Refined Analysis and Design of Concrete Bridge Decks

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Background

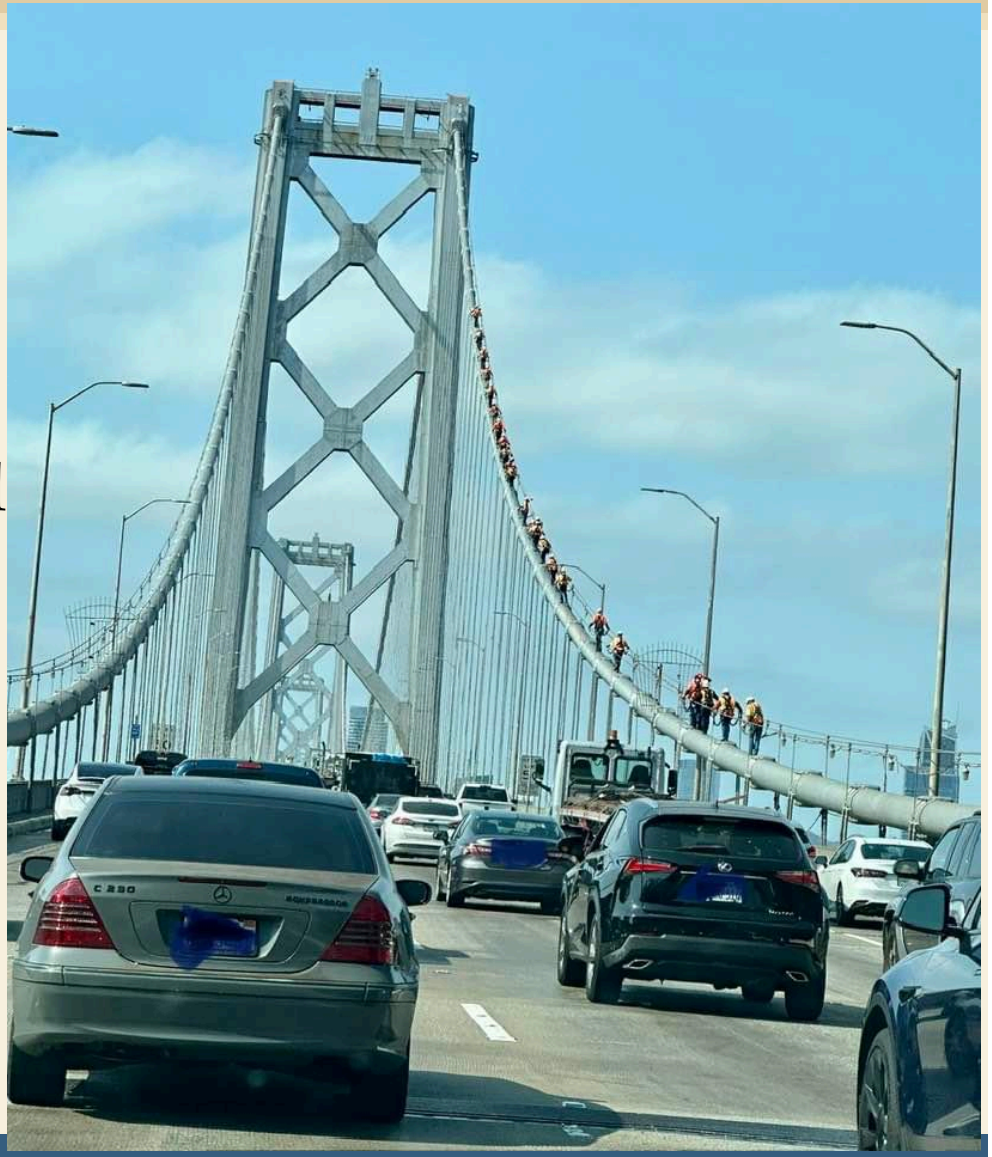
- Bridge live loads and truck volume have been continuously increasing since 1960's
- Truck loads and wheel configurations for bridge deck design no longer reflect the modern trucks, let alone larger permit vehicles (e.g., CA P-15), special hauling vehicles (SHV) and emergency vehicles (EV)
- Existing and new bridges are prone to loss of performance, cracking and failure under high-cycle fatigue loading caused by daily traffic during their service lives (Schijve 2009)
- Bridge deck analysis method categorized by AASHTO LRFD Bridge Design Specifications: (1) approximate method (lower accuracy and conservative); (2) refined method (preferred but lack guidance); and (3) empirical method (not allowed in CA)

Objectives

- To develop an updated LRFD-based bridge deck design procedure based on refined analysis methods
- To incorporate modern vehicle configurations, dynamic loads, flexural and shear demands into the refined analysis
- To conduct the state-of-the-art review of fatigue models for concrete bridge decks and provide a methodology for future consideration

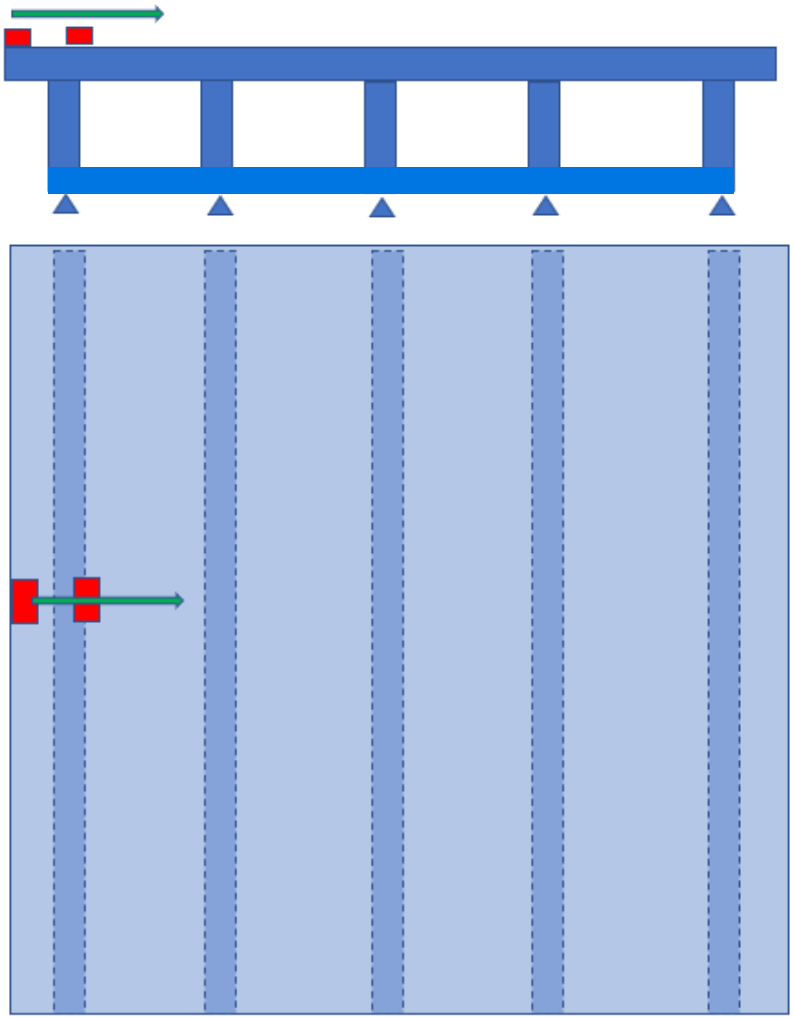
Planned Tasks

- Task **1** – Finite Element Modeling of Bridge Decks
- Task **2** – Literature Survey and Concrete Fatigue Model
- Task **3** – Parametric Studies and Capacity Demands Database
- Task **4** – Quantitative Assessment of Approximate Method
- Task **5** – Recommendations on Desk Design Method

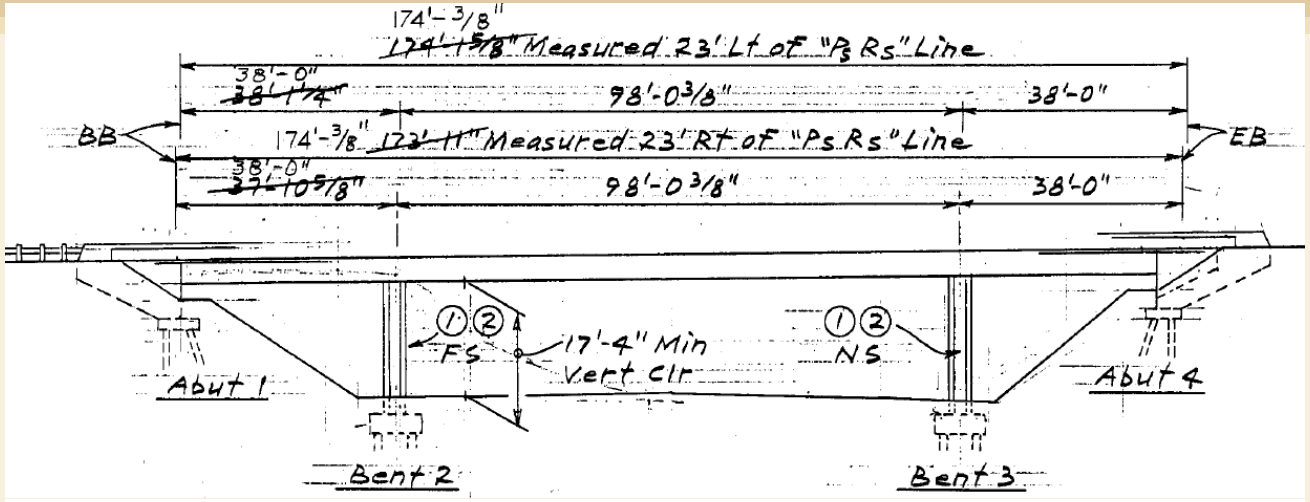


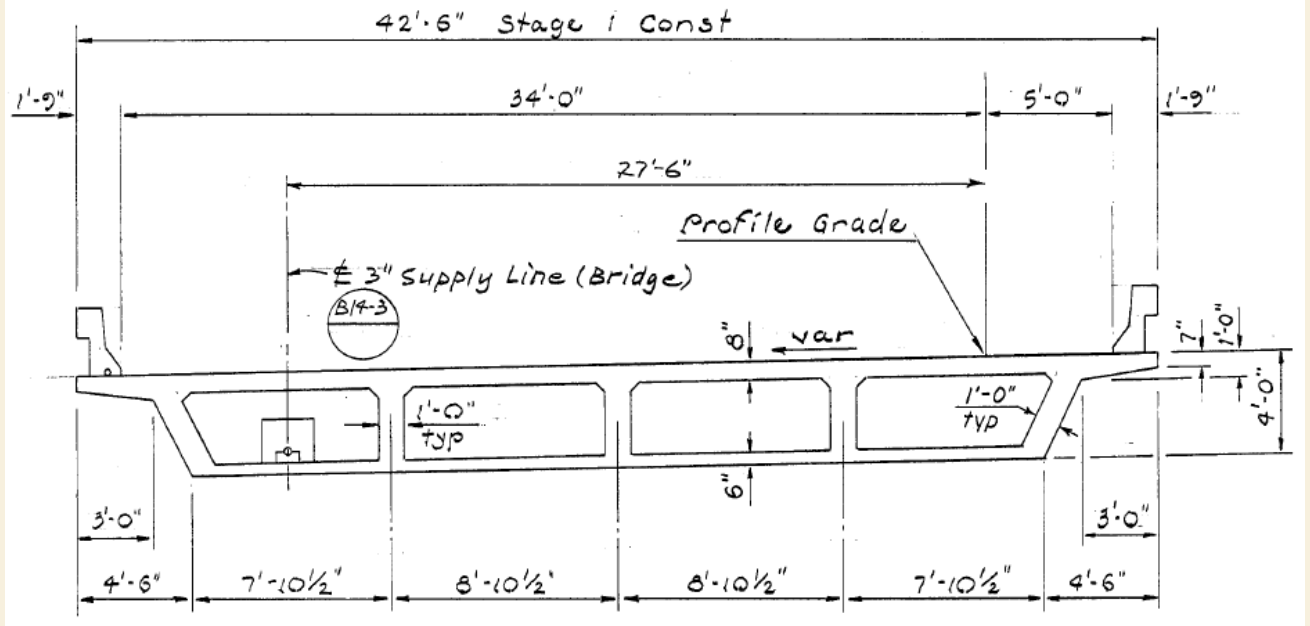
Task 1 – Finite Element Modeling of Bridge Decks

- Bridge type: cast-in-place/prestressed box girder (future: precast/prestressed "I" girders)
- Narrow down focused parameters to girder spacing, tire pressure, critical load combination, etc. and provide load demand database for deck design
- Strategy: use rigid support model as an alternative to conservatively envelope results of refined FE model, but still provide good reliability and be representative of real bridge cases (girders restrained from vertical movement yet allowed to rotate; HL-93 axle load; and 125 psi tire pressure 16×10")



Task 1 – CIP/PS Box - Example 1





Small box

As built Br# 49-0165L, 8/20/92

Span length: **38′ + 98′ + 38′**

Total width: 42′-6″

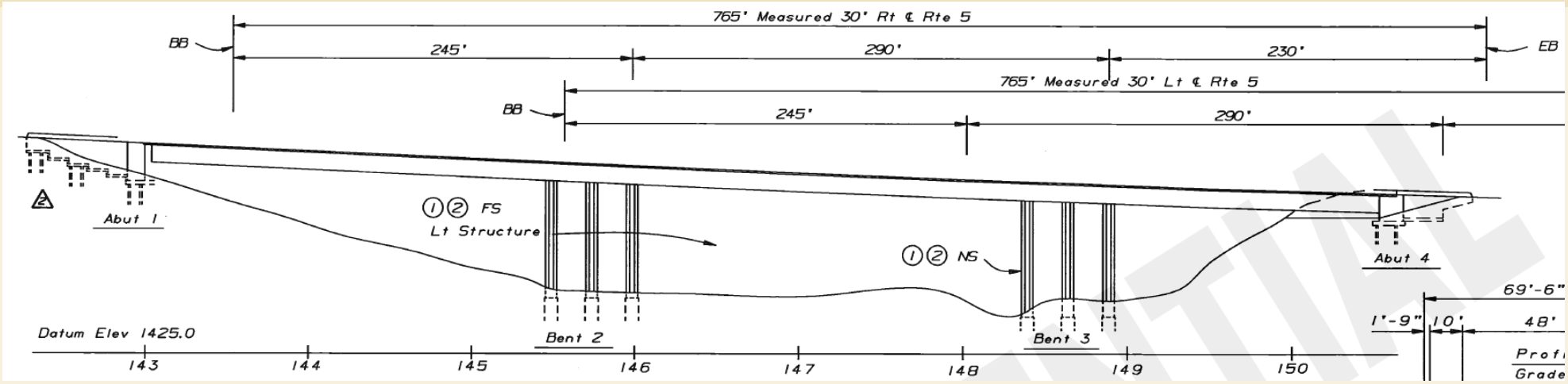
Four-cell box girder

Web thickness: 12″

Deck thickness: 8″

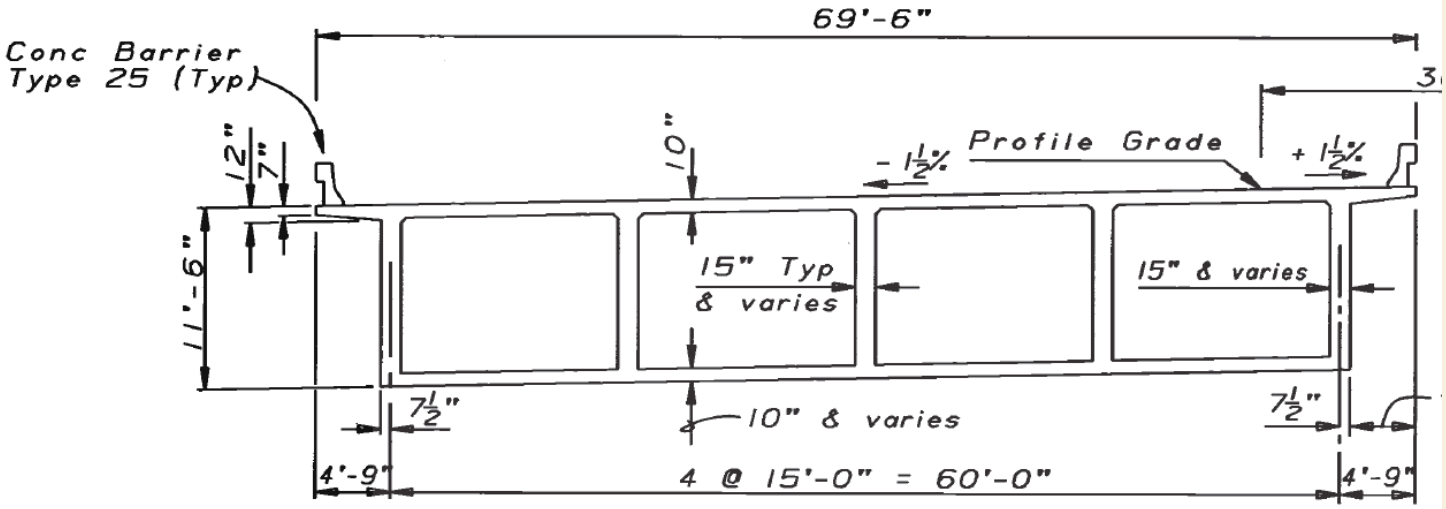
Soffit thickness: 6″

Task 1 – CIP/PS Box - Example 2



Large box

As built Br No 53-2790L, 1/26/94 Span length: **245′ + 290′ + 230′**



Total width: 69′-6″

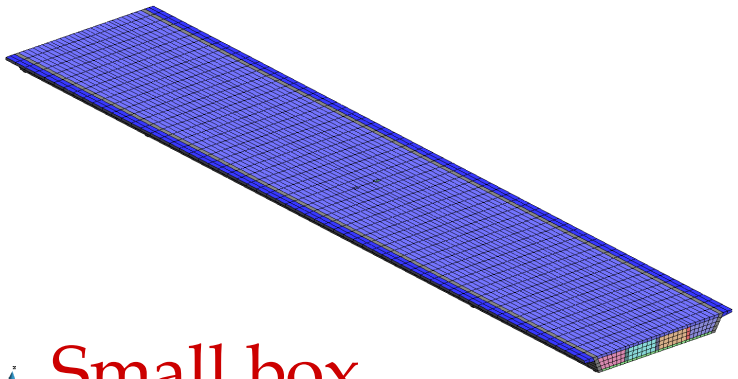
Four-cell box girder

Web thickness: 15″

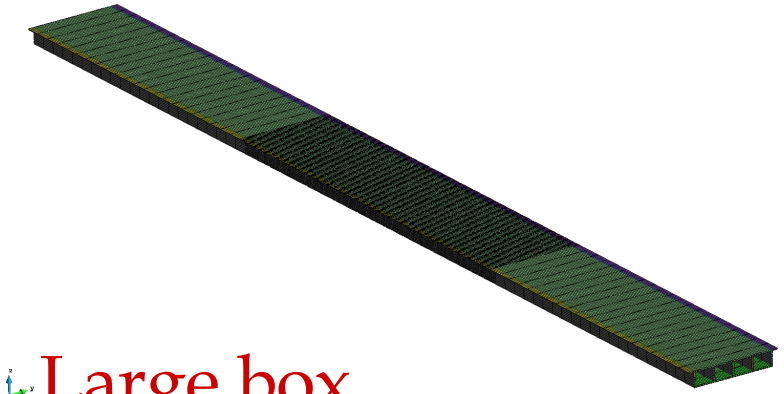
Deck thickness: 10″

Soffit thickness: 10″

Task 1 – FE Refined Model (ATENA)

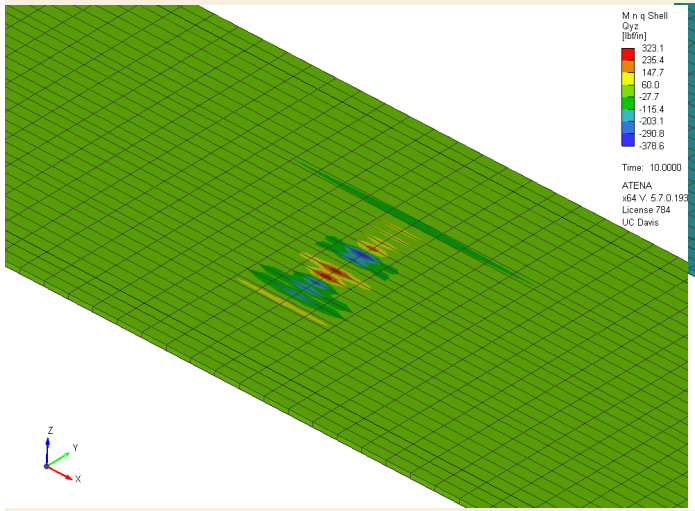


Small box

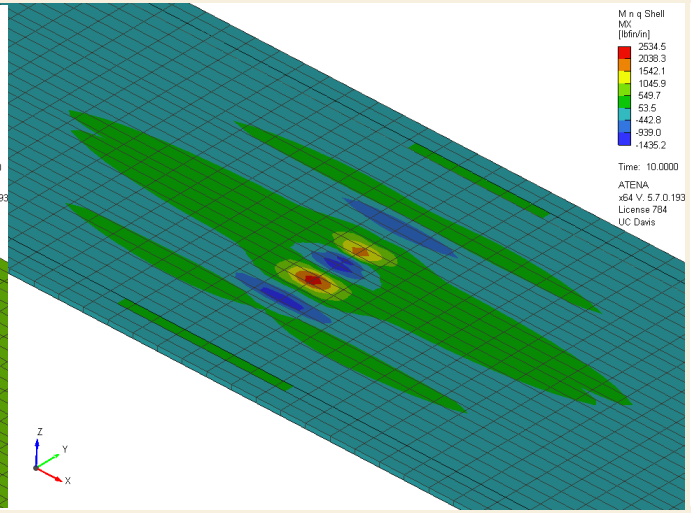


Large box

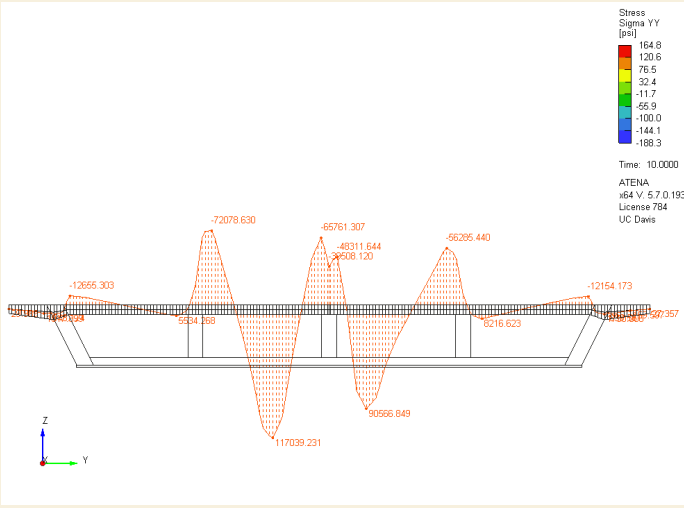
FE models in preprocessor GID



Shear (Q_{yz})



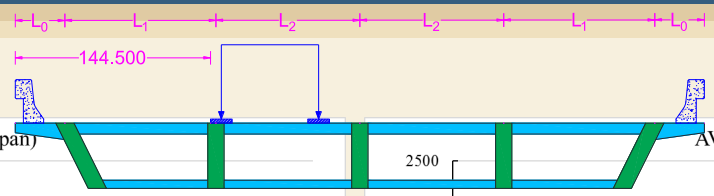
Moment (M_x)

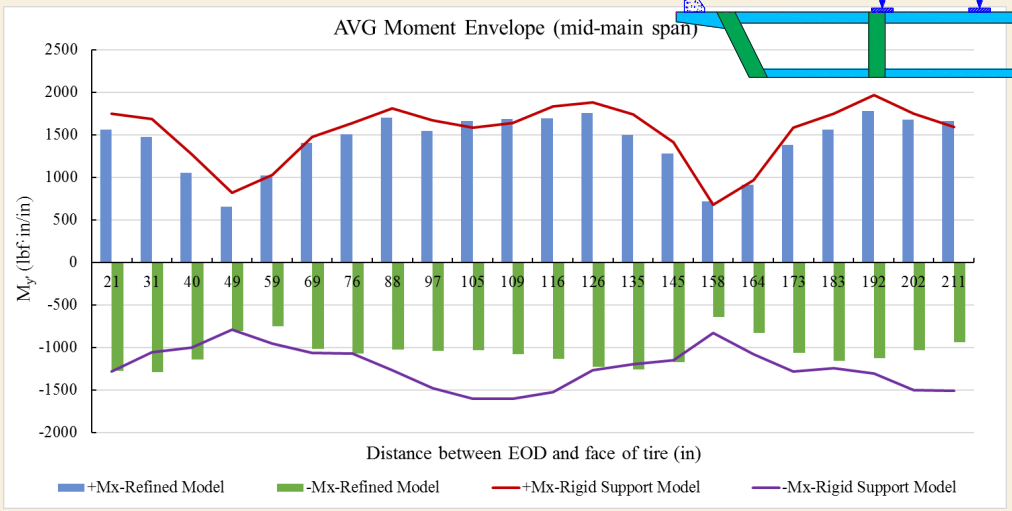


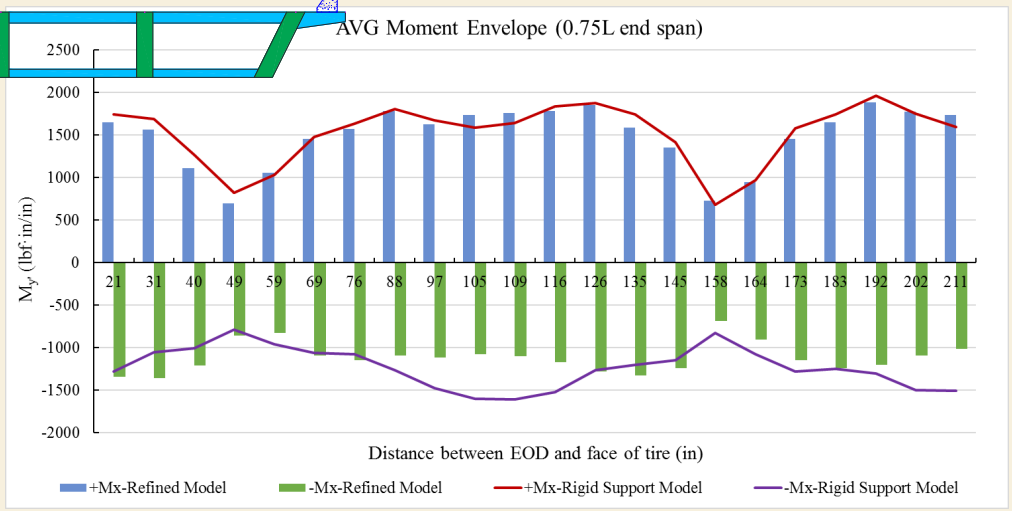
Moment (M_x) Diagram

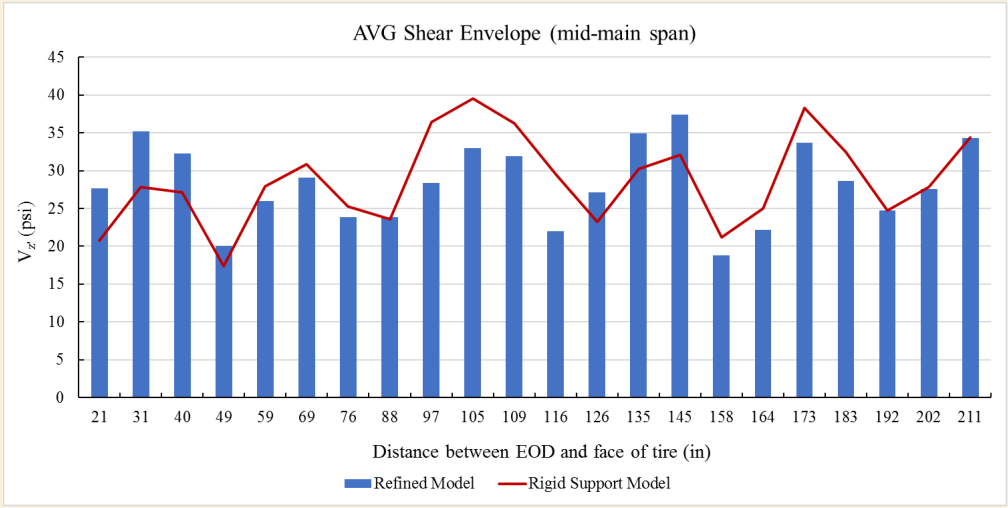
Task 1 – Analysis Results Summary

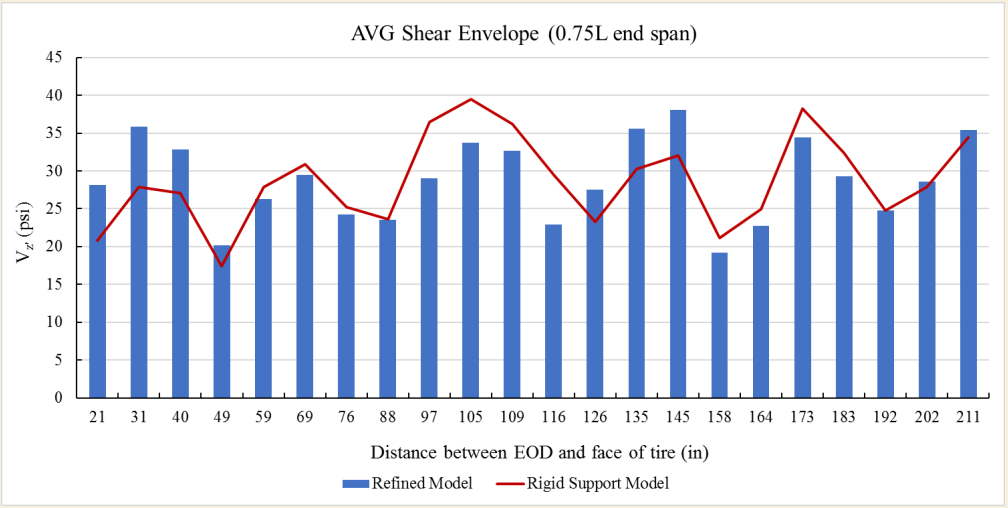
Small box











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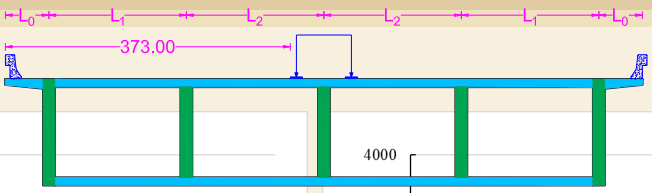

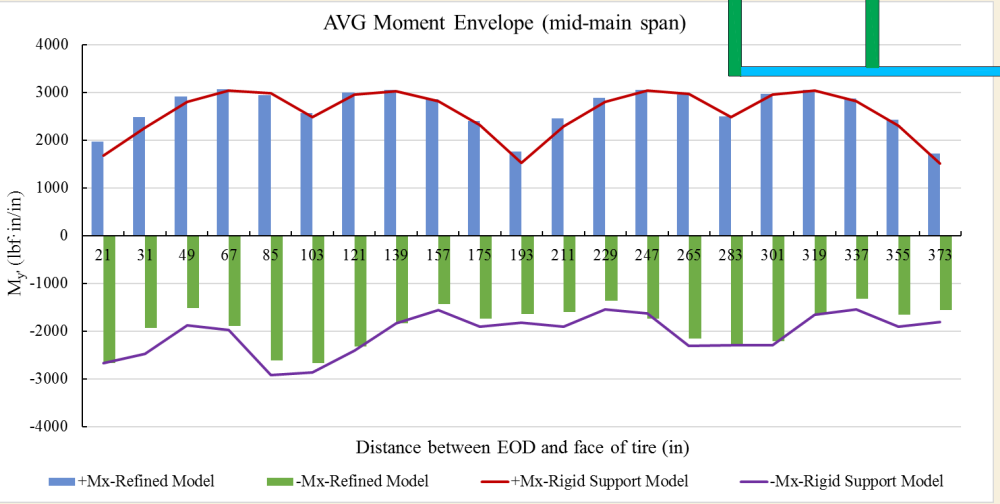

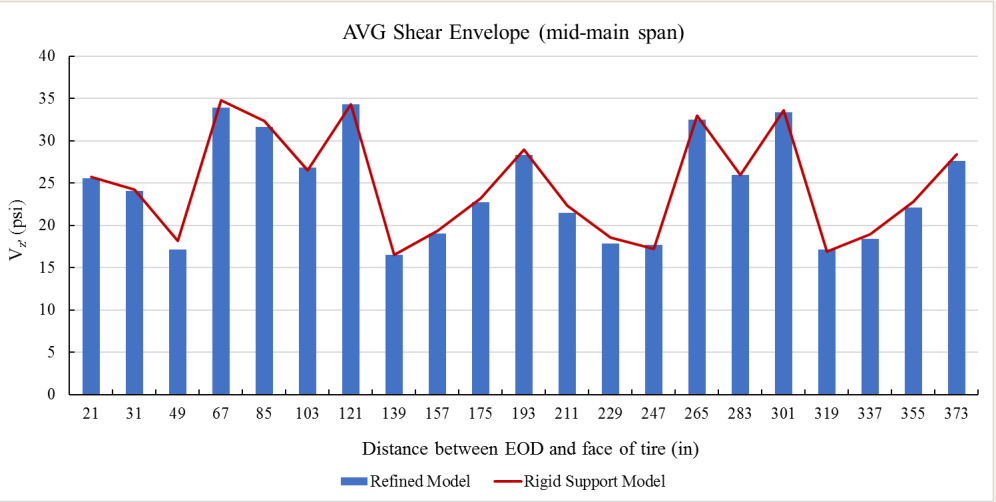

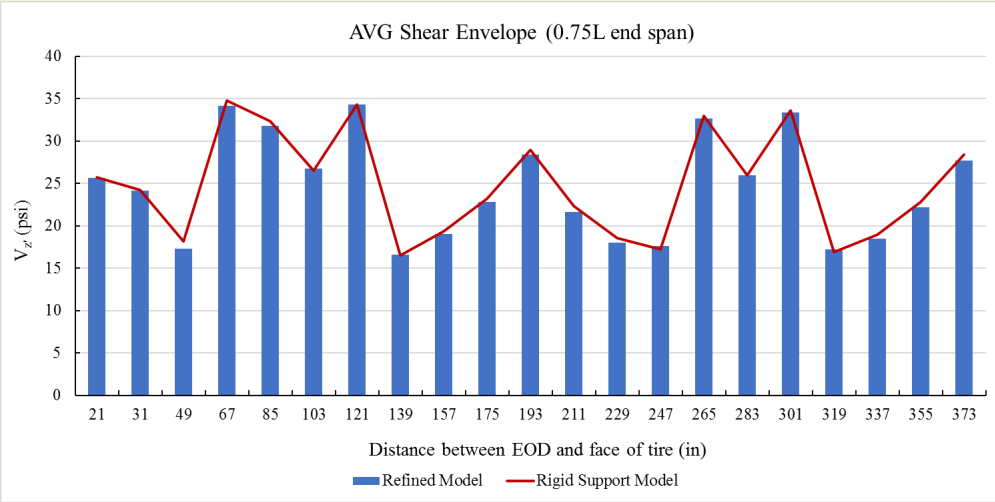

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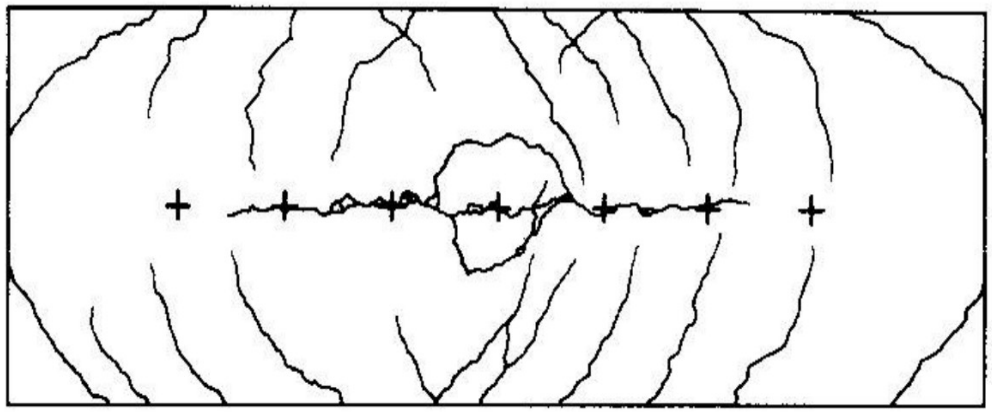
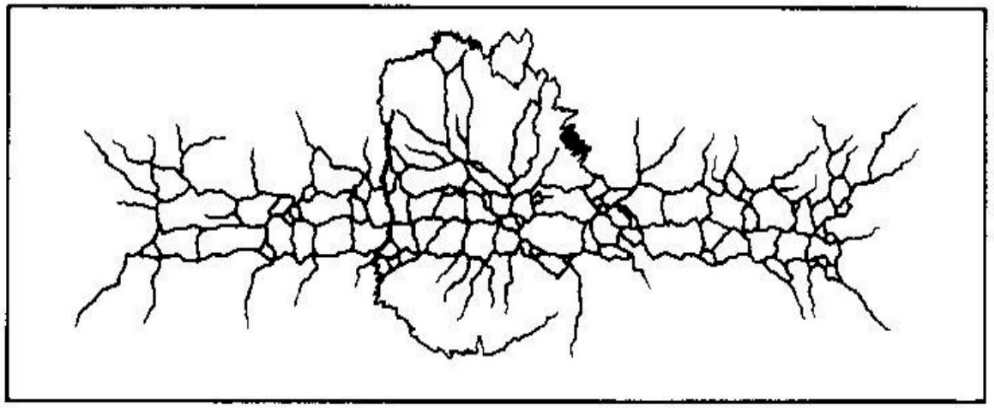


TOP SIDE



BOTTOM SIDE

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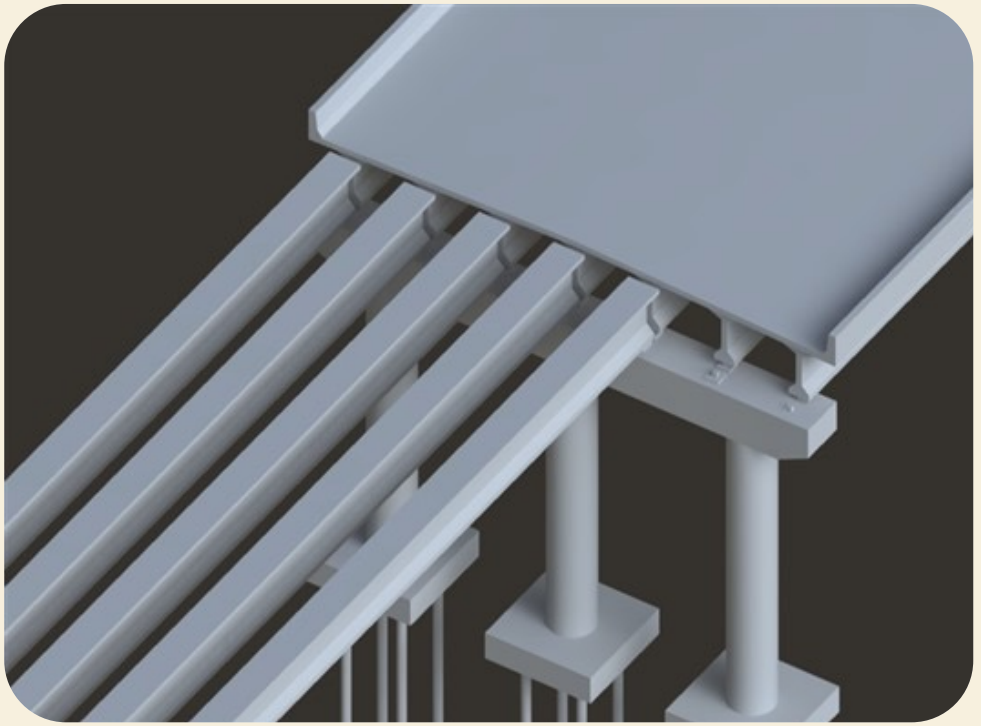
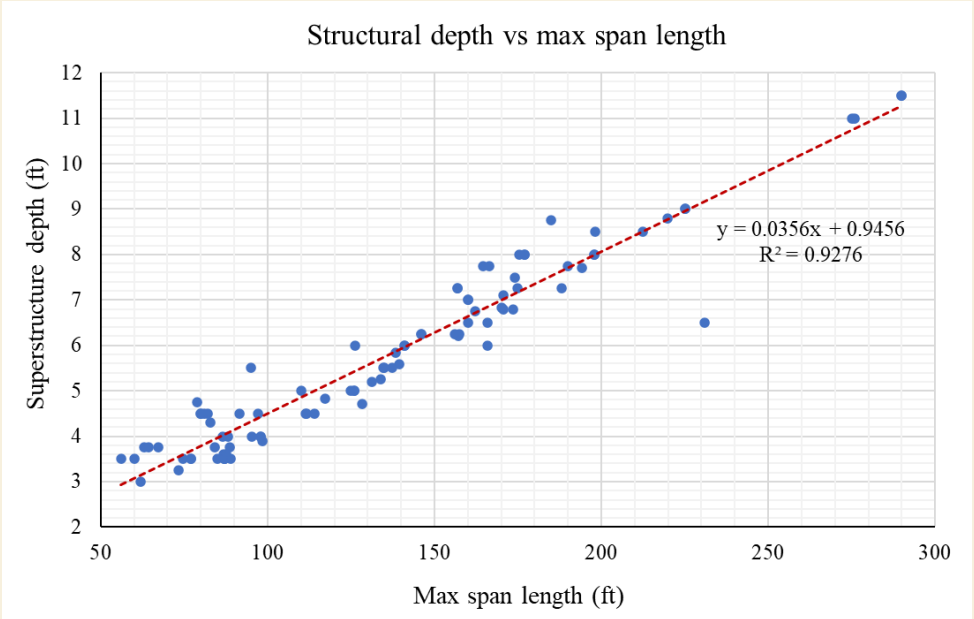


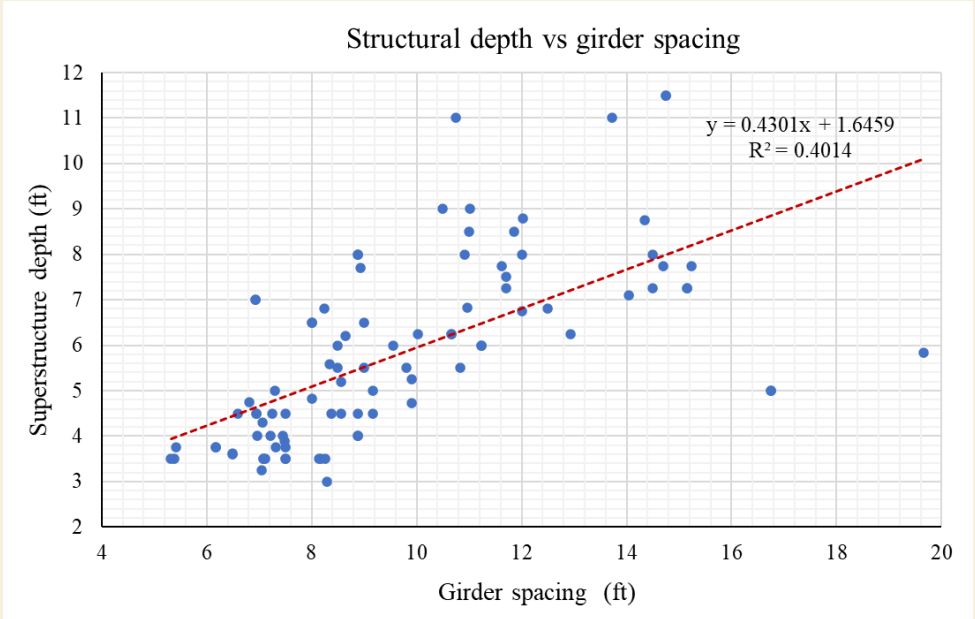
Task 3 - Parametric Studies & Capacity Demands Database

Summary of typical parameter ranges of 120+ bridges in the database

Parameter	Range	Parameter	Range
Max span length (ft)	59 – 290	Structural depth (ft)	3 – 11.5
Girder spacing (ft)	5.32 – 19.67	Total deck width (ft)	27.5 – 245.5
Top deck thickness (in)	6.75 – 10.43	Soffit thickness (in)	5.5 – 10.43
Single overhang width (ft)	2 – 7.08	Overhang/spacing	0.1 – 0.65
No. of cells	2 – 26	No. of spans	1 – 13

❖ Regression analysis for correlations among some of these parameters





Task 3 - Parametric Studies & Capacity Demands Database

Girder Spacing (ft)	No. of cells	BDM 9.4 Oct2021 Deck Thickness (in)	Clear Overhang Width (ft)	Total Deck Width (ft)	Type 732 Barrier (in)	Max. No. of Design Lanes
4	4	8	2	21	17	1
6	4	8	3	31	17	2
9	4	8.125	3	43	17	2
12	4	9.125	4	57	17	2
15	4	10.375	4	69	17	3
9	2	7.125	3	25	17	1
15	2	10.375	4	39	17	2

- Run deck slab rigid support analysis and check AASHTO Appendix A4.
- Utilizing existing two prototype bridge models (longitudinal Case C with 2 spans), run refined analysis for both small and large box girder bridges.
- Focus on HL-93 and P15 loading (tire pressure of 125 psi/no deck cross slope).
- Capture the average shear stress within deck thickness.
- Negligible difference in load demands by using truck axle load and entire truck load.

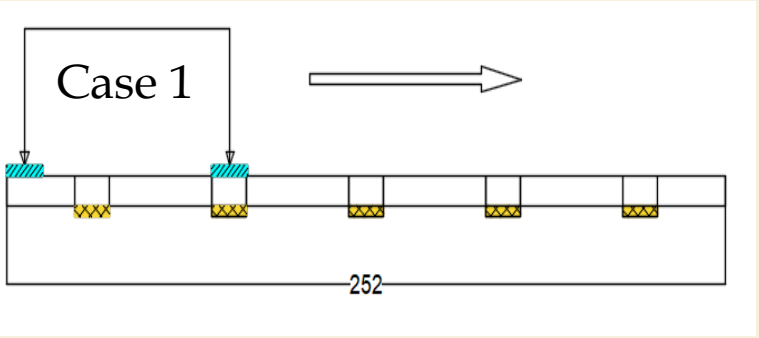
Girder S (ft)	# of Cell	Truck Cases	Total Comb
4	4	Case 1	19
6	4	Case 1	21
		Case 2	31
		Case 3 (4 ft apart)	25
		Case 3.5 (5 ft apart)	13
		Case 4 (6 ft apart)	12
9	4	Case 1	22
		Case 2	32
		Case 3 (4 ft apart)	16
		Case 3.5 (6.5 ft apart)	15
		Case 4 (9 ft apart)	13
12	4	Case 1	21
		Case 2	34
		Case 3 (4 ft apart)	18
		Case 3.5 (8 ft apart)	16
		Case 4 (12 ft apart)	15

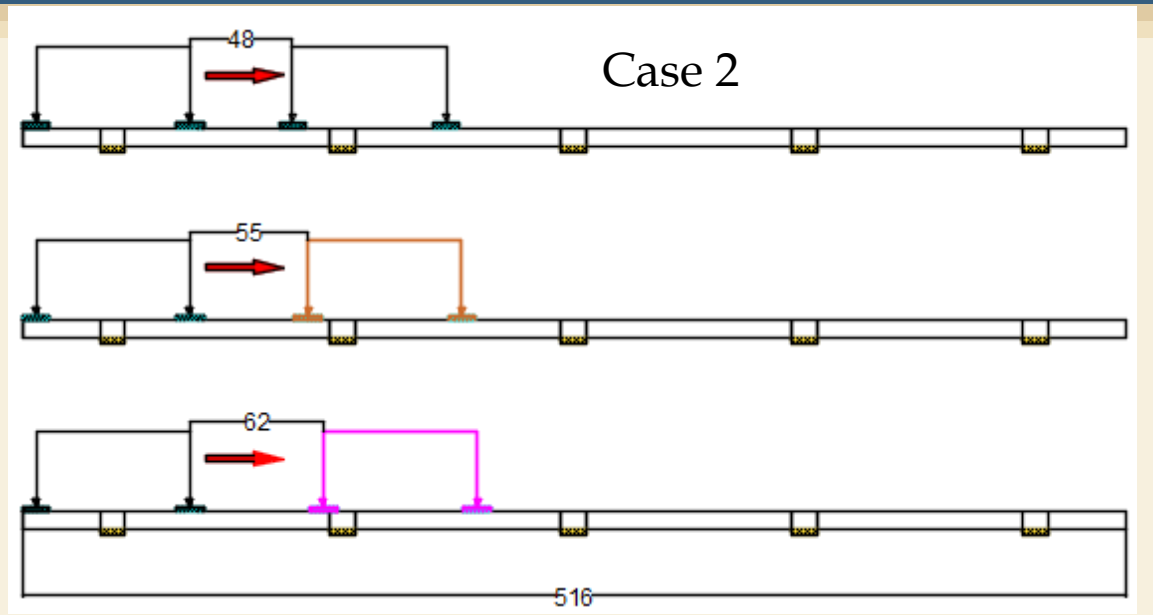
Girder S (ft)	# of Cell	Truck Cases	Total Combo
15	4	**Case 1**	**22**
		Case 2	36
		Case 3 (4 ft apart)	19
		Case 3.5 (9.5 ft apart)	17
		Case 4 (15 ft apart)	15
9	2	Case 1	12
15	2	Case 1	12
		Case 2	16
		Case 3 (4 ft apart)	9
		Case 3.5 (9.5 ft apart)	7
		Case 4 (15 ft apart)	5

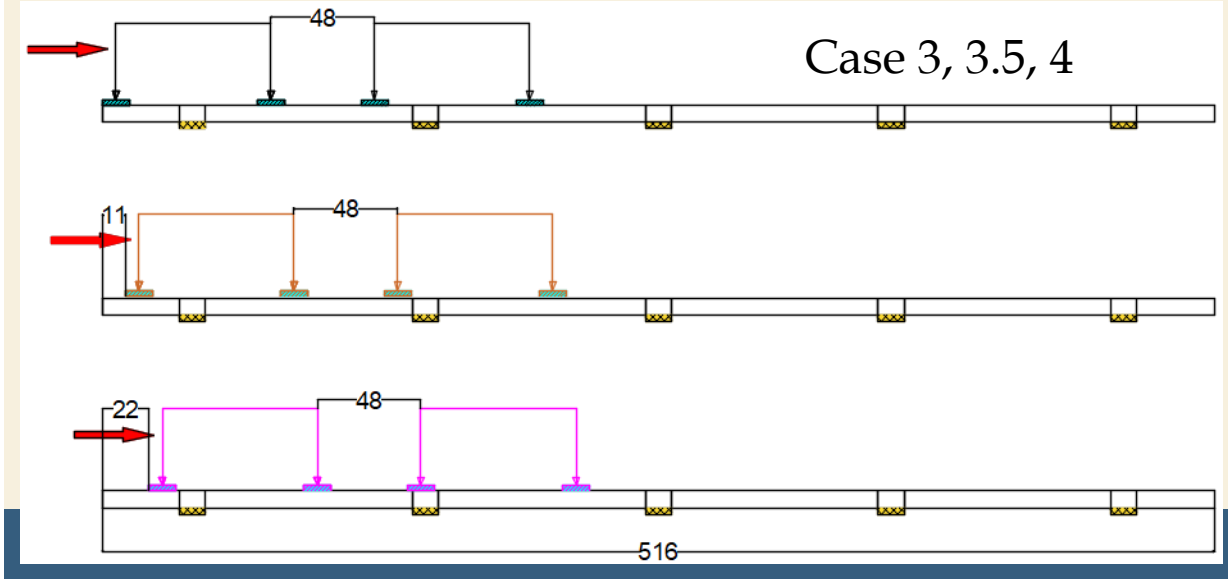
Total = 526 combinations

- **Case 1**: Single truck moving across
- **Case 2**: 1st truck stationary at girder end and 2nd truck moving away
- **Case 3**: 2 trucks 4-ft apart move together
- **Case 3.5**: 2 trucks 9.5 ft apart move together
- **Case 4**: 2 trucks 15-ft apart moving together

Task 3 - Parametric Studies & Capacity Demands Database



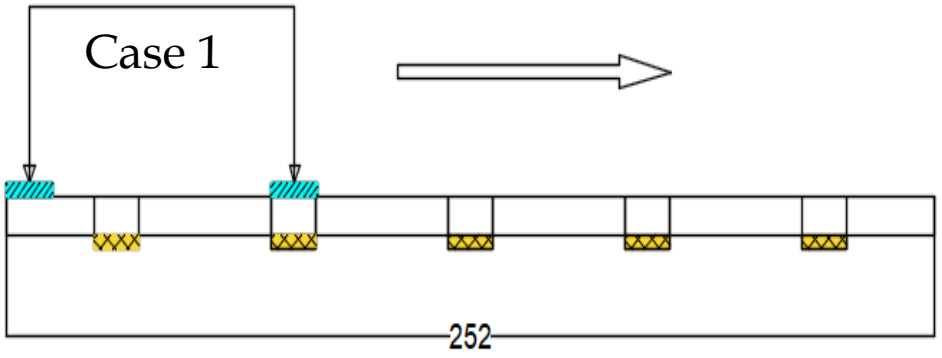




Task 3 - Parametric Studies & Capacity Demands Database

Single Truck Example:

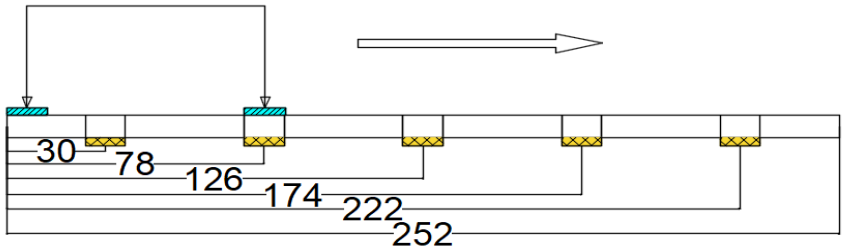
girder spacing = 4 ft



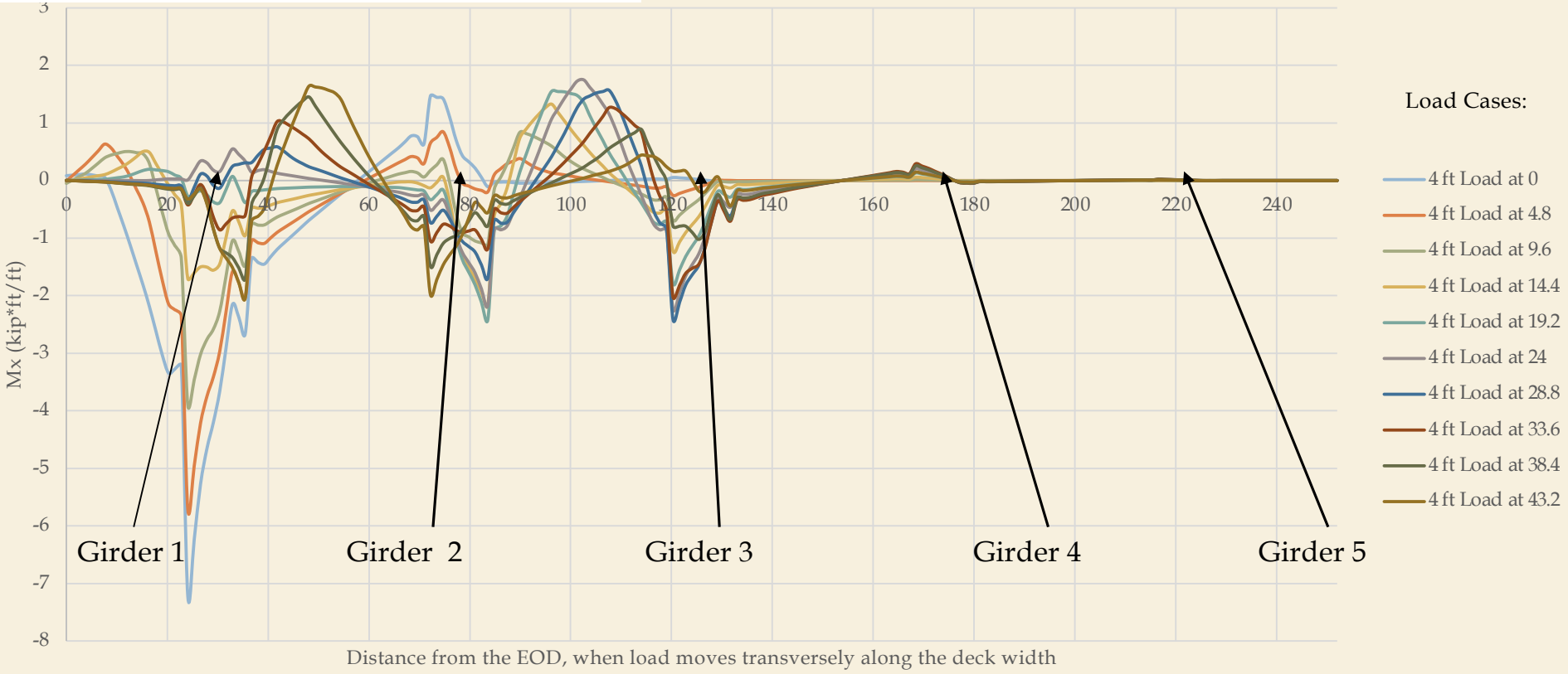
Comb #	Girder Spacing	Distance from the face of the tire to the EOD (in)
1	4 ft.	0
2		4.8
3		9.6
4		14.4
5		19.2
6		24
7		28.8
8		33.6
9		38.4
10		43.2

- Single truck moves transversely at 10% of girder spacing (10%x4 ft = 0.4 ft = 4.8 in) → a total of 10 combinations until one of the patch loads (truck tires) crosses the centerline of the bridge

Task 3 - Parametric Studies & Capacity Demands Database

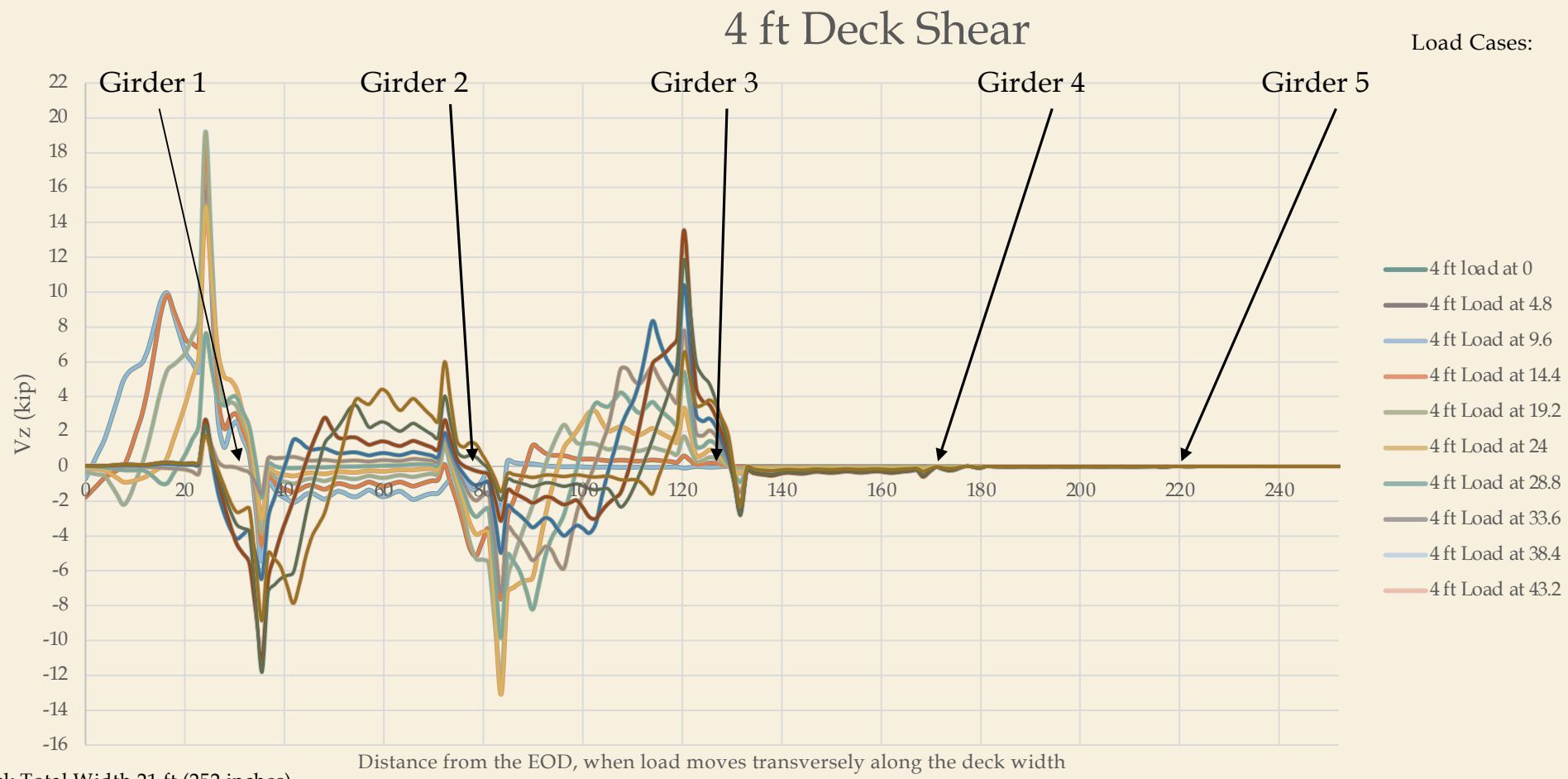


4 ft Deck Moment



* Deck Total Width 21 ft (252 inches)

Task 3 - Parametric Studies & Capacity Demands Database



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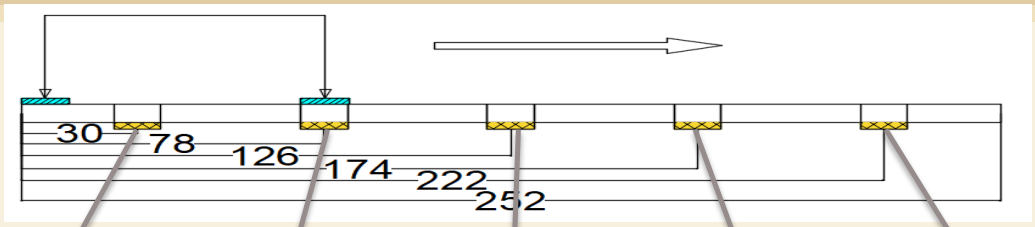
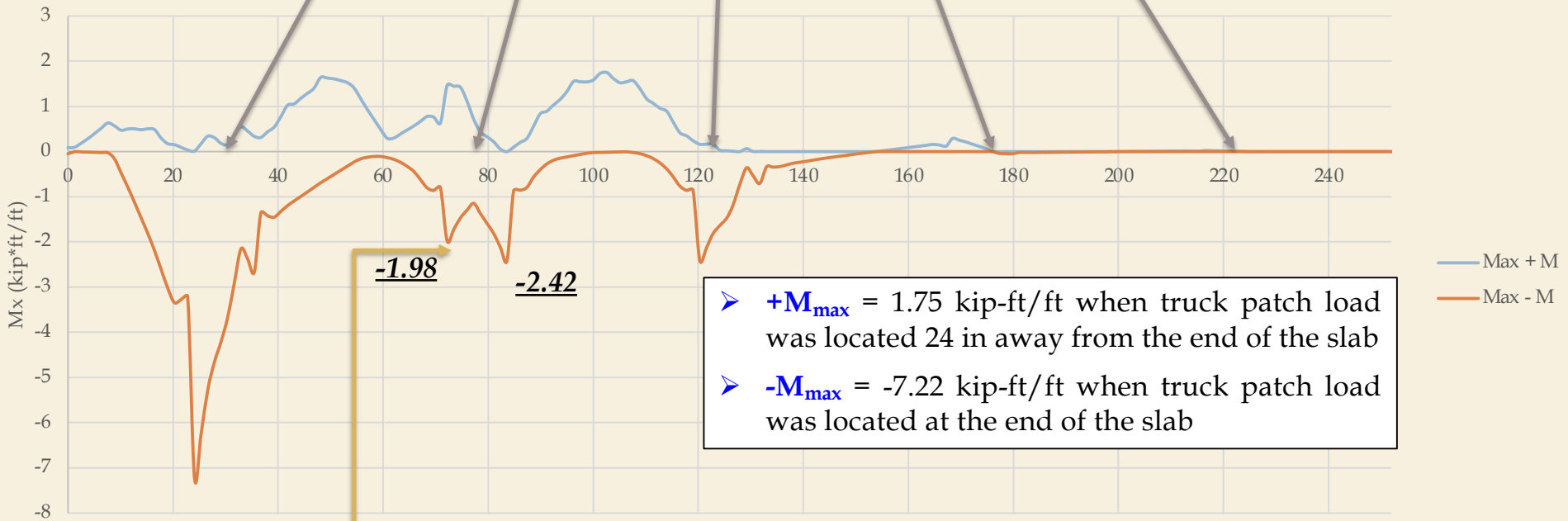
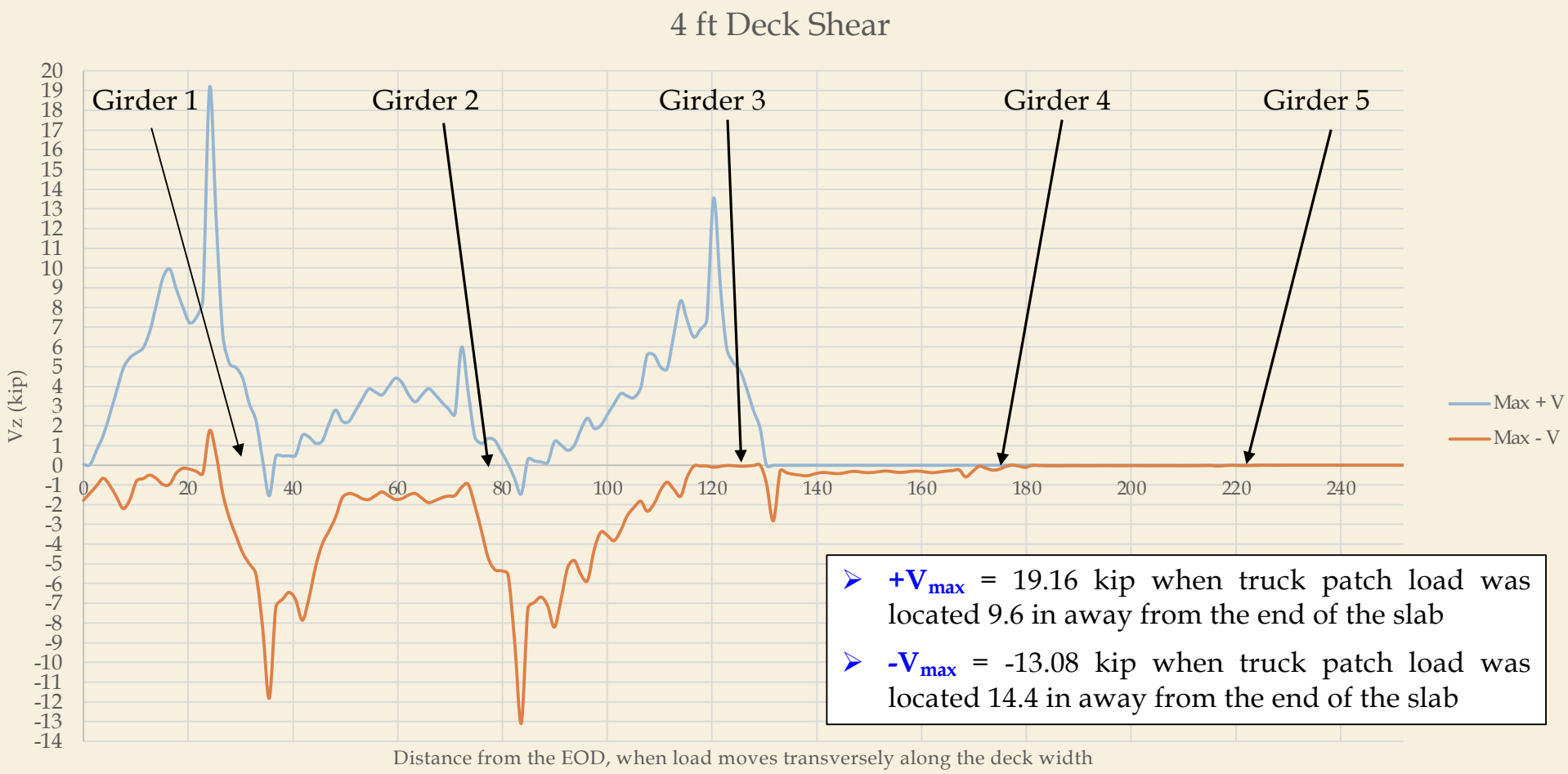




- $+M_{max}$ = 1.75 kip-ft/ft when truck patch load was located 24 in away from the end of the slab
- $-M_{max}$ = -7.22 kip-ft/ft when truck patch load was located at the end of the slab

Load placed at 4.4 ft (52.8 in) from the end of the deck

Task 3 - Parametric Studies & Capacity Demands Database



- $+V_{max}$ = 19.16 kip when truck patch load was located 9.6 in away from the end of the slab
- $-V_{max}$ = -13.08 kip when truck patch load was located 14.4 in away from the end of the slab

* Deck Total Width 21 ft (252 inches)

Deck Slab	Position of the first truck - from the face of the tire to the end of the Deck (ft)	Max	Unfactored Values	Factored Values **	The exact location of Max values (The distance from the face of the tire to the end of the Deck (ft)	Total Deck Length	CL of the Deck
4 ft	2 ft (24 in)	+ M (kip-ft/ft)	1.78	2.84	4.54 ft (54.45 in)	21 ft (252 in)	10.5 ft (125 in)
	0 ft (0 in)	- M (kip-ft/ft)	-2.53	-4.04	6 ft (72.19 in)		
	0.8 ft (9.6 in)	+ V (kip/ft)	11.5	-	7 ft (83.58 in)		
	1.2 ft (14.4 in)	- V (kip/ft)	-7.71	-	7 ft (83.58 in)		
6 ft	5.4 ft (64.8 in)	+ M (kip-ft/ft)	2.37	3.78	6 ft (72.9 in)	31 ft (372 in)	15.5 ft (186 in)
	0 ft (0 in)	- M (kip-ft/ft)	-3.4	-5.43	9 ft (108.4 in)		
	7.8 ft (93.6 in)	+ V (kip/ft)	9.25	-	9 ft (108.4 in)		
	9.97 ft (119.6 in)	- V (kip/ft)	-9.31	-	9.97 ft (119.6 in)		
9 ft	7.2 ft (86.4 in)	+ M (kip-ft/ft)	2.89	4.61	8 ft (95.94 in)	43 ft (516 in)	21.5 ft (258 in)
	0 ft (0 in)	- M (kip-ft/ft)	-4.29	-6.85	2.1 ft (14.5.2 in)		
	1.8 ft (21.6 in)	+ V (kip/ft)	11.3	-	3 ft (36.32 in)		
	7.2 ft (86.4 in)	- V (kip/ft)	- 10.42	-	13 ft (155.6 in)		
12 ft	9.6 ft (115.2 in)	+ M (kip-ft/ft)	3.47	5.54	10 ft (120.3 in)	57 ft (684 in)	28.5 ft (342 in)
	1.2 ft (14.4 in)	- M (kip-ft/ft)	-6	-9.58	16 ft (192.5 in)		
	2.4 ft (28.8 in)	+ V (kip/ft)	12.6	-	4 ft (48.13 in)		
	16.8 ft (201.6 in)	- V (kip/ft)	- 7.9	-	17 ft (202.8 in)		
15 ft	10.5 ft (126 in)	+ M (kip-ft/ft)	3.73	5.95	11 ft (133.1 in)	69 ft (828 in)	34.5 ft (414 in)
	0ft (0 in)	- M (kip-ft/ft)	-6.99	-11.16	19 ft (228.8 in)		
	12 ft (144 in)	+ V (kip/ft)	9.8	-	19.1 ft (228.8 in)		
	21 ft (252 in)	- V (kip/ft)	-5.7	-	20 ft (241.3 in)		
9 ft with 2 cells	6.3 ft (75.6 in)	+ M (kip-ft/ft)	3	4.79	7.2 ft (85.93 in)	25 ft (300 in)	12.5 ft (150 in)
	0 ft (0 in)	- M (kip-ft/ft)	-4.71	-7.52	12 ft (144.7 in)		
	1.8 ft (21.6 in)	+ V (kip/ft)	12.1	-	3 ft (36.19 in)		
	4.5 ft (54 in)	- V (kip/ft)	-9.8	-	12.9 ft (155.3 in)		
15 ft with 2 cells	10.5 ft (126 in)	+ M (kip-ft/ft)	3.73	5.95	10.8 ft (129.3 in)	39 ft (468 in)	19.5 ft (234 in)
	0 ft (0 in)	- M (kip-ft/ft)	-7.63	-12.18	4.1 ft (49.4 in)		
	12 ft (144 in)	+ V (kip/ft)	12.03	-	19 ft (228.1 in)		
	6 ft (72 in)	- V (kip/ft)	-10.05	-	20 ft (239.9 in)		

Task 3 - Parametric Studies & Capacity Demands Database

Preliminary Results (Factored, *IL*, *M*)					
Governing Case for HL93					
Girder Spacing (ft)	No. of Cell	Positive Moment	Negative Moment	Positive Shear	Negative Shear
4	4	Case 1	Case 1	Case 1	Case 1
6	4	Case 1	Case 1	Case 3	Case 2
9	4	Case 1	Case 1	Case 2	Case 3
12	4	Case 1	Case 3	Case 3	Case 2
15	4	Case 1	Case 3	Case 3	Case 2
9	2	Case 1	Case1	Case 1	Case 1
15	2	Case 1	Case 3	Case 3	Case 3

- **Case 1** (single truck scenario) dominates for majority cases; Case 3 observed in 12 ft and 15 ft cases (four cells) as well as 15 ft (2 cells)
- Difference is **small** though (max. = 10%)

Planned Tasks

- Task 1 – **Finite Element Modeling of Bridge Decks**
- Task 2 – **Literature Survey and Concrete Fatigue Model**
- Task 3 – **Parametric Studies and Capacity Demands Database**
- Task 4 – **Quantitative Assessment of Approximate Method**
- Task 5 – **Recommendations on Desk**

Task 4 – Quantitative Assessment of Approximate Method

- Verification of AASHTO Appendix A4, Table A4-1 Design Values
- Collaboration with National Bridge Group (Modjeski & Masters)

Table A4-1—Maximum Live Load Moments per Unit Width, kip-ft/ft

S	Positive Moment	Negative Moment						
		Distance from CL of Girder to Design Section for Negative Moment						
		0.0 in.	3 in.	6 in.	9 in.	12 in.	18 in.	24 in.
4 ft –0 in.	4.68	2.68	2.07	1.74	1.60	1.50	1.34	1.25
4 ft –3 in.	4.66	2.73	2.25	1.95	1.74	1.57	1.33	1.20
4 ft –6 in.	4.63	3.00	2.58	2.19	1.90	1.65	1.32	1.18
4 ft –9 in.	4.64	3.38	2.90	2.43	2.07	1.74	1.29	1.20
5 ft –0 in.	4.65	3.74	3.20	2.66	2.24	1.83	1.26	1.12
5 ft –3 in.	4.67	4.06	3.47	2.89	2.41	1.95	1.28	0.98
5 ft –6 in.	4.71	4.36	3.73	3.11	2.58	2.07	1.30	0.99
5 ft –9 in.	4.77	4.63	3.97	3.31	2.73	2.19	1.32	1.02
6 ft –0 in.	4.83	4.88	4.19	3.50	2.88	2.31	1.39	1.07
6 ft –3 in.	4.91	5.10	4.39	3.68	3.02	2.42	1.45	1.13
6 ft –6 in.	5.00	5.31	4.57	3.84	3.15	2.53	1.50	1.20
6 ft –9 in.	5.10	5.50	4.74	3.99	3.27	2.64	1.58	1.28
7 ft –0 in.	5.21	5.98	5.17	4.36	3.56	2.84	1.63	1.37
7 ft –3 in.	5.32	6.13	5.31	4.49	3.68	2.96	1.65	1.51
7 ft –6 in.	5.44	6.26	5.43	4.61	3.78	3.15	1.88	1.72
7 ft –9 in.	5.56	6.38	5.54	4.71	3.88	3.30	2.21	1.94
8 ft –0 in.	5.69	6.48	5.65	4.81	3.98	3.43	2.49	2.16
8 ft –3 in.	5.83	6.58	5.74	4.90	4.06	3.53	2.74	2.37
8 ft –6 in.	5.99	6.66	5.82	4.98	4.14	3.61	2.96	2.58
8 ft –9 in.	6.14	6.74	5.90	5.06	4.22	3.67	3.15	2.79
9 ft –0 in.	6.29	6.81	5.97	5.13	4.28	3.71	3.31	3.00
9 ft –3 in.	6.44	6.87	6.03	5.19	4.40	3.82	3.47	3.20
9 ft –6 in.	6.59	7.15	6.31	5.46	4.66	4.04	3.68	3.39
9 ft –9 in.	6.74	7.51	6.65	5.80	4.94	4.21	3.89	3.58

Task 4 – Quantitative Assessment of Approximate Method

❖ *Assumptions and Approach to Live Load Response Analysis*

- Flexibility of longitudinal girders supporting the deck was neglected.
- Wheel loads were simplified as concentrated forces corresponding to 32-kip truck axle.
- The width of traffic lanes was taken as 12.0 ft, and wheel loads were not closer than 2.0 ft from the edges of traffic lanes, and bridge railing.
- Effective strip widths to determine design moments per foot of deck were taken from AASHTO LRFD BDS Section 4.6.2.1.3.

❖ *Aligned with the next assumptions listed in Appendix A4:*

- Multiple presence factors and the dynamic load allowance were included.
- Cross sections for analysis were established considering a minimum of 3 girders and a width of at least 14.0 ft between centerlines of exterior girders. Stated minimum and maximum overhang widths and a railing system width of 21.0 in. were also used.
- Moments for deck overhangs were excluded from the analysis.

Task 4 – Quantitative Assessment of Approximate Method

S	Positive Moment		Diff. (%)	Negative Moment @ 0.0"		Diff. (%)	Negative Moment @ 6.0"		Diff. (%)
	AASHTO	Calculated		AASHTO	Calculated		AASHTO	Calculated	
9'-6"	6.59	6.53	-0.95	-7.15	-7.10	-0.68	-5.46	-5.25	-3.82

[k.ft/ft]

Table 1. Comparison between AASHTO and calculated design values.

Table A4-1—Maximum Live Load Moments per Unit Width, kip-ft/ft

S	Positive Moment	Negative Moment						
		Distance from CL of Girder to Design Section for Negative Moment						
		0.0 in.	3 in.	6 in.	9 in.	12 in.	18 in.	24 in.
4 ft –0 in.	4.68	2.68	2.07	1.74	1.60	1.50	1.34	1.25
4 ft –3 in.	4.66	2.73	2.25	1.95	1.74	1.57	1.33	1.20
4 ft –6 in.	4.63	3.00	2.58	2.19	1.90	1.65	1.32	1.18
4 ft –9 in.	4.64	3.38	2.90	2.43	2.07	1.74	1.29	1.20
5 ft –0 in.	4.65	3.74	3.20	2.66	2.24	1.83	1.26	1.12
5 ft –3 in.	4.67	4.06	3.47	2.89	2.41	1.95	1.28	0.98
5 ft –6 in.	4.71	4.36	3.73	3.11	2.58	2.07	1.30	0.99
5 ft –9 in.	4.77	4.63	3.97	3.31	2.73	2.19	1.32	1.02
6 ft –0 in.	4.83	4.88	4.19	3.50	2.88	2.31	1.39	1.07
6 ft –3 in.	4.91	5.10	4.39	3.68	3.02	2.42	1.45	1.13
6 ft –6 in.	5.00	5.31	4.57	3.84	3.15	2.53	1.50	1.20
6 ft –9 in.	5.10	5.50	4.74	3.99	3.27	2.64	1.58	1.28
7 ft –0 in.	5.21	5.98	5.17	4.36	3.56	2.84	1.63	1.37
7 ft –3 in.	5.32	6.13	5.31	4.49	3.68	2.96	1.65	1.51
7 ft –6 in.	5.44	6.26	5.43	4.61	3.78	3.15	1.88	1.72
7 ft –9 in.	5.56	6.38	5.54	4.71	3.88	3.30	2.21	1.94
8 ft –0 in.	5.69	6.48	5.65	4.81	3.98	3.43	2.49	2.16
8 ft –3 in.	5.83	6.58	5.74	4.90	4.06	3.53	2.74	2.37
8 ft –6 in.	5.99	6.66	5.82	4.98	4.14	3.61	2.96	2.58
8 ft –9 in.	6.14	6.74	5.90	5.06	4.22	3.67	3.15	2.79
9 ft –0 in.	6.29	6.81	5.97	5.13	4.28	3.71	3.31	3.00
9 ft –3 in.	6.44	6.87	6.03	5.19	4.40	3.82	3.47	3.20
9 ft –6 in.	6.59	7.15	6.31	5.46	4.66	4.04	3.68	3.39
9 ft –9 in.	6.74	7.51	6.65	5.80	4.94	4.21	3.89	3.58

Future Task

- Task 1 – **Finite Element Modeling of Bridge Decks**
- Task 2 – **Literature Survey and Concrete Fatigue Model**
- Task 3 – **Parametric Studies & Capacity Demands Database with P-15 Loading and other Special Vehicles**
- Task 4 – **Quantitative Assessment of Approximate Method**
- Task 5 – **Recommendations on Desk Design Method**

Thank you!

Questions & Comments?