mBrace3D, Influence surfaces and vehicle load optimization

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NSBA, Steel Bridge Design Handbook, Example 3 (revised 2022)

https://www.aisc.org/globalassets/nsba/design-resources/steel-bridge-design-handbook/b954_sbdh_appendix3.pdf

Steel Bridge Design Handbook

APPENDIX

Design Example 3: Three-Span Continuous Horizontally Curved Composite Steel I-Girder Bridge

February 2022

Smarter.
Stronger.
Steel.

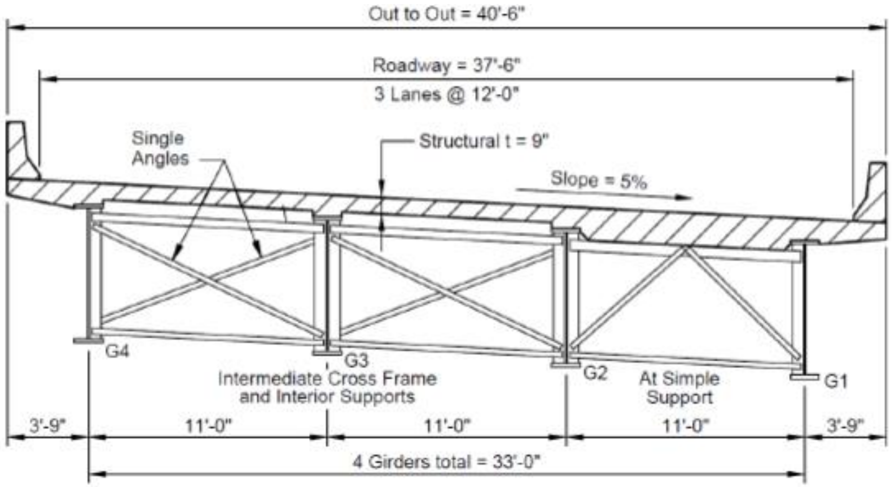


Figure 1: Typical Bridge Cross-Section

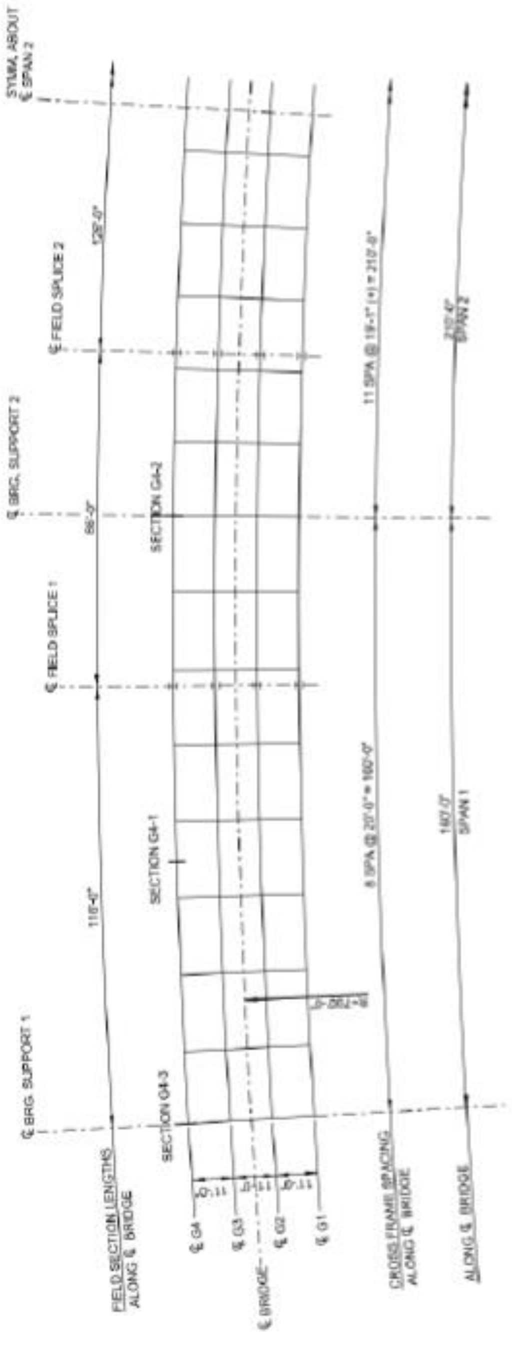
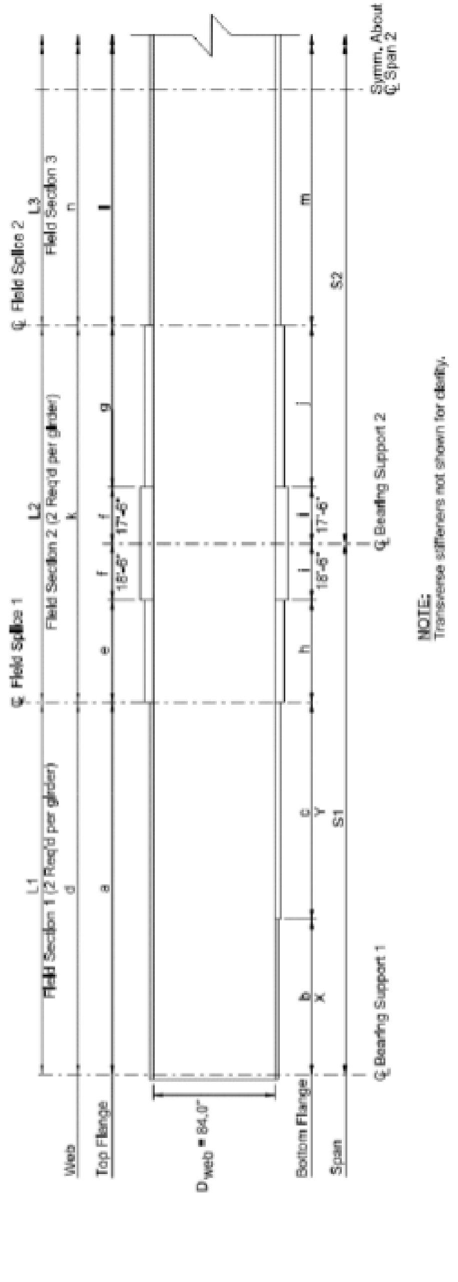


Figure 2: Framing Plan



Member Sizes (Shown In Inches)

	a	b	c	d	e	f	g	h	i	j	k	l	m	n
G1	16X1	n/a	16X1	84x9/16	21x1.25	21x2.5	21x1.25	21x1.50	21x3	21x1.50	84x5/8	18X1	18X1	84x9/16
G2	18X1	n/a	18X1	84x9/16	18x1.25	18x2.5	18x1.25	19x1.50	19x3	19x1.50	84x5/8	18X1	18X1	84x9/16
G3	18X1	n/a	18X1	84x9/16	20x1.25	20x2.5	20x1.25	21x1.50	21x3	21x1.50	84x5/8	18X1	20X1	84x9/16
G4	20X1	21X1	21X1.625	84x9/16	28x1.25	28x2.5	28x1.25	27x1.50	27x3	27x1.50	84x5/8	20X1	21X1.5	84x9/16

Dimensions (Shown In feet)

	L1	L2	L3	S1	S2	X	Y
G1	113.0	84.0	123.0	156.2	205.1	0	113.3
G2	115.1	85.3	125.0	158.7	208.4	0	115.1
G3	116.9	86.7	127.0	161.3	211.7	0	116.9
G4	118.7	88.0	129.0	163.8	215.0	33.0	85.7

Figure 3: Girder Elevation

Table 1 Girder G1 Unfactored Shears by Tenth Point

Girder G1 Unfactored Shears									
10th Point	Span Length	Dead Load				LL+I		Fatigue LL+I	
		$DC1_{STEEL}$	$DC1_{CONC}$	DC2	DW	Pos.	Neg.	Pos.	Neg.
	(ft)	(kip)	(kip)	(kip)	(kip)	(kip)	(kip)	(kip)	(kip)
0	0.00	14	66	17	13	109	-31	45	-11
1	15.62	9	45	6	9	87	-21	33	-5
2	31.25	5	26	2	5	69	-27	27	-8
3	46.87	1	9	2	2	55	-36	23	-12
4	62.49	-2	-9	0	-1	43	-46	19	-16
5	78.11	-5	-29	-4	-5	34	-58	13	-20
6	93.74	-9	-49	-8	-9	27	-73	9	-27
7	109.36	-14	-70	-12	-13	25	-89	8	-33
8	124.98	-20	-98	-14	-18	22	-106	8	-37
9	140.61	-28	-127	-23	-24	20	-125	7	-41
10	156.23	-40	-159	-35	-30	12	-146	4	-48
10	0.00	41	159	35	31	148	-12	49	-4
11	20.50	25	116	22	23	124	-24	39	-7
12	41.01	17	83	11	15	104	-31	36	-9
13	61.51	10	50	8	9	83	-33	29	-9
14	82.02	4	24	4	4	66	-37	24	-12
15	102.52	0	0	0	0	51	-52	19	-19
16	123.03	-5	-25	-4	-4	41	-66	15	-24
17	143.53	-10	-51	-7	-10	33	-81	11	-29
18	164.04	-16	-80	-12	-15	29	-102	9	-36
19	184.54	-26	-119	-21	-23	25	-121	7	-40
20	205.05	-41	-160	-36	-31	12	-152	4	-51
20	0.00	40	158	35	31	154	-11	52	-4
21	15.62	28	126	24	23	121	-18	43	-5
22	31.25	20	96	16	17	107	-21	39	-5
23	46.87	14	72	10	14	91	-25	33	-8
24	62.49	9	50	7	9	75	-30	28	-11
25	78.11	6	30	4	6	62	-34	24	-15
26	93.74	1	9	1	2	48	-44	17	-19
27	109.36	-1	-8	-1	-1	38	-55	13	-23
28	124.98	-5	-26	-3	-6	31	-69	9	-27
29	140.61	-9	-45	-7	-9	24	-86	8	-33
30	156.23	-14	-66	-17	-13	29	-108	9	-45

Note: Live load results include multiple presence factors, dynamic load allowance (impact), and centrifugal force effects.

Table 5 Girder G1 Unfactored Major-Axis Bending Moments by Tenth Point

Girder G1 Unfactored Major-Axis Bending Moments									
10th Point	Span Length	Dead Load				LL+I		Fatigue LL+I	
		$DC1_{STEEL}$	$DC1_{CONC}$	DC2	DW	Pos.	Neg.	Pos.	Neg.
	(ft)	(kip-ft)	(kip-ft)	(kip-ft)	(kip-ft)	(kip-ft)	(kip-ft)	(kip-ft)	(kip-ft)
0	0.00	0	0	0	0	0	0	0	0
1	15.62	178	889	184	188	1415	-381	529	-116
2	31.25	295	1478	288	311	2409	-718	873	-200
3	46.87	351	1767	327	375	3003	-1006	1049	-252
4	62.49	348	1754	316	373	3249	-1245	1103	-291
5	78.11	284	1438	260	313	3192	-1448	1067	-327
6	93.74	156	804	161	189	2875	-1605	955	-412
7	109.36	-42	-184	6	-6	2201	-2003	741	-512
8	124.98	-322	-1553	-229	-274	1465	-2569	463	-621
9	140.61	-716	-3348	-564	-619	770	-3305	181	-764
10	156.23	-1333	-5897	-1169	-1167	883	-5274	185	-991
10	0.00	-1333	-5897	-1169	-1167	883	-5274	185	-991
11	20.50	-569	-2719	-447	-505	842	-2755	232	-624
12	41.01	-123	-648	-78	-94	1694	-1796	588	-484
13	61.51	157	709	141	176	2655	-1485	917	-369
14	82.02	331	1554	293	347	3273	-1481	1085	-329
15	102.52	384	1812	335	400	3498	-1462	1144	-360
16	123.03	323	1513	272	338	3297	-1488	1089	-327
17	143.53	159	717	150	182	2678	-1528	924	-371
18	164.04	-131	-688	-87	-103	1705	-1871	597	-497
19	184.54	-575	-2733	-433	-489	906	-2700	261	-620
20	205.05	-1302	-5781	-1124	-1130	885	-5113	180	-956
20	0.00	-1302	-5781	-1124	-1130	885	-5113	180	-956
21	15.62	-726	-3371	-560	-617	776	-3236	191	-744
22	31.25	-323	-1555	-237	-277	1464	-2544	468	-612
23	46.87	-42	-187	0	-5	2196	-1980	744	-505
24	62.49	154	797	160	187	2866	-1567	956	-405
25	78.11	283	1433	262	313	3186	-1420	1068	-323
26	93.74	347	1750	315	373	3247	-1222	1107	-284
27	109.36	350	1761	323	372	3003	-988	1052	-251
28	124.98	294	1473	282	309	2420	-706	880	-204
29	140.61	177	881	183	184	1436	-376	543	-112
30	156.23	0	0	0	0	0	0	0	0

Note: Live load results include multiple presence factors, dynamic load allowance (impact), and centrifugal force effects.

Modelling assumptions

NSBA Steel Bridge Design Handbook vs. mBrace3D

6.1 Three-Dimensional Finite Element Analysis

A three-dimensional finite element analysis was used to analyze the superstructure in this design example. The girder webs were modeled using plate elements. The top and bottom flanges were modeled with beam elements. The girder elements were connected to nodes that were placed in two horizontal planes, one plane at the top flange and one plane at the bottom flange. The horizontal curvature of the girders was represented by straight elements that have small kinks at the nodes, rather than by curved elements. Nodes were placed at the top and bottom flanges along the girders at each cross-frame location and typically at the third points along the length of the girders between cross-frame locations.

The composite deck was modeled using a series of eight-node solid elements attached to the girder top flanges with beam elements, which represented the shear studs.

Bearings were modeled with dimensionless elements called "foundation elements." These dimensionless elements can provide six different stiffnesses, with three for translation and three for rotation. If a guided bearing is to be modeled and is oriented along the tangential axis of a girder, a stiffness of zero is assigned to the stiffness in the tangential direction. The stiffness of the bearing, and supporting structure if not explicitly modeled, is assigned to the direction orthogonal to the tangential axis.

Cross-frame members were modeled with individual truss elements connected to the nodes at the top and bottom flanges of the girders. Article 4.6.3.3.4 specifies that the influence of end-connection eccentricities is to be considered in the calculation of the equivalent axial stiffness of single-angle and flange-connected tee-section cross-frame members in the analysis. In lieu of a more accurate analysis, Article C4.6.3.3.4 recommends that a stiffness reduction factor of 0.65 be applied to the axial stiffness, AE, of the cross-frame members in a 3D analysis, or when computing the equivalent beam stiffness of the cross-frame members in a 2D analysis, to account for the influence of the end-connection eccentricities. Although this reduction factor was not applied in the analysis originally performed for this design example, the use of this stiffness reduction factor is strongly encouraged.

mBrace3D implements shell elements for the girder flanges and webs, as well as the concrete deck.

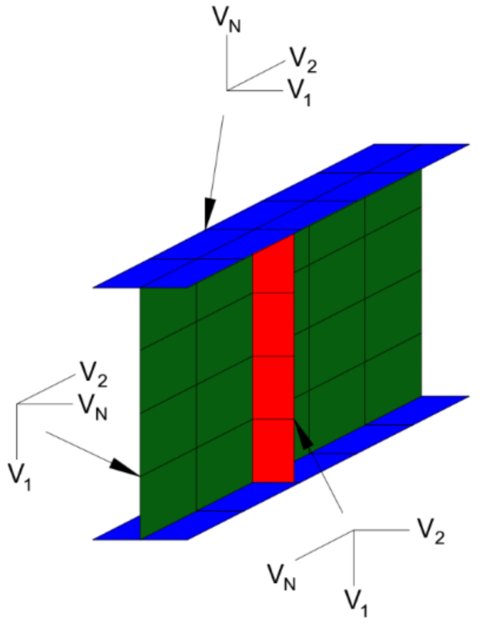
In mBrace3D, the mesh size is specified by the user. Typically, a 3-ft. mesh is good enough for the composite structure.

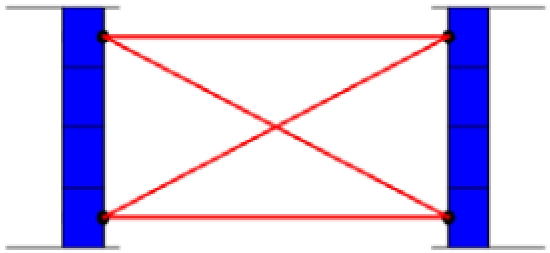
Shear studs are modelled as "rigid" link elements in mBrace3D

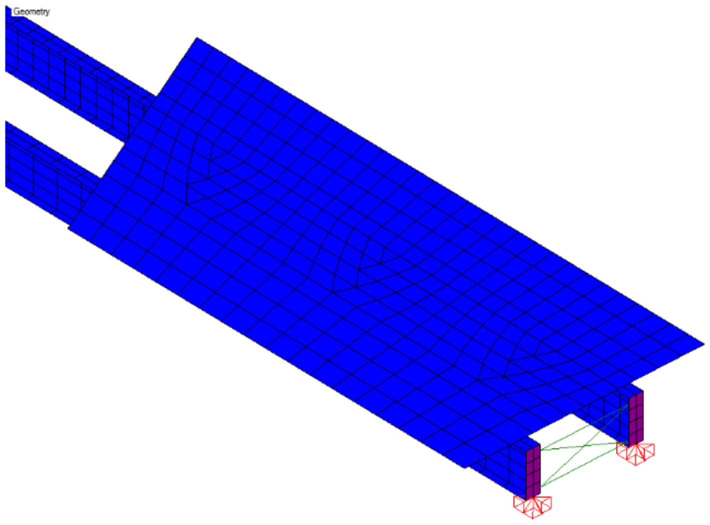
Piers and abutments are by default modelled as full fixities in mBrace3D (axial springs are also possible). For curved bridges, radial / tangential boundary conditions are implemented.

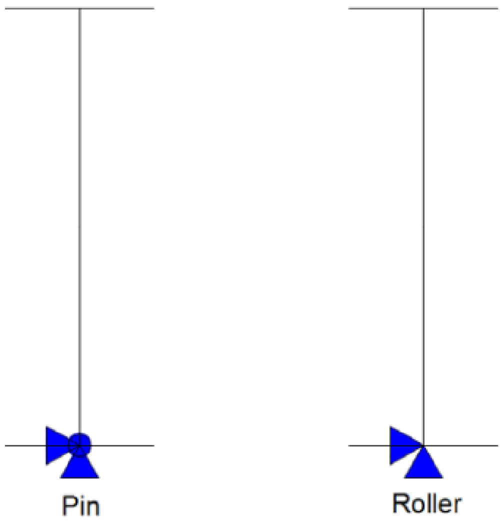
Stiffness reduction factors for the cross-frames (typically, 0.65) are available in mBrace3D. The software models all bracing members with bar elements (axial force only).

mBrace3D modelling assumptions – Key figures









Source: Paul Biju-Duval, Development of three-dimensional finite element software for curved plate girder and tub girder during construction, PhD Dissertation, The University of Texas at Austin, 2017

Advanced FEA model

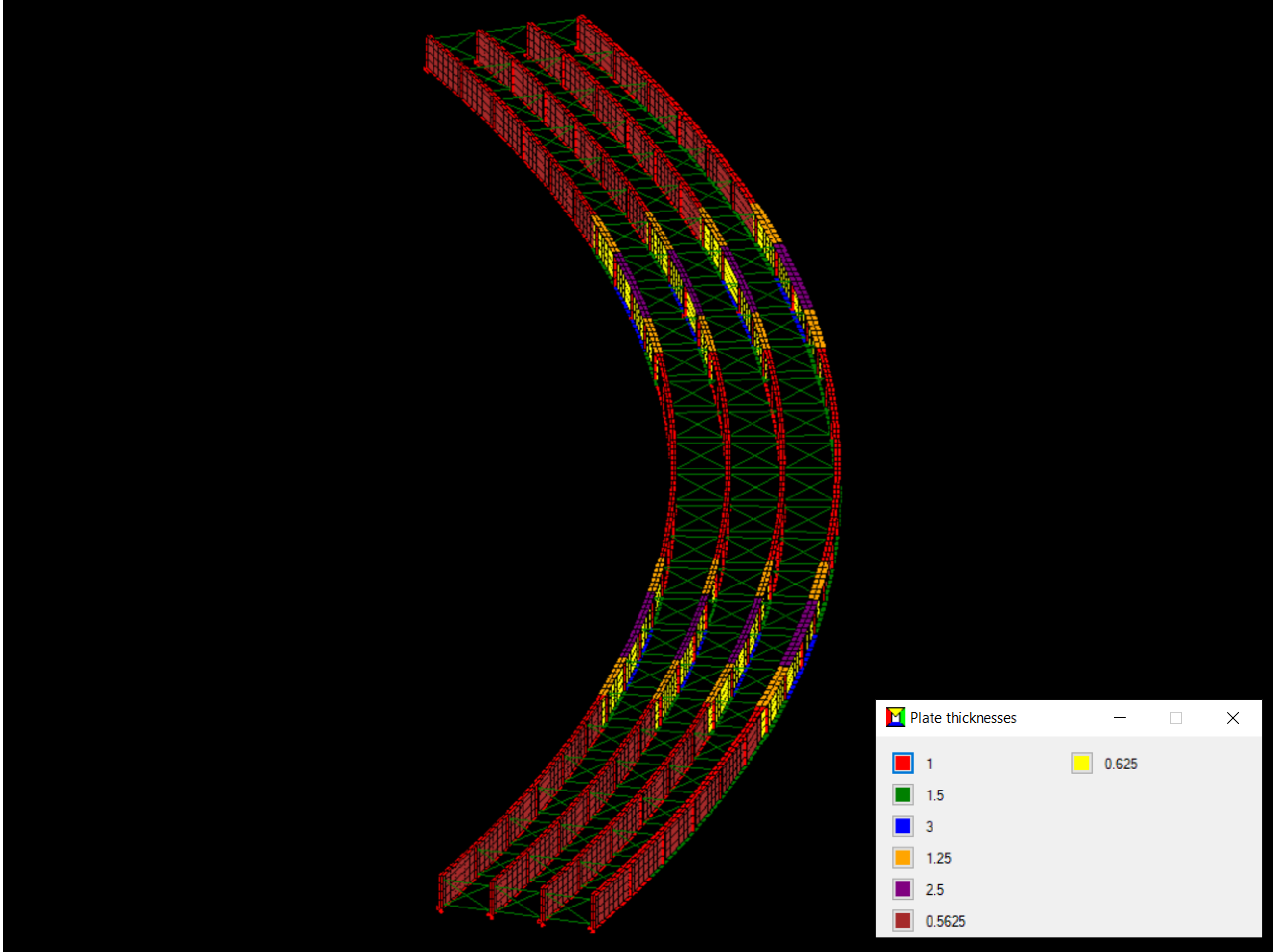
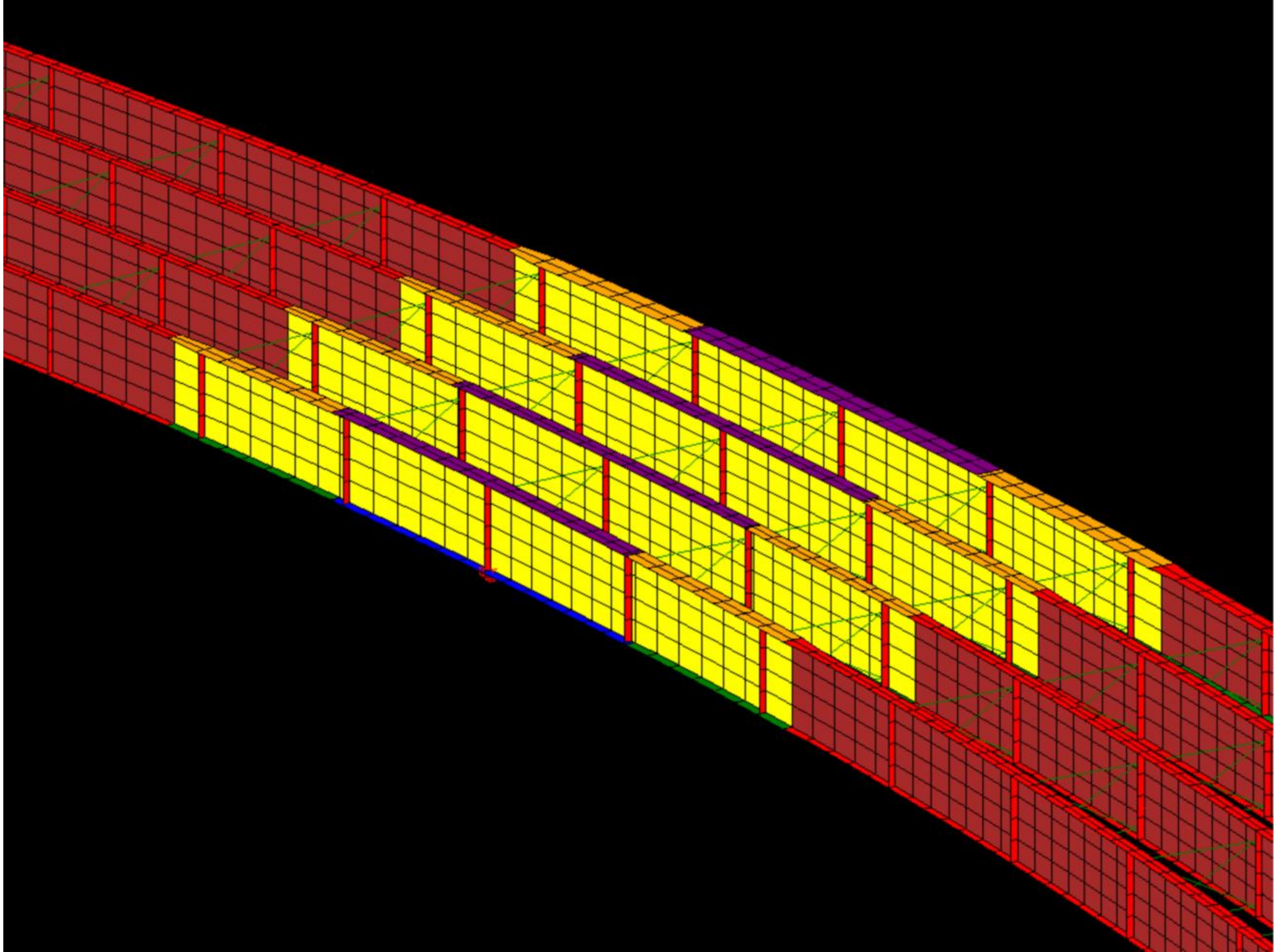
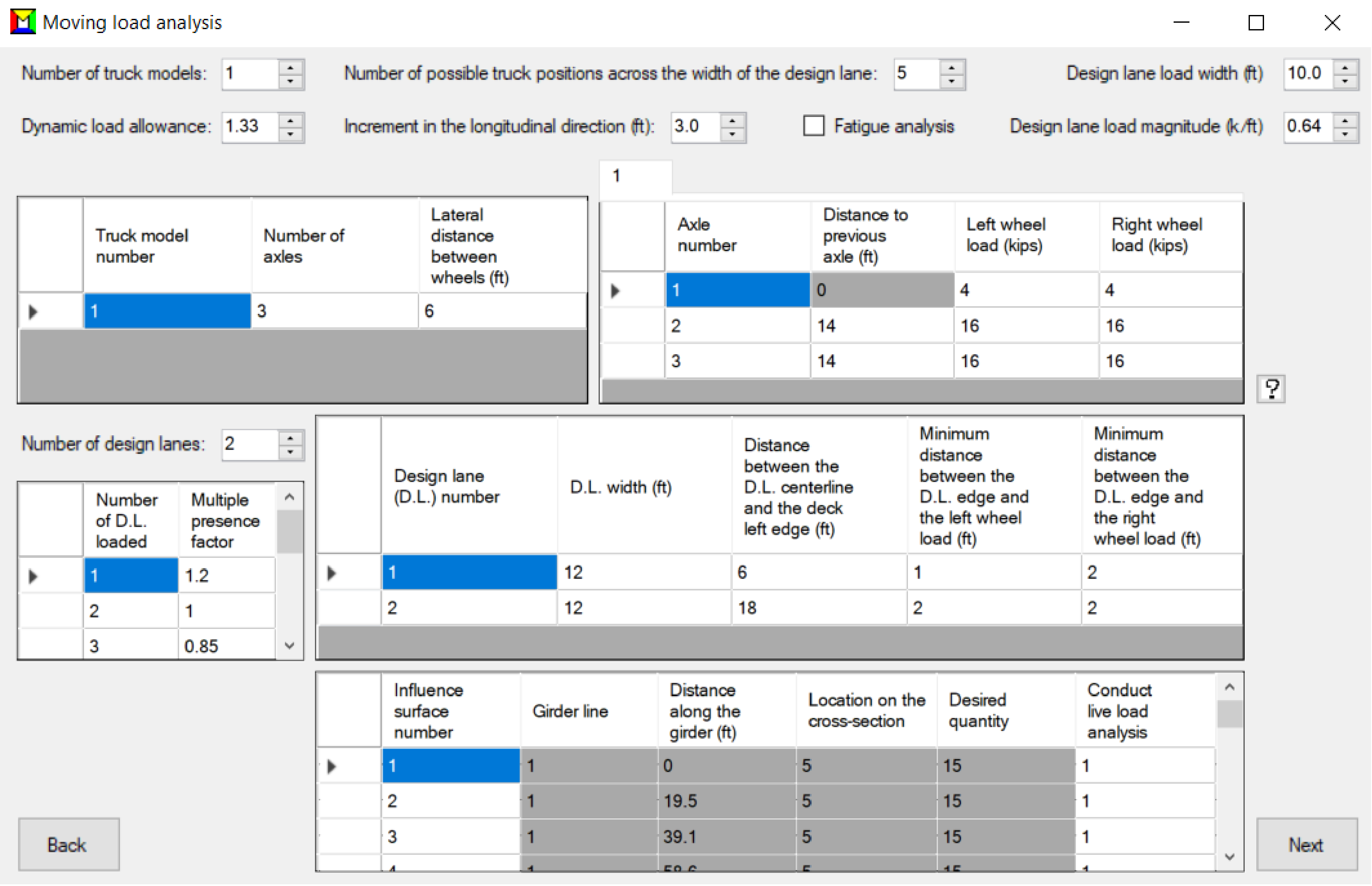


Plate thicknesses
1
0.625
1.5
3
1.25
2.5
0.5625



Vehicle load definition form (mBrace3D)


Moving load analysis
Number of truck models: 1
Number of possible truck positions across the width of the design lane: 5
Design lane load width (ft) 10.0
Dynamic load allowance: 1.33
Increment in the longitudinal direction (ft): 3.0
Fatigue analysis
Design lane load magnitude (k/ft) 0.64
Truck model number | Number of axles | Lateral distance between wheels (ft)
1 | 3 | 6
1
Axle number | Distance to previous axle (ft) | Left wheel load (kips) | Right wheel load (kips)
1 | 0 | 4 | 4
2 | 14 | 16 | 16
3 | 14 | 16 | 16
Number of design lanes: 2
Number of D.L. loaded | Multiple presence factor
1 | 1.2
2 | 1
3 | 0.85
Design lane (D.L.) number | D.L. width (ft) | Distance between the D.L. centerline and the deck left edge (ft) | Minimum distance between the D.L. edge and the left wheel load (ft) | Minimum distance between the D.L. edge and the right wheel load (ft)
1 | 12 | 6 | 1 | 2
2 | 12 | 18 | 2 | 2
Influence surface number | Girder line | Distance along the girder (ft) | Location on the cross-section | Desired quantity | Conduct live load analysis
1 | 1 | 0 | 5 | 15 | 1
2 | 1 | 19.5 | 5 | 15 | 1
3 | 1 | 39.1 | 5 | 15 | 1
Back
Next

Vehicle load optimization (VLO) algorithm

(Simplified) procedure to calculate the shear and composite moment influence surfaces

For all deck nodes

- Apply a unit vertical point load
- Solve for the displacement (first-order linear elastic)
- Compute the stresses along the bridge (assume the concrete deck is uncracked)
- At all points where the influence surface is to be calculated:
  - Integrate the vertical shear stresses on the web elements to get the resultant shear
  - Calculate the position of the elastic neutral axis of the composite section
  - Integrate the horizontal bending stresses on the flanges, web and deck elements to get the resultant moment

(Simplified) procedure to calculate the critical vehicle positions (Vehicle Load Optimization, aka VLO)

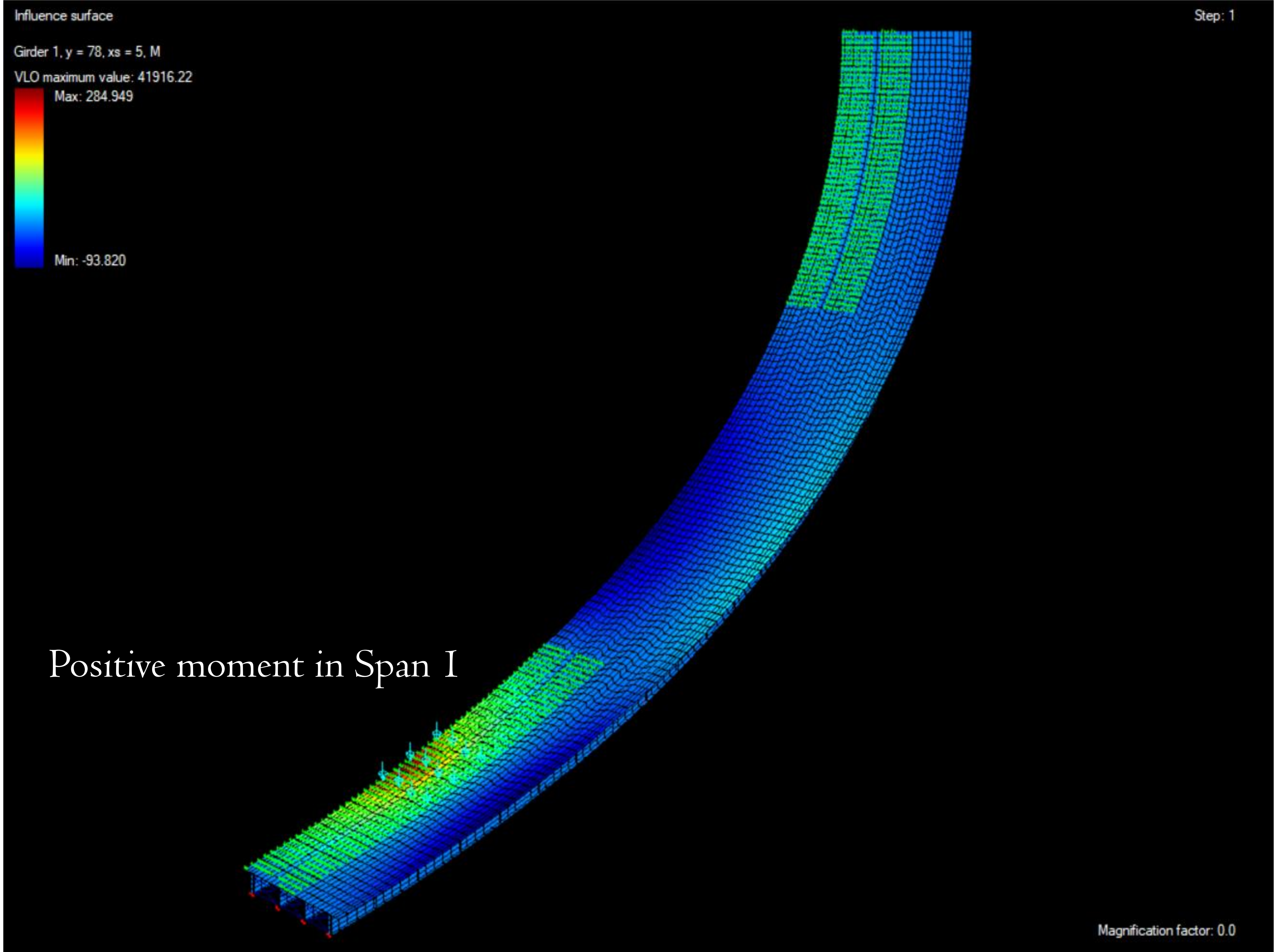
For all lanes

- For all longitudinal and transverse increments along the lane
    - Apply the truck load and get the resulting moment and shear based on the influence surfaces previously calculated

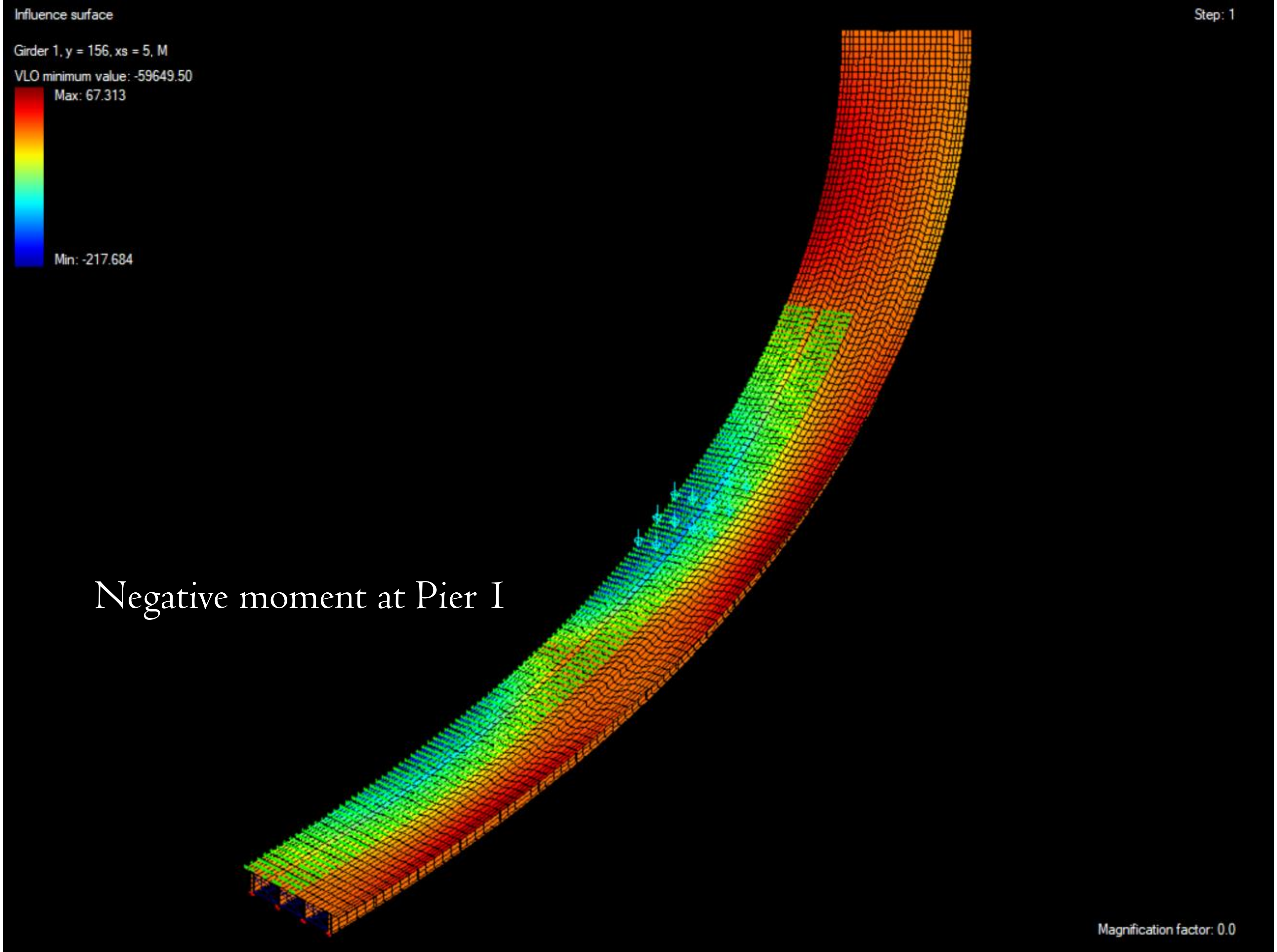
For all possible lane configurations (either 1 lane loaded, or 2 lanes loaded, etc.)

- Find the critical lane configuration, based on their respective effects weighted by the multiple presence factor

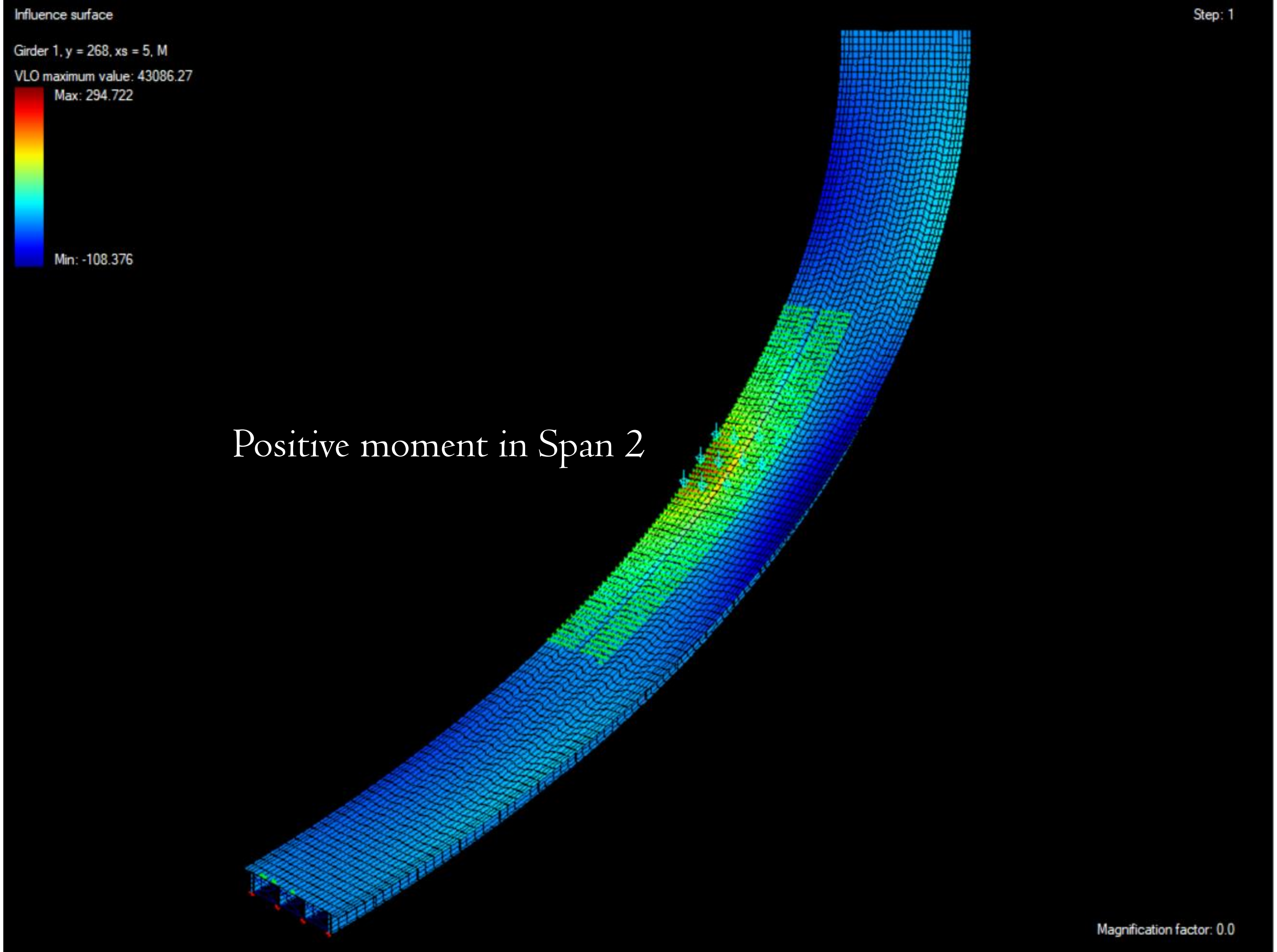
Influence surfaces – Moment



Positive moment in Span 1

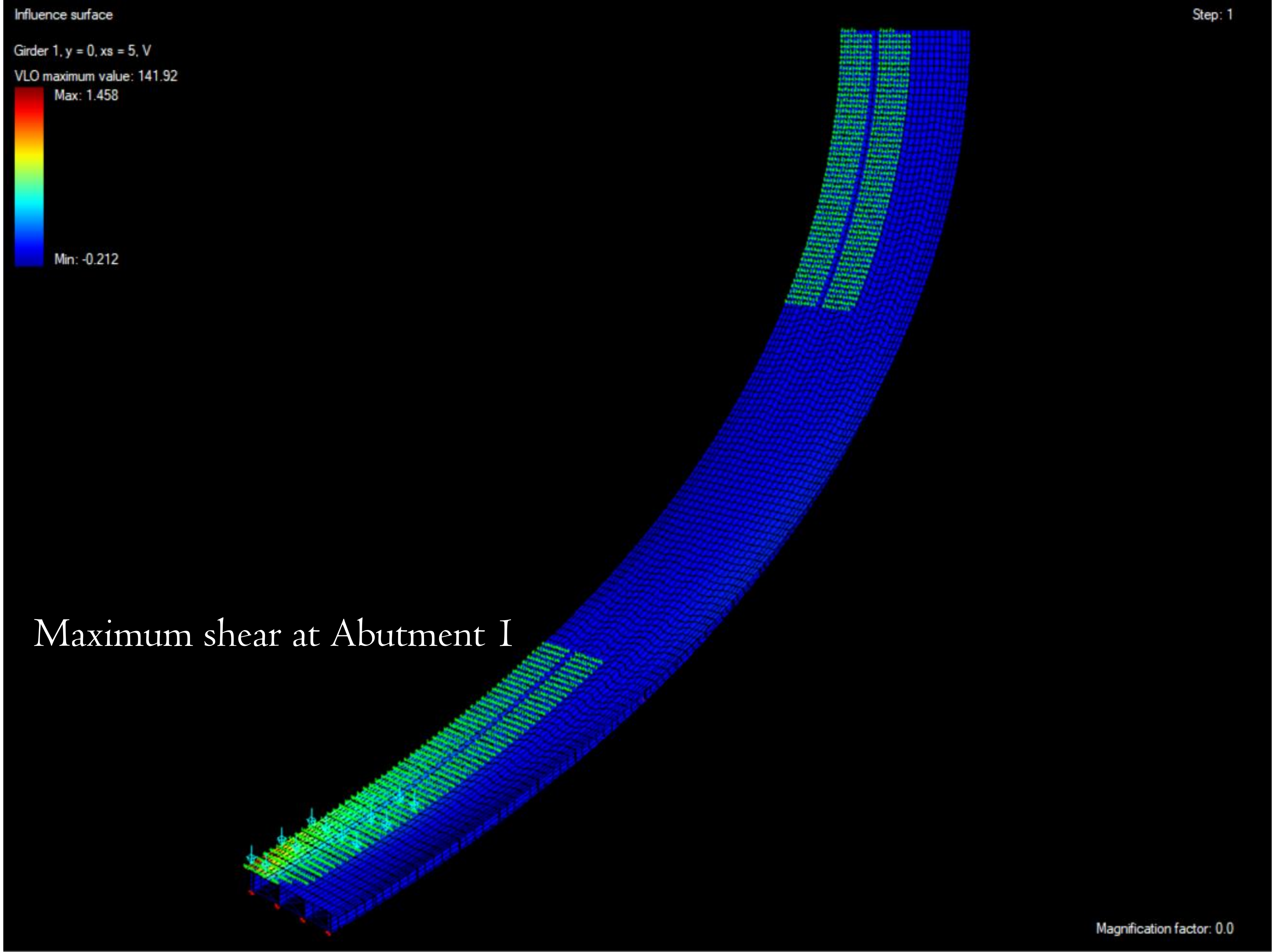


Negative moment at Pier 1

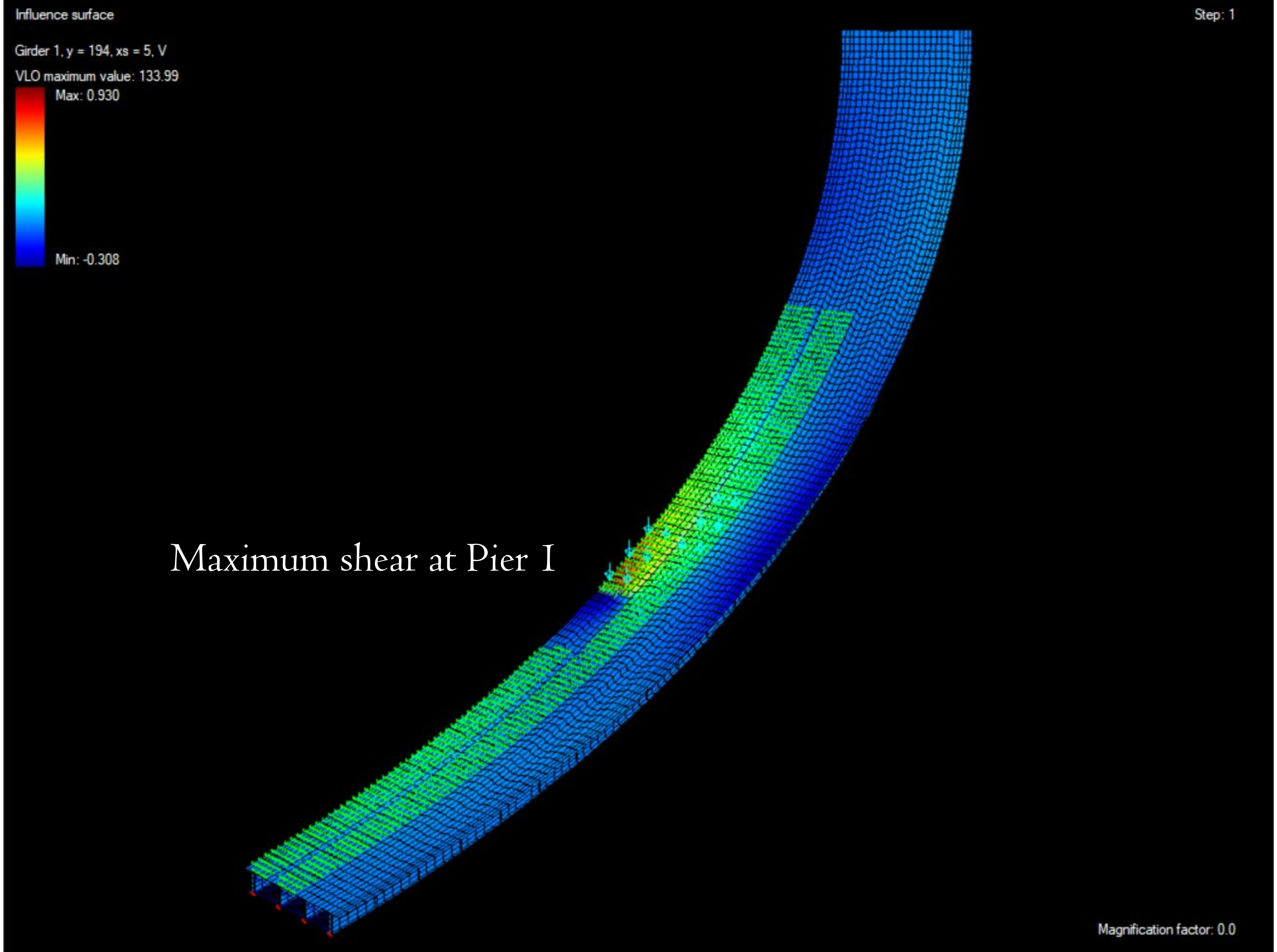


Positive moment in Span 2

Influence surfaces – Shear

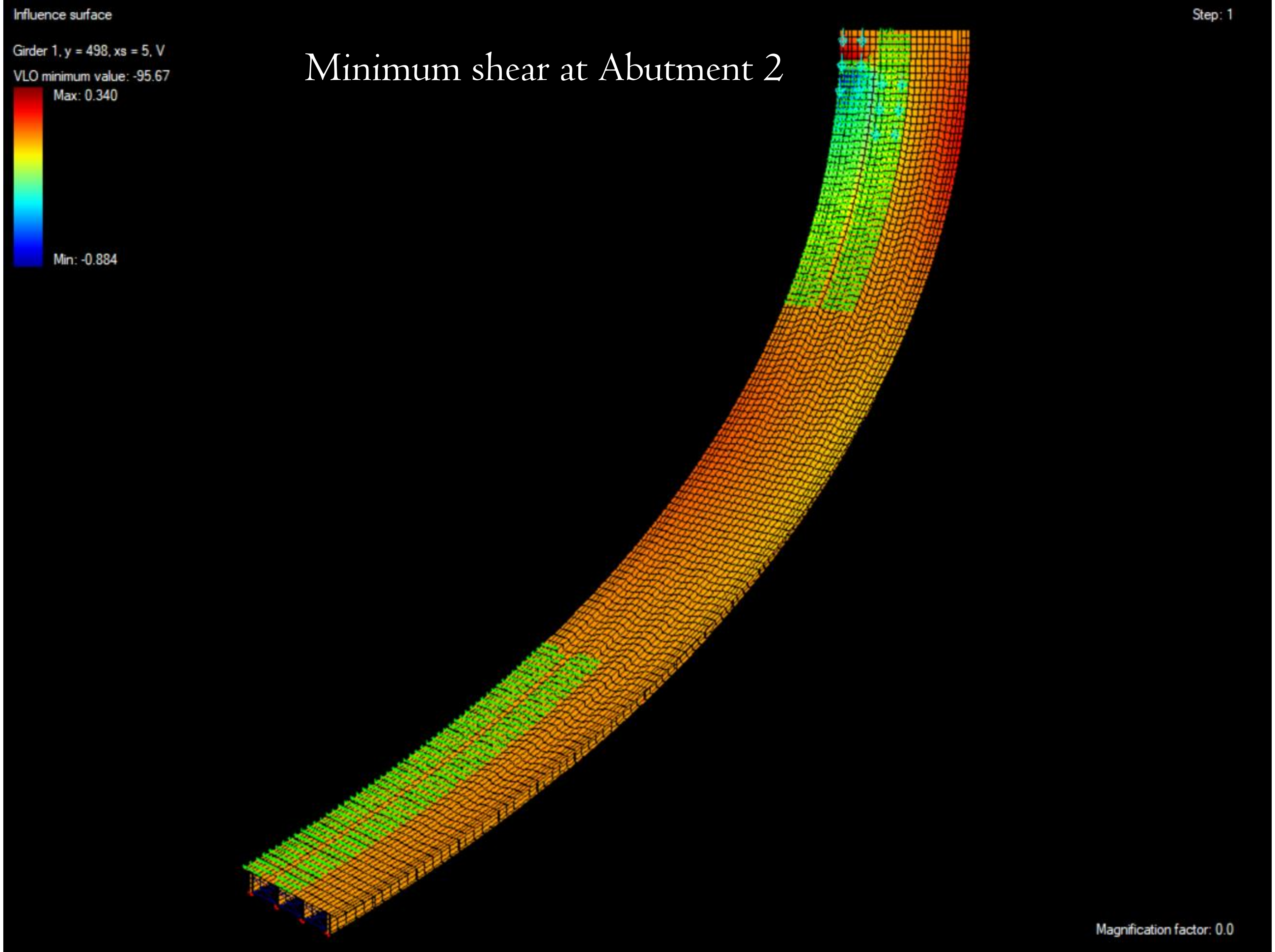


Maximum shear at Abutment I

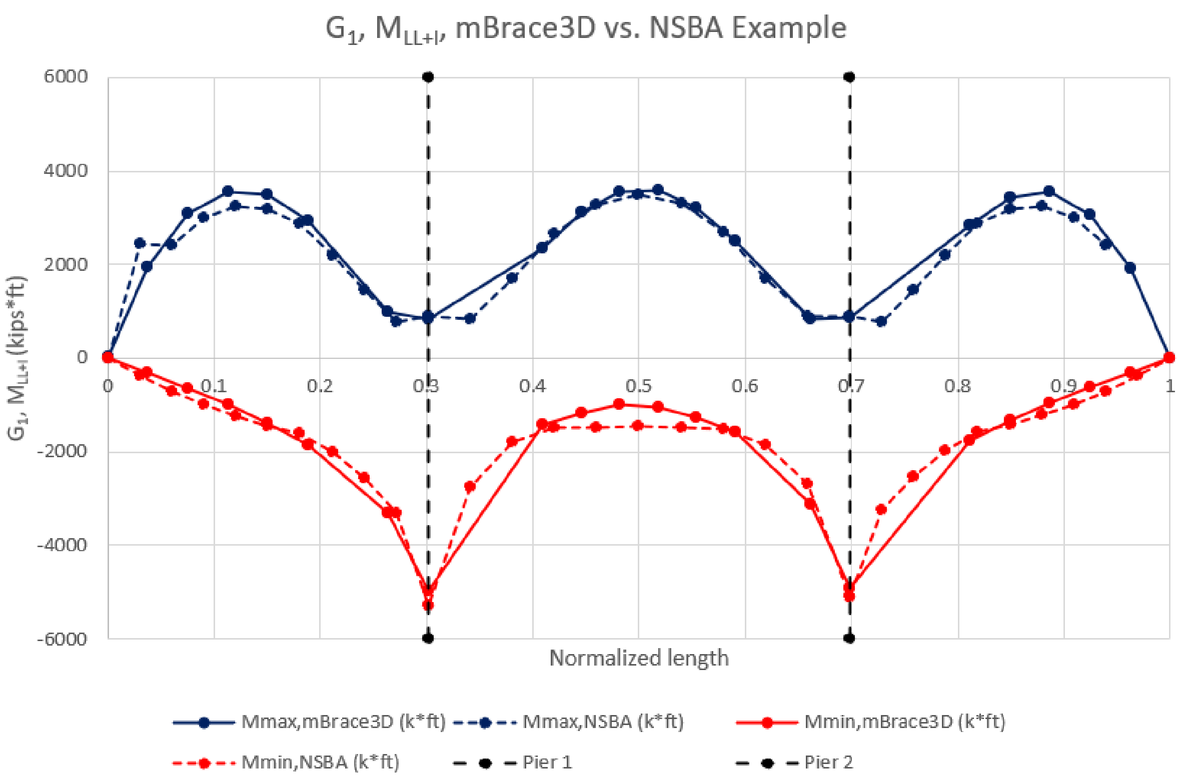


Maximum shear at Pier 1

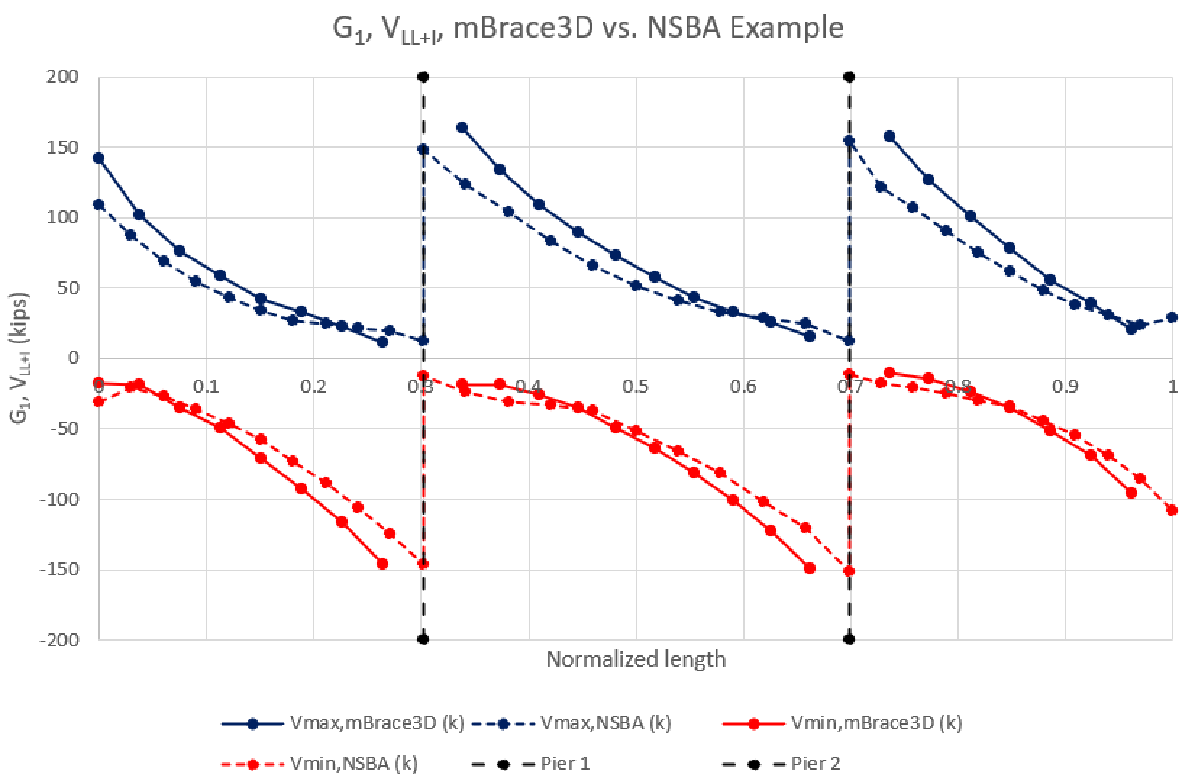
Minimum shear at Abutment 2



Envelope moment and shear diagrams



G_1, M_{LL+I}, mBrace3D vs. NSBA Example
G_1, M_{LL+I} (kips*ft)
Normalized length
Mmax,mBrace3D (k*ft)
Mmax,NSBA (k*ft)
Mmin,mBrace3D (k*ft)
Mmin,NSBA (k*ft)
Pier 1
Pier 2



G_1, V_{LL+I}, mBrace3D vs. NSBA Example
G_1, V_{LL+I} (kips)
Normalized length
Vmax,mBrace3D (k)
Vmax,NSBA (k)
Vmin,mBrace3D (k)
Vmin,NSBA (k)
Pier 1
Pier 2

mBrace3D vs. NSBA Design Example 3 – Conclusions

1. Simplified line load analyses are inappropriate for curved steel bridges, for which advanced FEA is the preferred method.
2. mBrace3D Vehicle Load Optimization (VLO) algorithm was tested and compared against NSBA Design Example 3 (three-span continuous horizontally curved composite steel I-girder bridge), for which results are publicly available but the method used to obtain them is not thoroughly described.
3. The results compare generally very well.
4. The method implemented to derive the influence surfaces and run the VLO were described.
5. mBrace3D allows for any type of vehicle load, which makes it appropriate for any design code.
6. mBrace3D also allows for cross-frame stiffness modifiers, which can be particularly useful for fatigue design.

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