bridge response during jacking

Inputs

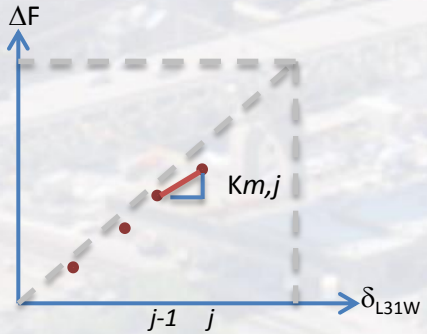




Field

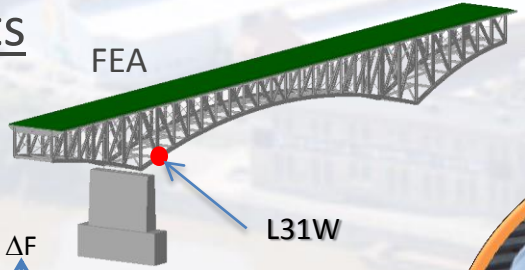
- *Instrumented members:* $\varepsilon, T \rightarrow \Delta F$
- *Restoring displacement:* δ_{L31W}

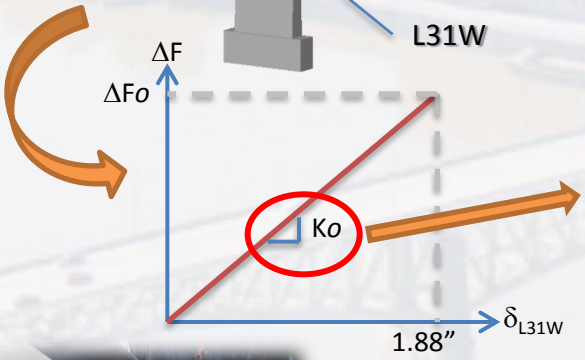
Outputs



Evaluating Bridge Response During Jacking

Inputs





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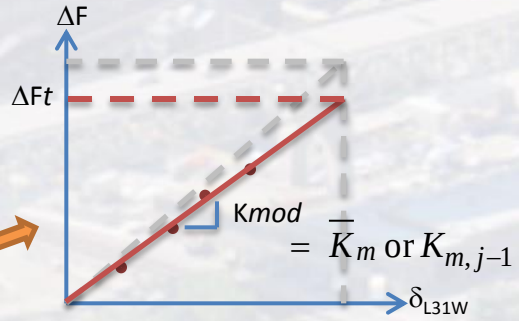
- *Restoring displacement:* δ_{L31W}

Outputs



Evaluating Bridge Response During Jacking

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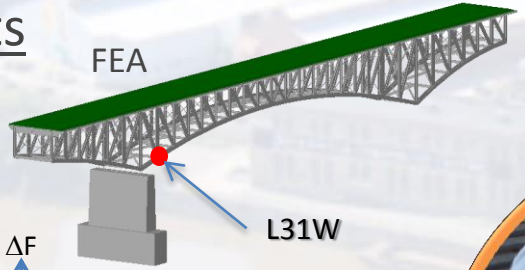

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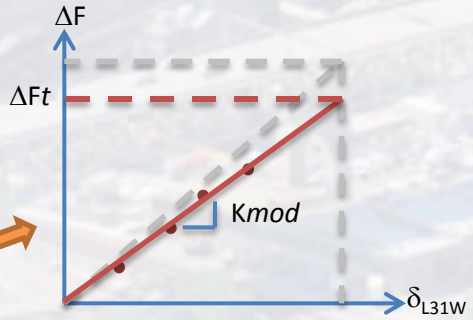
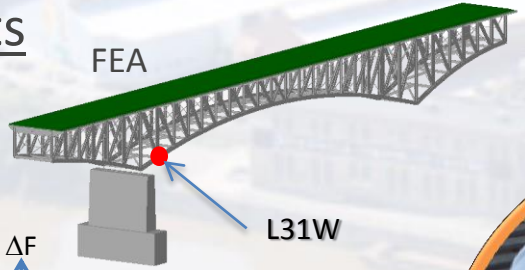
Outputs



$$\Delta P_i = K_{\text{mod}}\left(1.88'' - \delta_{L31W,i}\right)$$

Evaluating Bridge Response During Jacking

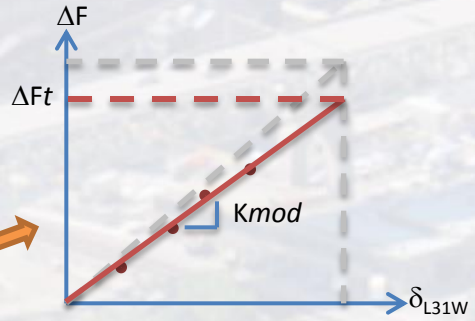
Inputs



Field

- *Instrumented members:* $\varepsilon, T \rightarrow \Delta F$
- *Restoring displacement:* δ_{L31W}

Outputs

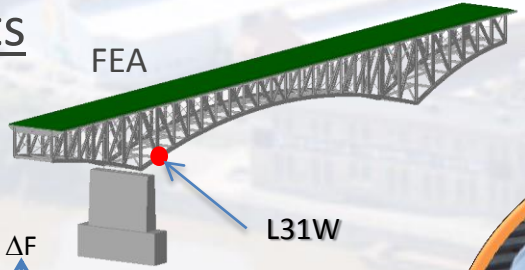


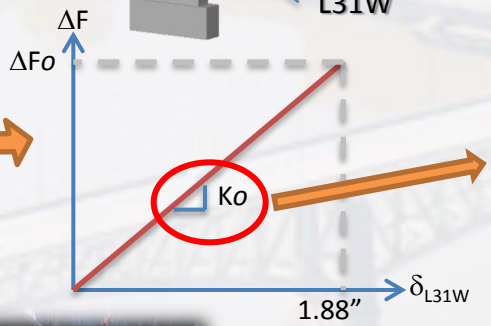
$$\Delta P_i = K_{\text{mod}}\left(1.88'' - \delta_{L31W,i}\right)$$

$$RF_i = f\left(C, DL + \Delta P_i, LL + IM\right)$$

Evaluating Bridge Response During Jacking

Inputs

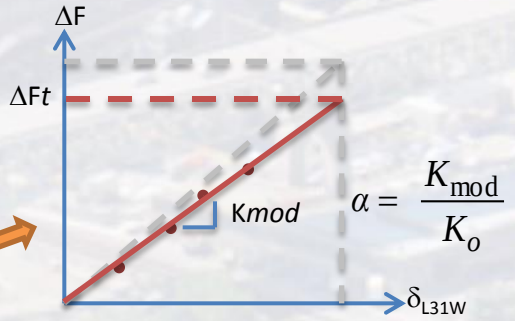




Field

- *Instrumented members:* $\varepsilon, T \rightarrow \Delta F$
- *Restoring displacement:* δ_{L31W}

Outputs



$$\alpha = \frac{K_{mod}}{K_o}$$

$$\Delta P_i = K_{mod}\left(1.88'' - \delta_{L31W,i}\right)$$

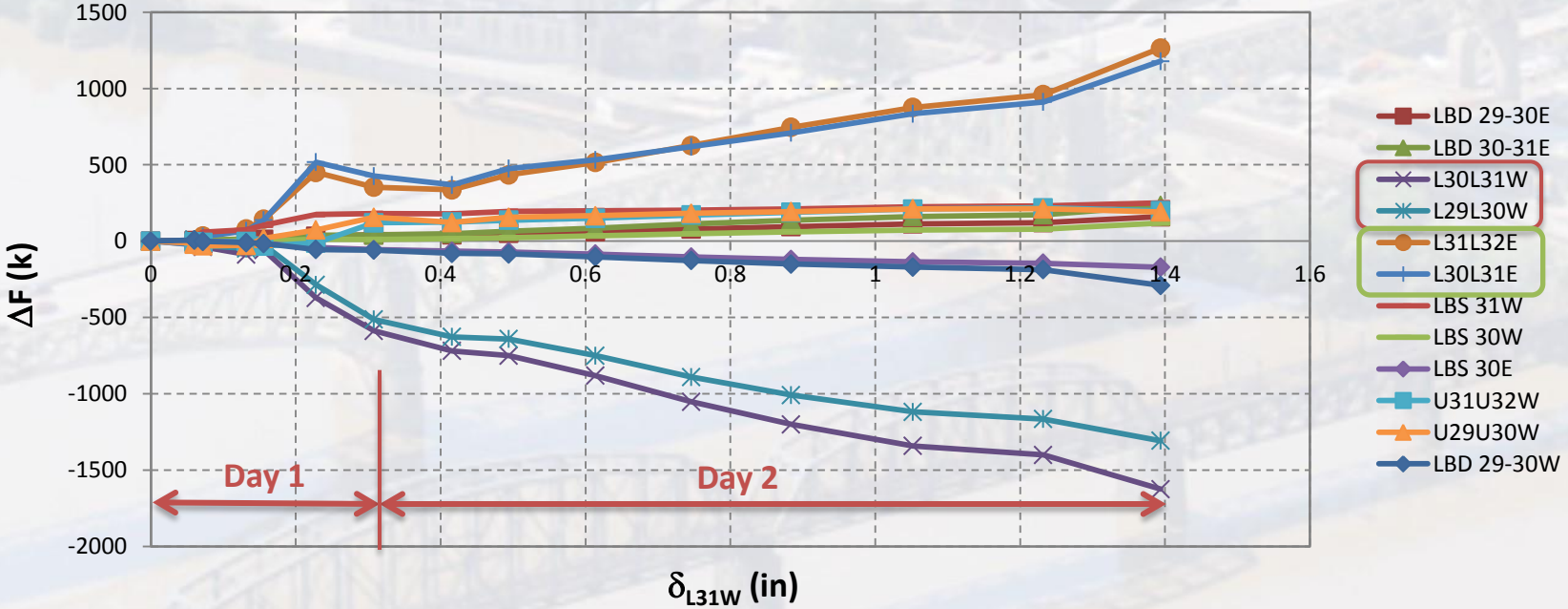
$$RF_i = f\left(C, DL + \Delta P_i, LL + IM\right)$$

Non-instrumented members:

$$K_{m,eq} = \alpha K_o$$

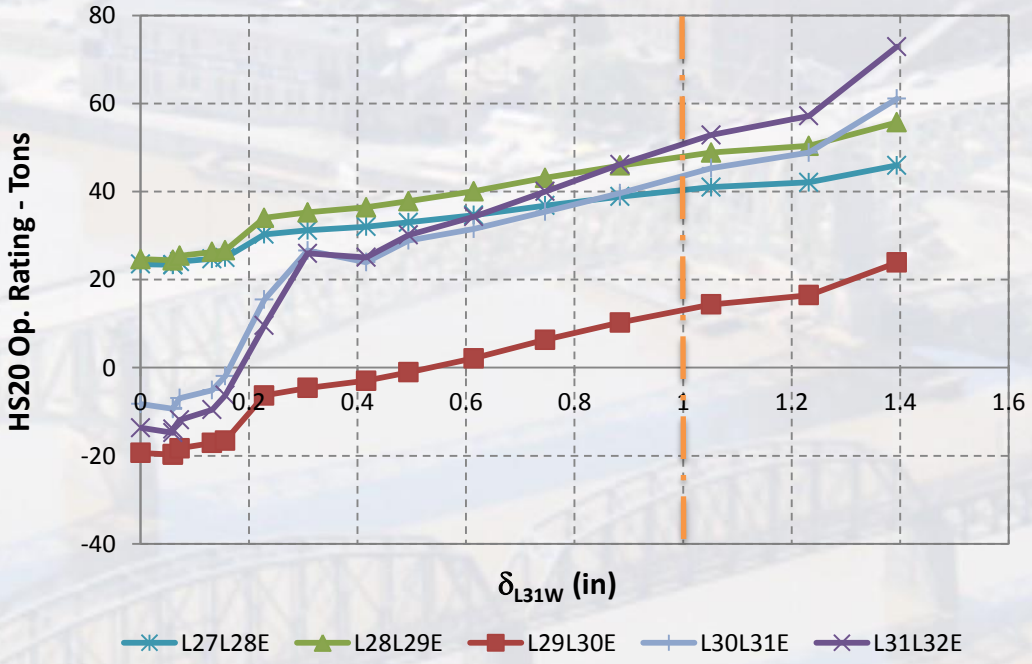
Collected Data

- Processed strain gage data (Restoring Forces) vs L31W Restoring Displacement



Real-time Ratings (During Jacking)

- Critical components = East (upstream) truss lower chord members



Web Plate Straightness

Early Jacking Stage

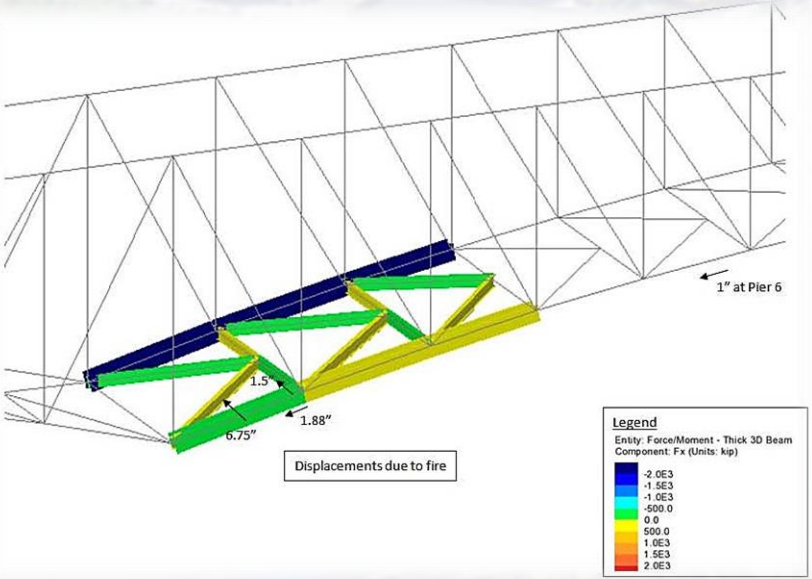
Later Jacking Stage

Web Plate Straightness

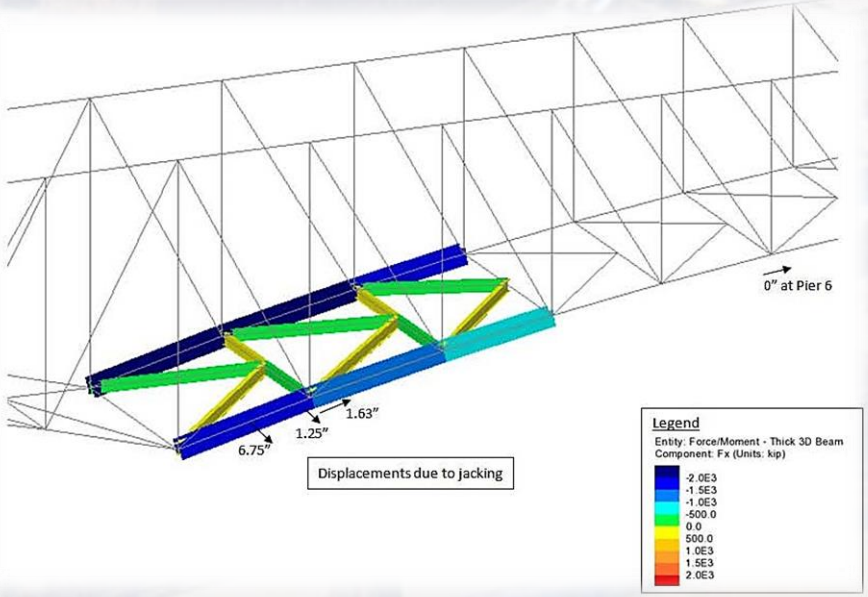
~End of Jacking

End of Jacking

- Maximum L31W Restoring Displacement < 1.88”



Post-fire

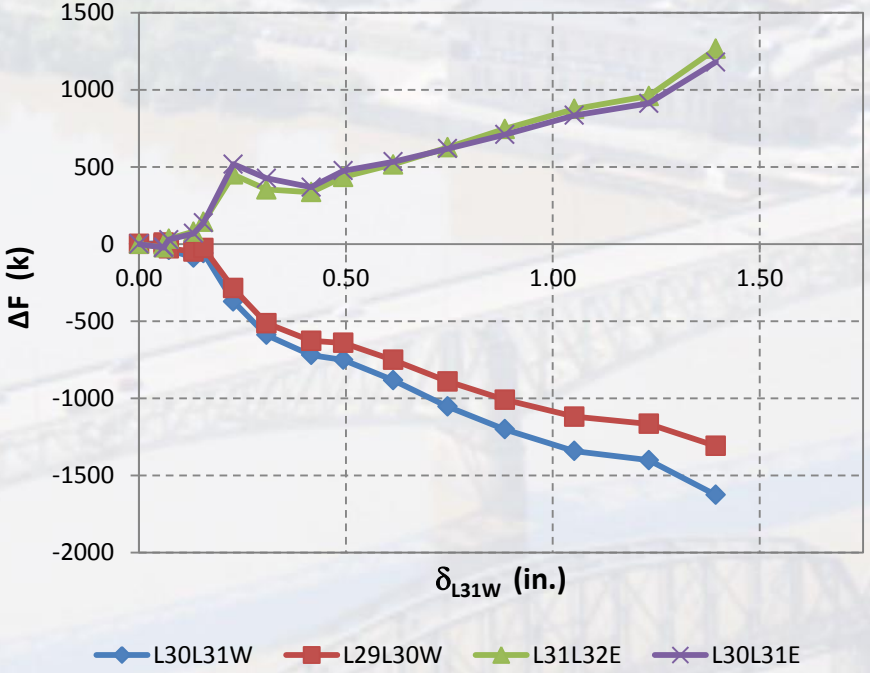


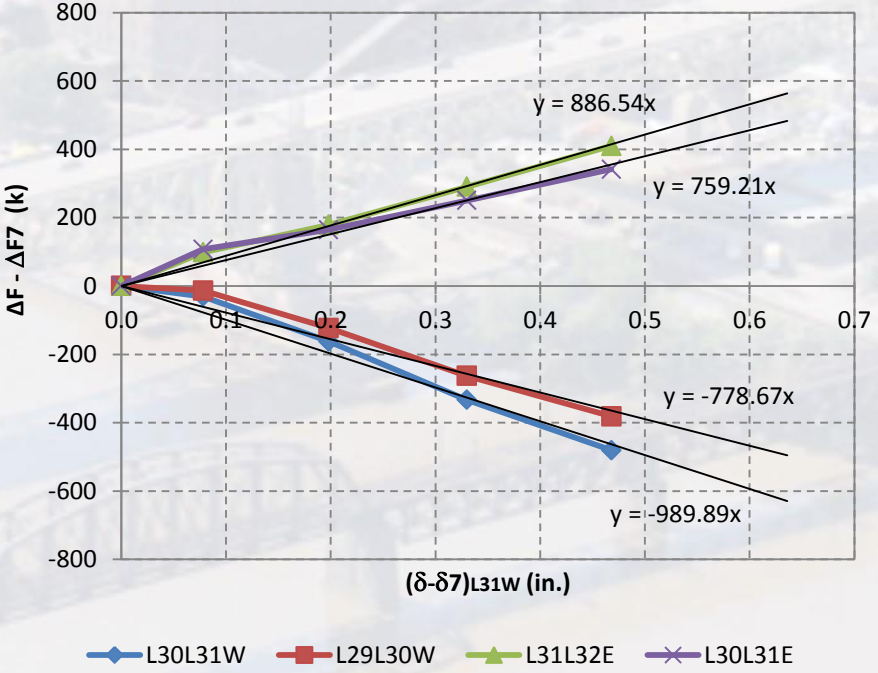
Post-jacking

Refined Stiffness Calcs

- Refined post-processing after jacking:

$$K_{mod} = \bar{\alpha} K_o, \quad \bar{\alpha} \approx 1.015$$





Results Post-Processing – After Jacking

- Loads and ratings for Stage 1D using field data post-processing:

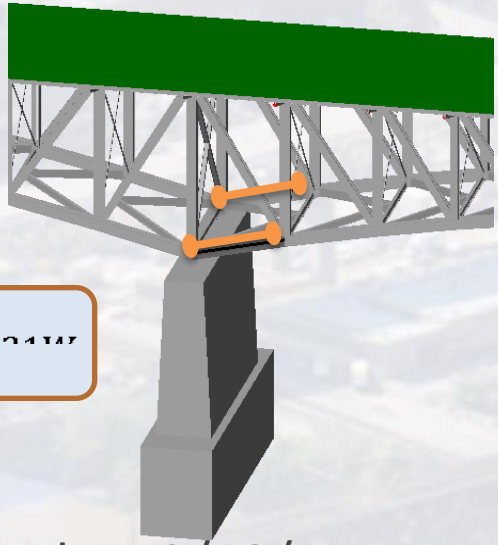
Member	P (pre-fire)	P (post-fire)	P (post-jacking*)	HS20 Tons*
L31L32E	-2609 k	-4595 k	-3122 k	64.9
L31L32W	-2003 k	30 k	-1477 k	-
LB 30-31E	-9 k	-441 k	-120 k	-
LB 30-31W	9 k	441 k	120 k	-
L29L30E	-1468 k	-2749 k	-1799 k	18.7

Posting → 9 Ton
Bridge Re-opening
Monday, 9/26/16

- * 1.39” restored displacement (Day 2, Saturday, 9/24/16)
- Day 3 → δ_{L31W} = 1.63”, HS20 OR = 21 Tons

Post-jacking Work

- 30 Ton Weight Limit Restored on 9/29/16
  - 98 in^2 of steel added to L29L30E

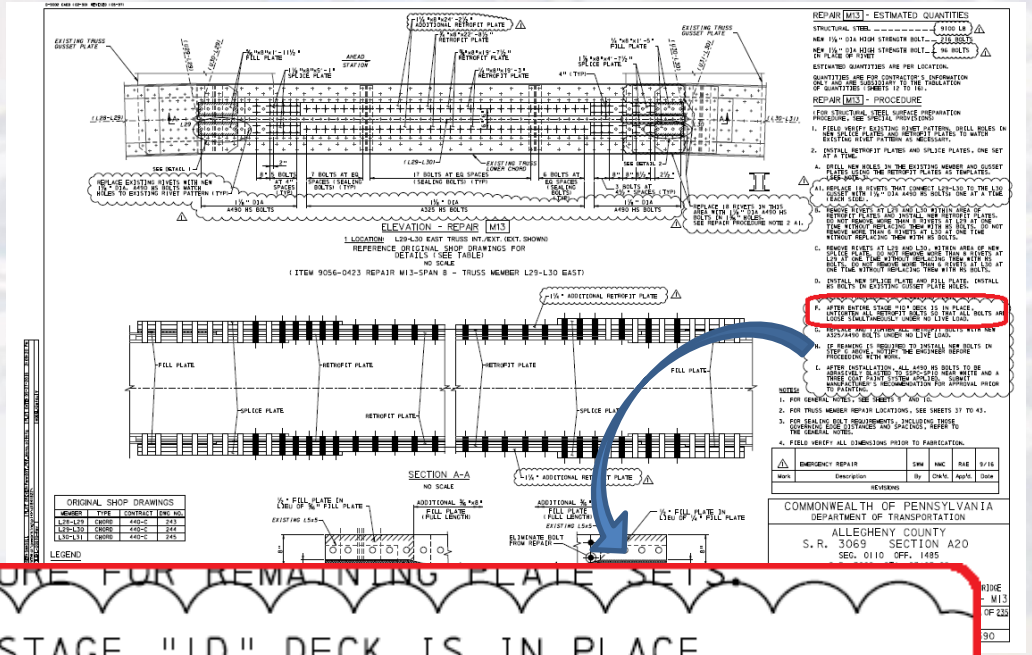


$$\Delta L \approx 3/8" \approx 1.88 - \delta_{new}$$

- Jacking Removal on 3/18/17
- Final differential length between east and west L31L32 members measured on 4/25/17

Ratings after Jacking Removal

- Shift Forces: $\Delta P_i \approx K_{calib.}\ 3/8"$
- Temporary **3D** effect from construction not included
  - Truss members were either not repaired or repaired prior to any deck removal
  - Except for critical truss member L29L30E repaired after the fire but ...



E. REPEAT PROCEDURE FOR REMAINING PLATE SETS.

F. AFTER ENTIRE STAGE "ID" DECK IS IN PLACE, UNTIGHTEN ALL RETROFIT BOLTS SO THAT ALL BOLTS ARE LOOSE SIMULTANEOUSLY UNDER NO LIVE LOAD.

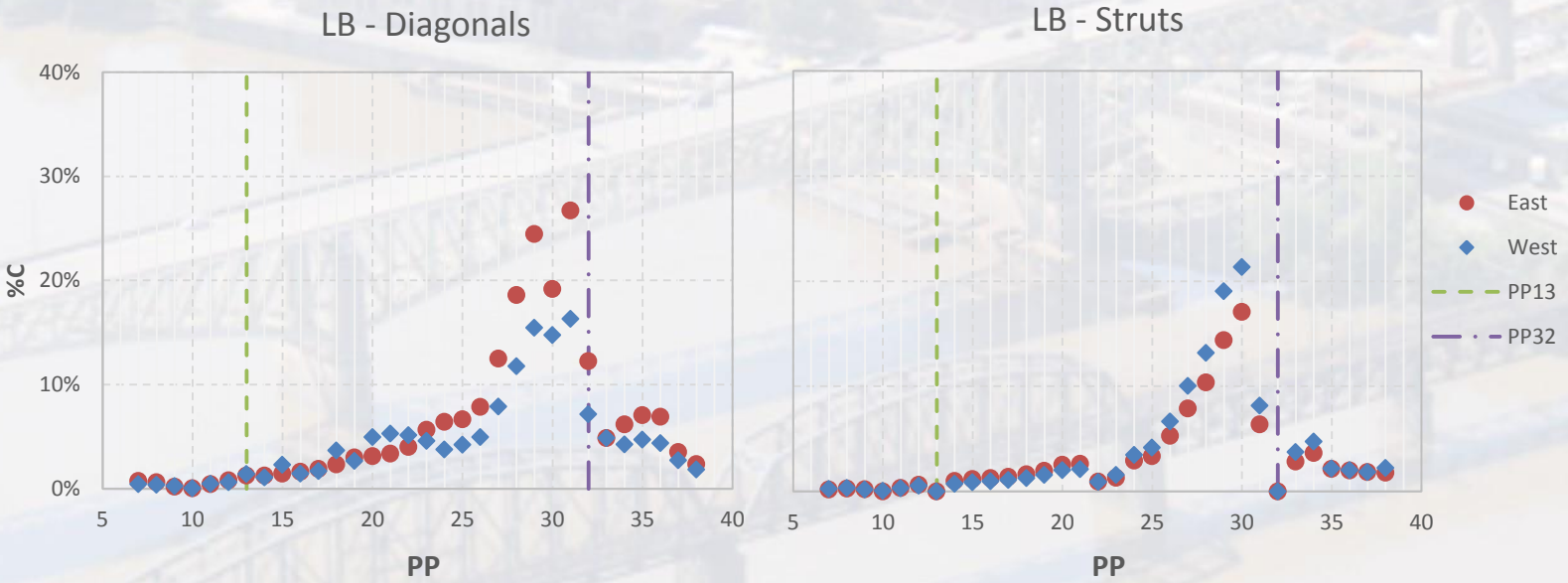
Ratings after Jacking Removal

- East Truss Members: HS20 ORF > 1.5

Vehicle	Inventory Rating						Operating Rating					
	RF	Tons	Stress	Member Location			RF	Tons	Stress	Member Location		
				Span	Type	ID				Span	Type	ID
H20	0.95	19.0	C	8	LC	L27L28	1.59	31.7	C	8	LC	L27L28
HS20	0.95	34.2	C	8	LC	L27L28	1.59	57.1	C	8	LC	L27L28
TK527	1.71	68.5	C	7	LC	L8L9	2.86	114.4	C	7	LC	L 8L 9
ML80	1.78	65.3	T	8	UC	U15U16	2.97	109.0	T	8	UC	U15U16
P82 (Single)	-	-	-	-	-	-	2.20	224.0	T	8	UC	U15U16

Bottom Lateral Bracing Assessment

- Remaining effects of the fire load shift expressed as a percentage of their capacity



Bottom Lateral Bracing Assessment

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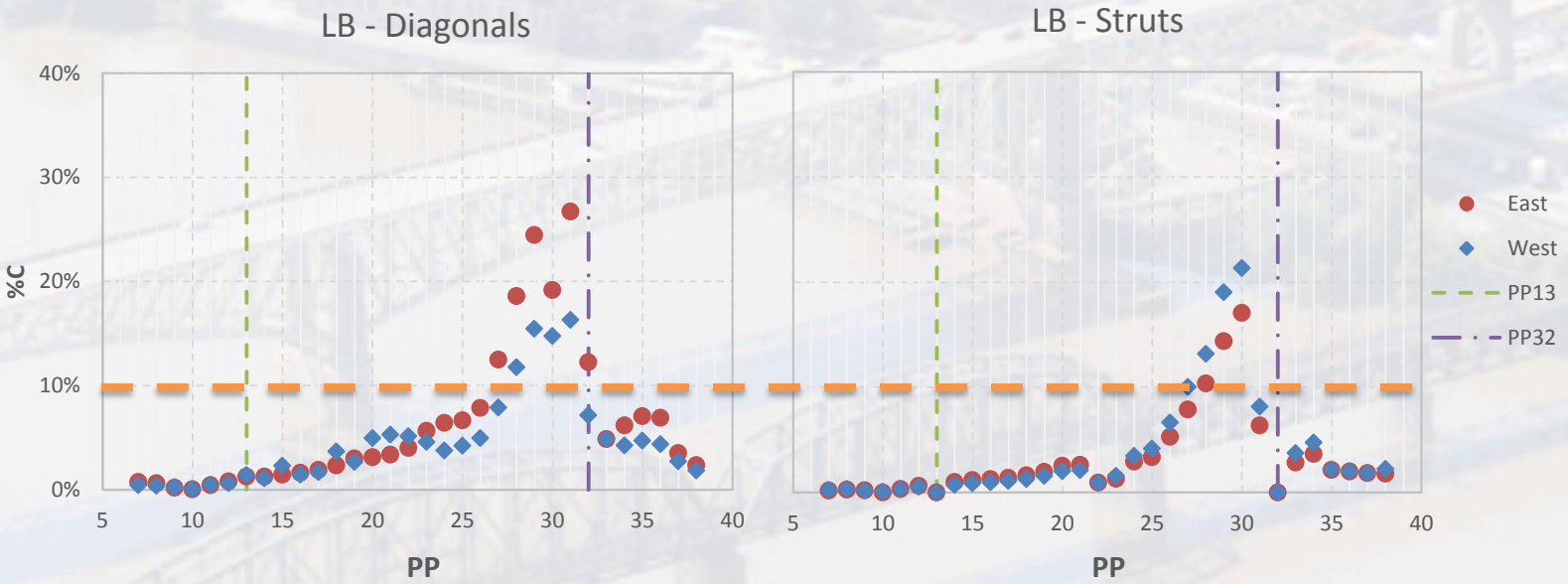
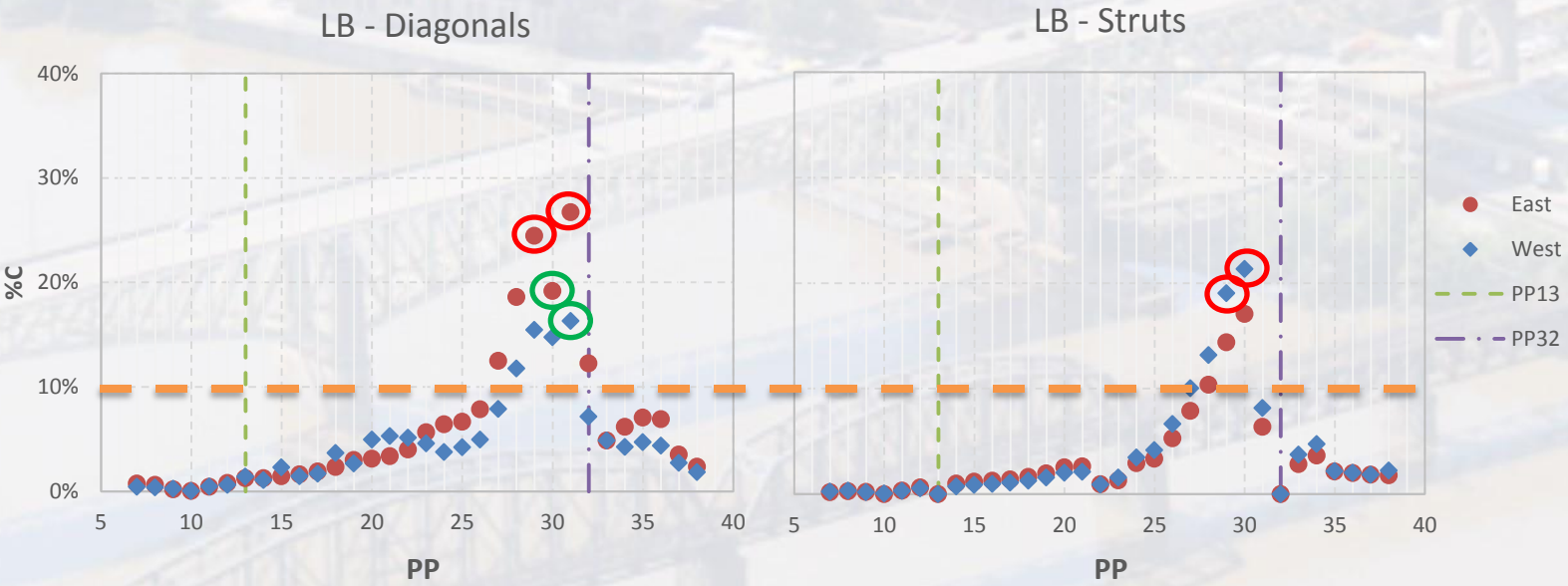


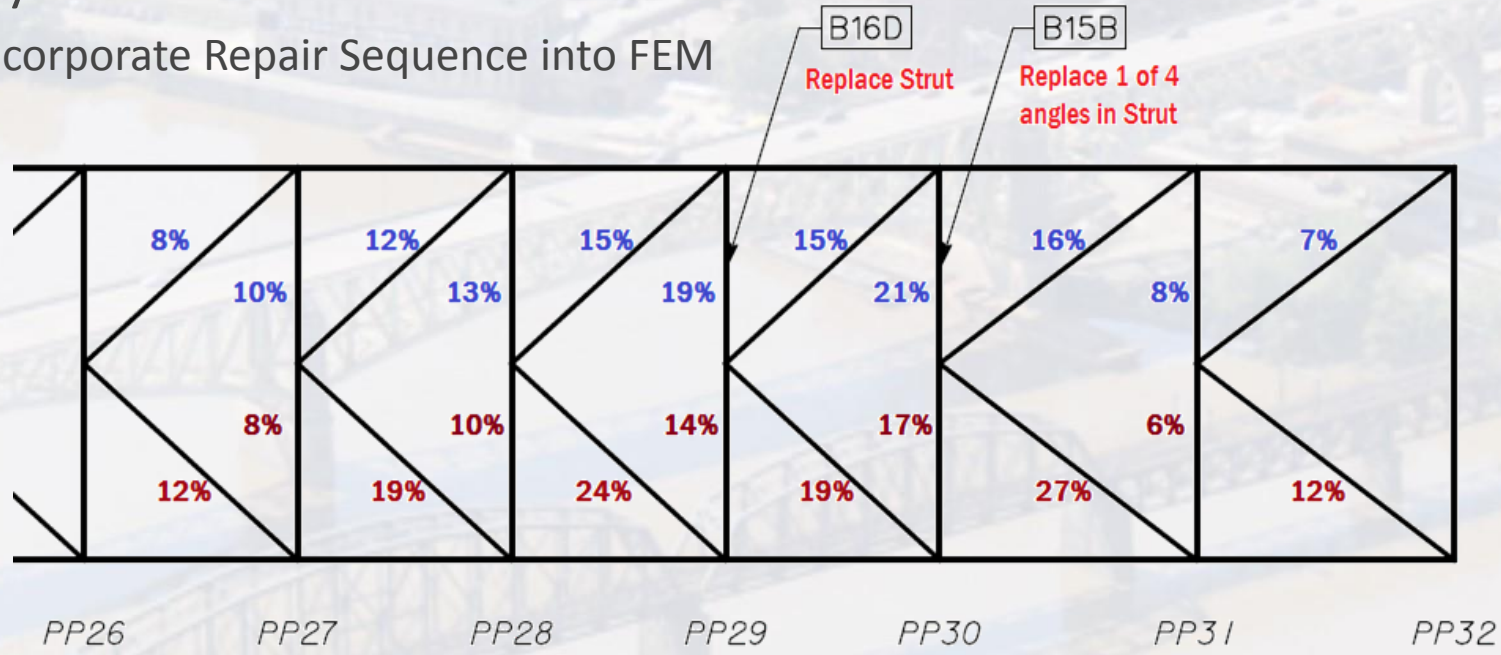
Bottom Lateral Bracing Assessment

- Remaining effects of the fire load shift expressed as a percentage of their capacity



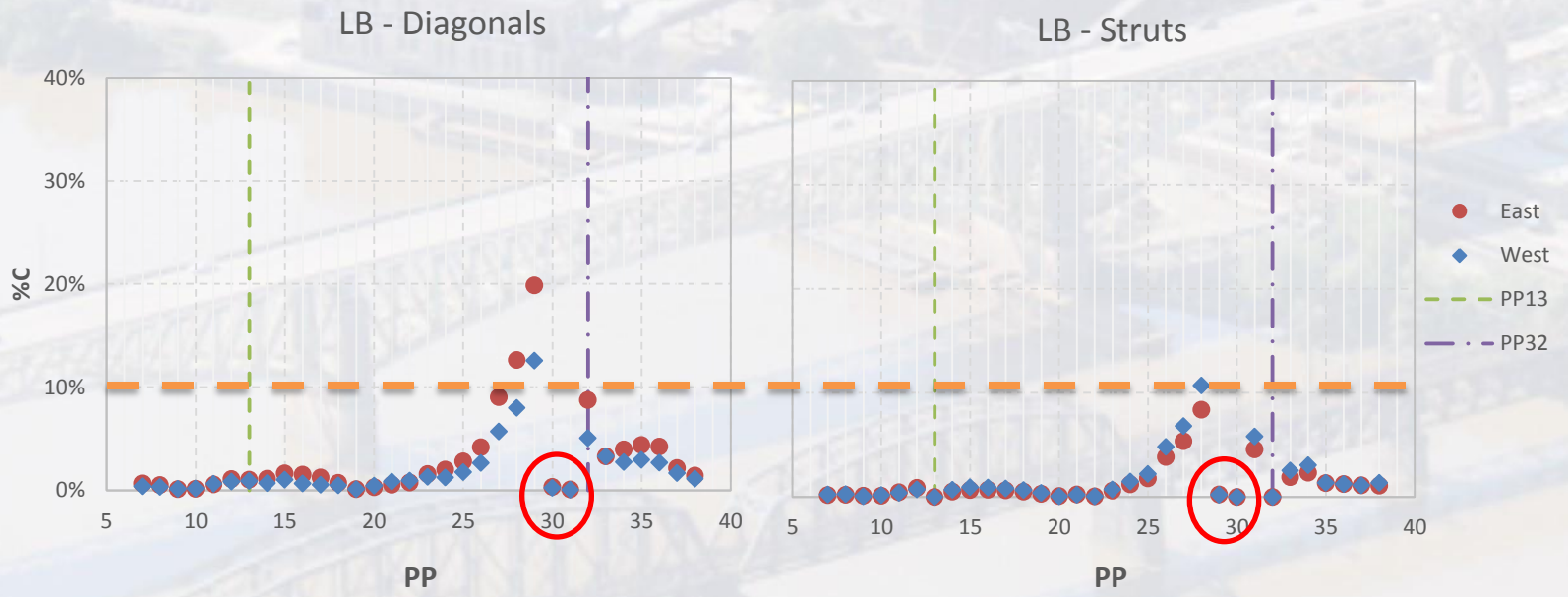
Bottom Lateral Bracing Assessment

- HDR (2015 Rehab. Engineer of Record): Effects of Upcoming Repairs on BLB system
  - Incorporate Repair Sequence into FEM



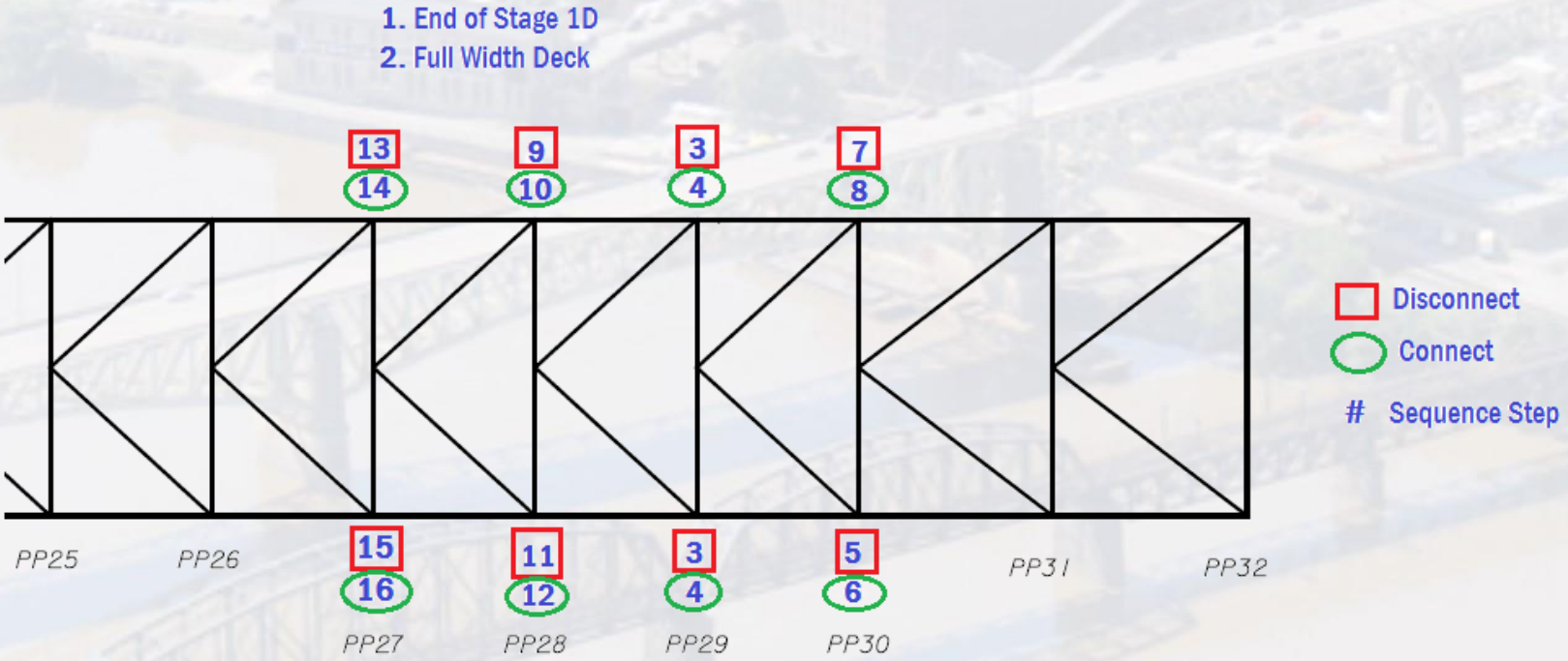
Bottom Lateral Bracing Assessment

- Original Repair Sequence: Remaining Effects



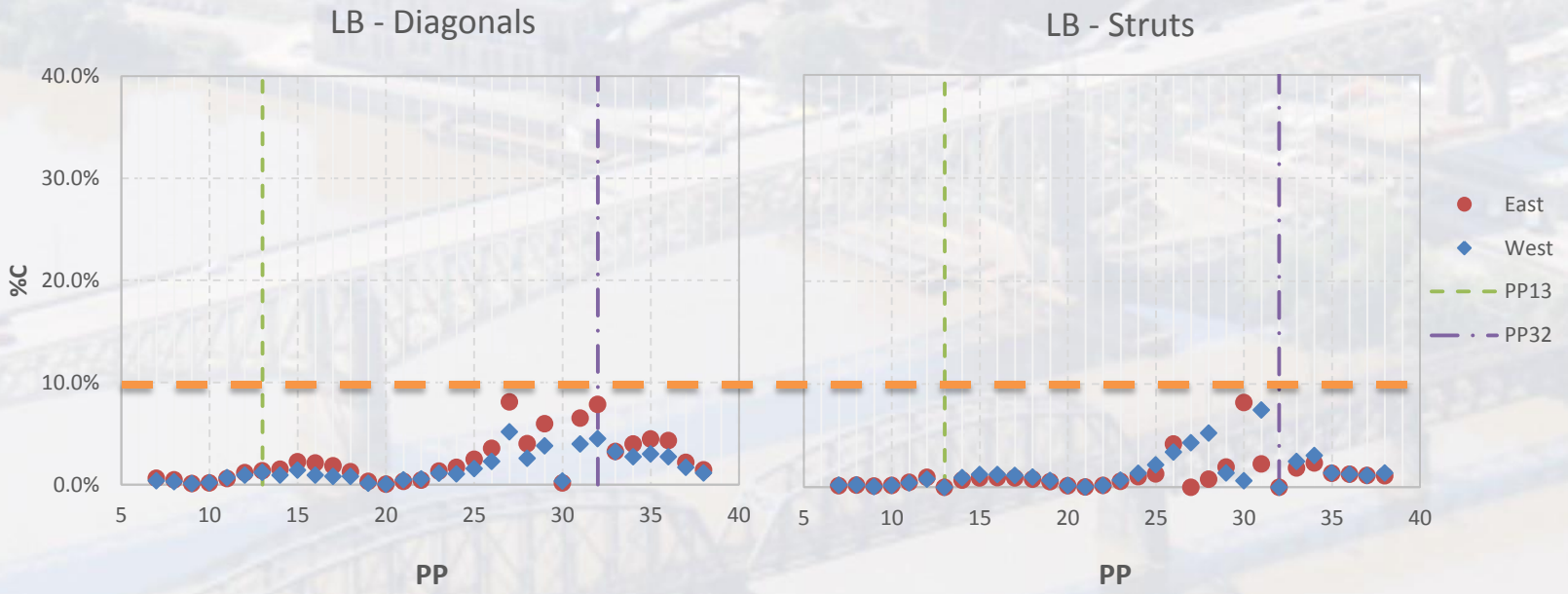
Bottom Lateral Bracing Assessment

- Proposed Repair Sequence:



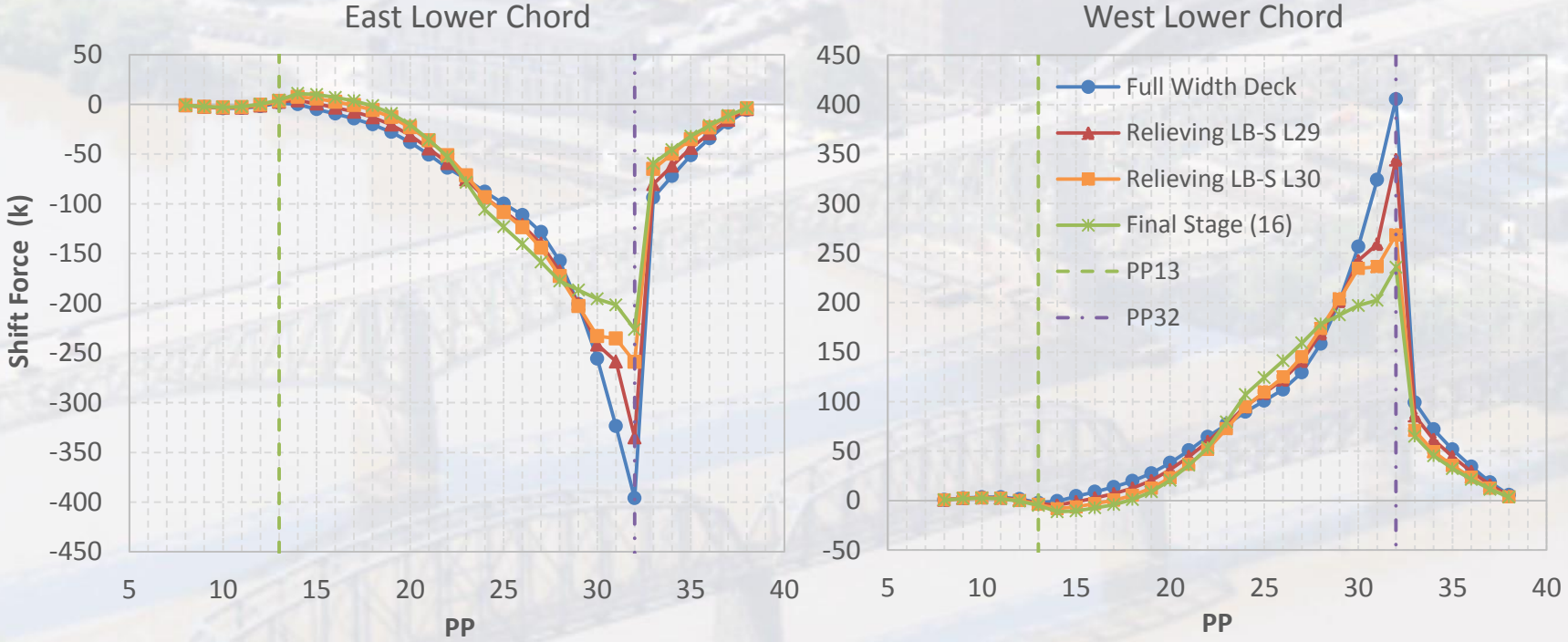
Bottom Lateral Bracing Assessment

- Proposed Repair Sequence: Remaining Effects



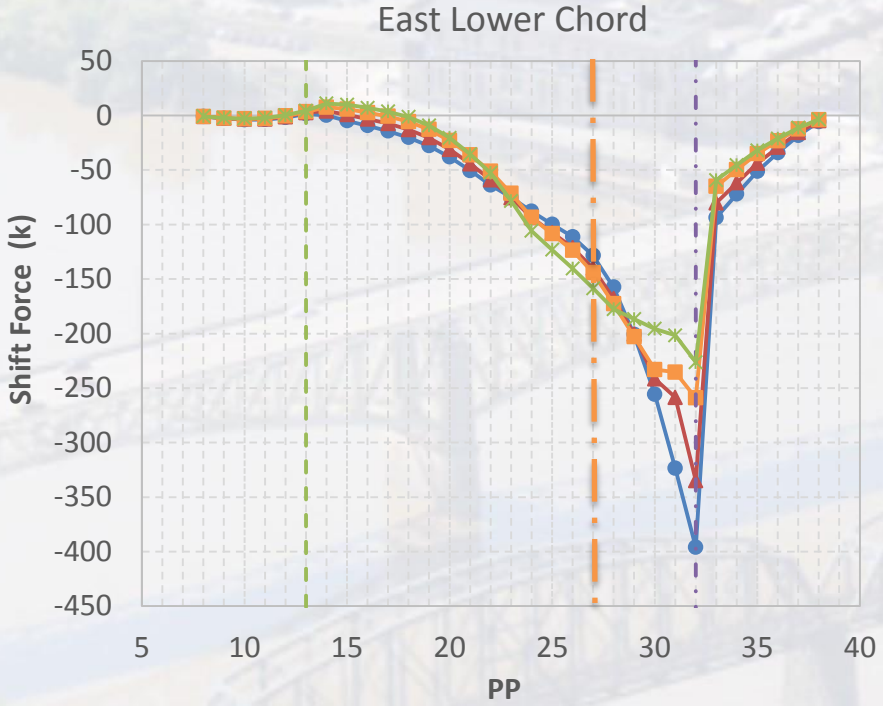
Bottom Lateral Bracing Assessment

- Proposed Repair Sequence: Effects on Truss Members



Final Ratings

- East Truss Members: HS20 ORF > 1.5



Vehicle	Operating Rating					
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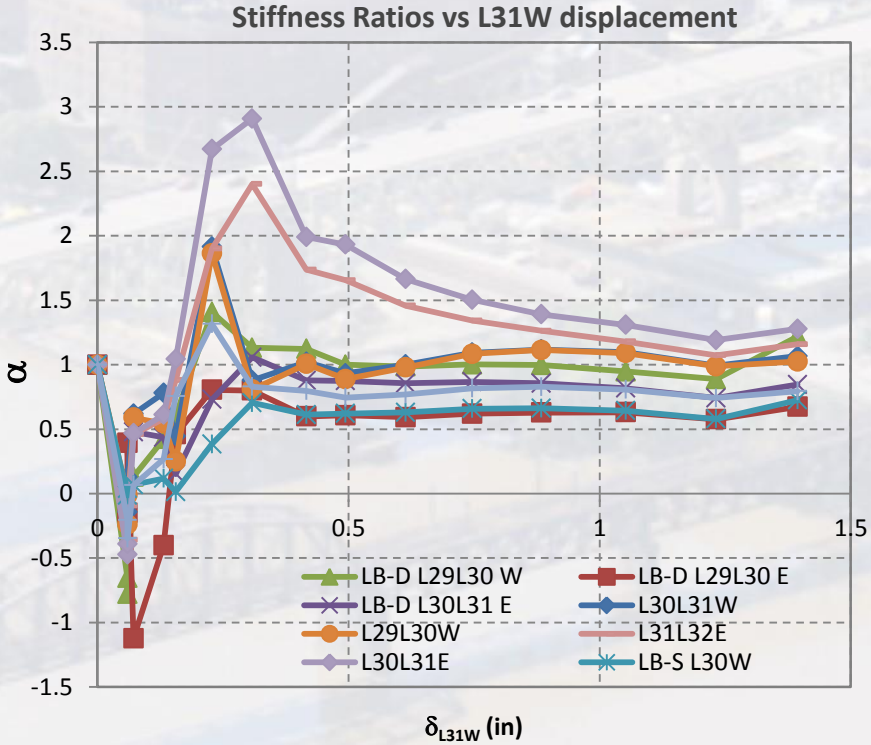
ML80	2.97	108.8	T	8	UC	U15U16
P82 (Single)	2.19	223.7	T	8	UC	U15U16

Issues Encountered

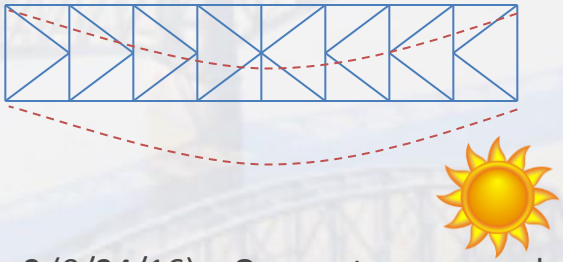
- Initial large deviations in stiffness
  - Initial engagement between the jacking frame and the bridge, stabilization of instrumentation



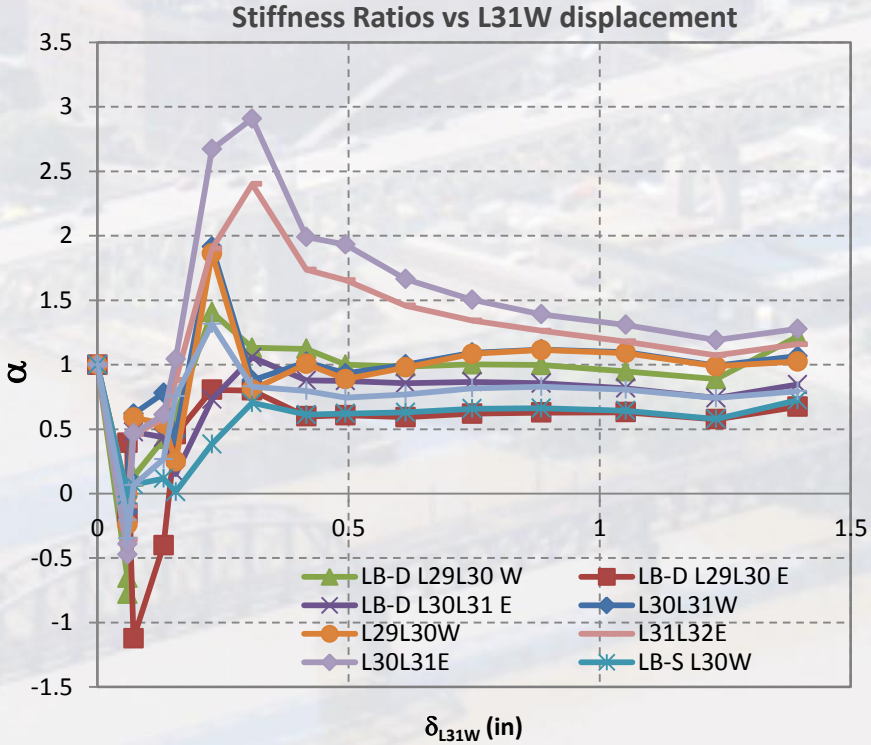
Issues Encountered

- Initial large deviations in stiffness
  - Temperature effects
    - Day 1 (9/23/16) – Sunny - measured steel temperatures

	Morning	Evening
East Truss	102°F	88°F
West Truss	93°F	96°F



    - Day 2 (9/24/16) – Overcast - measured steel temperatures relatively constant ~67°F



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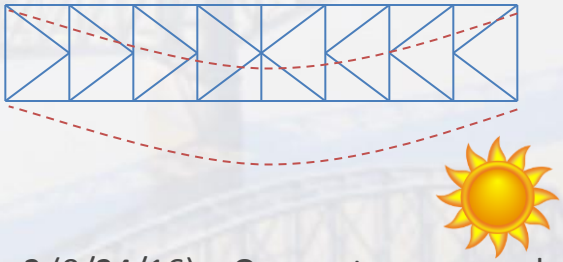
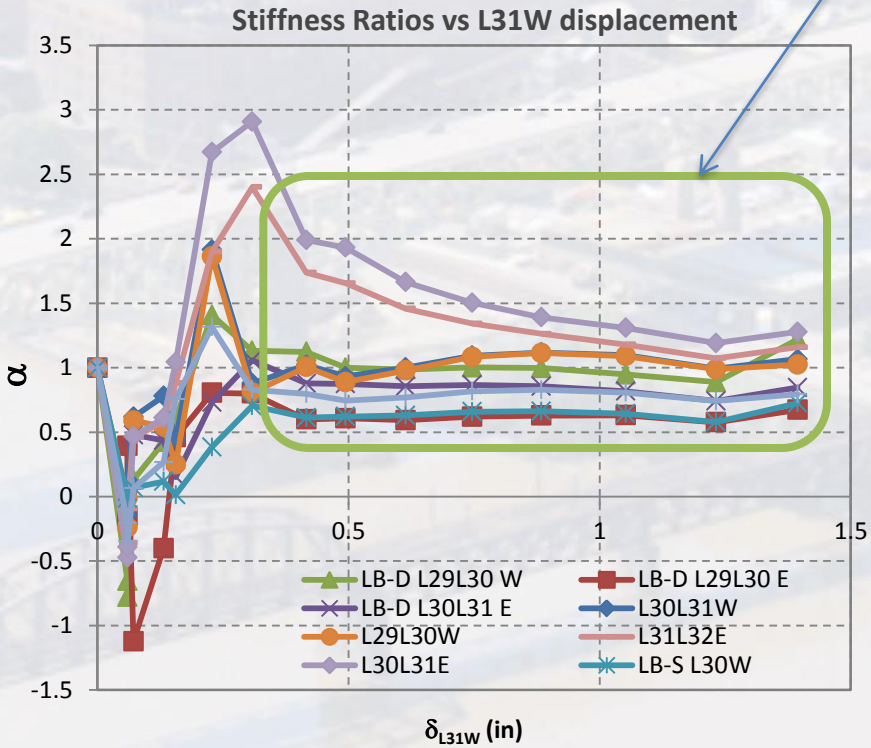


    - Day 2 (9/24/16) – Overcast - measured steel temperatures relatively constant ~67°F

Day 2 data used in calculation of Stiffness Ratios, α, for final post-processing of data

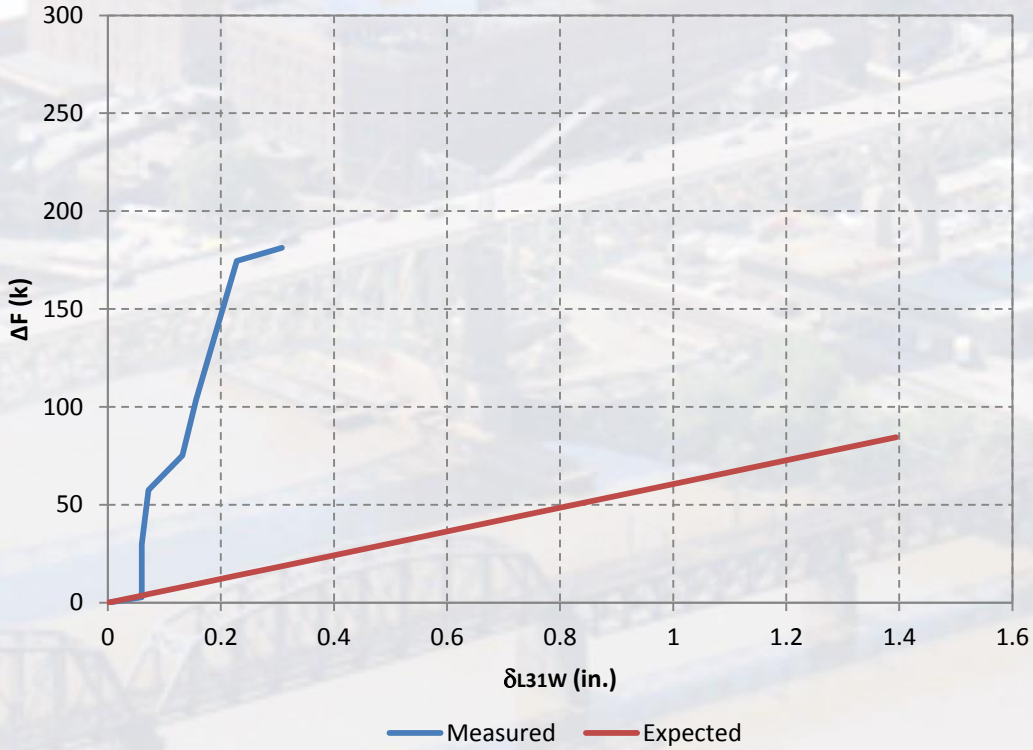


Issues Encountered

- Measurement of L31-L32W panel length
  - Value is critical to determining stiffnesses to compare w/FEA
  - Started using survey data from targets on inboard side
    - Rotation of joint due to lateral jacking influenced and caused inaccuracy of these values
  - Updated methodology to use survey measurements of targets on inboard and outboard side

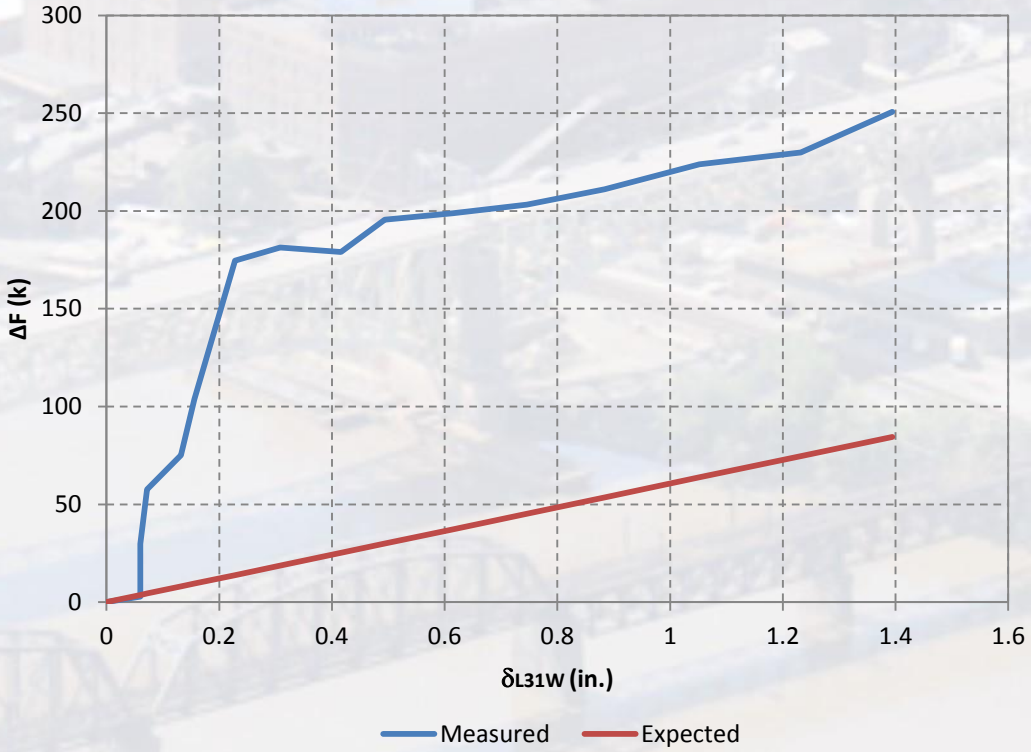
Issues Encountered

- L31W Strut
  - DL in post-fire condition ≈ 120 k (compression)
  - Capacity ≈ 320 k (tension)
  - Measured vs. expected shift forces (+ = tension added)



Issues Encountered

- L31W Strut
  - Large initial forces due to lateral jacking near L31W
  - Jacking team informed to stop increasing lateral jack force
  - Once lateral jacking force was backed off, stiffness closely matched expected



Concluding Remarks of MM's work

- Correlate model with field observations:
  - Deck system adds significant stiffness to structure
- Consider all sources of asymmetric conditions:
  - Loads
  - Stiffness
- Plastic deformations are difficult to recover and have to be considered in the development of the jacking operations
- Lateral bracing systems become primary members after unexpected and asymmetric events affect the structure, such as the fire on Liberty Bridge

Thank you: Truly a team effort!

Acknowledgements

- PennDOT D-11
  - Jim Foringer
  - Lou Ruzzi
  - Doug Thompson
  - Jason Zang
- HDR
  - Roger Eaton
  - Nick Burdette
- Internal MM folks
  - Tom Murphy – Leadership, technical direction, and coolness under pressure
  - Chris Smith – Ratings, refined capacities
  - Dr. John Kulicki – Wisdom and guidance, rating reviews

Thank you!

Questions?

If not, go grab some lunch!

Lunch delivery on the Liberty Bridge