Michael Baker INTERNATIONAL

We Make a Difference

Steel I-Girder Bridge Fit Research

Western Bridge Engineers' Seminar, September 7, 2017

Research Team

- Georgia Tech:
  - Dr. Don White
  - Dr. Thanh Nguyen
- HDR Engineering
  - Domenic Coletti
  - Dr. Brandon Chavel
- M A Grubb & Associates:
  - Mike Grubb
- Brayman Construction
  - Calvin Boring

Outline

- Fit Condition
- Research Basis
- Erection Considerations
- Influence of Framing Arrangements
- Effects of Fit Condition
- Lack-of-Fit Forces
- Construction Inspection
- Formal Recommendations

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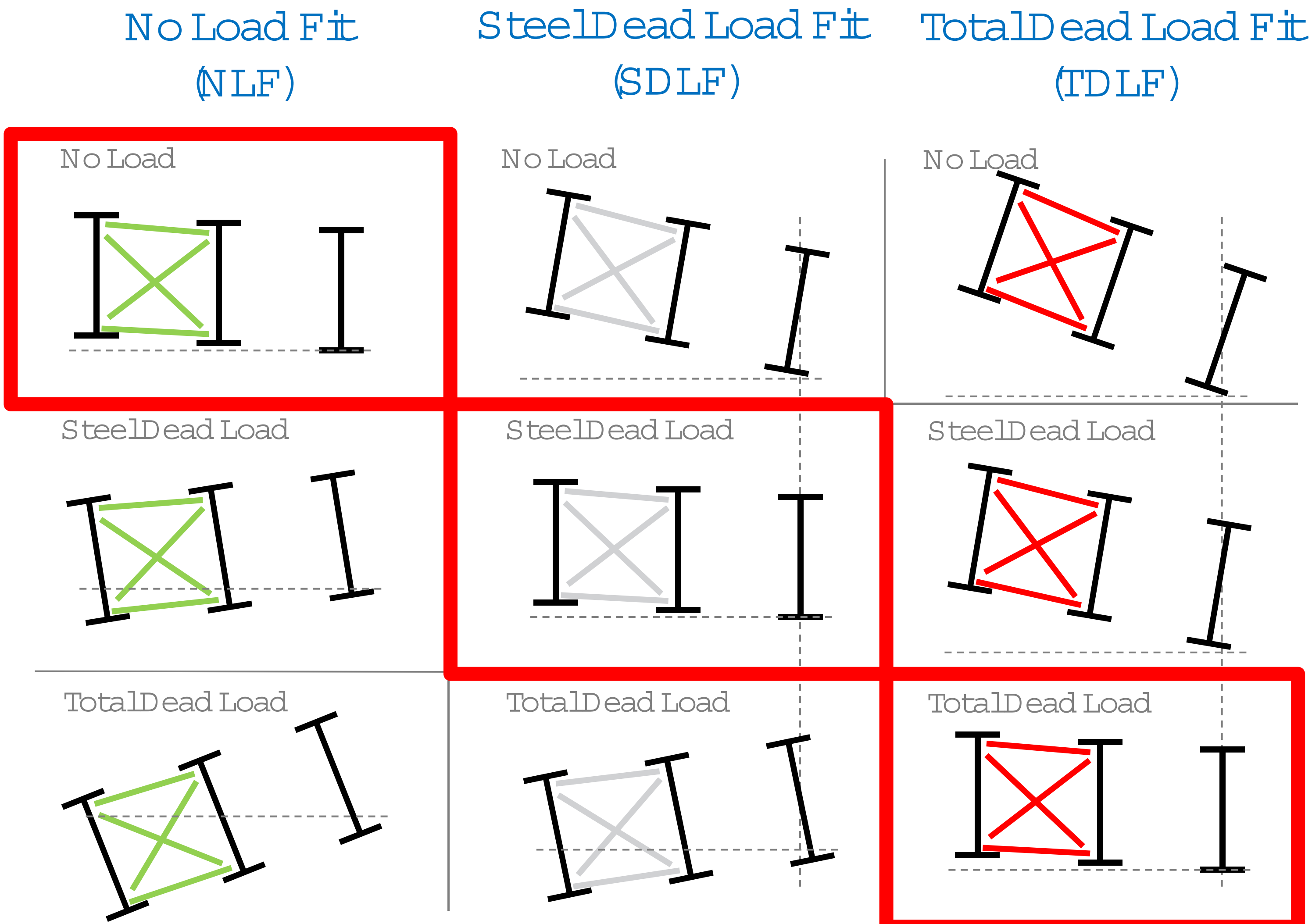
- What is "Fit?"

Common Fit Conditions		
Condition	Alternate Name	Description
No-Load Fit (NLF)	Fully-Cambered Fit	The cross-frames are detailed to fit to the girders in the fabricated, fully-cambered and plumb position of the girders under zero load.
Steel Dead Load Fit (SDLF)	Erected Fit	The cross-frames are detailed to fit to the girders in an ideal plumb position where the girders are assumed deflected vertically under the self-weight of the structural steel at the completion of the steel erection.
Total Dead Load Fit (TDLF)	Final Fit	The cross-frames are detailed to fit to the girders in an ideal plumb position where the girders are assumed deflected vertically under the total as-constructed dead loads.

- Webs can only be plumb under one condition



- Why should you care?
  - Choice of fit condition affects ease of fit-up during construction
  - Choice of fit condition affects locked-in stresses

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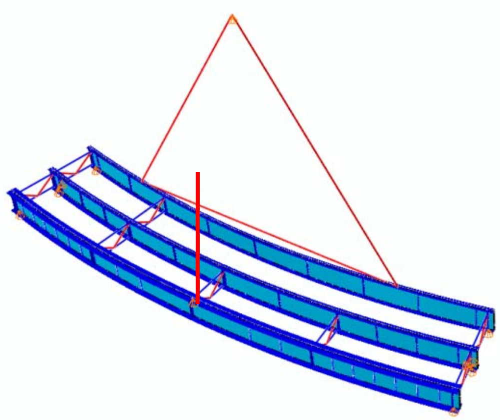
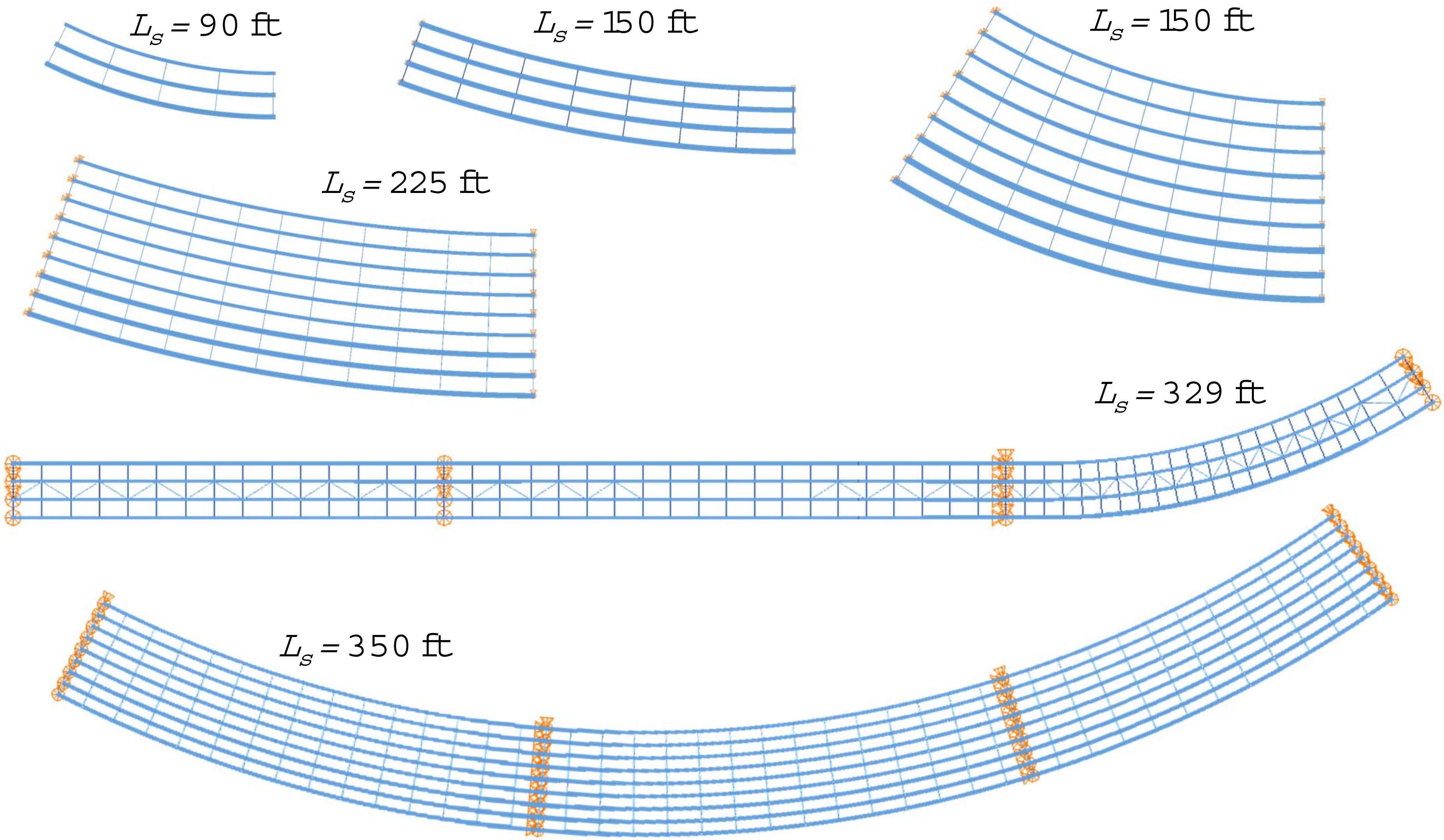
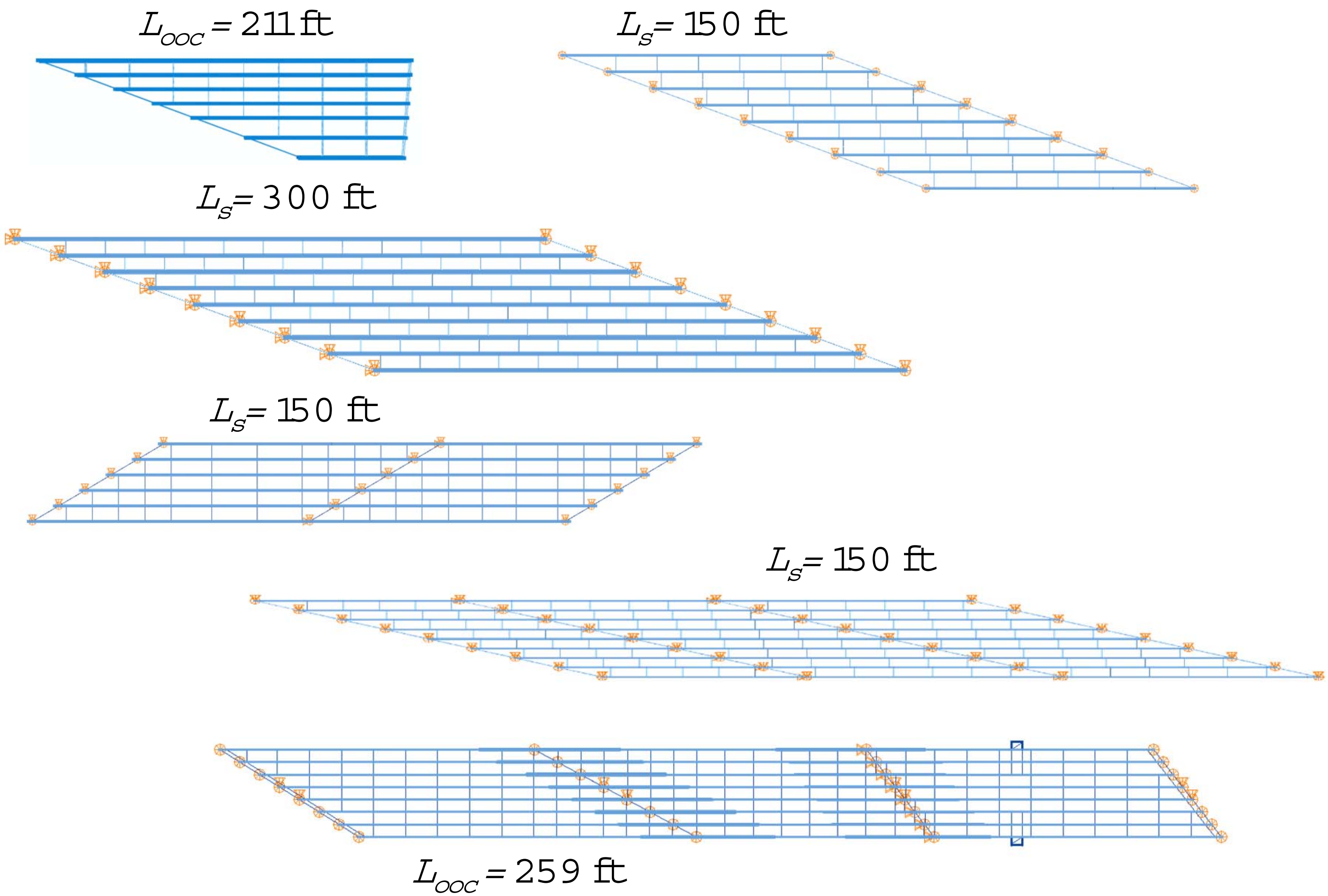
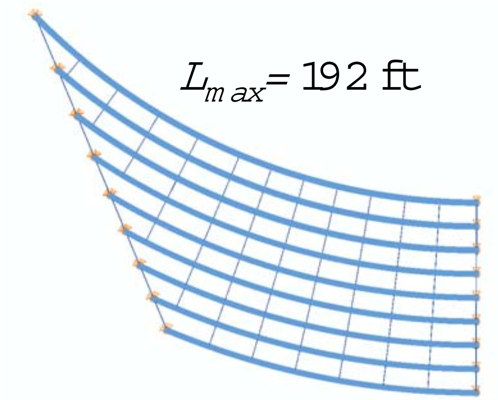
- Research Goals
  - Provide design guidance to facilitate reliable fit-up
  - Provide clearer understanding of implications of:
    - Erection procedures
    - Framing arrangements
    - Choice of fit condition

- Research Scope
  - 21 bridges studied
  - Curved and/or skewed
  - Parametric 3D FEA studies
    - Range of erection schemes
    - Range of framing arrangements
    - Range of fit conditions

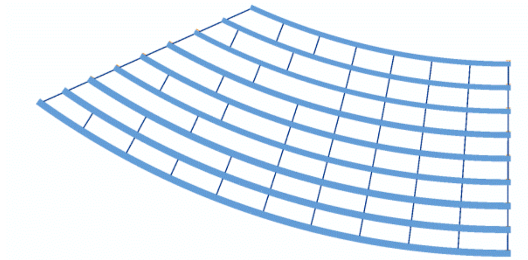



$L_s = 90$ ft
$L_s = 150$ ft
$L_s = 150$ ft
$L_s = 225$ ft
$L_s = 329$ ft
$L_s = 350$ ft

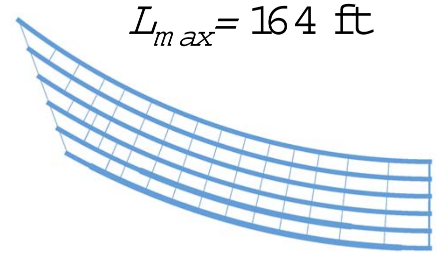

L_{ooc} = 211 ft
L_s= 150 ft
L_s= 300 ft
L_s= 150 ft
L_s= 150 ft
L_{ooc} = 259 ft



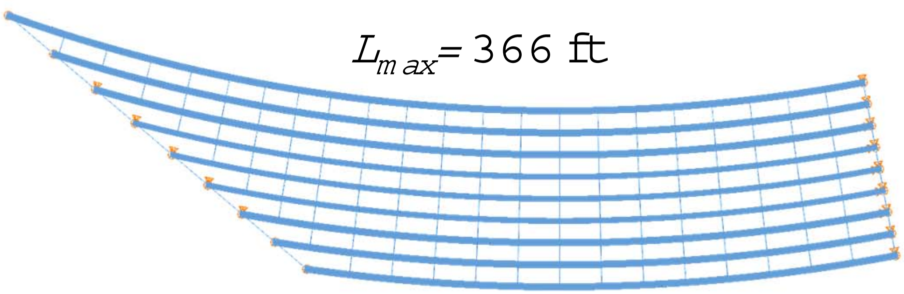
L_{max}= 192 ft



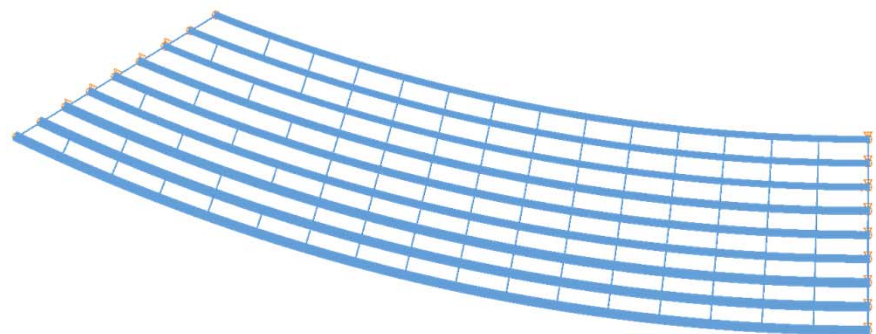
L_{max}= 195 ft



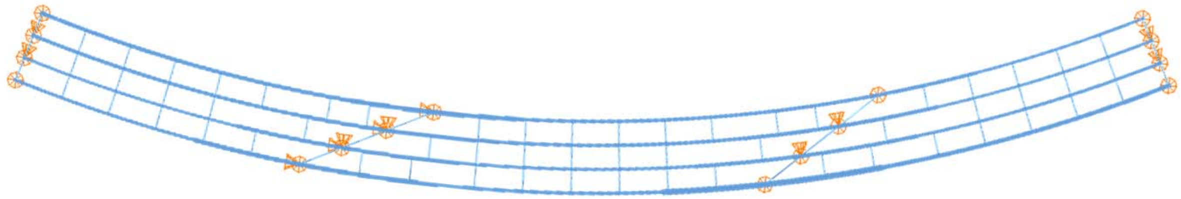
L_{max}= 164 ft



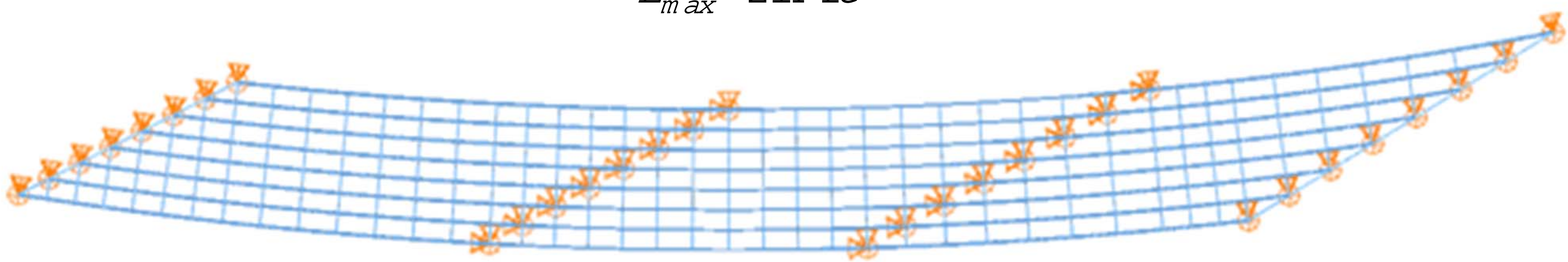
L_{max}= 366 ft



L_{max}= 340 ft



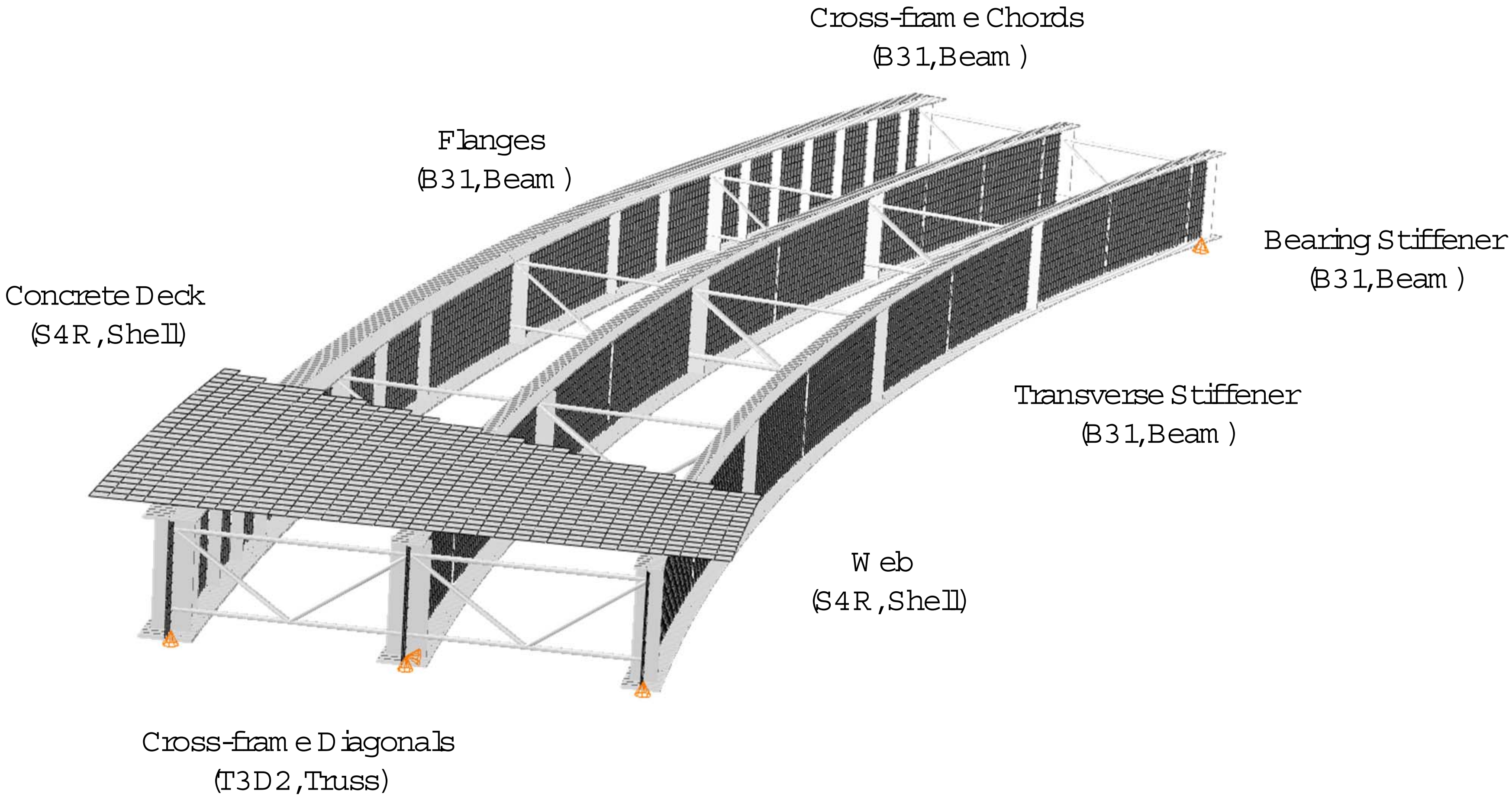
L_{max} = 214 ft



L_{max} = 279 ft

L_{max} = 326 ft

- Analytical Models



- Estimated Fit-Up Forces
  - Force applied by erector to connect steel
  - Analytically calculated as forces induced at cross-frame top and bottom connections
  - Practical simplifying assumptions:
    - No yielding
    - No incidental restraint
    - Geometry built as specified
    - Negligible "play" in connections

- Estimated Fit-Up Forces
  - Factors that influence the actual bridge erection but cannot be accounted for in practical erection analysis:
    - Tolerances and play at connections,
    - Adjustments of crane and support elevations
    - Tolerances on support elevations
    - Changes in geometry due to thermal movements, etc.
  - Sensitivity studies showed:
    - The effects of these factors were limited
    - Results were generally reliable for predicting trends in behavior

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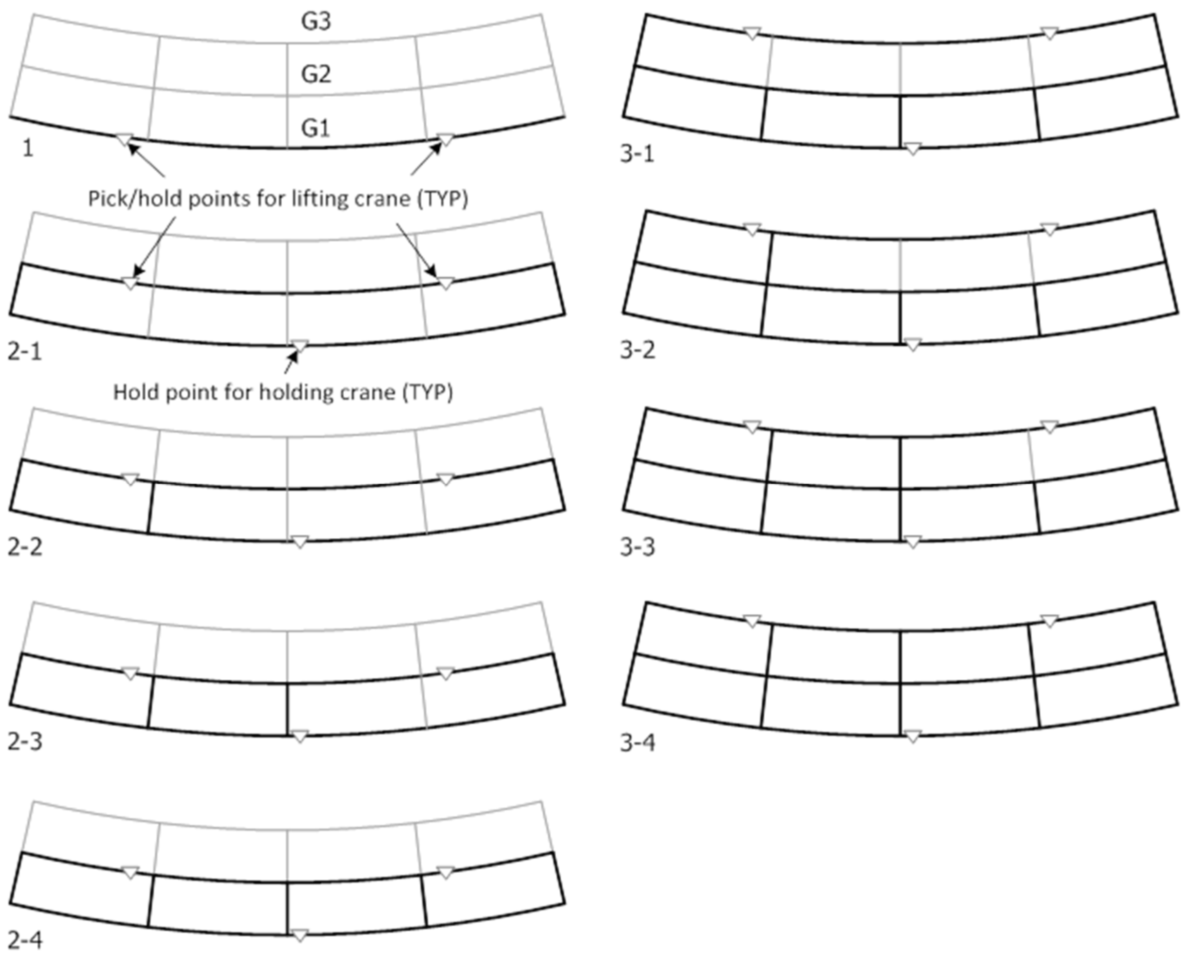
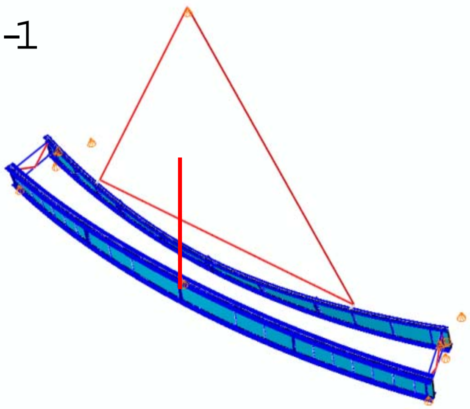
- Lifting cranes, hold cranes, temporary shoring, tie-downs all affect fit-up
- Erection sequence affects fit-up
  - Curved girder bridges
    - Erect girders from outside-in
    - Cross-frames help control geometry
  - Straight skewed bridges
    - Order of girders less important
    - Install minimal cross-frames until all girders erected
  - Curved and skewed bridges
    - Must evaluate case by case

- Example Simple Span Erection Sequence

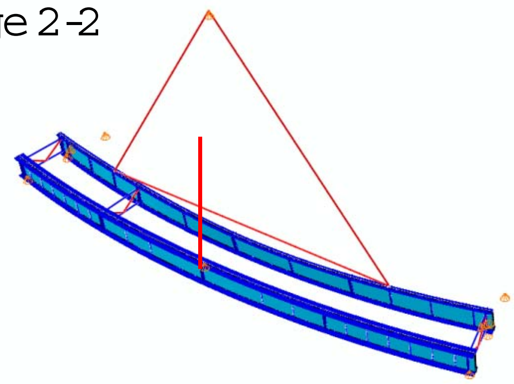


- Example Simple Span Erection Sequence

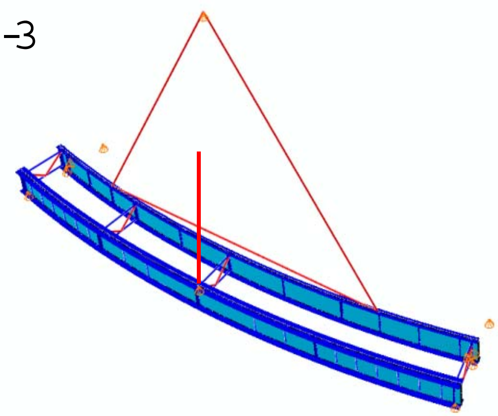
Stage 2-1



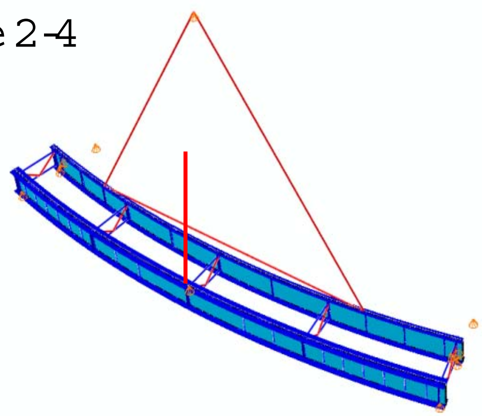
Stage 2-2



Stage 2-3

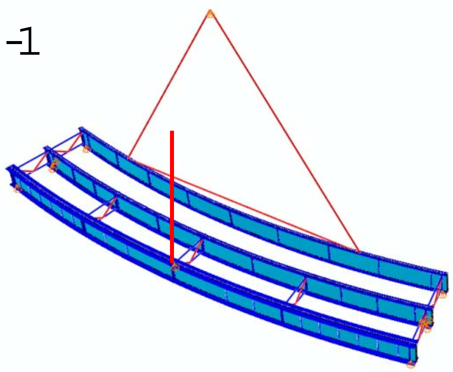


Stage 2-4

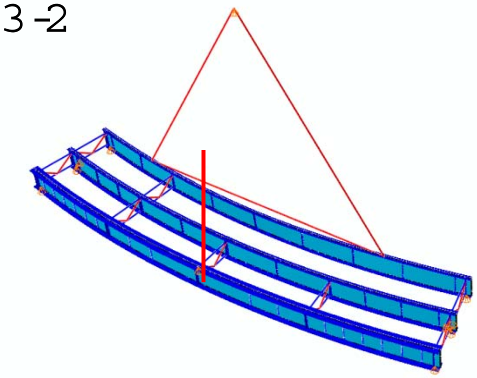


- Example Simple Span Erection Sequence

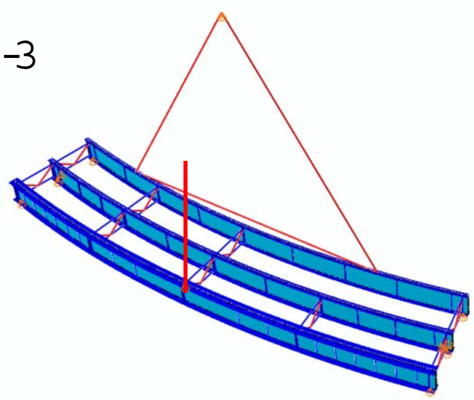
Stage 3-1



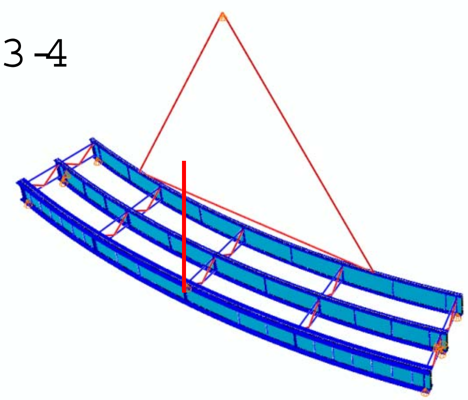
Stage 3-2



Stage 3-3



Stage 3-4



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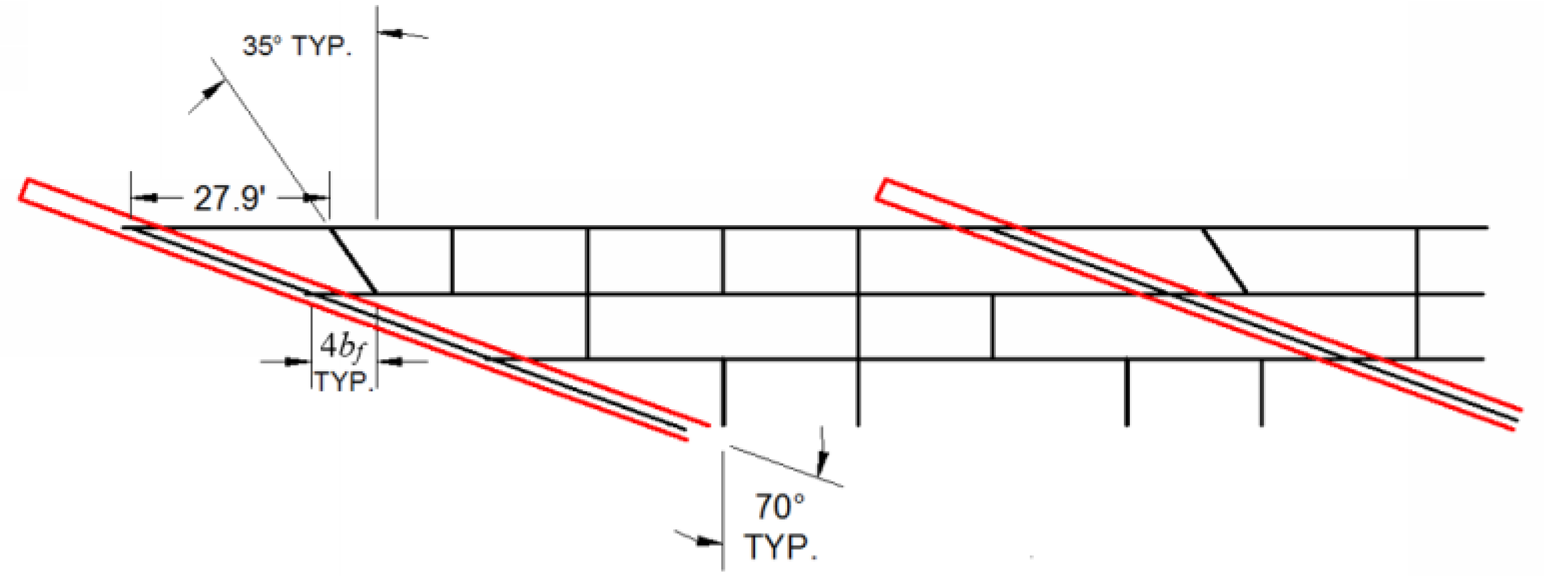
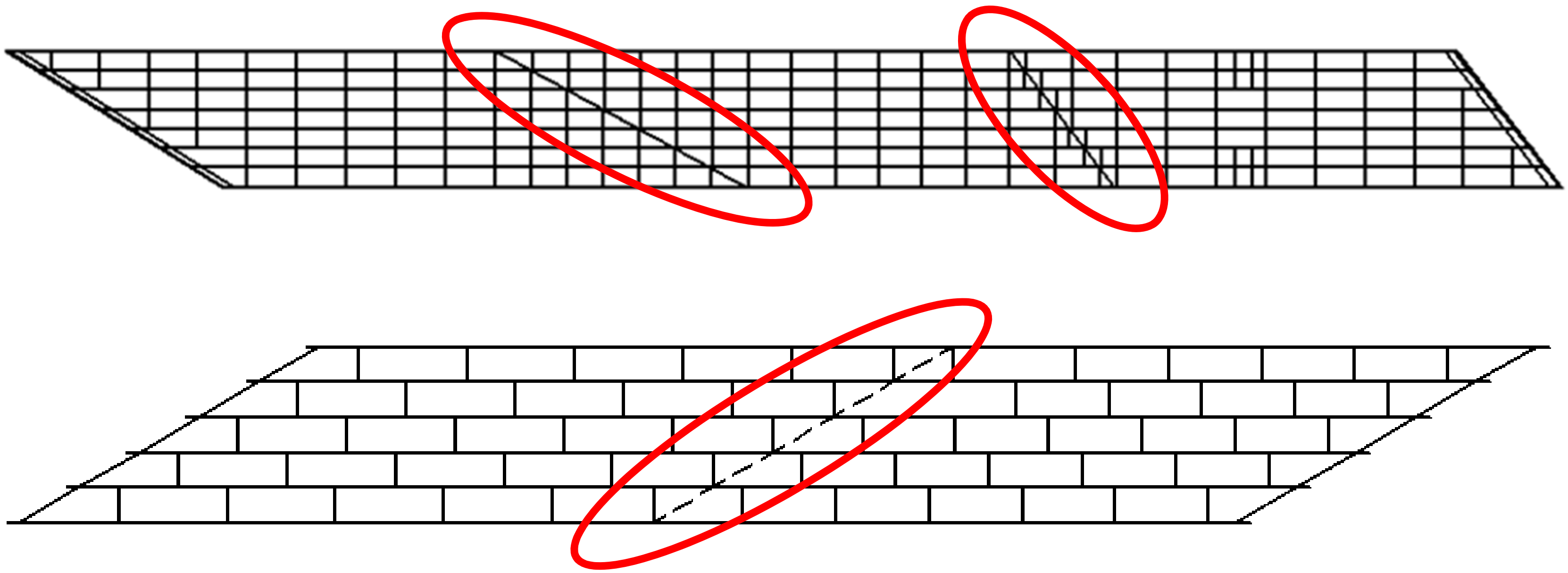
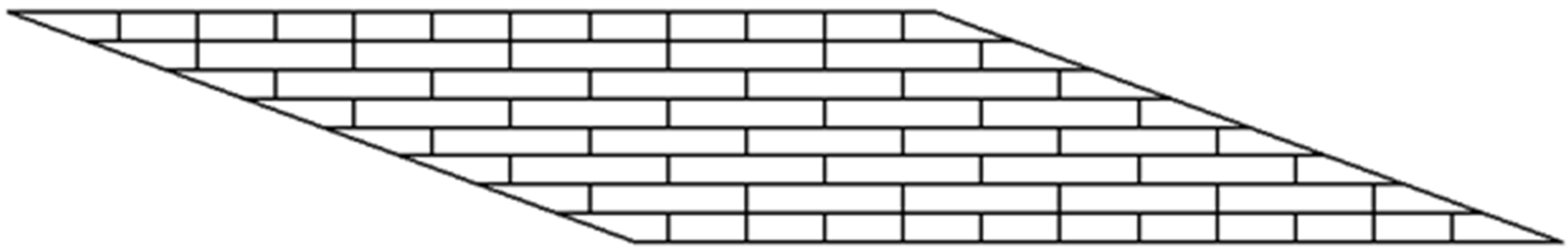
- Recommendations for skewed bridges
  - Offset first cross-frame $4b_f$ or $0.4L_b$ from skewed supports to avoid excessively large forces



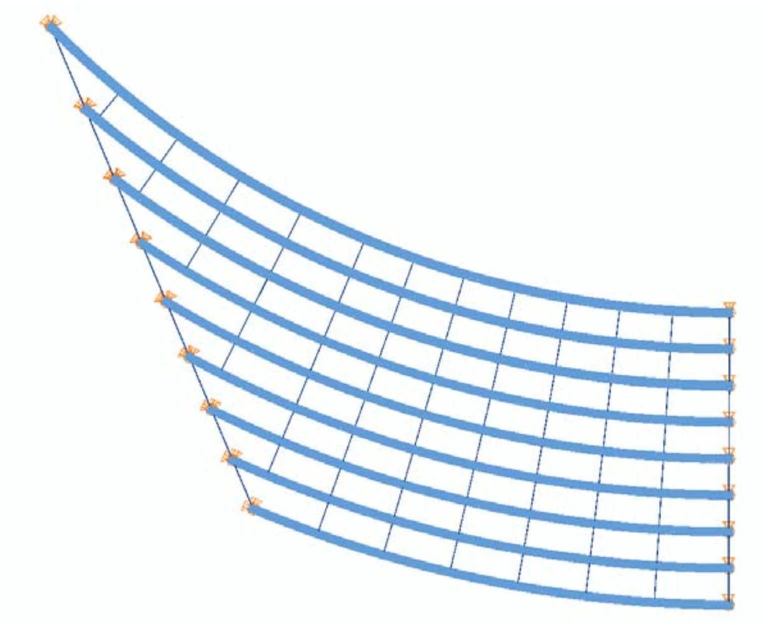
- Recommendations for skewed bridges
  - Avoid framing cross-frames directly into intermediate bearing locations

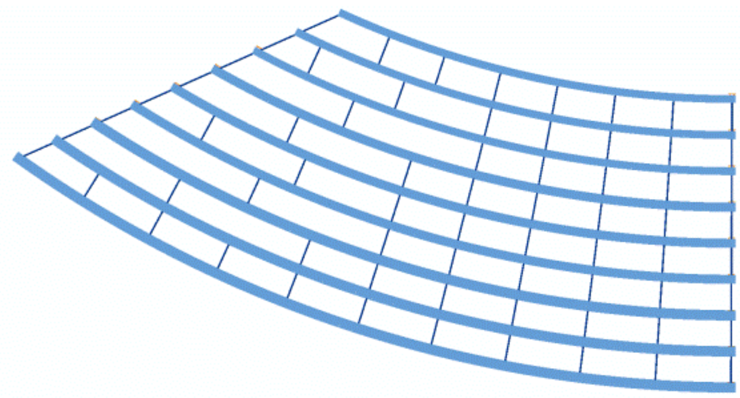


- Recommendations for skewed bridges
  - Stagger intermediate cross-frames parallel to the skew
  - Omit select cross-frames



- Recommendations for curved and skewed bridges
  - Generally use continuous cross-frames
  - Consider omitting select cross-frames near skewed supports
  - Balance goals → Cross-frame forces, flange lateral bending, uplift, etc.





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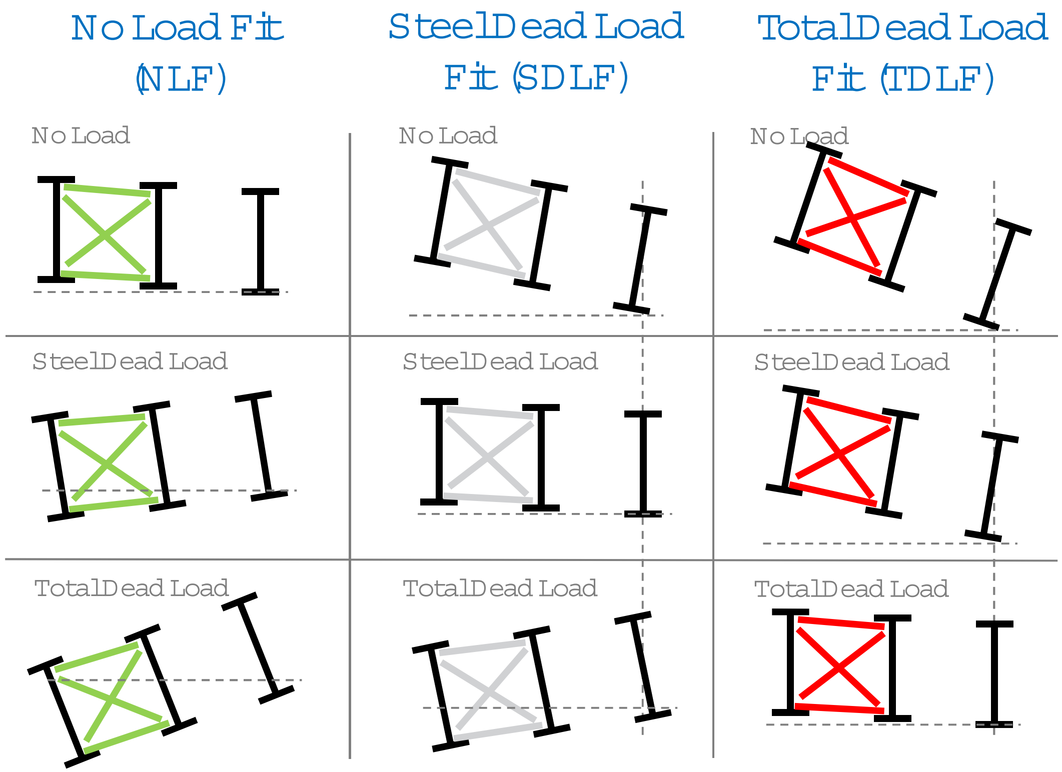
- For all studied bridges, all parametric variations
  - All 3 Fit Conditions investigated for most bridges
  - NLF not investigated for straight skewed bridges



- Fit-up forces for curved, radially-supported bridges

Bridge	L_s (ft)	w_g (ft)	R (ft)	n_g	L_s/R	L_s/w_g	Max Fit-Up Forces (kip)		
							NLF	SDLF	TDLF
(A) EISCR1	90	17.5	200	3	0.45	5.1	3.3	7.4	22.3
(B) NISCR2, Scheme 1	150	24.0	438	4	0.34	6.2	16.6	28.7	**54.0**
(B) NISCR2, Scheme 2A	"	"	"	"	"	"	**84.4**	**82.5**	**80.2**
(B) NISCR2, Scheme 2B	"	"	"	"	"	"	40.4	19.4	**50.5**
(C) NISCR7	150	74.0	280	9	0.54	2.0	21.3	35.9	**75.3**
(D) NISCR10	225	74.0	705	9	0.32	3.0	18.6	20.4	21.8
(E) EICCR11	322/417/329	40.4	∞/∞/411	4	0/0/**0.80**	8.0/**10.3**/8.1	37.5	**86.3**	**130.0**
(F) NICCR12	350/350/280	74.0	909	9	**0.39**/**0.39**/0.31	4.7/4.7/3.8	28.4	38.6	**57.4**
(G) EICCR4	219/260/211/ 162/256/190	36.7	968/3@1108 /968/∞	4	0.198/0.235/0.190/ 0.146/**0.264**/0	6.0/**7.1**/5.7/ 4.4/7.0/5.2	12.3	12.6	16.0

- Fit-up forces for straight, skewed bridges

Bridge	L_{max} (ft)	L_{min} (ft)	w_g (ft)	θ (deg)	n_g	I_s	L_{max}/w_g	L_{min}/w_g	Max Fit-Up Forces (kip)	
									SDLF	TDLF
(H1) EISSS57	211	63	61.0	69.5/-4.4	7	0.77	3.5	1.0	5.0	15.0
(H2) EISSS57	"	"	"	"	"	"	"	"	5.0	14.2
(I1) NISSS14	150	150	74.0	70	9	1.36	2.0	2.0	3.6	15.3
(I2) NISSS14	"	"	"	"	"	"	"	"	2.5	7.5
(J1) NISSS54	300	300	74.0	70	9	0.68	4.1	4.1	9.2	**73.5**
(J2) NISSS54	"	"	"	"	"	"	"	"	8.4	**47.9**
(K1) EICSS12	150/139	150/139	41.0	59.6	6	0.47/**0.50**	3.7/3.4	3.7/3.4	0.6	6.3
(K2) EICSS12	"	"	"	"	"	"	"	"	0.4	7.7
(K3) EICSS12	"	"	"	"	"	"	"	"	1.2	17.0
(L) NICSS16	120/**150**/**150**	120/150/150	74.0	70	9	**1.69**/1.36/1.36	1.6/2.0/2.0	1.6/2.0/2.0	0.8	36.9
(M1) EICSS2	**259**/255/220	241/183/220	66.6	58/61.8/38/38	8	0.48/**0.49**/0.23	3.9/3.8/3.3	3.6/2.7/3.3	4.9	**46.9**
(M2) EICSS2	"	"	"	"	"	"	"	"	0.8	2.8

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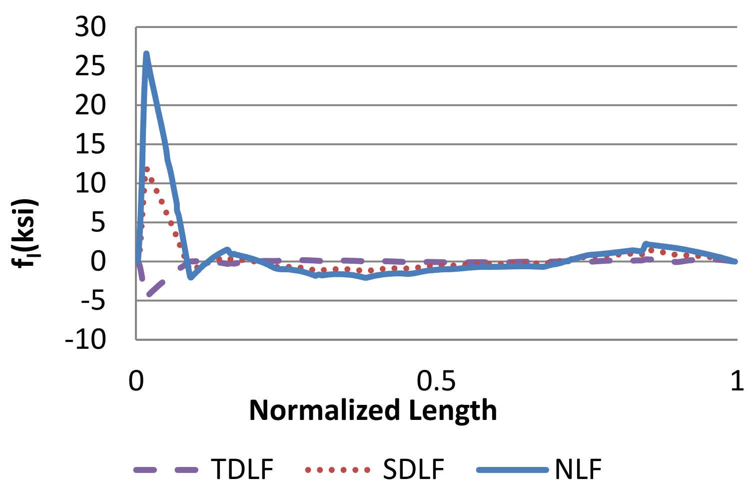
- SDLF, TDLF → Lack-of-Fit (LOF)
- LOF → "Force fit" → "Locked in" forces
- Later DL Forces
  - Straight skewed bridges → Generally relieving
  - Curved girder bridges → May be additive
- Engineers rarely consider these effects…

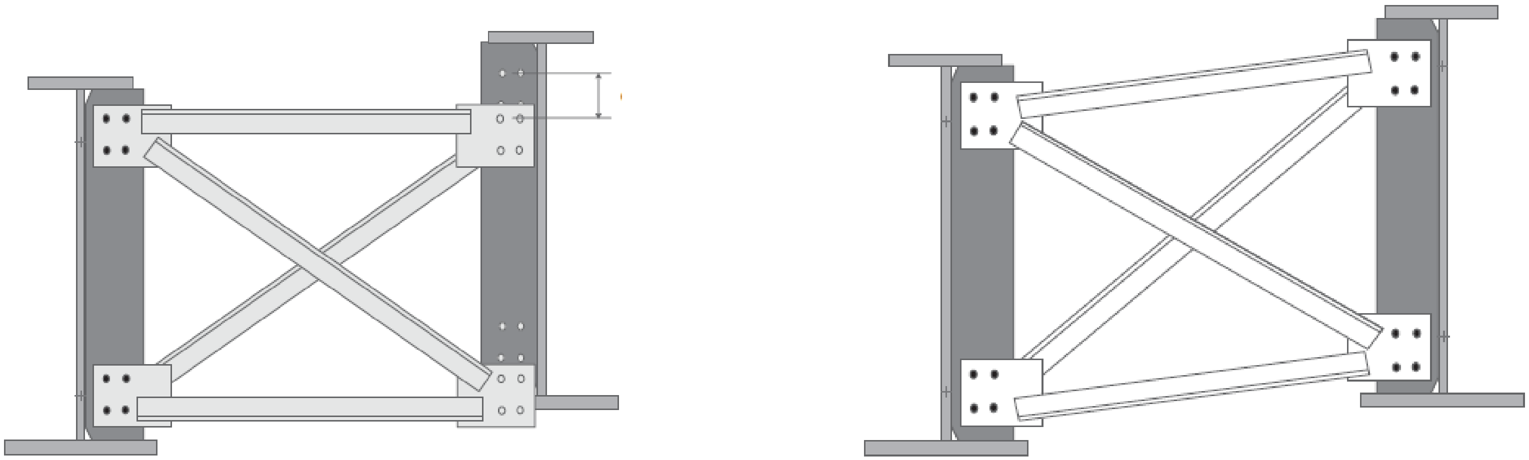


- Rigorous approach to LOF analysis
  - Calculate initial strains

Engineering strain $\varepsilon_{initial} = \frac{L_2 * \cos(\alpha) - L_1}{L_1}$

Rotated engineering strain $\varepsilon_{initial} = \frac{L_2 - L_1}{L_1}$

Log strain $\varepsilon_{initial} = ln \frac{L_2}{L_1}$



L_1 L_2

- Rigorous approach to LOF analysis
  - Fundamentally not difficult, but…
  - Challenging in practical terms
    - Time consuming by hand
    - Considerable efforts via analysis software
- Alternatives:
  - Simplified load factor approach for straight, skewed bridges with TDLF – AASHTO LRFD BDS C6.7.4.2

$$\left(\gamma_{\mathrm{p}}\right)_{\mathrm{red}} = \left(\gamma_{\mathrm{p}} - 0.4\right)$$

  - Georgia Tech software tool

- Georgia Tech LOF analysis tool
  - Developed as part of research project
  - Procedures and examples in research report
- Required input
  - Framing layout
  - Girder, cross-frame sizes
  - Boundary conditions
- Output
  - Fixed end forces (for 2D grid analysis)
  - Initial strains (for 3D FEA)

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- Bridge behavior is reasonably predictable
- Construction inspectors should:
  - Know and understand the Fit Condition
  - Assess constructed geometry:
    - At end of erection
    - After deck placement
  - Know when to do something
  - Know when to do nothing
  - Know when to call the engineer

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- NSBA Fit Paper Recommendations

Straight Bridges

Square Bridges and Skewed Bridges up to 20 deg +/- Skew			
	Recommended	***Acceptable***	***Avoid***
Any span length	Any		None
Skewed Bridges with Skew > 20 deg +/- and $I_s \le 0.30$ +/-			
	Recommended	***Acceptable***	***Avoid***
Any span length	TDLF or SDLF		NLF
Skewed Bridges with Skew > 20 deg +/- and $I_s > 0.30$ +/-			
	Recommended	***Acceptable***	***Avoid***
Span lengths up to 200' +/-	SDLF	TDLF	NLF
Span lengths greater than 200' +/-	SDLF		TDLF & NLF

$$\text{Skew Index, } I_s = \frac{w_g \tan\theta}{L}$$

- NSBA Fit Paper Recommendations

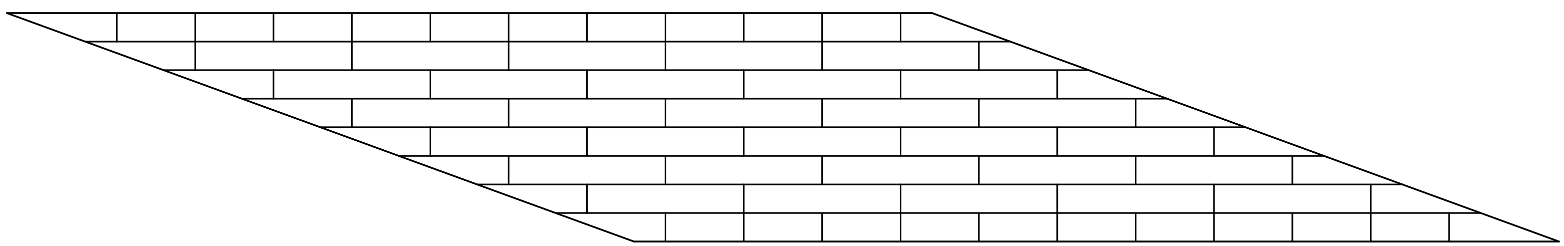
Curved Bridges

Curved Bridges with Radial or Skewed Supports			
	Recommended	***Acceptable***	***Avoid***
Span lengths greater than 250' +/- and *L*/*R* > 0.1 +/-	NLF	SDLF	TDLF
All other cases	SDLF	NLF	TDLF

- AASHTO LRFD BDS 8th Ed. Revisions
  - 6.7.2: More explicit language about specifying the Fit Condition, with recommendations
  - C6.7.2: Extensive revisions
    - Substantial discussion about the Fit Condition
    - Modified load factor approach for reducing design forces when TDLF is used in straight skewed bridges

$$\left(\gamma_{\mathrm{p}}\right)_{\mathrm{red}} = \left(\gamma_{\mathrm{p}} - 0.4\right)$$

- AASHTO LRFD BDS 8th Ed. Revisions
  - C6.7.4.2: Extensive revisions, presenting suggestions for efficient framing arrangements in skewed bridges
    - Offset first cross-frame 4b_f or 0.4L_b from skewed supports (skew > 20 deg)
    - Suggested minimum stagger dimension
    - Recommendations for omitting select cross-frames



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Recap

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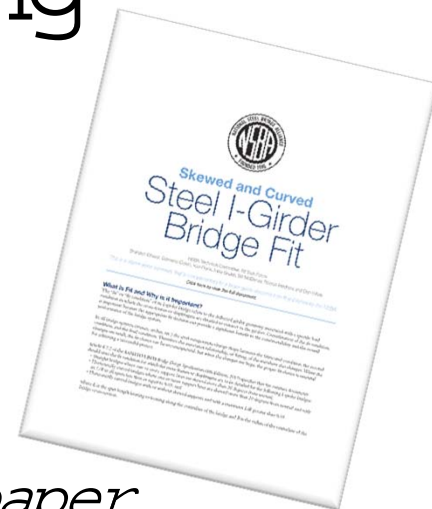
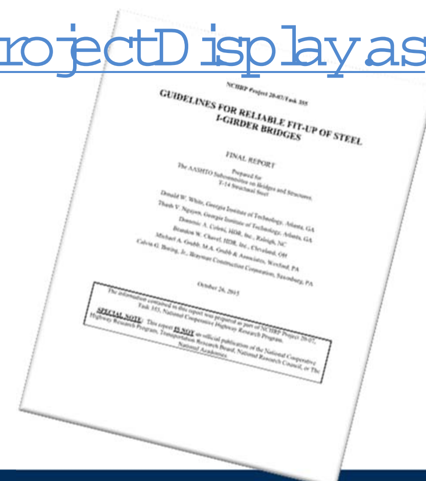
Recommended Reading



- NSBA Fit Paper (executive summary)
  - www.steelbridges.org/bridgefit
- NSBA Fit Paper (full length)
  - *Link provided in the executive summary paper*
- NCHRP 20-07 Task 355 Final Report
  - http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3735



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Questions?