MIDAS Civil
Curved Bridge Analysis
Comparison of Methods &
Construction Staging

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WOOLPERT

Introduction – Curved Bridge Modeling

Types of Models to be Discussed

- Traditional Girder Line with V-Load Analysis
- Two-Dimensional (Grillage) Analysis and “Grillage 2D+”
- Three-Dimensional Analysis

Project Background – CVG CONRAC Unit 2

- Comparison of Model Creation and Loading
- Comparison of Results from Modeling Approaches

Construction Sequencing and Constructability

- Purpose
- Implementation within Programs
- Comparison – Grillage and All-plate

Project – ODOT GUE-513-08.65, Temporary Supports and Staged Construction

Conclusions

Modeling – Girder Line & V-Load

Girder Line Modeling

- Uses standard AASHTO LLDF
- Can be done in minimal time, not a complicated analysis
- In this case used Merlin DASH
- Use results to populate a V-Load analysis spreadsheet or hand calculation, and iterate with a target utilization ratio (1.00 – anticipated V-Load increase)
- Typically produces good results for dead load approximations for noncomposite and composite bridges with radial crossframes or bracing
- Live load can be much more variable based on lateral stiffness, geometry, and resulting intermittent influence surface
- Typically a good method for preliminary engineering purposes

Modeling – Girder Line & V-Load

V-Load Theory

- Many references available
- Essentially, straighten girder and analyze based on true length as a straight member, then apply external forces to induce resultant internal forces corresponding to the curved structure under vertical loads
- From past projects, results have been very close to MIDAS Civil or other FEM for larger radii, say R > 1000-ft
- Per AASHTO Section C4.6.2.2.4 has a number of limitations which do not qualify for required analysis methods for curved structures and may underestimate deflections, reactions, twist

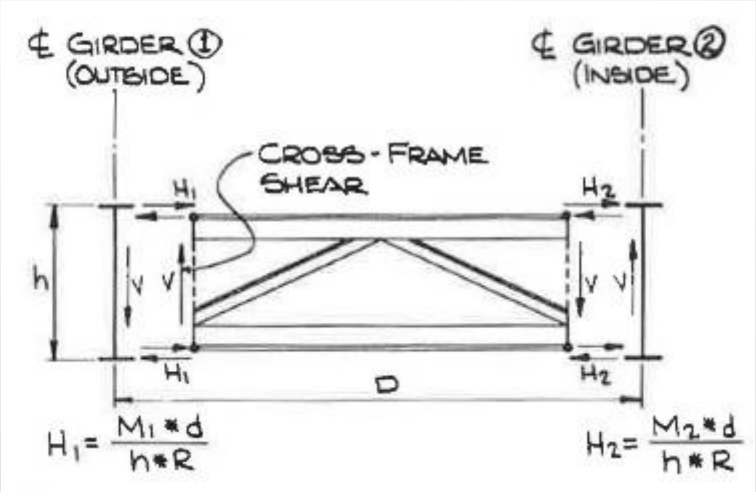


Figure from *Horizontally Curved I-Girder Bridge Analysis: V-Load Method* By Grubb, M.A.

Modeling – Two-Dimensional (Grillage)

Grillage Analysis

- Uses beam elements for each beam/girder and a grid, usually plates attached to the same nodes as beam elements, but with different offset (eccentric beam)
- Alternatively, primary beam elements are used with full composite section properties, and secondary virtual beams are used for load distribution
- Provides a more accurate distribution of live loads through influence surface
- Lateral stiffness of deck is not modeled using this approach
- Superimposed dead loads are distributed more accurately, however internal forces due to curvature are not captured

Modeling – Two-Dimensional+ (Grillage)

2D+ Grillage Analysis/Limited 3D Analysis

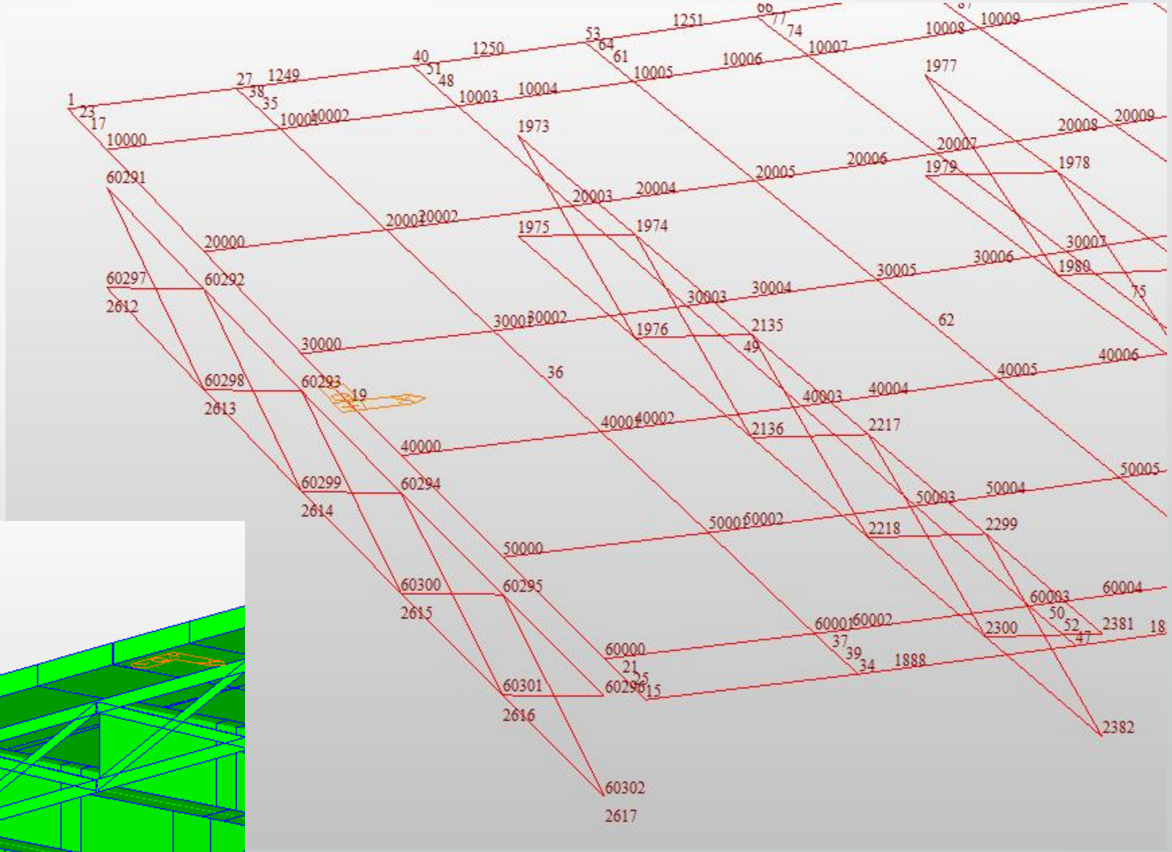
- Similar to standard grillage, but with multiple sets of nodes with rigid links (master-slave)
- Beams/girders are modeled using beam elements then rigid linked nodes modeling the deck plates and nodes for crossframe members in 3D
- Provides an accurate distribution of live loads through influence surface
- Lateral stiffness of crossframes and deck are modeled using this approach
- Internal forces are captured using this approach, appropriate for curved girder design
- In MIDAS, this is the default for the “Deck as Plate, Beam as Frame” modeling approach
- The “All Frame” modeling approach also uses this method, but with the deck modeled by virtual transverse beams
- Seventh degree of freedom included for warping effects

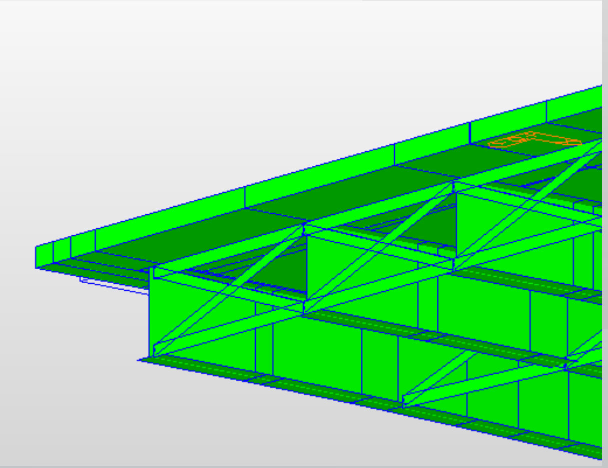
Modeling – Two-Dimensional+ (Grillage)

2D+ Grillage Analysis/Limited 3D Analysis

Tip:

- Renumber nodes & elements by beam/girder
  - 10001-10xxx (Girder 1)
  - 20001-20xxx (Girder 2)
- Makes manipulation and output much easier/quicker





Modeling – Three-Dimensional

Full 3D Analysis

- Similar to the Grillage+, but the beam is split into plate elements for each flange and web, in addition to plates for the deck
- Provides an accurate distribution of live loads through influence surface
- Lateral stiffness of crossframes and deck are modeled using this approach
- Internal forces are captured using this approach, appropriate for curved girder design
- Effects of tension-field action can be captured for shear
- Girder/Beam rotations can be explicitly extracted – very important for construction cases in highly curved members
- In MIDAS, this is the "All Plate" modeling approach

Modeling – Three-Dimensional

Full 3D Analysis

- Effects of tension-field action, post-buckling web strength

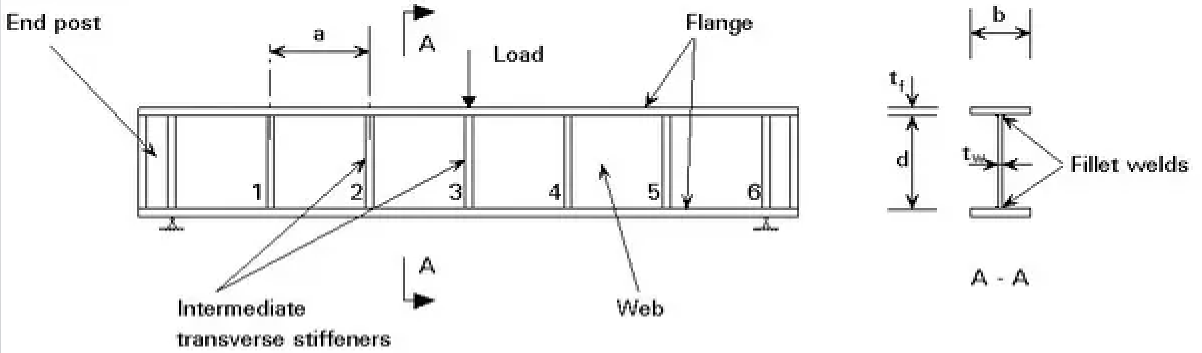


Figure 1 Elevation of a typical plate girder

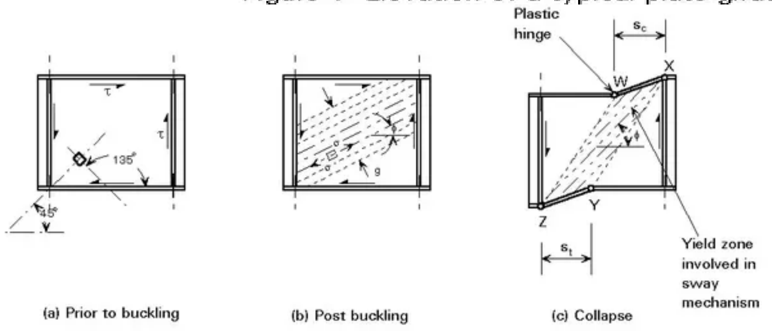


Figure 4 Phases in behaviour up to collapse of a typical panel in shear

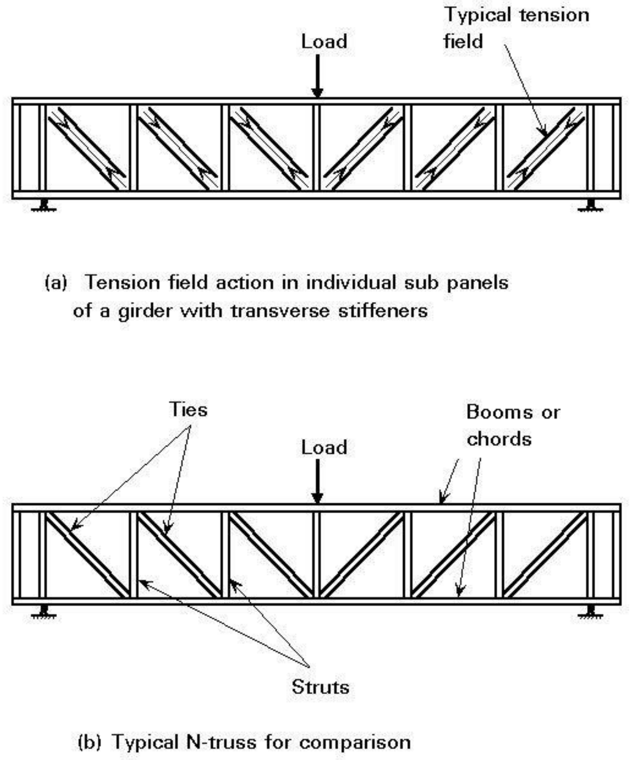
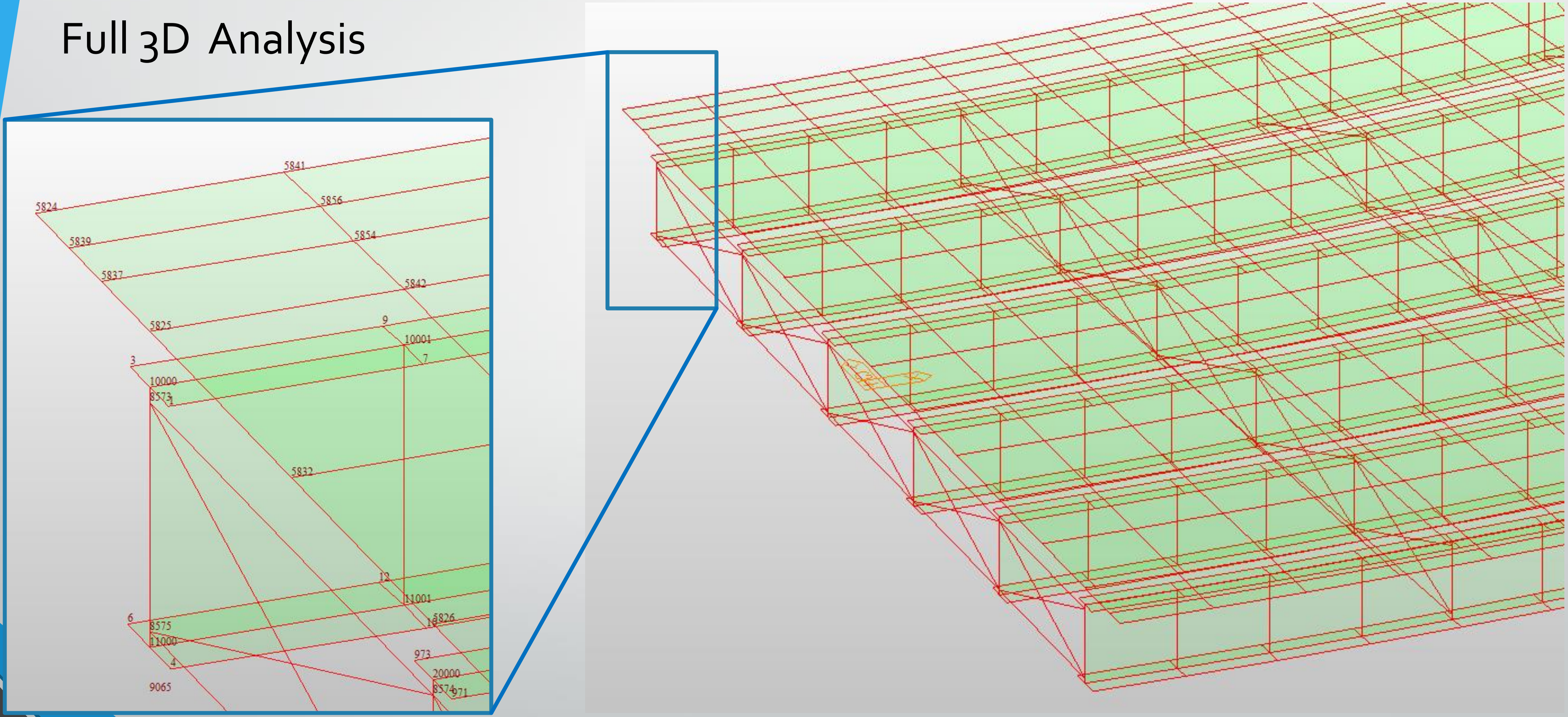


Figure 3 Tension field action

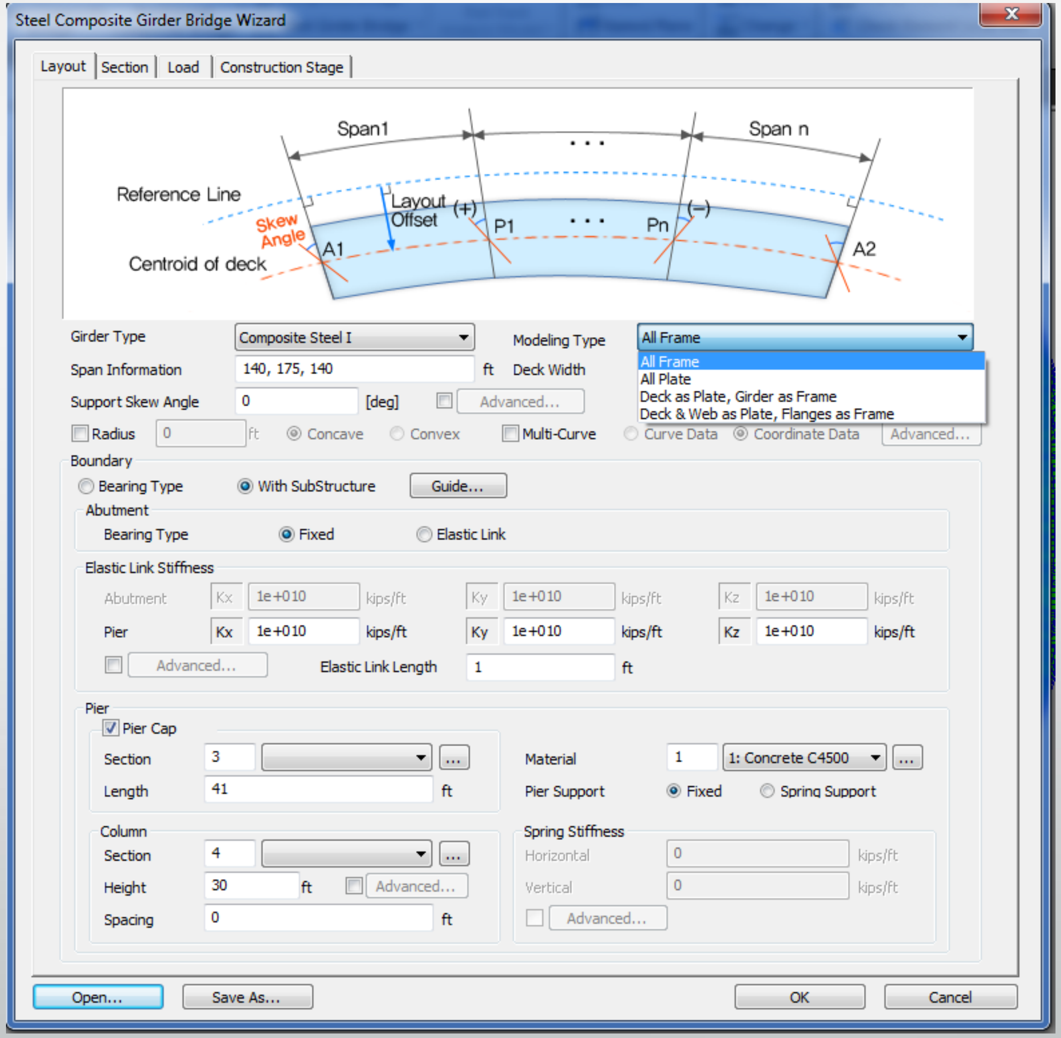
Modeling – Three-Dimensional

Full 3D Analysis



Modeling Types

Where to find in MIDAS:



Project Background – CVG CONRAC

CVG Airport (Cincinatti)

Project Background – CVG CONRAC

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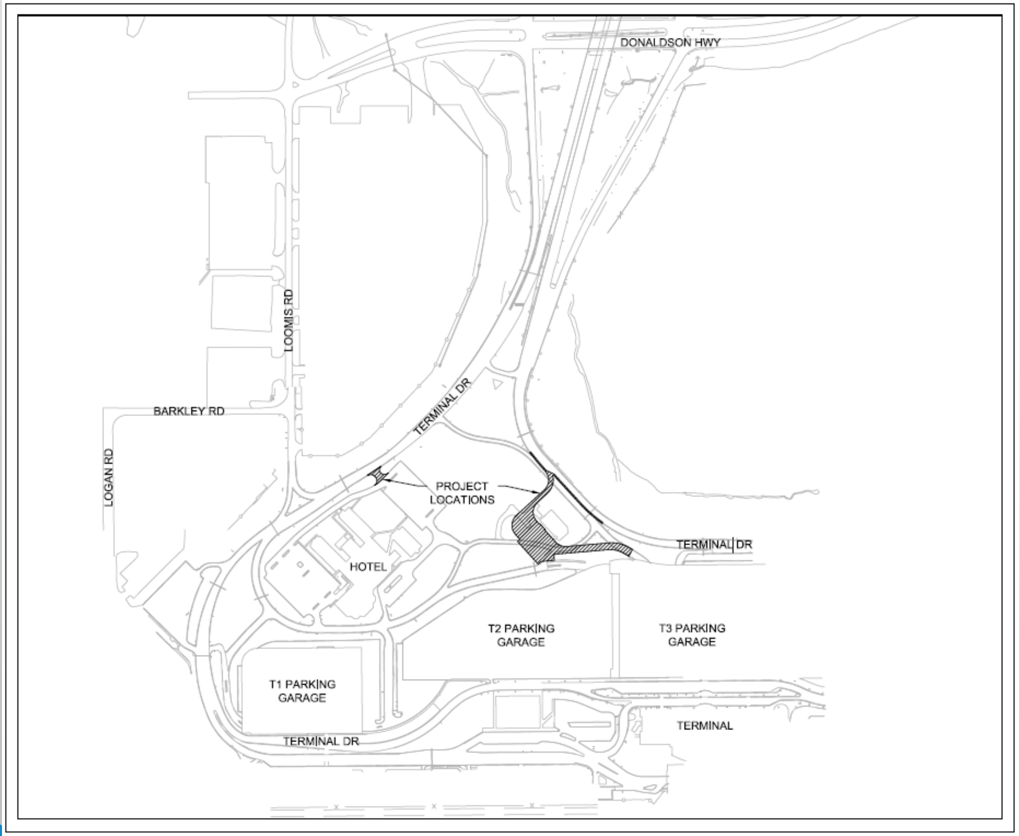
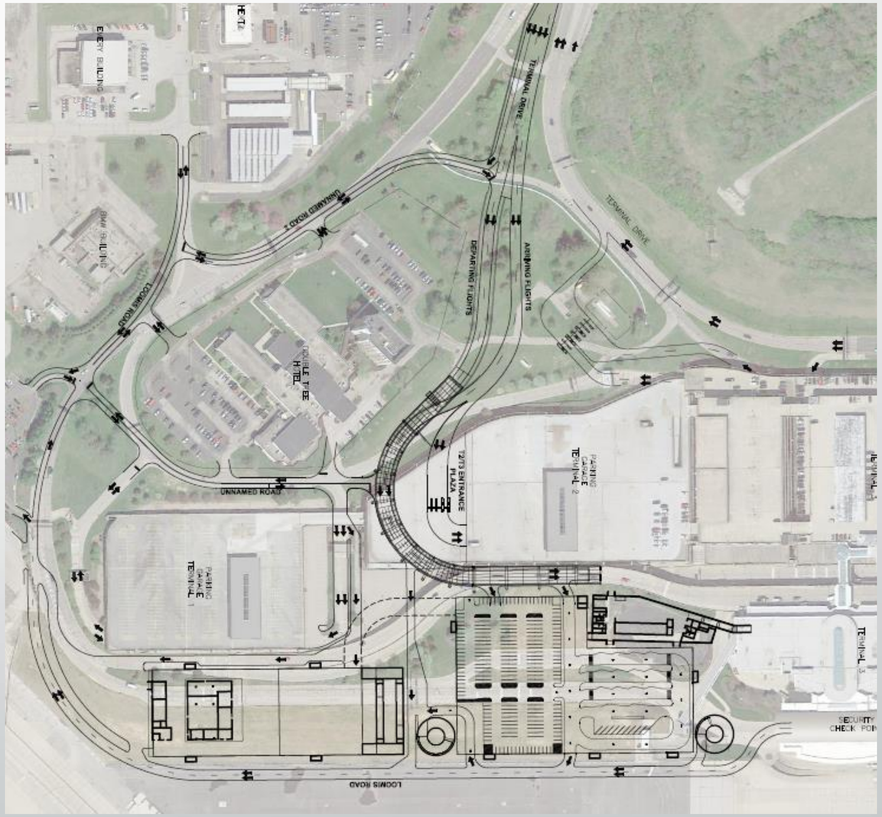
Original Condition



Final Proposed Condition

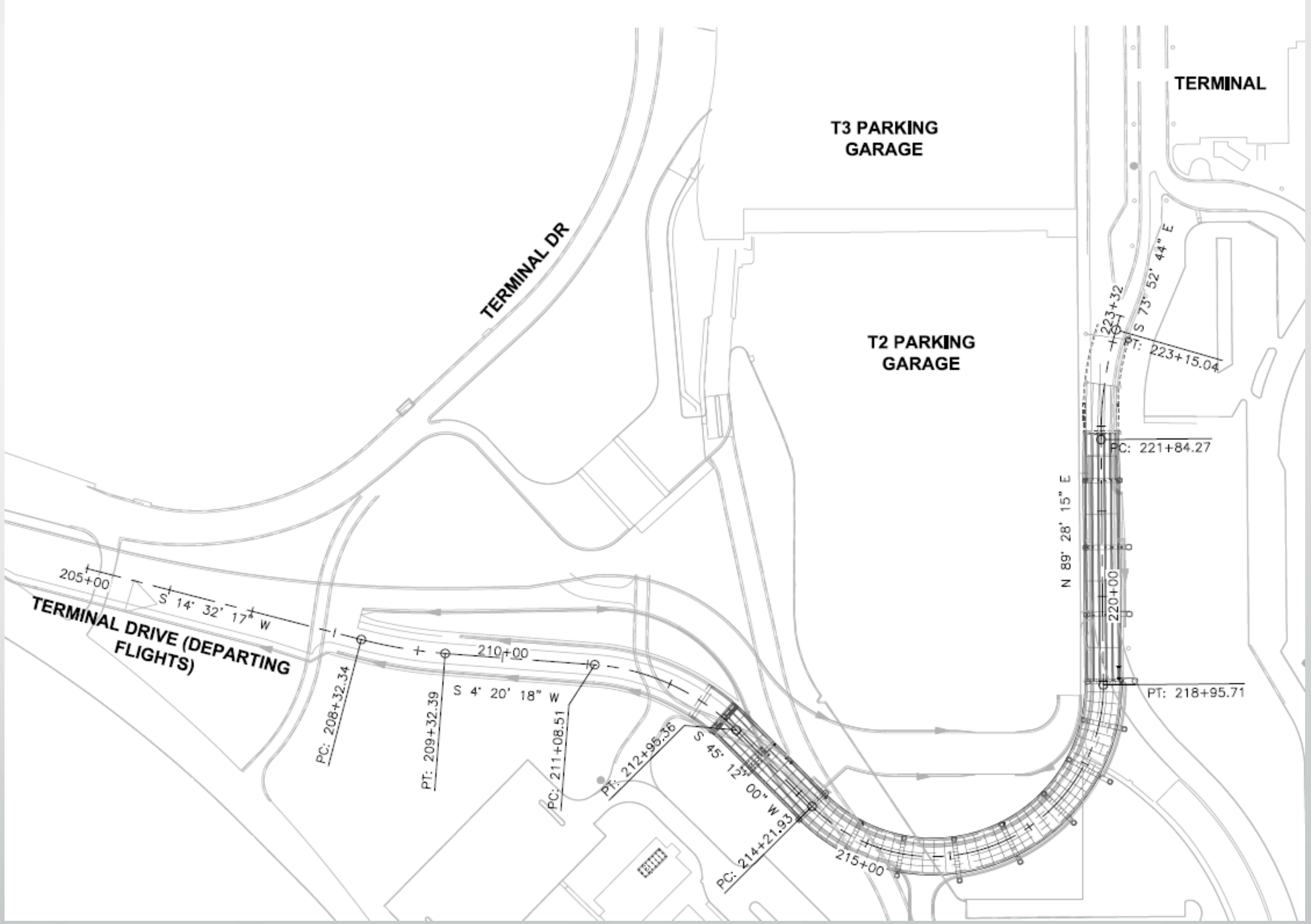


Project Background – CVG CONRAC

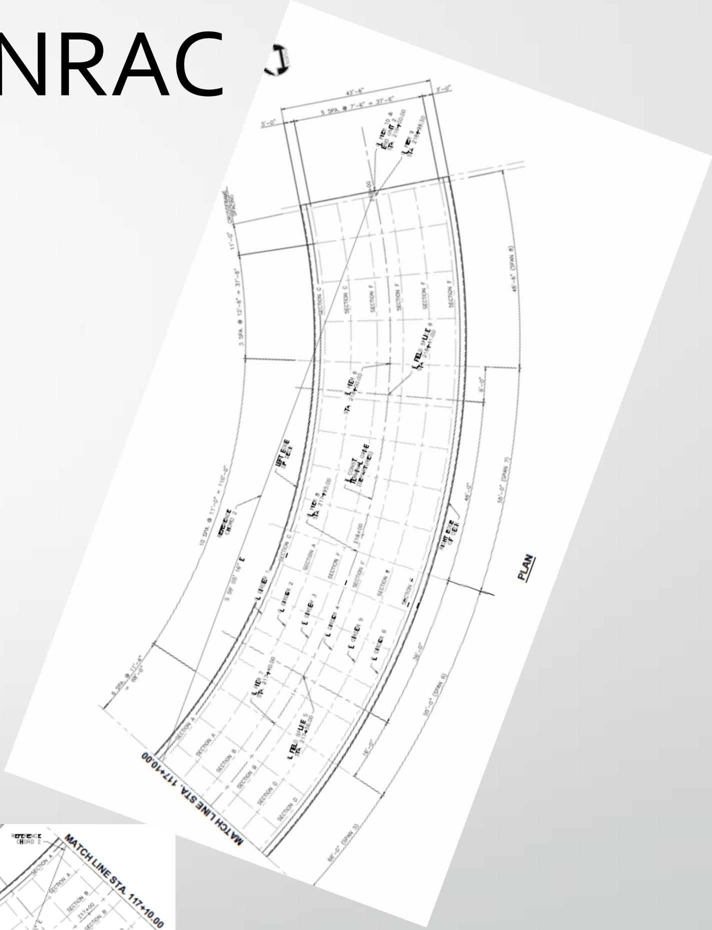
MSE Buildup

Three Elevated Structures

- Unit 1: Straight Rolled Beams
- Unit 2: Curved Plate Girders
- Unit 3: Prestressed I Beams

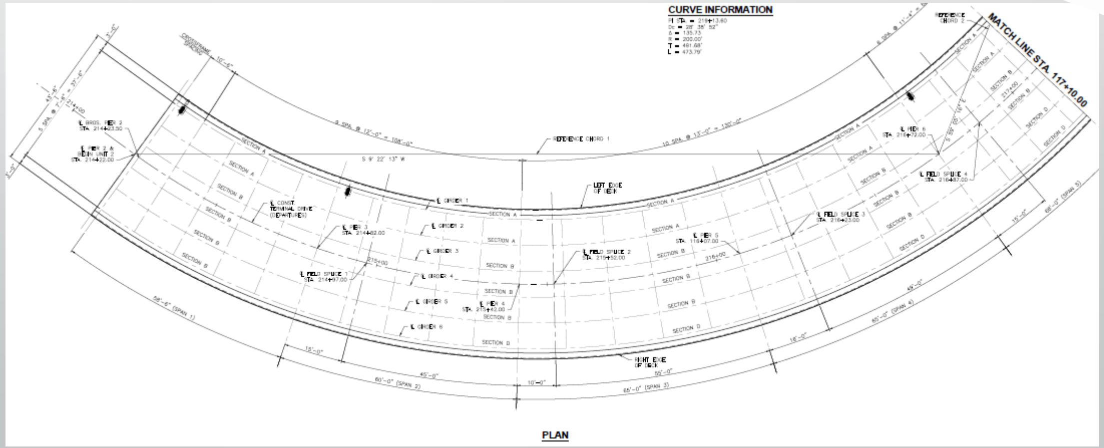


Project Background – CVG CONRAC



Unit 2: Curved Steel Plate Girder Bridge

- R = 200.00 ft
- Minimum Girder R = 181.25 ft
- Dc = 28^{0} 38′ 52″
- Δ = 135.73^{0}
- All crossframes and girders radial
- 8 Spans, range from 48.5-ft to 68-ft



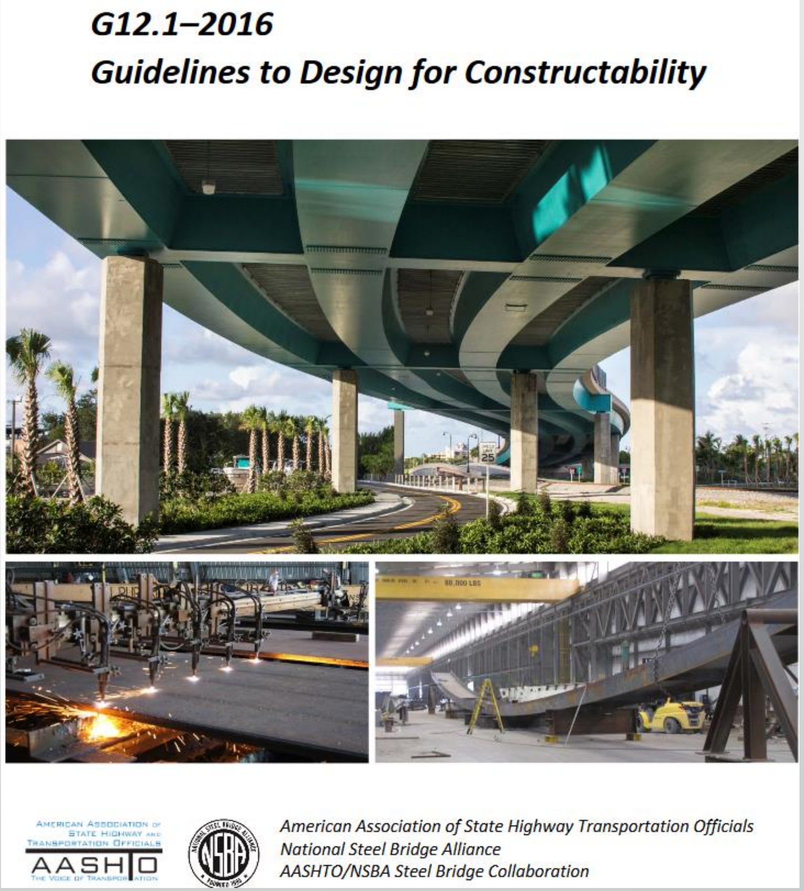
Project Background – CVG CONRAC

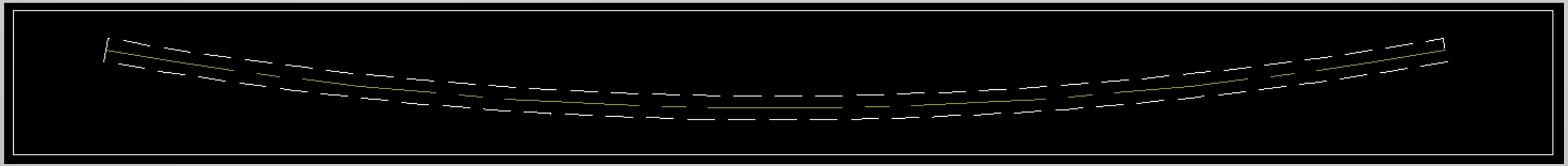
Site and Geometric Constraints

- Access below, multiple entry/exits
- Plate mill runs, need to make sure it is possible to cut

Table 1.4.1.A: Example Maximum Plate Length Availability ASTM A709 Grades 36, 50, 50W (all dimensions in inches)

Plate Thickness	Plate Width				
	72	84	96	108	120
½	972	972	972	972	972
¾	1035	1035	1035	1035	1035
1	1035	1035	1035	980	808
1½	1035	1035	1035	720	680
2	1035	1035	1035	720	680
2½	1035	1006	880	720	680
3	970	838	734	652	587
3½	830	920	800	635	600
4	720	800	685	600	600





Project Background – CVG CONRAC

Shop splice versus field splice considerations

- From AISC, there are guidelines to determine if cost effective
- Analyzed to determine for this bridge, would require 0.5"-0.625" thickness differential in field section from positive moment to negative moment.
- Example: 16" x 80 lbs/in = 1280 lbs

Table 1.5.2.A: Weight Saving Factor per Inch of Plate Width
For ASTM A709 Grade 50 Non-Fracture Critical Flanges Requiring Zone 1 CVN Testing

Multiply weight savings/inch x flange width (length of butt weld)							
Thinner Plate at Splice (inches)	**Thicker Plate at Splice (inches)**						
	1.0	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
1.0	70	70	70				
1.5		80	80	80	80		
2.0			90	90	90	70	70
2.5				100	100	80	80
3.0					110	90	90
3.5						110	110
3.5						110	110
4.0							130

6	218.75	Length (ft)	80.5314		81.5314		82.5314		83.5314		84.5314		85.5314		86.5314	
		LL | LS	47.5781	32.9533	38.2812	43.2502	42.6562	39.8752	32.8124	50.719	35	49.5314	19.6876	65.8438	19.6876	66.8438
		Top Flange W (in)	16		16		16		16		16		16		16	
		TL | TS	0.875	1.25	1.375	1.25	1	1.25	1.375	1.125	1.375	1.125	1.125	0.875	1.25	1
		Factor from table	72.5		72.5		72.5		72.5		72.5		72.5		70	
		Req'd Savings (lbs)	1160		1160		1160		1160		1160		1160		1120	
		Saved (lbs)	673		294		543		690		674		896		910	
			No Shop Splice		No Shop Splice		No Shop Splice		No Shop Splice		No Shop Splice		No Shop Splice		No Shop Splice	
6	218.75	Length (ft)	80.5314		81.5314		82.5314		83.5314		84.5314		85.5314		86.5314	
		LL | LS	47.5781	32.9533	38.2812	43.2502	42.6562	39.8752	32.8124	50.719	35	49.5314	19.6876	65.8438	19.6876	66.8438
		Bot Flange W (in)	16		16		16		16		16		16		16	
		TL | TS	1	1.375	1.5	1.25	1.25	1.25	1.375	1.125	1.375	1.125	1.125	1	1	1
		Factor from table	72.5		72.5		72.5		72.5		72.5		72.5		70	
		Req'd Savings (lbs)	1160		1160		1160		1160		1160		1160		1120	
		Saved (lbs)	673		589		0		690		674		448		0	
			No Shop Splice		No Shop Splice		No Shop Splice		No Shop Splice		No Shop Splice		No Shop Splice		No Shop Splice	

Unit 2 Modeling – Preliminary Engineering

- V-Load Analysis used during preliminary engineering
  - Predicted max ~11% increase in moments due to curvature
  - Designed for 0.85 Utility Ratio to account for girder warping and secondary effects
  - Estimated 5.5 kips for cross frame forces due to curvature effects

Appoximate Curvature Effects on Moment

p $= 5.5 \left[1 + (R_{in}/R_{out})^2 \right] m\, L_c^2 / C R_{out} D$ (Eq. 11.37, p. 11.52)

Percent increase in moment in the outside stringer due to curvature effects.

where

R_{in}	231.25 ft	Radius of the inside stringer.	
R_{out}	268.75 ft	Radius of the outside stringer.	
m	6	Number of stringers.	
L_c	ft	Arc-length of the outside stringer between inflection points.	
C	1.40	Coefficient based on the number of stringers.	(Table 11.21, p.11.51)

m	2	3	4	5	6	7	8	9	10
C	1.00	1.00	1.11	1.25	1.40	1.56	1.72	1.88	2.04

D 37.50 ft Distance between inside and outside stringers.

Estimate the Increase in Moment in the Outside Stringer

$p / L_c^2 = 5.5 \left[1 + (R_{in}/R_{out})^2 \right] m / C R_{out} D$

0.0040706 /ft^2

Span		1	2	3	4	5	6	7	8
L_c	ft	51.60	38.70	41.93	41.93	43.86	35.48	35.48	43.00
p	ft	**10.8%**	**6.1%**	**7.2%**	**7.2%**	**7.8%**	**5.1%**	**5.1%**	**7.5%**

Unit 2 Modeling – Preliminary Engineering

- V-Load Analysis used during preliminary engineering
- Note that grillage and plate model results showed significantly higher crossframe forces than the V-load
- Sizes:

Preliminary (V-Load)

GIRDER SECTIONS			
SECTION	TOP FLANGE	WEB	BOTTOM FLANGE
A	14" x 1.25"	33" x 0.5"	14" x 1.25"
B	12" x 1.25"	33" x 0.5"	12" x 1.25"
C	12" x 1.125"	33" x 0.5"	12" x 1.125"
D	14" x 0.875"	33" x 0.5"	14" x 0.875"
E	12" x 0.875"	33" x 0.5"	12" x 0.875"
F	12" x 0.75"	33" x 0.5"	12" x 0.75"

Final (Grillage/All-Plate)

GIRDER SECTIONS			
SECTION	TOP FLANGE	WEB	BOTTOM FLANGE
A	12" x 1.00"	33" x 0.375"	14" x 1.00"
B	14" x 1.00"	33" x 0.375"	16" x 1.00"
C	12" x 0.875"	33" x 0.375"	14" x 0.875"
D	14" x 1.00"	33" x 0.375"	16" x 1.125"
E	14" x 0.875"	33" x 0.375"	16" x 1.00"
F	14" x 0.875"	33" x 0.375"	16" x 0.875"

Unit 2 Modeling – Detailed Design, Grillage+

- A Grillage+ model in MIDAS with beams as frame was used for the detailed design
- Tips:
  - Node and Beam Element Numbering is key
  - Checked the geometry created by wizard through CAD by using a scratch basemap with origin and angle aligned to MIDAS output
  - Note that some variation occurs through composite girder wizard due to conversion to metric and concatenation occurring during the wizard generation
  - Local Coordinates – use geometry and excel to develop the local angle (Beta Angle) at each node then paste into MIDAS menu, $\beta_i = 90 + \tan^{-1}(\Delta y_i/\Delta x_i)$; where Δy_i and Δx_i are distances from the MIDAS center point/origin to the nodal location (x_i, y_i).
  - Similar geometry and excel can be used to calculate "length along" the beam at each node for output to plans
  - Bearing conditions and boundary conditions are a critical consideration
  - By default MIDAS is performing a No Load Fit (NLF) analysis. This is a very important distinction and should be indicated on the plans for the fabricator.

Unit 2 Modeling – Detailed Design, Grillage+

I recommend the presentation by AISC, "Top 10 Changes in the 8th Edition AASHTO LRFD Steel Specifications" if you have not watched it. The handouts are available here:

https://www.aisc.org/webinarhandouts121317/

Loading Condition Fit	Construction Stage Fit	Description
No-Load Fit (NLF)	Fully-Cambered Fit	The cross-frames are detailed to fit to the girders in their fabricated, plumb, fully-cambered position under zero dead load.
Steel Dead Load Fit (SDLF)	Erected Fit	The cross-frames are detailed to fit to the girders in their ideally plumb as-deflected positions under bridge steel dead load at the completion of the erection.
Total Dead Load Fit (TDLF)	Final Fit	The cross-frames are detailed to fit to the girders in their ideally plumb as-deflected positions under the bridge total dead load.

Additional Camber Consideration

- When determining camber, if Radii is greater than 1000-ft need to account for additional camber from settling of the curved structure per AASHTO 6.7.7.3

C6.7.7.3

Part of the camber loss is attributable to construction loads and will occur during construction of the bridge; total camber loss will be complete after several months of in-service loads. Therefore, a portion of the camber increase should be included in the bridge profile. In lieu of other guidelines, camber may be adjusted by one-half of the camber increase. Camber losses of this nature, but generally smaller in magnitude, are also known to occur in straight beams and girders.

$$\Delta = \frac{\Delta_{DL}}{\Delta_M}\left(\Delta_M + \Delta_R\right) \qquad (6.7.7.3\text{-}1)$$

in which:

$$\Delta_R = \frac{0.02L^2F_{yf}}{EY_o}\left(\frac{1{,}000 - R}{850}\right) \qquad (6.7.7.3\text{-}2)$$

Unit 2 Modeling – Comparisons

- MIDAS Grillage+ versus LEAP Steel Grillage
- LEAP uses a STAAD.Pro Engine for analysis
- LEAP Steel serves as a GUI & Wizard
- STAAD Model is accessible, but is deep in directory
- LEAP model is faster to assemble and run
- LEAP output is more difficult to use (at least currently)
  - Limited data sorting and exclusion
  - Limited capacity for visual representation of data, compared with MIDAS
  - The above is my personal opinion (disclaimer)

Feature	MIDAS	LEAP Steel
Tabular Input		X
Model Readily Accessible	X	
Tabular Output	X	X
Output Sorting Functions	X	
Detailed Calculations Output	X	X
Data Restricting Functions	X	
Visual Output	X	
Visual Display of Live Loads for Max Effect	X	

Unit 2 Modeling – Comparisons

SECTION	BEAM	MIDAS - Grillage			MIDAS - All Plate			Mdash		LEAP Steel	
		Stage 1 Defl. (in)	Final SDL Defl (in)	Final DL Defl. (in)	Stage 1 Defl. (in)	Final SDL Defl (in)	Final DL Defl. (in)	Stage 1 Defl. (in)	Final DL Defl. (in)	Stage 1 Defl. (in)	Final DL Defl. (in)
1	1	0.092	0.045	0.209	0.099	0.05	0.265	0.052	0.4668	0.051	0.275
	2	0.121		0.296	0.129		0.34			0.068	0.361
	3	0.146		0.364	0.155		0.408			0.082	0.432
	4	0.170	0.034	0.422	0.182	0.031	0.48			0.097	0.507
	5	0.197		0.474	0.213		0.561	0.1036	0.8443	0.114	0.589
	6	0.226	0.121	0.517	0.25	0.14	0.654	0.1059	0.9141	0.133	0.677
3	1	0.073	0.039	0.169	0.071	0.05	0.2	0.0385	0.3453	0.04	0.213
	2	0.093		0.231	0.091		0.251			0.051	0.277
	3	0.111		0.276	0.108		0.298			0.062	0.326
	4	0.128	0.020	0.313	0.126	0.016	0.346			0.072	0.377
	5	0.146		0.341	0.145		0.399	0.0754	0.6138	0.084	0.428
	6	0.163	0.090	0.357	0.168	0.109	0.459	0.0822	0.6129	0.096	0.474
5	1	0.093	0.039	0.220	0.101	0.053	0.236	0.0496	0.4388	0.051	0.267
	2	0.119		0.290	0.127		0.293			0.066	0.342
	3	0.142		0.343	0.151		0.345			0.08	0.403
	4	0.164	0.020	0.386	0.174	0.025	0.399			0.094	0.462
	5	0.187		0.420	0.2		0.456	0.0972	0.779	0.109	0.523
	6	0.211	0.087	0.443	0.229	0.116	0.521	0.1086	0.7765	0.125	0.583

Unit 2 Modeling – Comparisons

- MIDAS Grillage+ versus MIDAS All Plate

		MIDAS - Grillage													MIDAS - All Plate										Comparison				
UNIT	BEAM	Total DC = SDL + DC1	SDL = DC2	DC1 Initial = Steel	DC1 Final = Steel + Deck	DW	LL + I, max	LL +I, min	Total DL	SDL	DC1 Initial	DC1 Final	Total DW	Uplift Check	Total DC	SDL	DC1 Initial	DC1 Final	DW	Total DL	SDL	DC1 Initial	DC1 Final	Total DW	Total DL	SDL	DC1 Initial	DC1 Final	Total DW
PIER 2	1	24.2	9.5	5.0	14.7	5.7	52.1	-10.9	177.90	28.7	40.2	149.2	55.7	2.705	28.8	10.60	4.90	18.20	5.9	178.50	28.60	40.20	149.90	55.5	-0.34%	0.35%	0.00%	-0.47%	0.36%
	2	28.6	1.9	5.8	26.7	9.5	63.4	-4						18.74	23.1	0.80	5.90	22.30	8.9										
	3	26.6	0.6	6.9	26.0	10.2	76.9	-3.8						17.29	25.5	0.10	6.90	25.40	10.1										
	4	27.3	0.8	7.2	26.5	10.5	77.5	-4.4						16.87	27.3	0.60	7.20	26.70	10.4										
	5	30.2	2.3	7.3	27.9	10.4	66	-5.1						18.255	30.4	2.70	7.50	27.70	10.6										
	6	41.0	13.6	8.0	27.4	9.4	59.8	-9.4						20.45	43.4	13.80	7.80	29.60	9.6										
PIER 3	1	75.0	28.6	15.8	46.4	17.2	73.5	-14.2	495.40	72.4	112.1	423	158.4	42.65	90.8	32.60	15.80	58.20	19.3	491.20	82.20	112.10	409.00	158.5	0.85%	-13.54%	0.00%	3.31%	-0.06%
	2	87.4	7.2	16.6	80.2	29.7	103.7	-8.5						63.785	64.8	2.20	16.70	62.60	26.5										
	3	74.8	-0.3	19.5	75.1	29.6	117	-7.6						54.02	68.8	-1.20	19.40	70.00	29.3										
	4	79.6	1.3	20.2	78.3	30.3	120.4	-8.5						56.765	73.3	0.70	20.10	72.60	30.1										
	5	85.5	6.7	20.4	78.8	29.6	103.1	-9.8						59.8	83.0	7.60	20.80	75.40	30.5										
	6	93.1	28.9	19.6	64.2	22	83	-13.1						60.865	110.5	40.30	19.30	70.20	22.8										
PIER 4	1	69.9	28.2	14.7	41.7	16	75.4	-15.4	468.20	75.7	103.4	392.5	146.4	35.96	89.5	32.60	14.70	56.90	17.8	469.80	76.50	102.90	393.30	146.2	-0.34%	-1.06%	0.48%	-0.20%	0.14%
	2	79.2	5.9	15.4	73.3	27.9	103.8	-10.1						53.605	63.3	1.60	15.50	61.70	24.5										
	3	72.5	-1.0	18.0	73.5	27.5	117.8	-9.5						48.625	65.5	-2.00	17.90	67.50	27.2										
PIER 8	1	58.0	25.3	12.0	32.7	12.8	68.2	-15.2	394.90	64.4	86	330.5	124.9	25.6	78.5	30.20	12.60	48.30	15	398.60	65.20	89.50	333.40	125.5	-0.94%	-1.24%	-4.07%	-0.88%	-0.48%
	2	69.1	4.7	13.8	64.4	24.5	103	-13.1						39.265	53.5	0.70	13.70	52.80	21.6										
	3	58.6	-2.5	14.8	61.1	23	113.1	-10.6						34.19	53.7	-3.10	15.40	56.80	23.4										
	4	60.1	-1.4	15.2	61.5	23.7	115.2	-12.3						32.565	56.2	-2.20	15.80	58.40	23.9										
	5	80.5	8.9	15.7	71.6	26.9	107	-17.4						42	64.6	3.80	16.50	60.80	24.2										
	6	68.6	29.4	14.5	39.2	14	70.2	-12.9						39.165	92.1	35.80	15.50	56.30	17.4										
PIER 9	1	64.9	26.8	13.4	38.1	14.7	69.6	-11.2	442.70	72.7	95.3	370.0	140	38.81	81.0	30.50	13.20	50.50	16.5	432.50	72.30	95.60	360.20	139.7	2.30%	0.55%	-0.31%	2.65%	0.21%
	2	76.1	5.3	14.4	70.8	26.3	100.5	-8.2						54.14	58.1	1.20	15.00	56.90	23.9										
	3	65.3	-1.9	16.6	67.2	26	114.2	-6.8						46.87	58.6	-2.30	16.30	60.90	25.7										
	4	70.0	-0.2	17.1	70.2	27	116.6	-7.5						49.875	63.4	-0.70	17.00	64.10	26.9										
	5	84.1	10.3	17.3	73.8	29.6	104.9	-10.1						58.015	72.4	6.20	17.80	66.20	26.8										
	6	82.3	32.4	16.5	49.9	16.4	71.2	-8.7						58.845	99.0	37.40	16.30	61.60	19.9										
PIER 10	1	20.2	8.9	4.0	11.3	4.5	48.6	-8.7	141.30	22.9	30.9	118.4	44.5	2.955	25.6	10.30	4.00	15.30	4.8	141.50	23.00	30.90	118.50	44.5	-0.14%	-0.44%	0.00%	-0.08%	0.00%
	2	23.4	1.2	4.7	22.2	7.8	60.7	-4.8						12.66	18.3	0.10	4.70	18.20	7.4										
	3	20.9	-0.4	5.4	21.3	8.3	75.3	-4.5						10.935	19.4	-0.70	5.30	20.10	8.2										
	4	21.7	-0.2	5.5	21.9	8.7	75.6	-5.1						10.605	21.0	-0.50	5.60	21.50	8.7										
	5	24.8	1.8	5.5	23.0	8.8	64.3	-5.7						12.345	22.7	1.70	5.60	21.00	8.2										
	6	30.3	11.6	5.8	18.7	6.4	53.9	-8.8						11.87	34.5	12.10	5.70	22.40	7.2										
Total		3620.7	580.2	800.0	3040.5	1139.3	4973.1	-542.6	3620.70	580.20	800.00	3040.50	1139.30		3589.1	591.0	802.5	2998.1	1139.9	3589.10	591.00	802.50	2998.10	1139.90	**-0.88%**	**1.83%**	**0.31%**	**-1.41%**	**0.05%**

Unit 2 Modeling – Comparisons

- MIDAS Grillage versus LEAP Grillage Moment/Flange Stresses

Girder 6															
MIDAS Element Range		60000	60027	60028	60048	60049	60073	60074	60100	60101	60130	60131	60166	60167	60193
Location		Segment 1		Segment 2		Segment 3		Segment 4		Segment 5		Segment 6		Segment 7	
bftop		14.0		14.0		14.0		14.0		14.0		14.0		14.0	
tftop		1.000		1.000		1.000		1.000		1.000		0.875		0.875	
bfbot		16.0		16.0		16.0		16.0		16.0		16.0		16.0	
tfbot		1.000		1.125		1.125		1.125		1.125		0.875		0.875	
Slt		81.429		87.524		87.524		87.524		87.524		71.250		71.250	
Slb		71.250		76.583		76.583		76.583		76.583		62.344		62.344	
Effect		Mu+	Mu−	Mu+	Mu−	Mu+	Mu−	Mu+	Mu−	Mu+	Mu−	Mu+	Mu−	Mu+	Mu−
Element − MIDAS		60009	60022	60035	60046	60057	60069	60080	60094	60109	60124	60161	60149	60185	60171
Location − LEAP		24.609	63.984	96.797	129.609	165.156	200.703	236.25	271.797	308.984	346.172	376.25	406.328	436.406	466.484
fbu	LEAP (ksi)	26.742	30.605	15.146	27.277	20.981	30.985	19.903	33.239	25.040	31.267	16.746	26.398	19.577	28.241
	MIDAS (ksi)	21.897	31.027	12.731	26.757	16.025	28.020	14.965	30.833	17.133	29.851	24.692	12.427	25.452	17.954
MI	MIDAS (Mz), (k−in)	955.740	1115.200	1084.060	1134.520	948.620	1237.600	800.640	1371.120	809.270	1287.410	877.750	998.240	1015.750	1103.930
flt	LEAP (ksi)	18.059	22.522	7.566	27.060	14.188	28.299	11.707	27.663	14.578	25.197	18.048	23.832	12.971	25.561
	MIDAS (ksi)	11.737	13.695	12.386	12.962	10.838	14.140	9.148	15.666	9.246	14.709	12.319	14.010	14.256	15.494
flb	LEAP (ksi)	18.059	22.522	7.566	27.060	14.188	28.299	11.707	27.663	14.578	25.197	18.048	23.832	12.971	25.561
	MIDAS (ksi)	13.414	15.652	14.155	14.814	12.387	16.160	10.454	17.904	10.567	16.811	14.079	16.012	16.293	17.707
fbut + 1/3flt	LEAP (ksi)	32.762	38.112	17.668	36.297	25.710	40.418	23.805	42.460	29.899	39.666	22.762	34.342	23.901	36.761
	MIDAS (ksi)	25.809	35.593	16.860	31.078	19.638	32.733	18.015	36.054	20.215	34.754	28.799	17.098	30.204	23.119
fbub + 1/3flb	LEAP (ksi)	32.762	38.112	17.668	36.297	25.710	40.418	23.805	42.460	29.899	39.666	22.762	34.342	23.901	36.761
	MIDAS (ksi)	26.368	36.245	17.450	31.695	20.154	33.407	18.450	36.800	20.655	35.454	29.385	17.765	30.883	23.856
fnc	LEAP (ksi)	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000
	MIDAS (ksi)	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000
LEAP Ratio		0.66	0.76	0.35	0.73	0.51	0.81	0.48	0.85	0.60	0.79	0.46	0.69	0.48	0.74
MIDAS Ratio		0.53	0.72	0.35	0.63	0.40	0.67	0.37	0.74	0.41	0.71	0.59	0.36	0.62	0.48
Governing Ratio		0.66	0.76	0.35	0.73	0.51	0.81	0.48	0.85	0.60	0.79	0.59	0.69	0.62	0.74

Continuously Braced

17.904 < 30 = 0.6fy OK

Discretely Braced

Unit 2 Modeling – Comparisons

- Reactions
  - MIDAS Grillage versus Plate Total Reaction Differences between 0.05% and 1.83% on overall structure
  - MIDAS Grillage versus Plate Individual piers reactions generally had minimal differences, ~1.0% on average, 3% worst case
  - MIDAS Grillage versus LEAP Grillage differed in reaction distribution, average 10% difference
  - MIDAS Grillage versus MDASH Girder Line showed a larger difference
- Moment comparisons between grillage and all plate are not readily available
- Can calculate beam stresses from grillage, then compare to direct plate outputs
- LEAP Grillage and MIDAS Grillage provided similar flange stress outputs and required plate sizes, though utility (demand versus capacity) varied. This is due to program interpretations of several parameters, such as lateral bracing
- LEAP results included higher lateral bending stresses but very similar overall combined stress

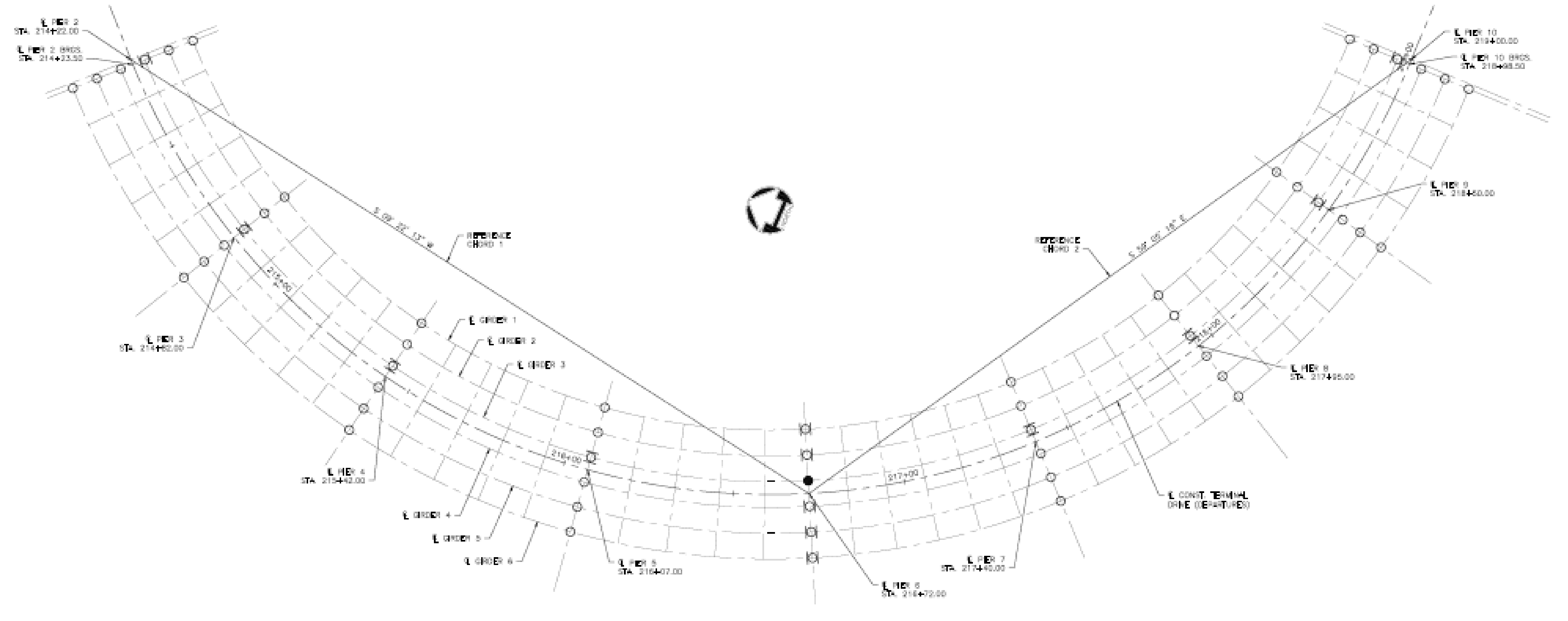
Unit 2 Modeling – Comparisons

- Take-aways:
  - Girder Line Analysis over-estimated deflections substantially in final condition
  - Girder Line Analysis under-estimated initial stage deflection
  - LEAP slightly overestimated deflections versus MIDAS All-Plate
  - MIDAS Grillage slightly underestimated deflections versus MIDAS All-Plate
  - In general the LEAP Grillage/MIDAS Grillage/MIDAS All-Plate were within 1/8-in of each other. Given that sacrificial haunch is 2-inches thick to make up for variations, and there is a 1/16-in tolerance on steel fabrication and 1/8-in tolerance on concrete, this is not as much of a concern in this case
  - On deeper girders, this difference could become more substantial and all-plate analysis becomes more critical for camber predictions
  - MIDAS Grillage provided very similar final reactions to MIDAS All-plate
  - Note MIDAS All-plate does not have code check capability at this time

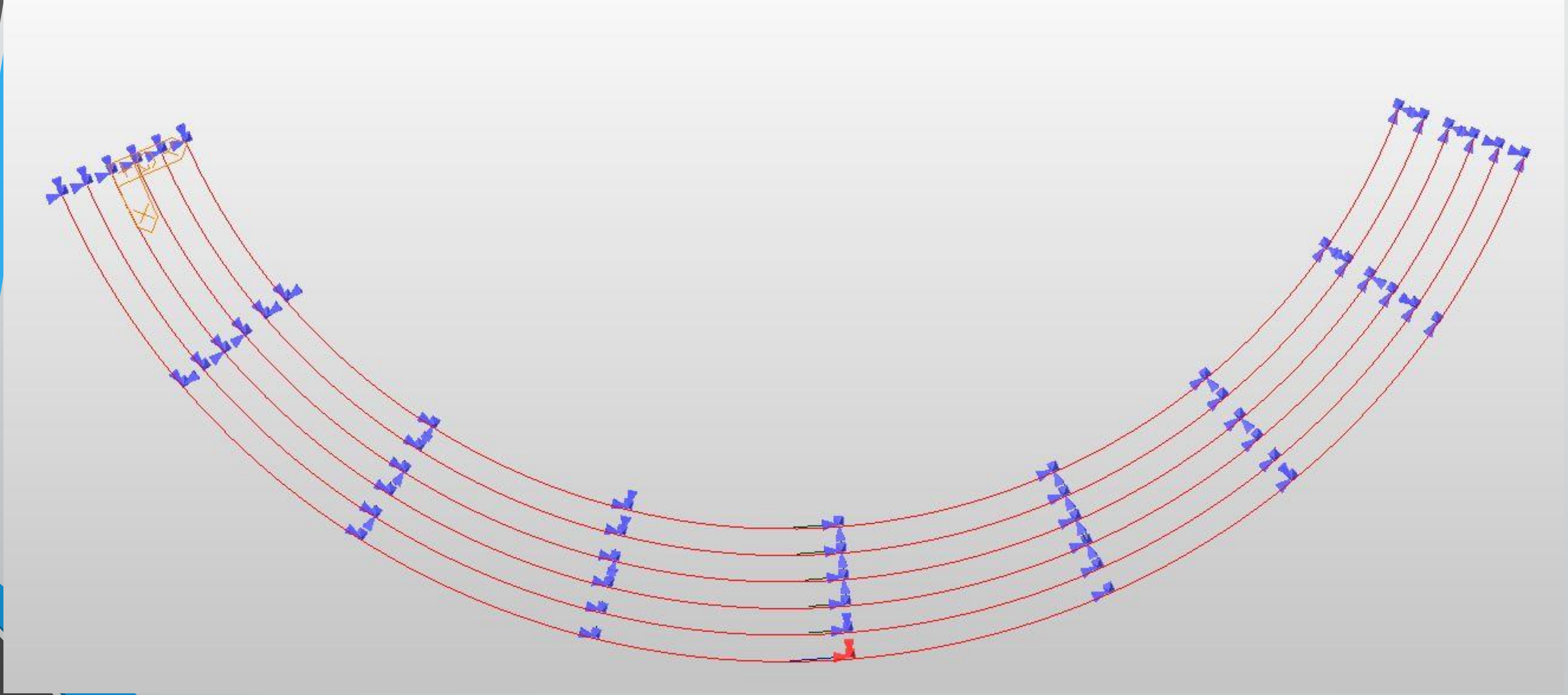
Code Commentary – Flange Lateral Stress

- In design of flanges there were several locations where lateral bending stress exceeded 0.6Fy = 30 ksi, but overall combined stress was less than capacity
- Normal check equation = fbu + 1/3 x fl
- In commentary Section 6.10.1.6 it states:
  - *"The provisions of Article 6.10 for handling the combined vertical and flange lateral bending are limited to I-sections that are predominantly in major-axis bending. For cases in which the elastically computed flange lateral bending stress is larger than approximately 0.6Fyf, the reduction in the major-axis bending tends to be greater than that determined based on these provisions. The service and strength limit state provisions of these Specifications are sufficient to ensure acceptable performance of I girders with elastically computed fl values somewhat larger than this limit."*
- The term "somewhat larger" is unclear. As engineering judgment, the flange lateral bending stresses were limited to around 10-20% over 0.6Fy, provided utility ratio remains below 1.0.

Modeling – Boundary Conditions



Modeling – Boundary Conditions

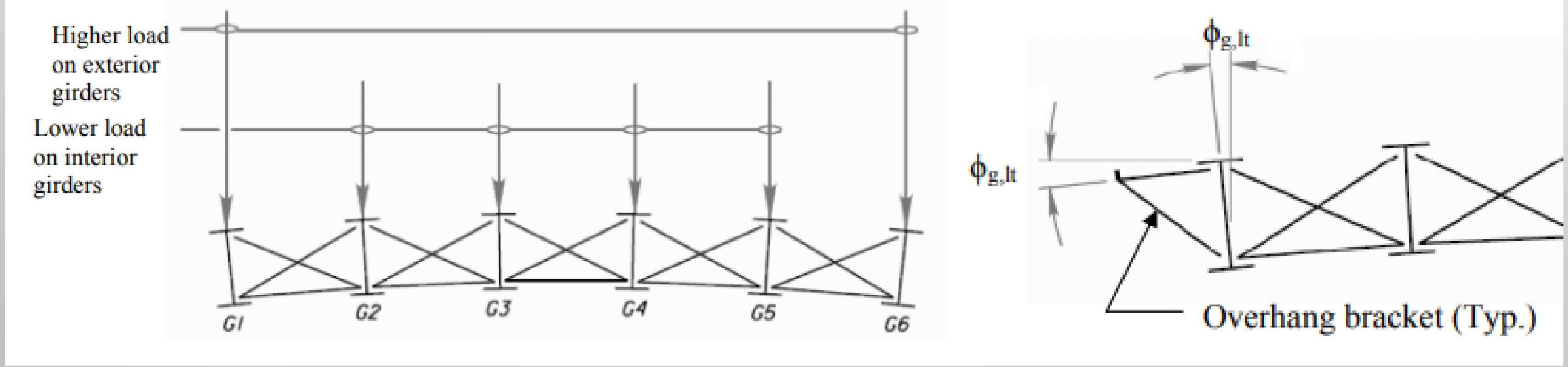


Construction Sequencing – Deck Pours

- Normally would have poured ends, then positive moment regions, then negative moment
  - This is to help prevent cracking in the negative moment regions during the next positive moment pour
  - As the positive moment wet concrete load is added it creates negative moment over the pier
- In this case, reversal areas were so close that this did not make sense
- Instead, poured ends for hold down, then worked towards the middle
- Positive and negative moment regions are poured together up to contra-flexure points to attempt to minimize effect of next pour in sequence

Construction Sequencing – Deck Pours

- Connectivity between beams/girders and crossframes/diaphragms is essential during the construction process, particularly for curved structures.
- Due to connectivity, deflections and twisting of the beams/girders will occur during deck pours. This can cause loss of deck thickness or cover during deck pours.
- The three primary sources are:
- 1. Global Superstructure Distortion, caused by differential deflections between girder lines.



Figures from The Ohio Department of Transportation *Bridge Design Manual*

Construction Sequencing – Deck Pours

- 2. Oil-Canning, caused by additional lateral load on a beam/girder from the cantilevered formwork on a web. Usually only a concern for deeper beams/girders.

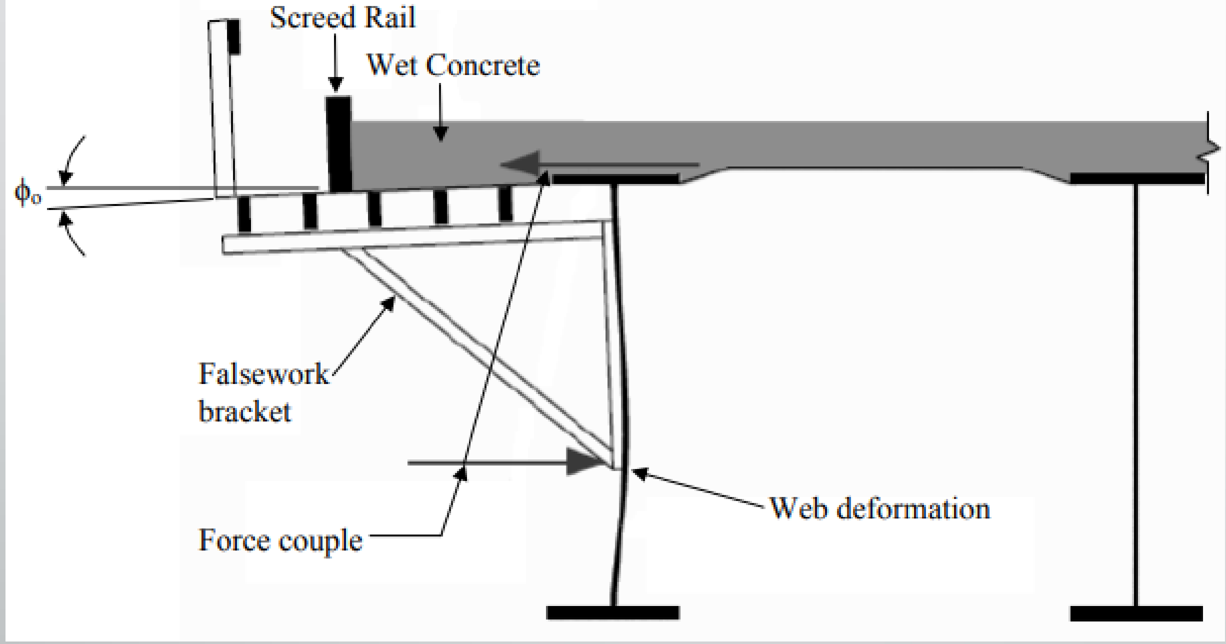


Figure from The Ohio Department of Transportation *Bridge Design Manual*

Construction Sequencing – Deck Pours

- 3. Girder Warping, caused by additional torsional load from wet concrete deck overhang, formwork loads, and screed loads.
- For straight bridges, often calculated using the Torsional Analysis of Exterior Girders (TAEG) program developed by the Kansas DOT. This software is free, and can be downloaded at http://www.ksdot.org/kart
- In MIDAS, a more explicit calculation is possible for items 1 and 3, with some limitations

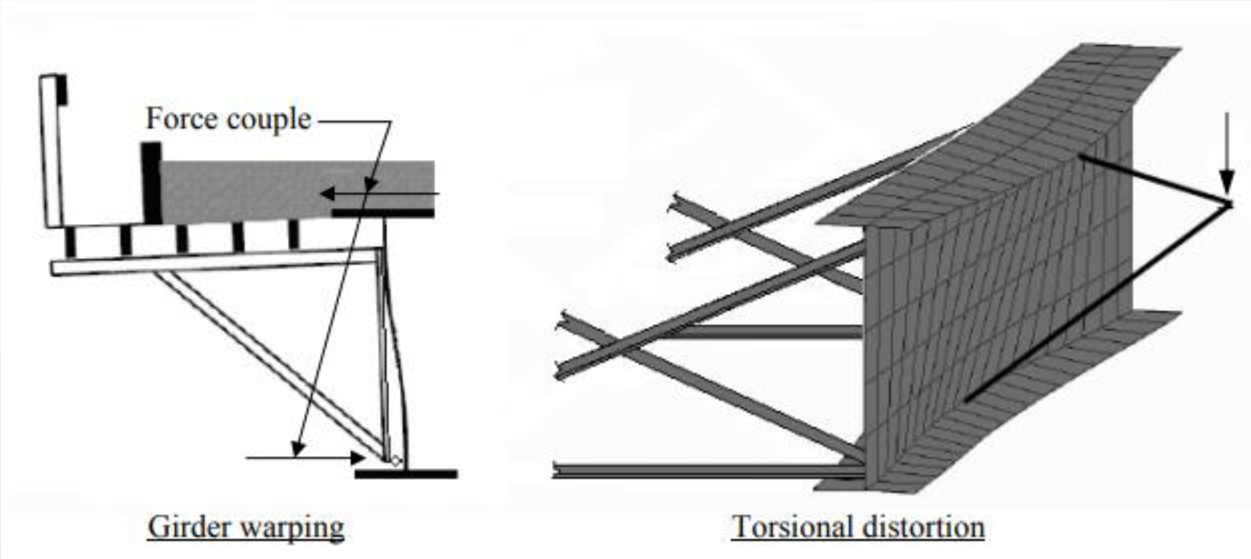


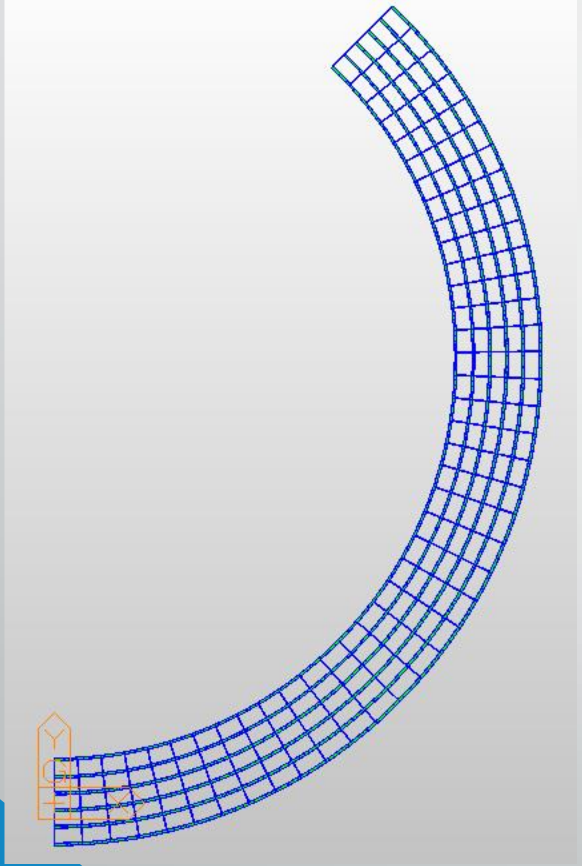
Figure from The Ohio Department of Transportation *Bridge Design Manual*

Construction Sequencing – Deck Pours

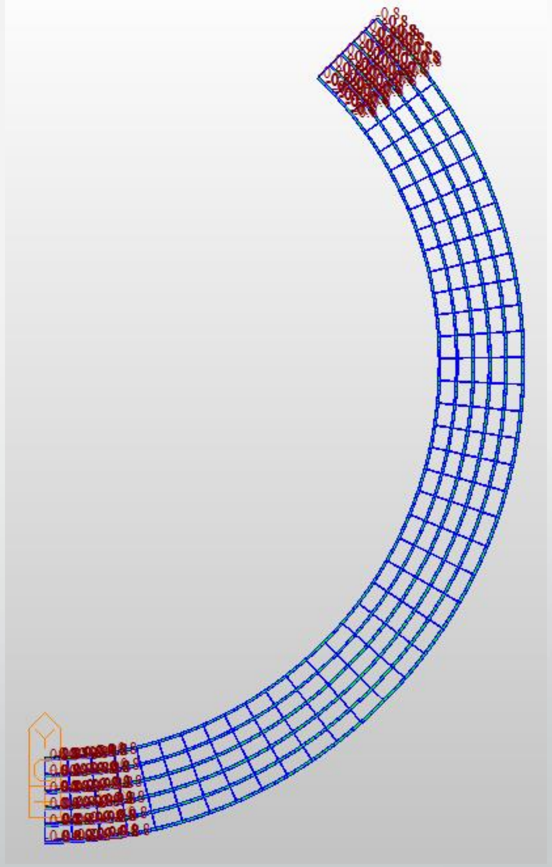
- Future MIDAS development – moving screed loads during construction staging
- Can currently apply loads manually – over piers, at positive moment regions
- Alternatively, analyze for all loads except screed machine in MIDAS and use stress outputs into TAEG for just screed load and oil-canning as a very localized effect (between crossframes)
- All plate model used for construction sequencing and dead load verification

Construction Sequencing – Deck Pours

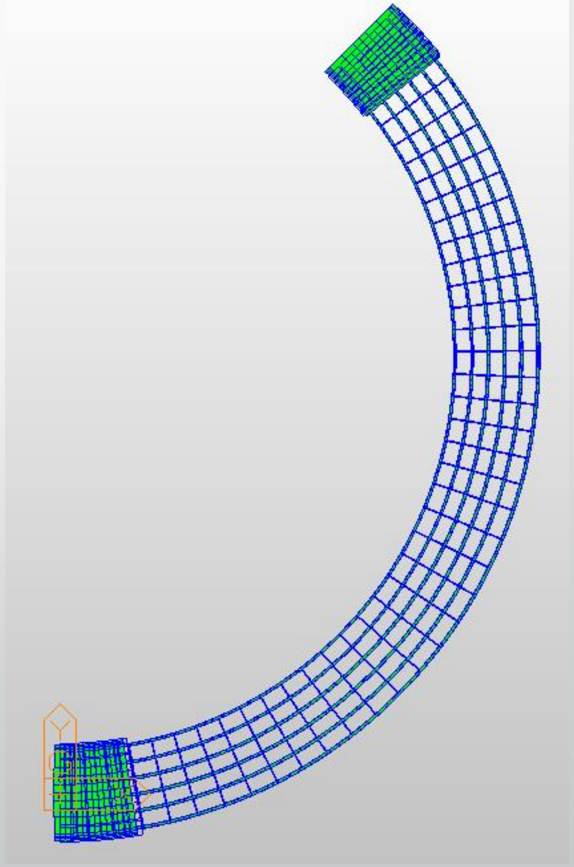
Stage 1 – Initial Steel Set



Stage 2-1: Wet Concrete, Pour 1

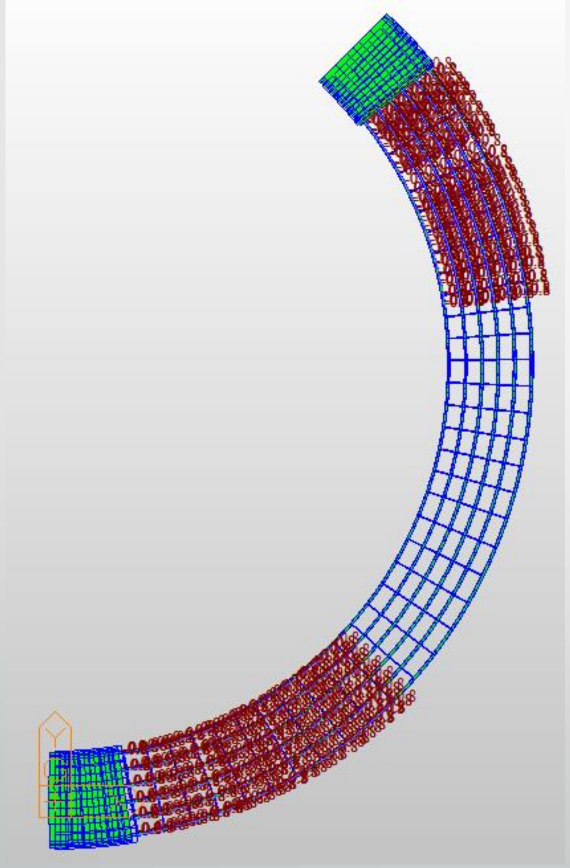


Stage 2-2: Hardened Pour 1

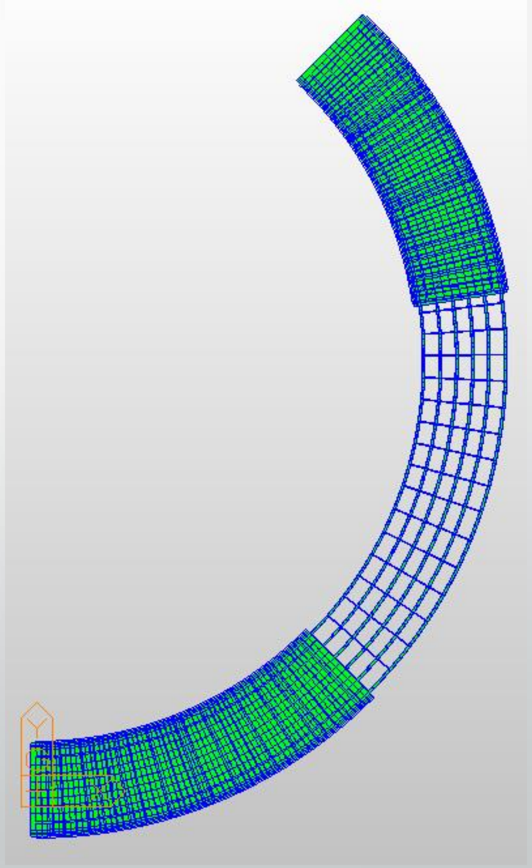


Construction Sequencing – Deck Pours

Stage 2-3: Wet Concrete, Pour 2

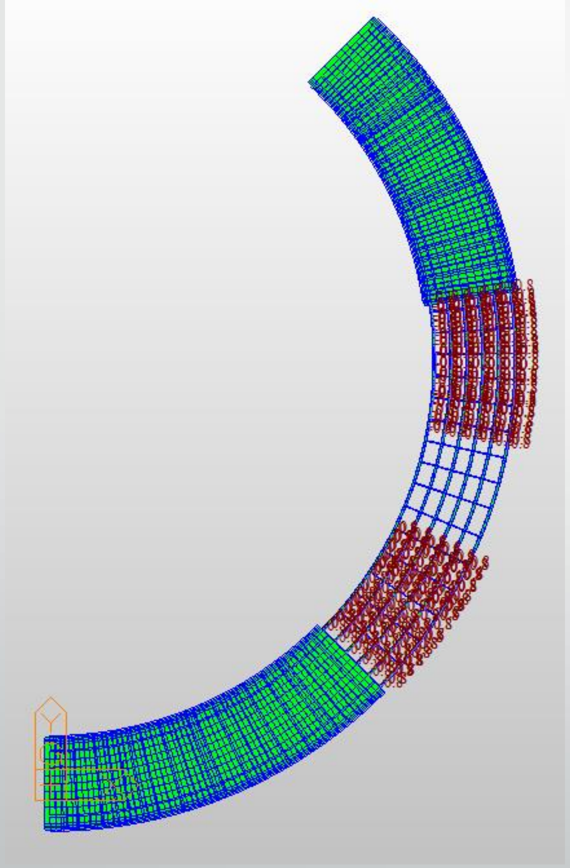


Stage 2-4: Hardened Pour 2

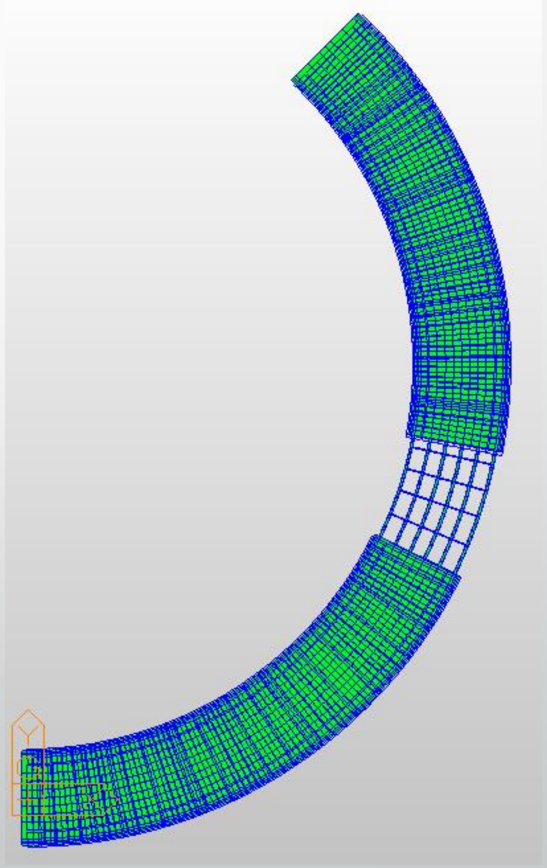


Construction Sequencing – Deck Pours

Stage 2-5: Wet Concrete, Pour 3

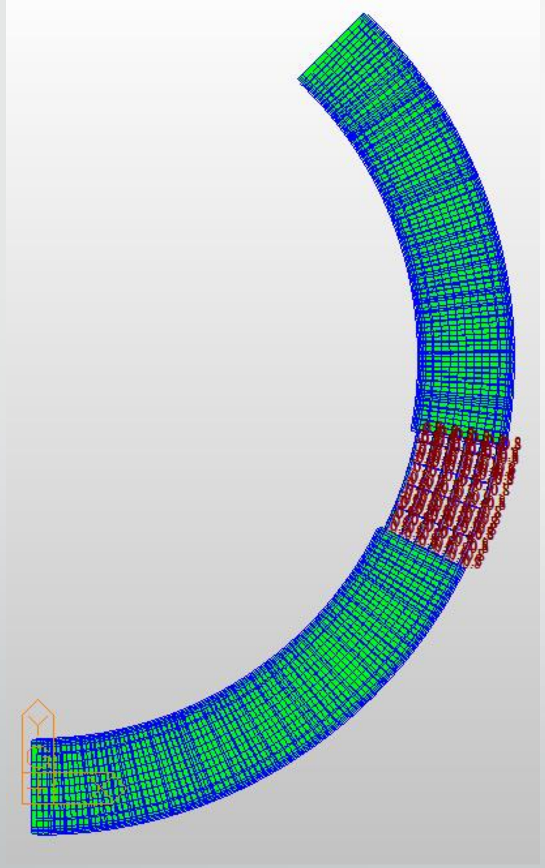


Stage 2-6: Hardened Pour 3

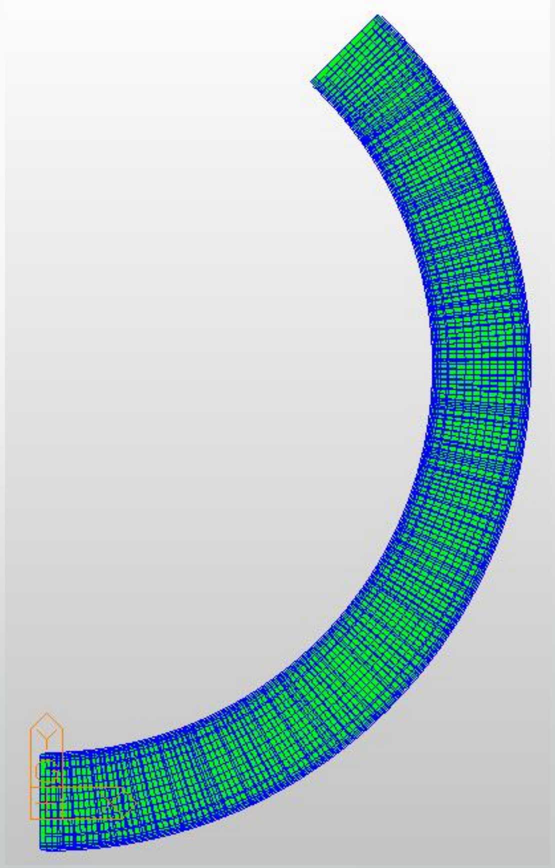


Construction Sequencing – Deck Pours

Stage 2-7: Wet Concrete, Pour 4

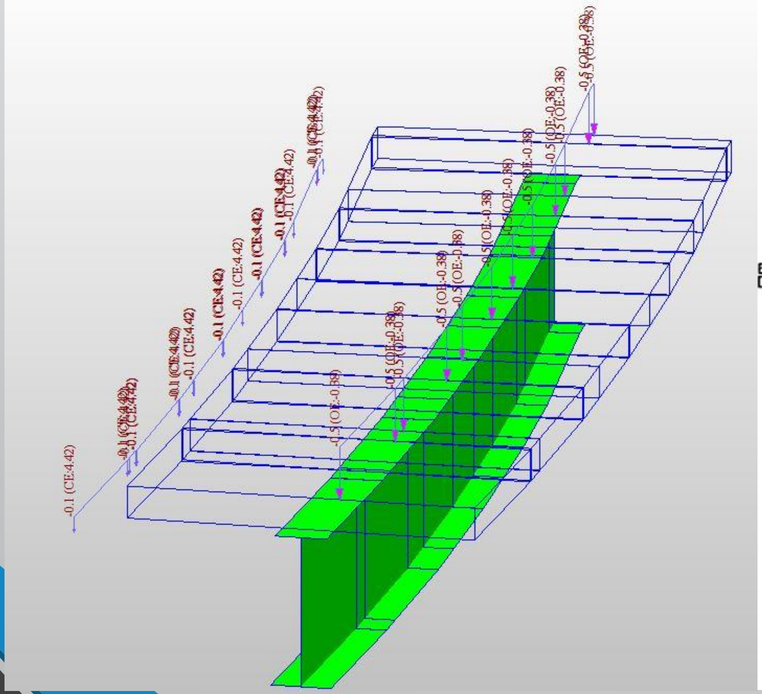


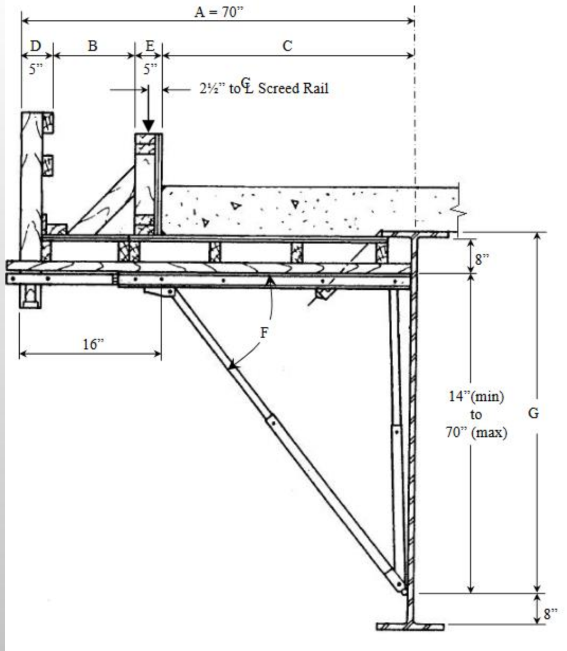
Stage 2-8: Hardened Pour 4



Construction Sequencing – Grillage vs. Plate

- Loadings
- Grillage model used vertical distributed line loads with eccentricity
- Could also use vertical distributed line load at centroid of beam, and distributed line moment, but would require 2x the inputs





Assumptions for TAEG Bracket Data Input

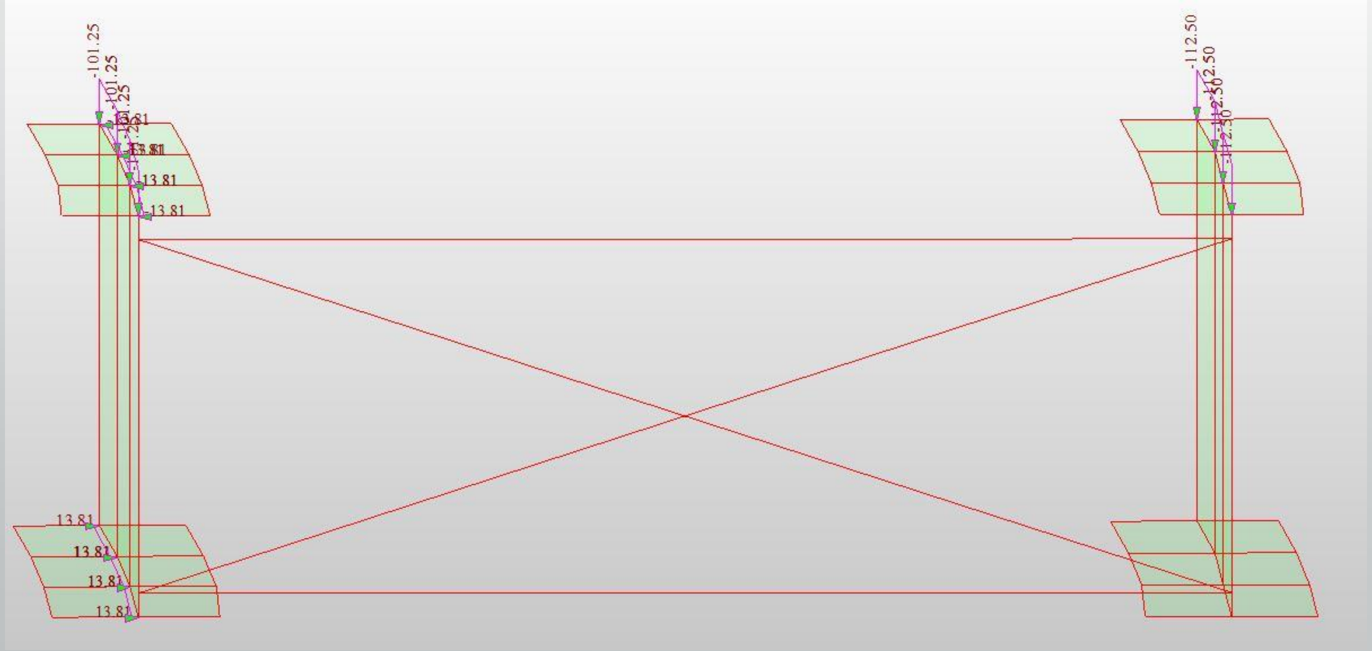
E. Load Data:

1. Live Load on Walkway..........50 lb/ft^2
2. Live Load on Slab..........50 lb/ft^2
3. Dead Load of Formwork..........10 lb/ft^2
4. Dead Load of Concrete..........150(t_{avg}) lb/ft^2
   (t_{avg} = Average thickness [ft.] of deck slab overhang)
5. Wheel Spacing [1-2-3]..........36” – 31” – 36”
6. Maximum Wheel Load:

   To estimate the total finishing machine length required for placement along the skew, add the rail-to-rail length and the extra end length from the following table using the plan specified skew rounded to the nearest 5 degrees. W is the rail-to-rail length as measured perpendicular to the centerline of the bridge.

Construction Sequencing – Grillage vs. Plate

- Plate model does not allow for eccentric line load or distributed moment
- Plate loadings do, however, allow for line loading under the "edge loading" method
- In order to apply the proper lateral moments, used eccentricity and line load to determine line moment, then converted line moment into a line-force-couple to apply as edge loading
- While this took a few steps in excel, it simplified input from applying point loads/moments



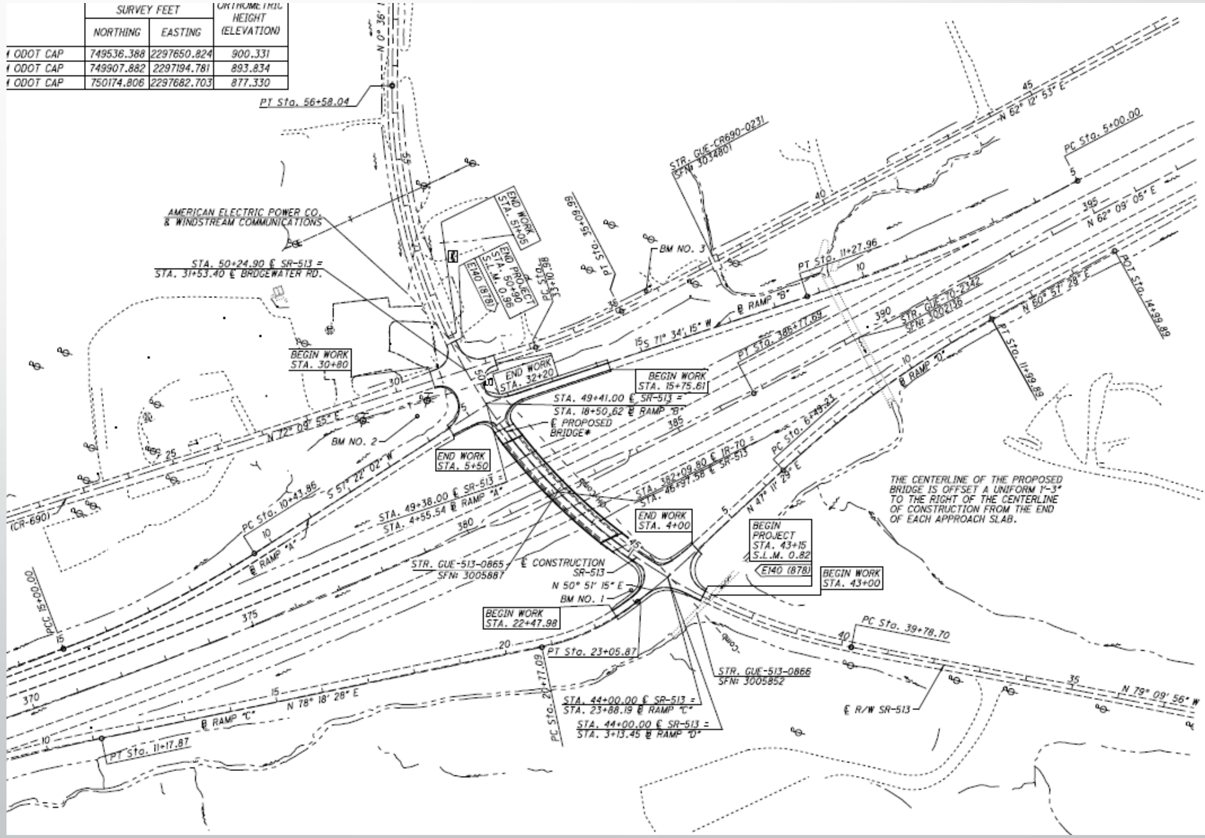
Construction Sequencing – Grillage vs. Plate

- General rule on rotation limitation = 1/8 in/ft, or 0.0104 radians (10.4×10^{-3}), however this is not a code provision, but engineer's judgment
- Used local rotation, and "current step displacement" in MIDAS
- Worst case is during first end pour, all subsequent pours are less
- All-plate model is more accurate than frame/grillage model, produced much higher rotations
- Conclusion: while grillage+ model is adequate for loads and final condition design, a full plate model is strongly recommended for evaluation of lateral deformation during construction sequencing
- Solution: as a short girder, used ¼ in/ft (20.8×10^{-3}) as upper limit on rotations, but provide temporary timber blocking at one-half the crossframe spacing within regions where deck is being poured

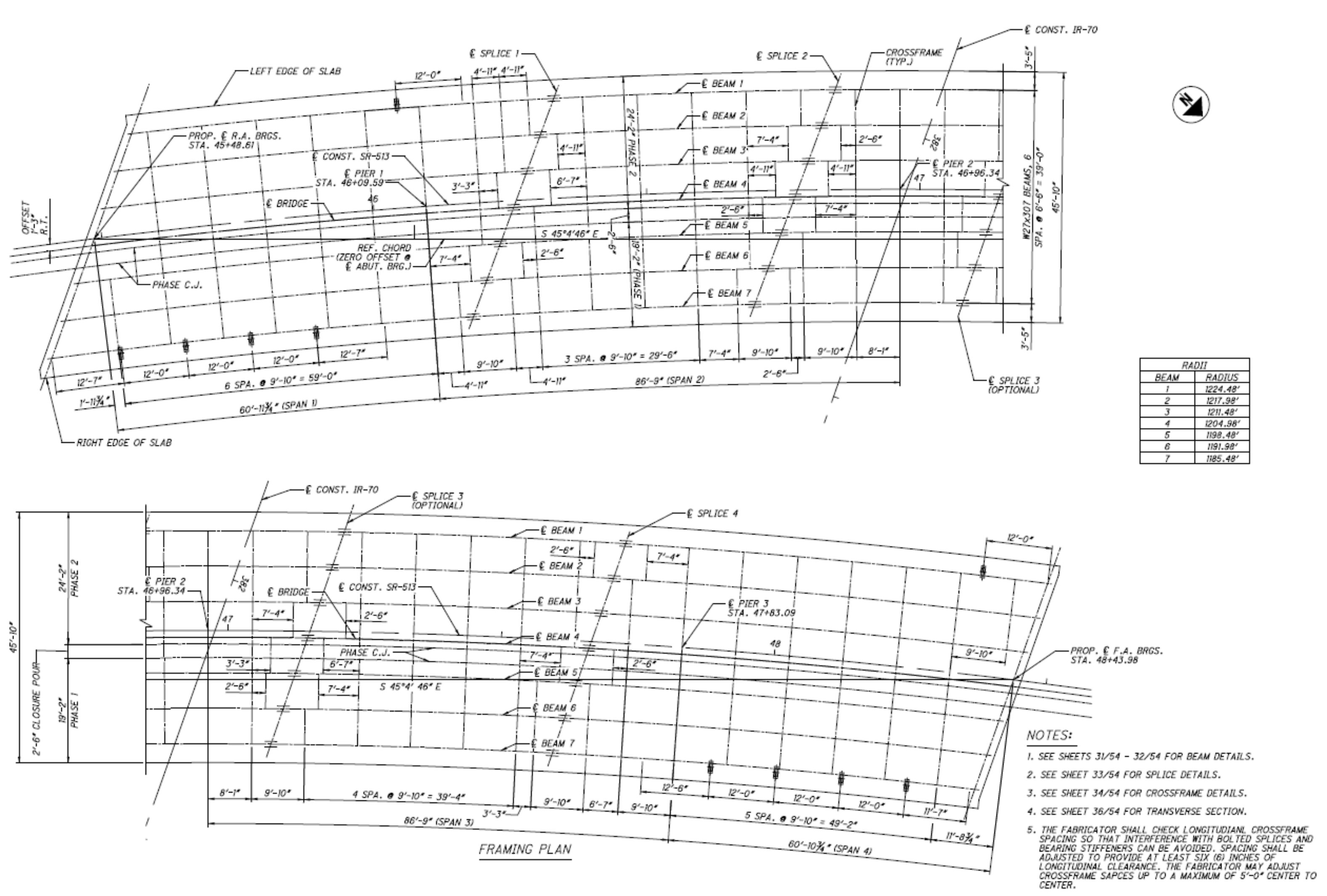
Lateral Rotation (Rad x 10^{-3})			
Stage	Grillage+	All Plate	Note
Stage 1	0.502	2.969	Steel
Stage 2-1	3.318	18.617	Pour 1
Stage 2-2	0.046	11.290	
Stage 2-3	2.280	13.990	Pour 2
Stage 2-4	0.230	9.350	
Stage 2-5	2.155	13.476	Pour 3
Stage 2-6	0.889	8.828	
Stage 2-7	1.137	7.896	Pour 4
Stage 2-8	0.187	8.616	
Stage 3	0.238	6.434	Final

Project – ODOT GUE-513-08.65

- SR-513 over IR-70, Curved 4-Span Bridge (60’-11.75”, 2 @ 86’-9”, 60’-10.75”)
- Skewed 19° 32’ 07” to reference chord
- Composite on curved rolled steel beams
  - R = 1206.23 ft
  - Minimum Girder R = 1185.48 ft
  - Dc = 4° 45’ 00”
  - Δ = 79° 46’ 07”
  - All crossframes and girders radial
  - Vertical Sag Curve
- Part-width construction, including pier caps



Project – ODOT GUE-513-08.65



RADII	
BEAM	RADIUS
1	1224.48'
2	1217.98'
3	1211.48'
4	1204.98'
5	1198.48'
6	1191.98'
7	1185.48'

NOTES:

1. SEE SHEETS 31/54 - 32/54 FOR BEAM DETAILS.
2. SEE SHEET 33/54 FOR SPLICE DETAILS.
3. SEE SHEET 34/54 FOR CROSSFRAME DETAILS.
4. SEE SHEET 36/54 FOR TRANSVERSE SECTION.
5. THE FABRICATOR SHALL CHECK LONGITUDIANL CROSSFRAME SPACING SO THAT INTERFERENCE WITH BOLTED SPLICES AND BEARING STIFFENERS CAN BE AVOIDED. SPACING SHALL BE ADJUSTED TO PROVIDE AT LEAST SIX (6) INCHES OF LONGITUDINAL CLEARANCE. THE FABRICATOR MAY ADJUST CROSSFRAME SAPCES UP TO A MAXIMUM OF 5'-0" CENTER TO CENTER.

Project – ODOT GUE-513-08.65

- Not a structural issue, but Amish Horse & Buggy use bridge and needed to be included in analysis: single lane signalized. Needed ramp queue and red time clear analyses

Project – ODOT GUE-513-08.65

- MIDAS used for design, after girder line with V-Load analysis for preliminary
- No change in beam size from V-load to MIDAS, similar results, but larger radius than CONRAC
- Separate MIDAS model created for temporary support analysis and design
- Important to include relative stiffness of concrete column versus steel temporary support columns. Used full moment of inertia for column. If moment is significantly great, would need to include cracked moment of inertia/stiffness, particularly for elastic analysis
- MIDAS design analysis was very useful – could output design results of concrete columns, composite beams, and steel temporary support all from the same model file.
- In this case, used existing footings/extensions for foundation of temporary support, so relative stiffness of foundation was not included
- If using temporary shoring on matting, would need to account for the stiffness of matting and foundation as well. This is possible in MIDAS through spring assignments at foundations.
- Need to provide room for adjustment during construction. In this case hydraulic jacks to provide positive contact with pier cap, grout under base plates for leveling

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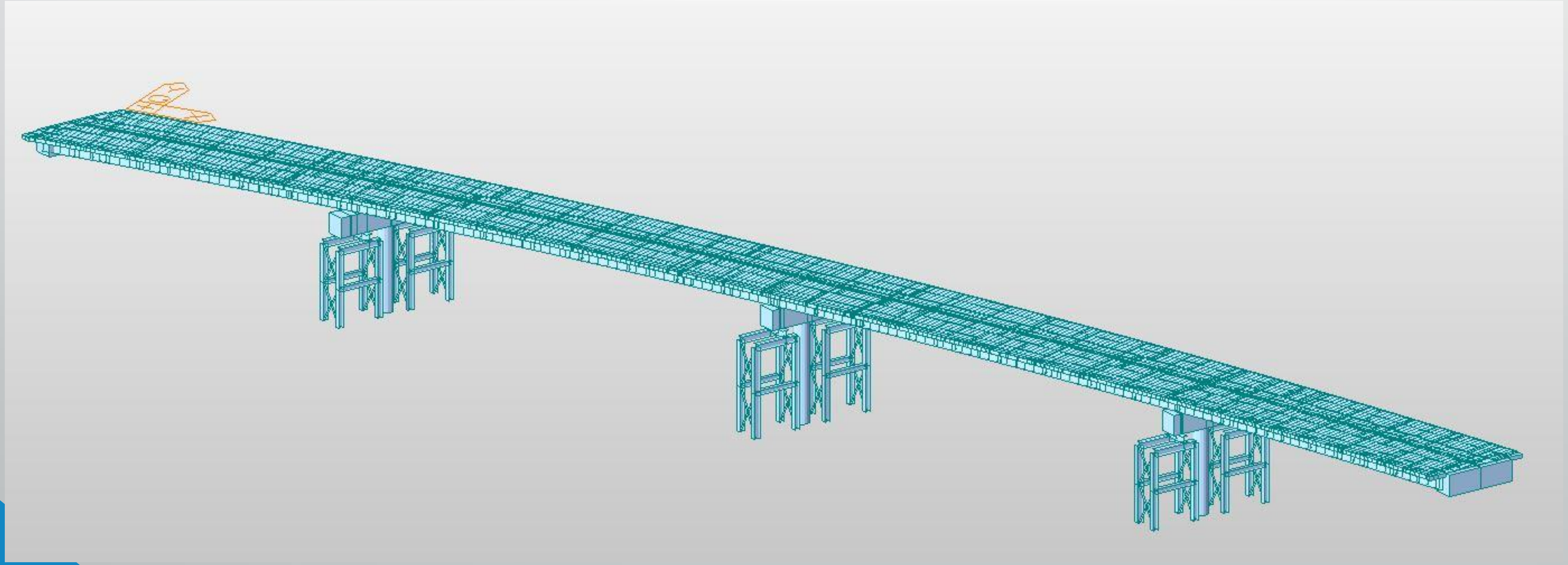
- Originally used one tower with compression and tension connection (bearings & tension rods)
- After discussion with ODOT, added a second tower for redundancy.
- Order of preference: Compression -> Tension -> Shear



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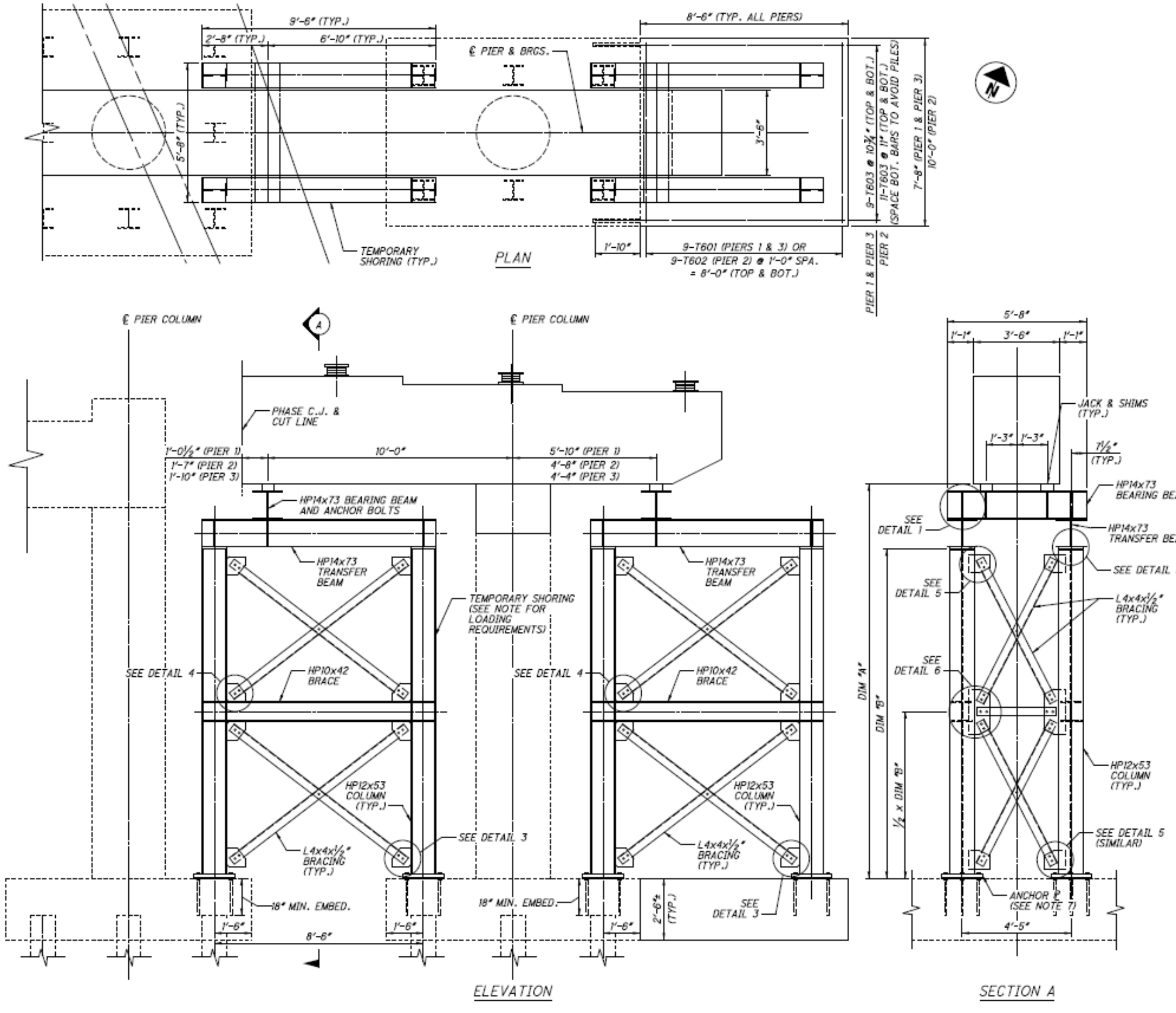

TEMP. SUPPORT FOOTING (FOR INFORMATIONAL PURPOSES ONLY)

MARK	TOTAL	LENGTH	WEIGHT (LBS)	TYPE
T601	36	7'-2"	388	ST.
T602	18	9'-6"	257	ST.
T603	58	10'-1"	879	ST.
TOTAL			1524	

PIER	DIM. A	DIM. B
1	16'-0 7/8"	13'-3 5/8"
2	18'-10 3/4"	16'-1 5/8"
3	16'-2 5/8"	13'-5 1/2"

NOTES:

1. TEMPORARY SHORING SHALL BE PLACED FOLLOWING PHASE I PIER CAP REMOVAL AND PRIOR TO PHASE I CONSTRUCTION. PIER BEARINGS AND ANCHORS SHALL BE IN PLACE BEFORE CONCRETE DECK IS POURED.
2. THE TEMPORARY SUPPORT IS DESIGNED TO RESIST THE FOLLOWING FACTORED LOADING, WHICH INCLUDES DEAD, LIVE, AND WIND LOADS (LRFD METHOD):
   AXIAL COMPRESSION (DOWNWARDS): 117.2 KIPS
   HORIZONTAL FORCE IN THE Y-AXIS (PARALLEL TO PIER CAP): 6.5 KIPS
   HORIZONTAL FORCE IN THE X-AXIS (PERPENDICULAR TO PIER CAP): 13.0 KIPS

   THESE FACTORED LOADS ARE APPLIED AT THE MIDSPAN OF THE BEARING BEAM. THESE LOADS WERE DEVELOPED BASED ON THE STIFFNESS OF THE TEMPORARY SUPPORT AND THE CONCRETE CAP AND COLUMN, AND ANY DESIGN ALTERNATIVE PROPOSED BY THE CONTRACTOR SHALL ACCOUNT FOR THE STIFFNESSES IN THE PROPOSED SYSTEM WHEN DETERMINING DESIGN LOADS.
3. TEMPORARY SUPPORT STEEL SHALL BE ASTM A709 GRADE 50 UNLESS OTHERWISE NOTED. HP SECTIONS SHALL BE ASTM A572 GRADE 50. ALL STEEL SHALL BE CVN.
4. ALL BOLTS AND ANCHORS SHALL BE ASTM A325 AND INCLUDE WASHERS AND NUTS.
5. SHIM AND JACK TO PROVIDE FULL CONTACT AND SUPPORT OF PIER CAP. JACKS WITH SHIMS WERE ASSUMED TO BE 6 INCHES IN HEIGHT. ADJUST STEEL HEIGHT AS NEEDED BASED ON ACTUAL DIMENSIONS.
6. SEE SHEETS 26/54 - 28/54 FOR PIER CAP ELEVATIONS.
7. SEE SHEET 13/54 FOR DETAIL 1, DETAIL 2, AND PIER CAP ANCHOR BOLT ASSEMBLY.
8. SEE SHEET 14/54 FOR DETAIL 3 THRU DETAIL 5, AND FOOTING ANCHOR PLATE LAYOUT.
9. TEMPORARY SUPPORT AND ASSOCIATED FOOTING, FOOTING REINFORCING, AND DOWELS SHALL BE PAID FOR UNDER ITEM 516 - JACKING AND TEMPORARY SUPPORT OF SUPERSTRUCTURE, AS PER PLAN.

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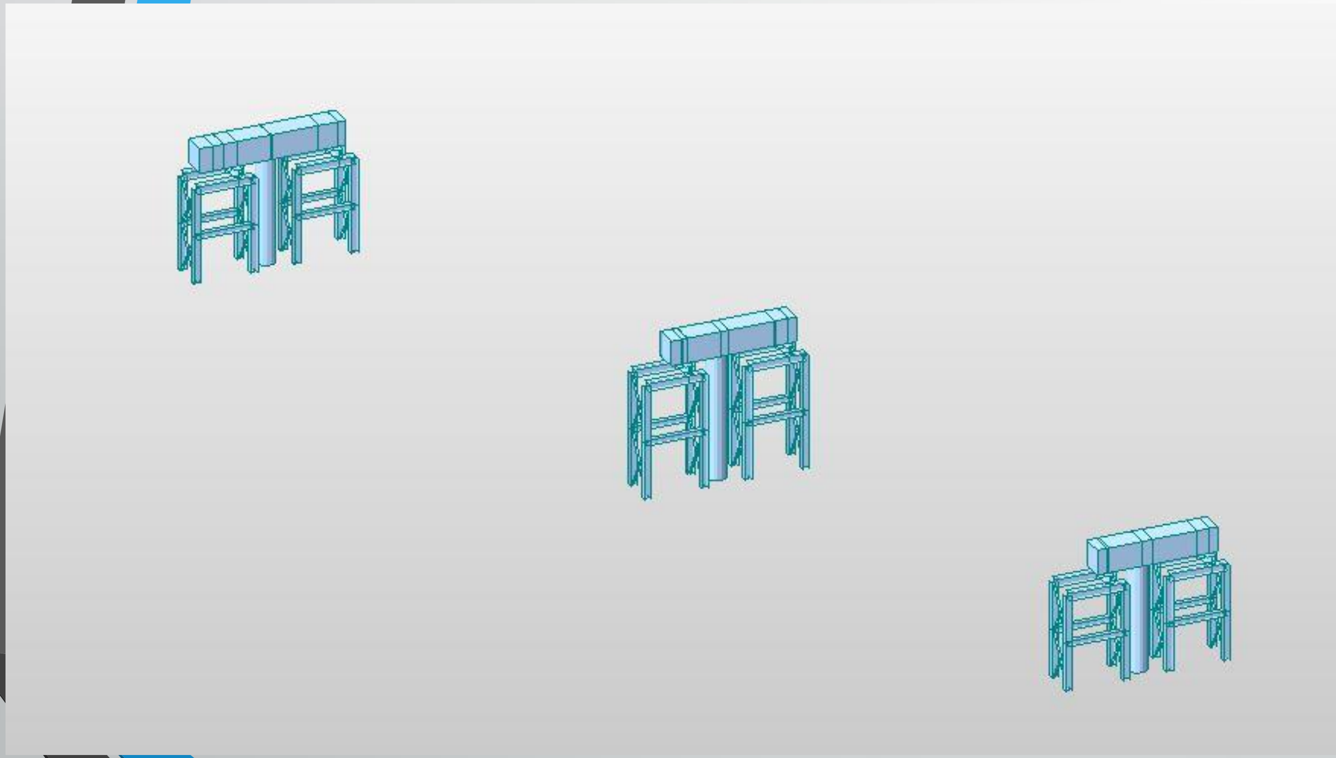
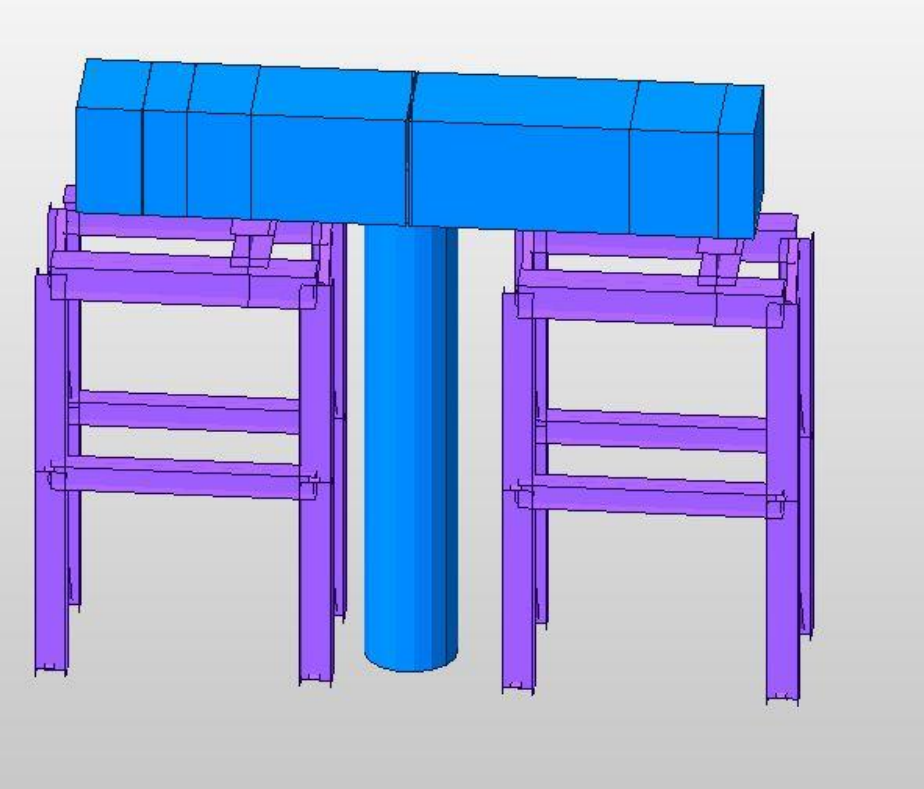
- Stage 1





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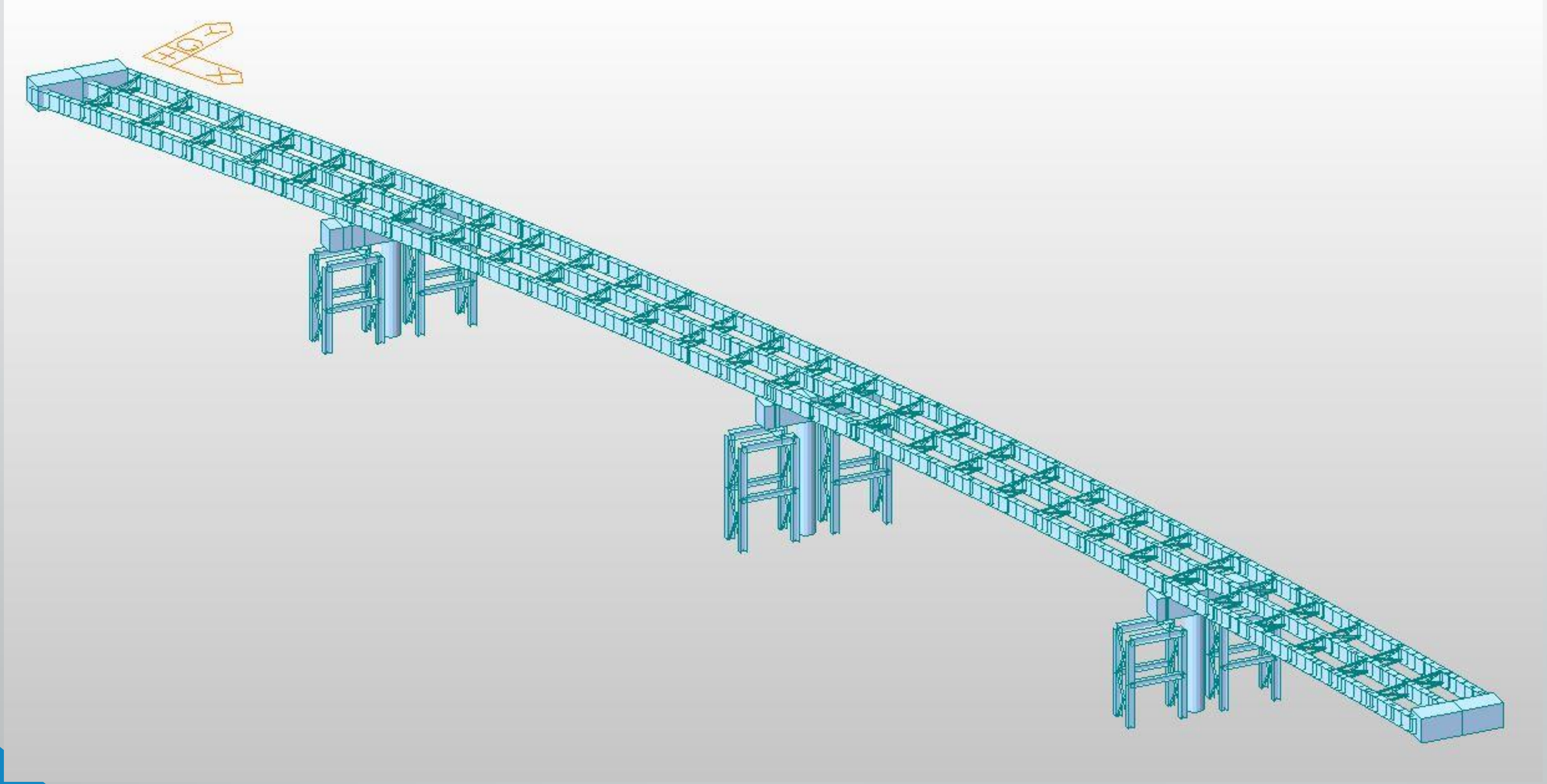
- Stage 2



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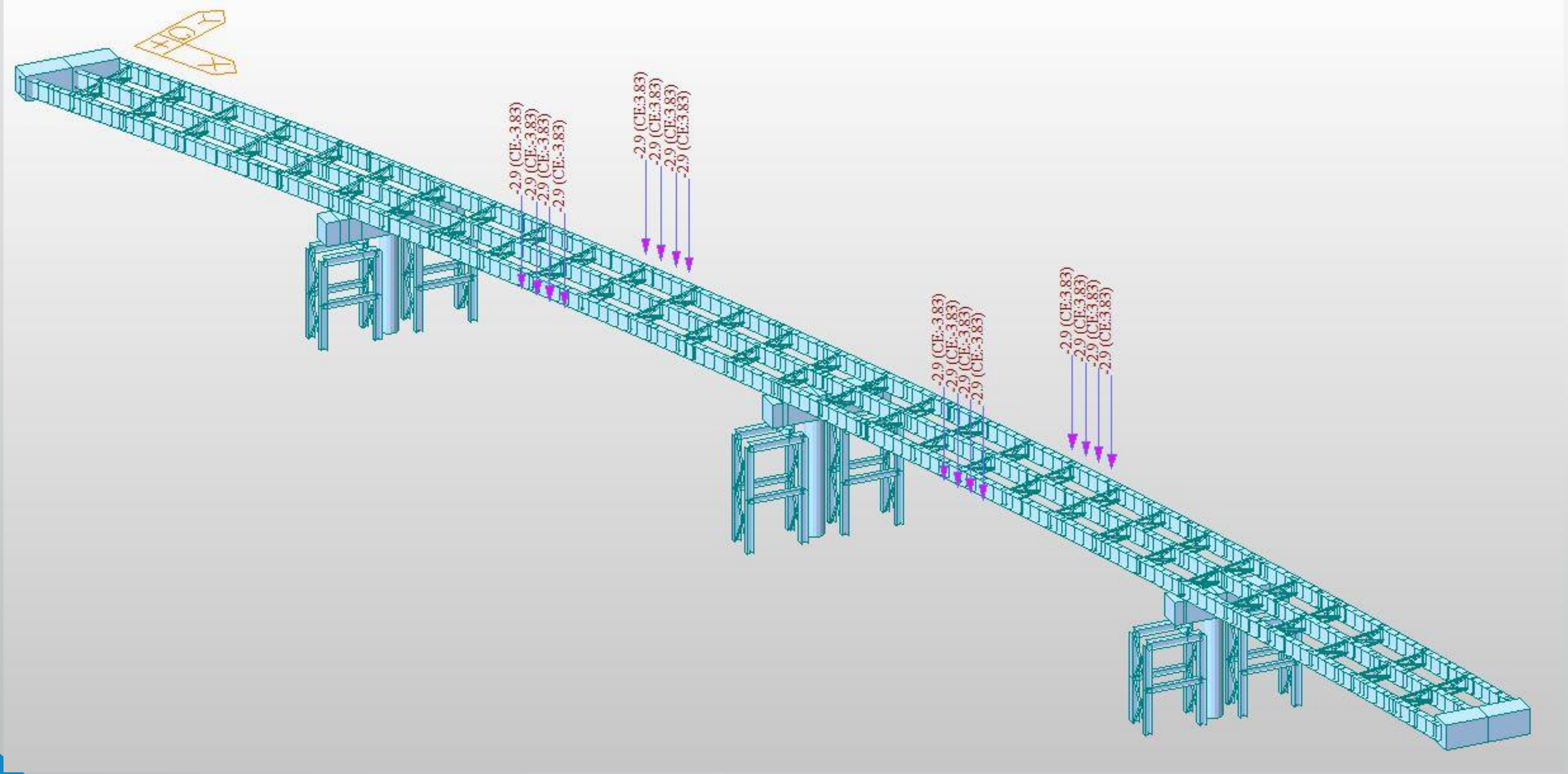
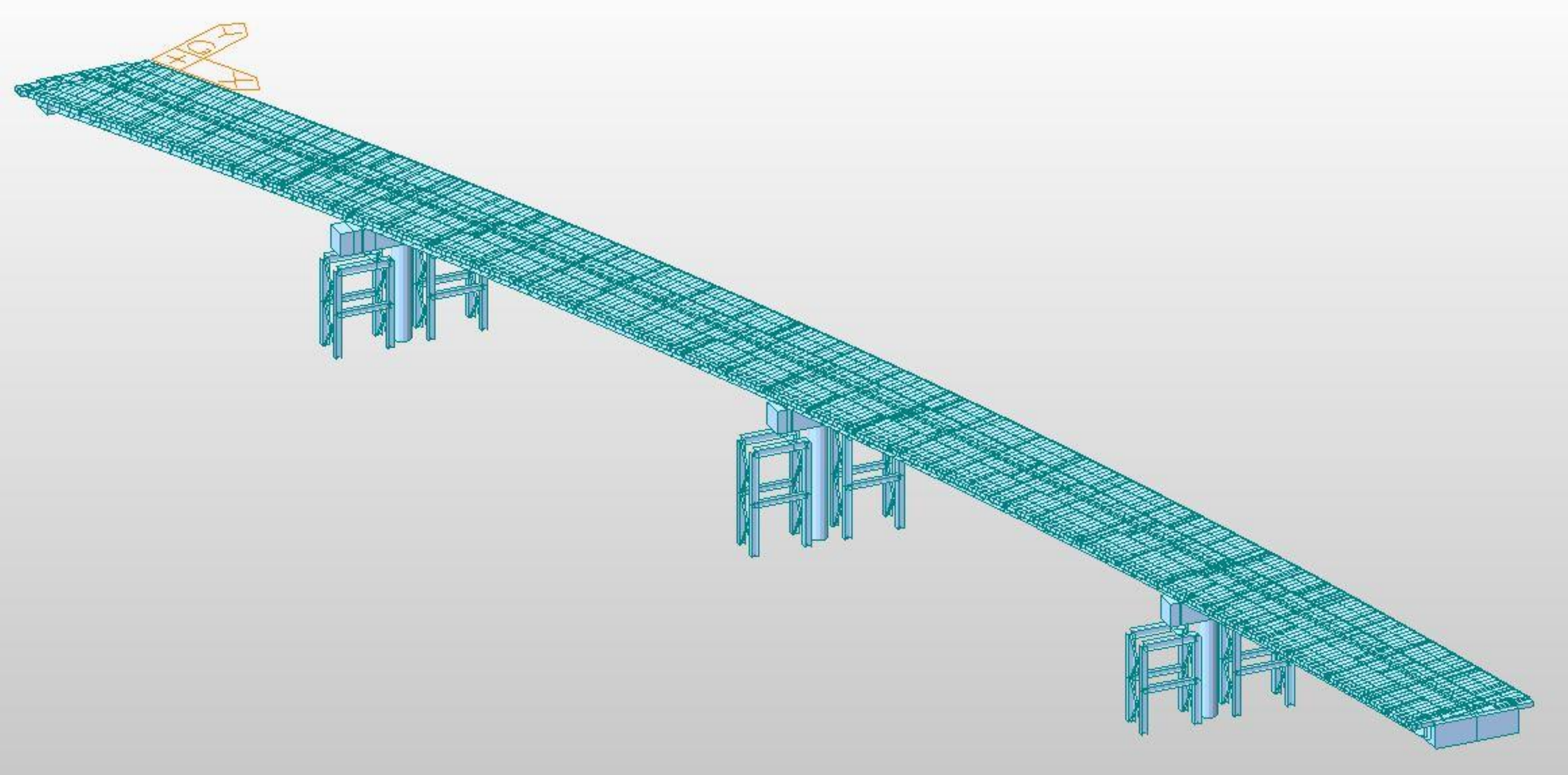
- Stage 3



Project – ODOT GUE-513-08.65

- Stage 4



Conclusions

- MIDAS capabilities for construction staging and ability to analyze and design multiple stages as well as design multiple material types within a single model is very advantageous
- Proper analysis of construction cases is a key aspect in modern bridge engineering
- Refer to AISC/NSBA guides for very useful constructability guidelines
- V-Load & Girder Line analysis is accurate for larger girder radii, but becomes less so for very small radii. Need to provide contingency for additional girder warping and internal force effects, but is still a useful tool in preliminary engineering
- MIDAS Grillage and LEAP Grillage provided similar results overall with variation in details. LEAP was faster to set up and run model but is more difficult to extract output and model is less readily available
- Grillage+ (limited 3D) modeling provides good results for design of girders in the final condition, and forces during construction, but underestimates girder rotation
- All-plate model is recommended to verify constructability cases and in particular girder rotations during deck pour sequence

Recognition

- Best practice for finite element design – independent models by independent designers, with common checker and final reviewer. Cross review by designers.
- Special thanks to the following people:
  - Paige Sechrist, PE – Design Engineer/Modeling, MIDAS Grillage and Plate (CONRAC)
  - Pat Plews, PE – Independent Review, LEAP Grillage (CONRAC)
  - Mike Avellano, PE, SE, PMP – Project Manager, Checking and Independent Review (GUE-513, CONRAC)
  - Ron Mattox, PE – Independent Review (GUE-513)

Questions?