As-Built Seismic Analysis of the Golden Gate Bridge Main Suspension Spans

HDR

GOLDEN GATE BRIDGE
HIGHWAY & TRANSPORTATION DISTRICT

Western Bridge Engineers' Seminar
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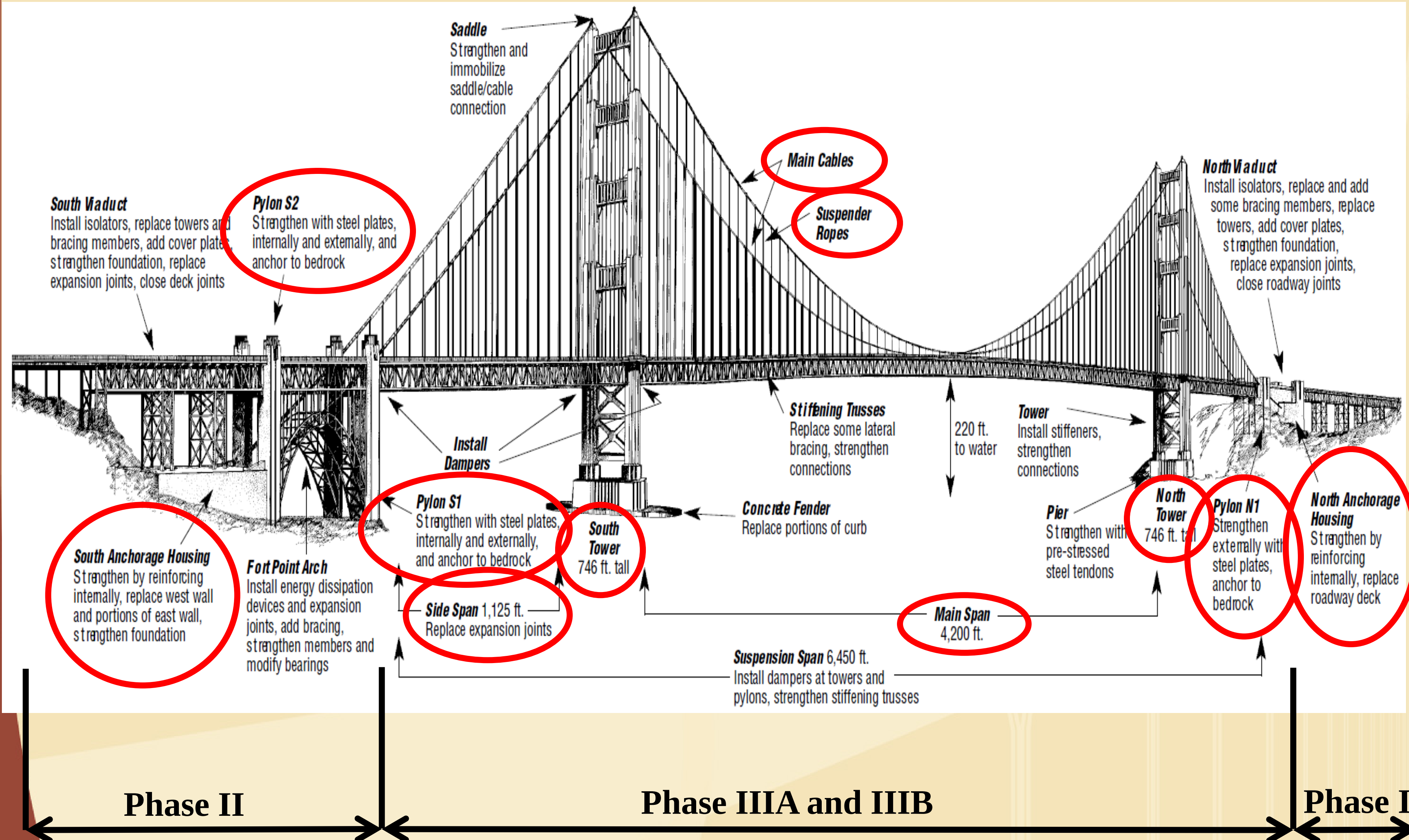
HDR Engineering

Project Background – Seismic Retrofit Program

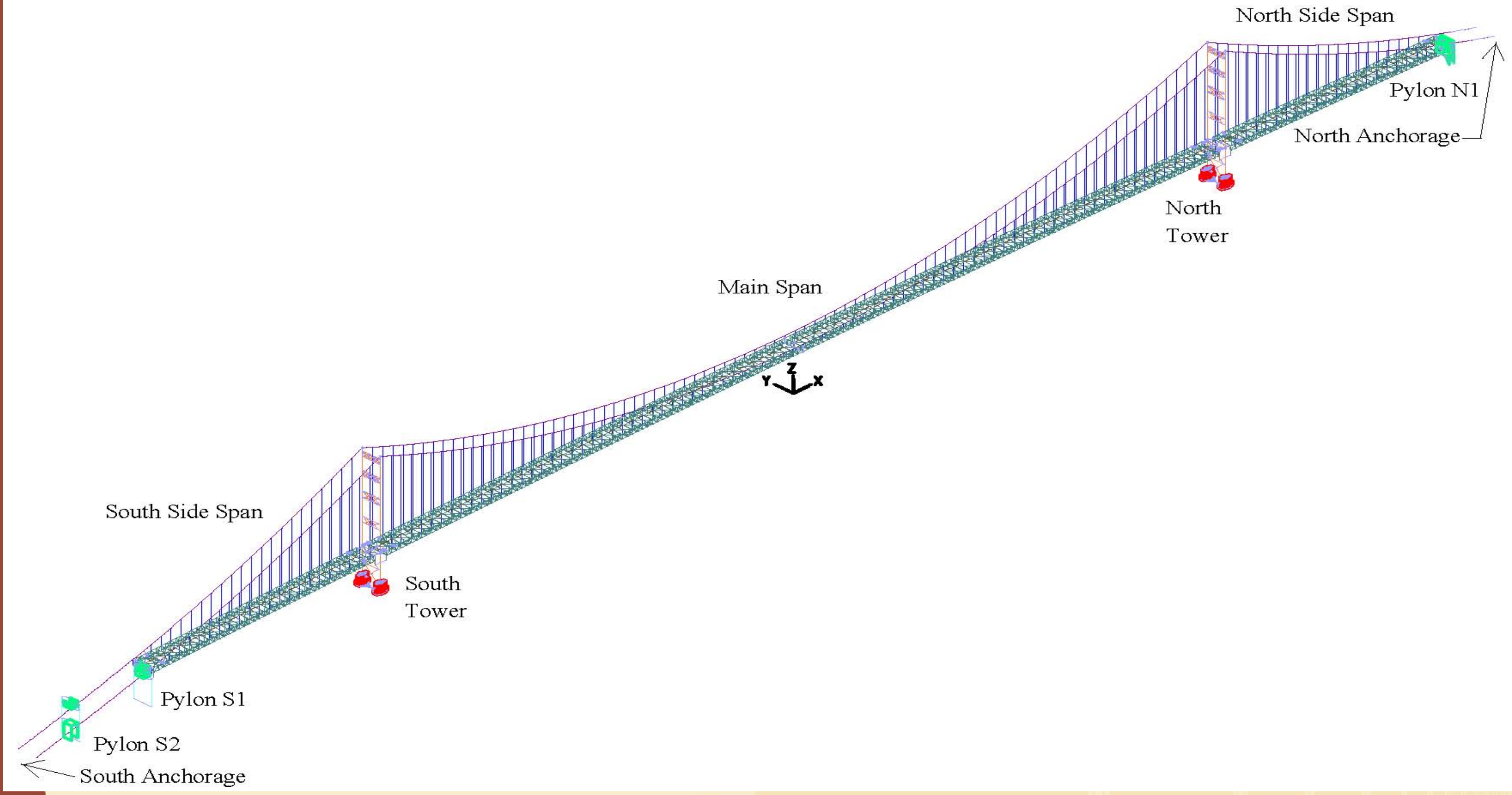


Project Background – Seismic Criteria

- Project Specific GGB Design Criteria for Seismic Retrofit Measures, 1992
- AASHTO LRFD Bridge Design Specifications 2007 edition
- Caltrans Seismic Design Criteria Version 1.6

ADINA Global Computer Model

- Isometric view - 11,420 node, 3D model



Model Summary

- Finite Element Groups
- Material Nonlinearity
- Geometric Nonlinearity
- Section Properties, Capacities & Material Properties based on:
  - shop drawings
  - design drawings
  - Chief Engineer's Report

Element Group		Element		Element Group Formulation	
No.	**Description**	**Type**	**No.**	**Material**	**Displacement**
100	Tower Bases	Shell	10,636	Linear Elastic	Small
150	Tower Base Vertical Supports	Spring	512	Nonlinear (Compression-Only)	Small
155	Tower Base Vertical Dampers	Damper	512	Linear	Small
160	Tower Base Longitudinal Supports	Spring	512	Linear	Small
170	Tower Base Transverse Supports	Spring	512	Linear	Small
180	Tower Base Anchorage Posts	Truss	48	Plastic-Bilinear (Tension Rupture)	Small
200	Tower Shafts & Struts	Beam	330	Linear Elastic	Large
300	Pylon S1 Legs	Beam	8	Linear Elastic	Small
301	Pylon S2 Legs	Beam	10	Linear Elastic	Small
302	Pylon N1 Legs	Beam	9	Linear Elastic	Small
350	Pylon S1 Shear Walls & Diaphragms	Shell	19	Linear Elastic	Small
351	Pylon S2 Shear Walls & Diaphragms	Shell	12	Linear Elastic	Small
352	Pylon N1 Shear Walls & Diaphragms	Shell	22	Linear Elastic	Small
400	Main Cables	Cable	352	Linear Elastic	Large
401	Main Cable Dampers	Damper	352	Linear	Small
450	Suspenders & Tie-Downs	Cable	254	Nonlinear-Elastic (Tension-Only)	Large
451	Suspender & Tie-Down Dampers	Damper	254	Linear	Small
500	Stiffening Trusses	Beam	7,298	Linear Elastic	Small
550	Stiffening Truss Rocker Links	Beam	12	Linear Elastic	Large
590	Stiffening Truss Center Struts	Beam	134	Linear Elastic	Small
600	Windlock Connections	Spring	20	Linear & Nonlinear	Small
700	Main Cable Restraints	Spring	16	Linear & Nonlinear	Small
	Total Number of Elements in Model =		**21,834**		

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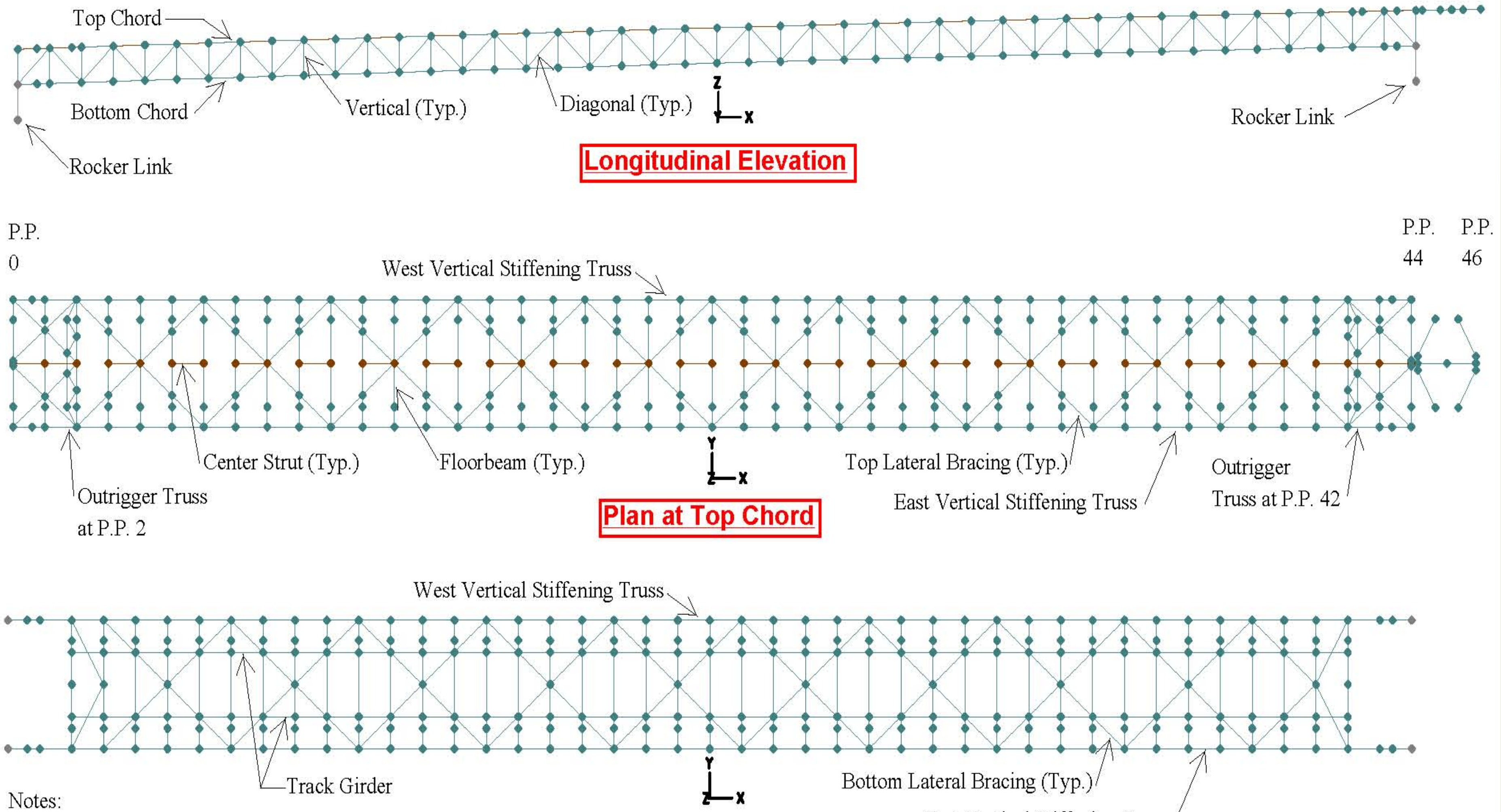
Stiffening Truss Modeling

- 2 Side Span & 1 Main Span Stiffening Truss System
- Connected at Pylons & Towers through Windlock System
- Beam elements modeled between work points to accurately represent the stiffness
- Truss Members Include:
  - top chords, bottom chords, diagonals, verticals, rocker links, floor beams, kicker bracing, top & bottom lateral bracing, outriggers, and portals

Stiffening Truss Modeling



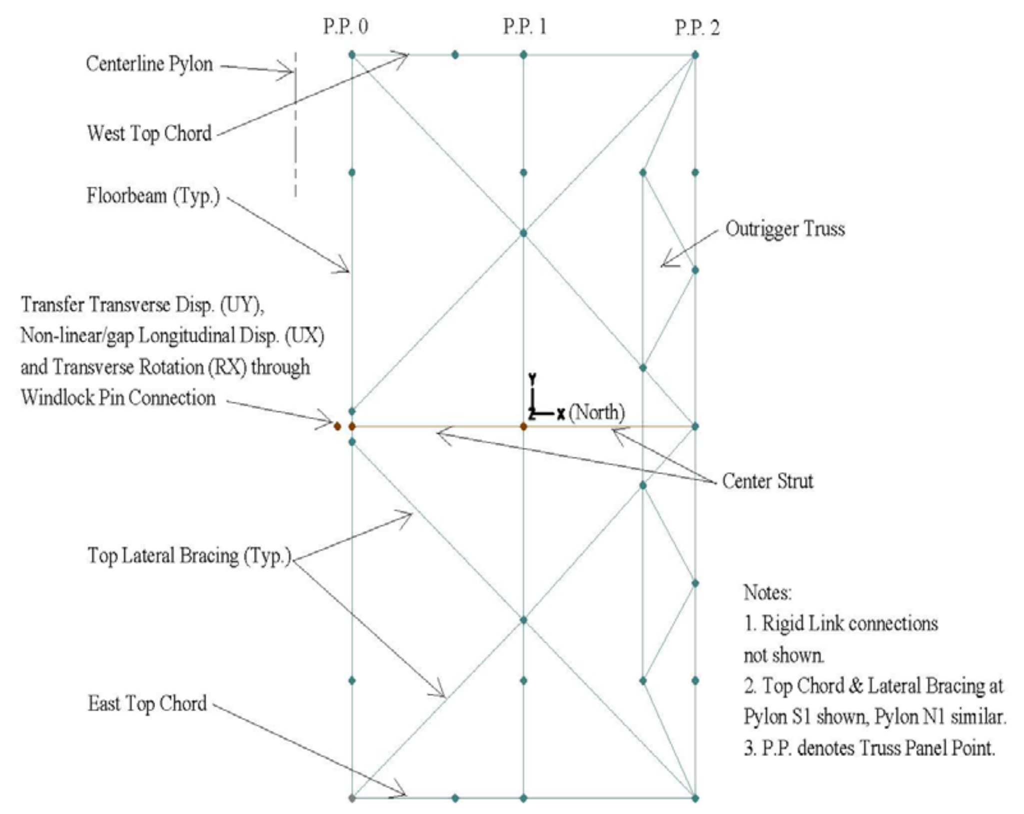
Notes:

1. South Side Span shown, North Side Span similar.
2. P.P. denotes Truss Panel Point.

Side Span Elevation & Plan Views

Stiffening Truss Modeling - Windlock Connections at Pylons

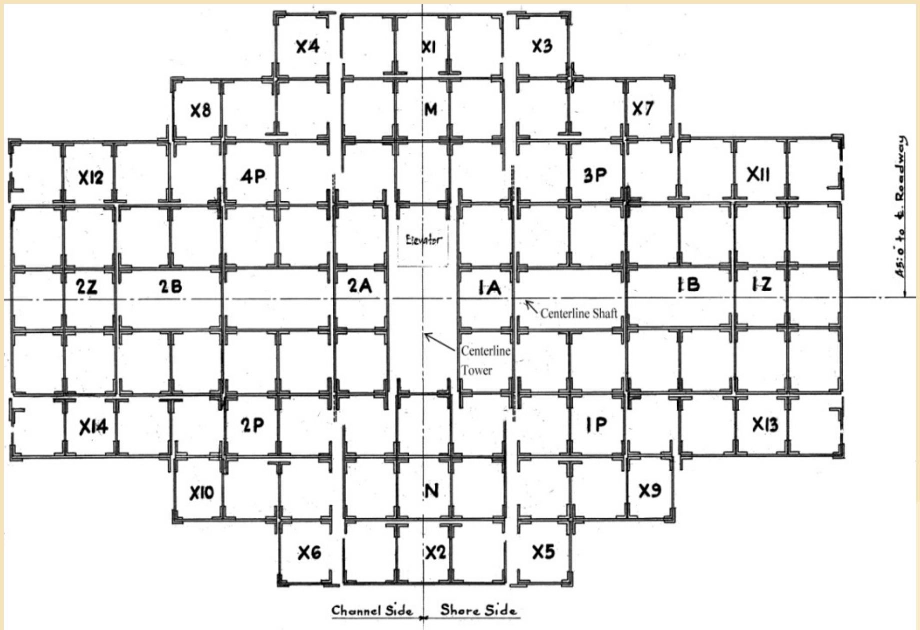
- As-Built Articulation
- Complete and Representative Load Transfer Paths in All Directions
- Nonlinear Longitudinal Gap Element



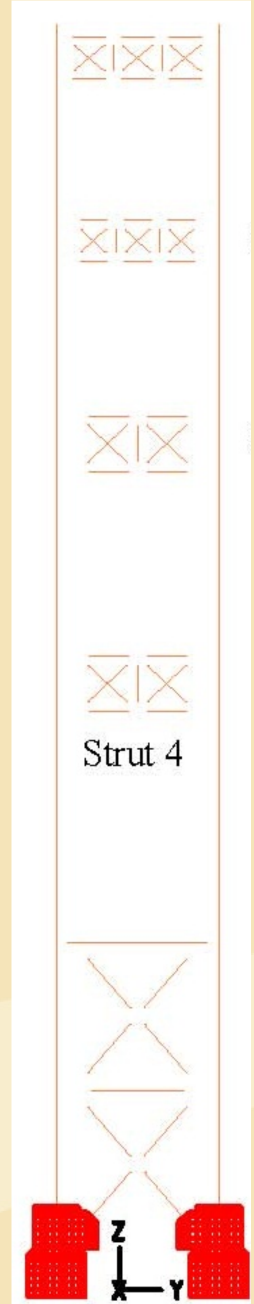
Plan

Tower Modeling

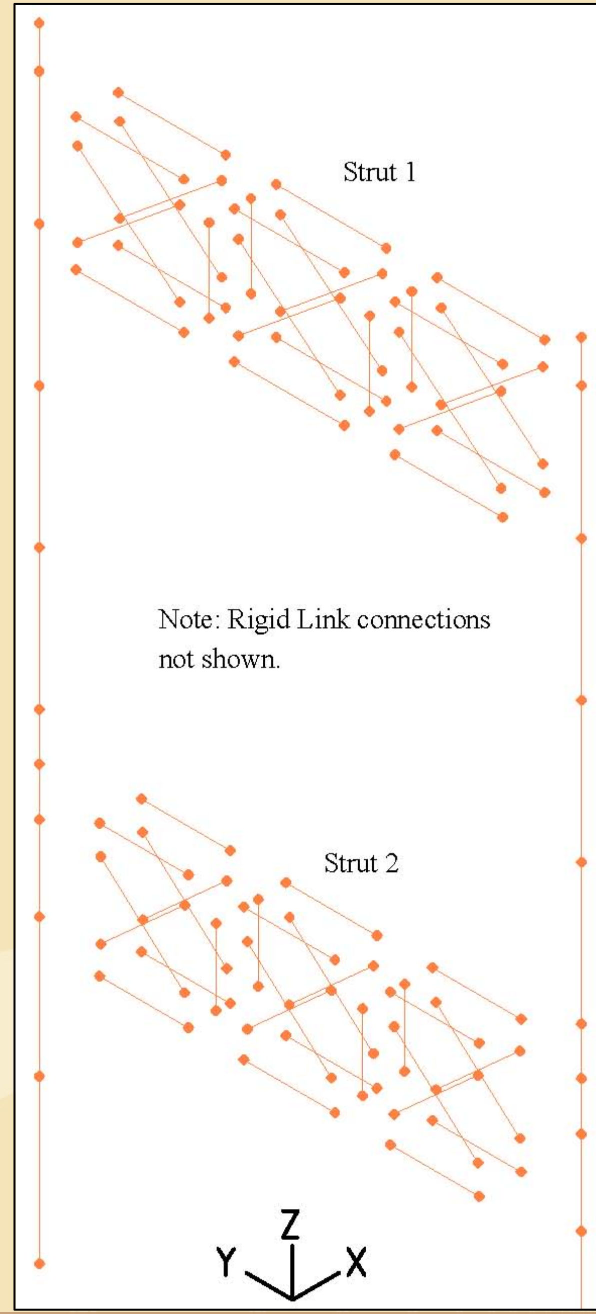
- Typical - Beam Elements
- Base - Shell Elements
- Parametric Studies



Section at Base



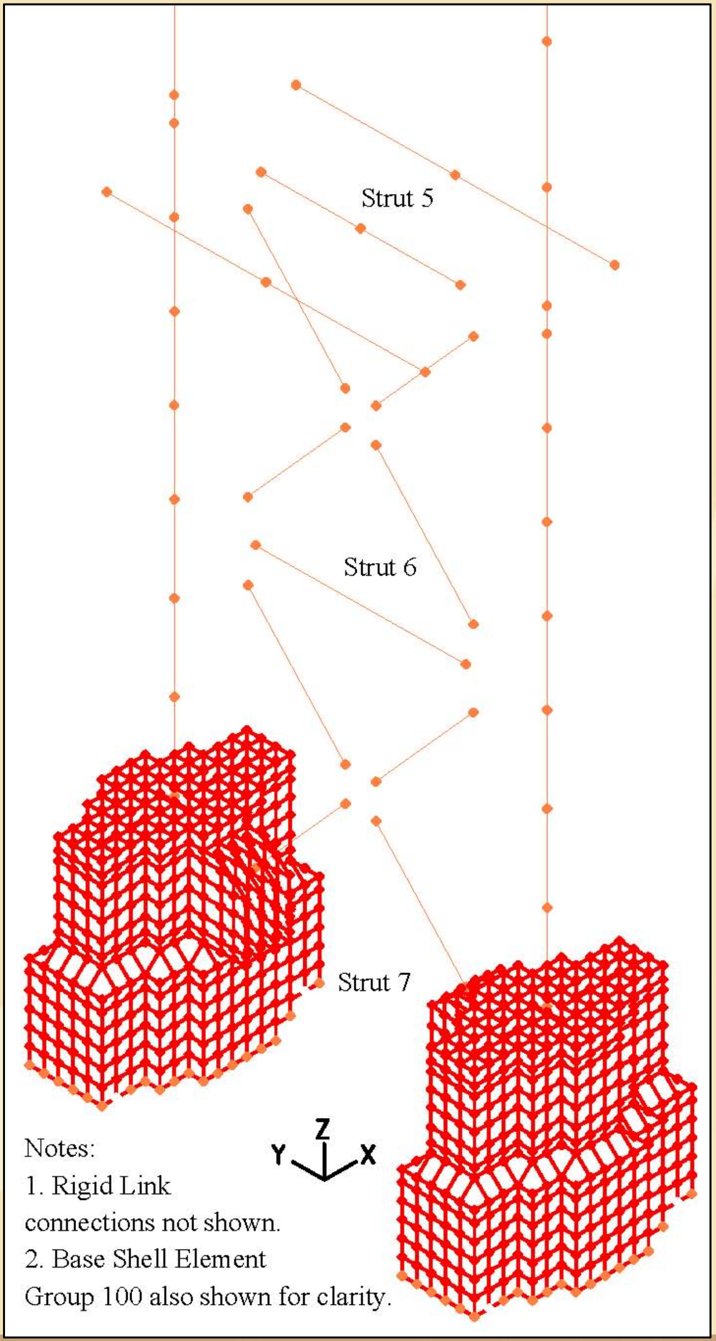
Elevation



3D Isometric View at Top

Tower Modeling

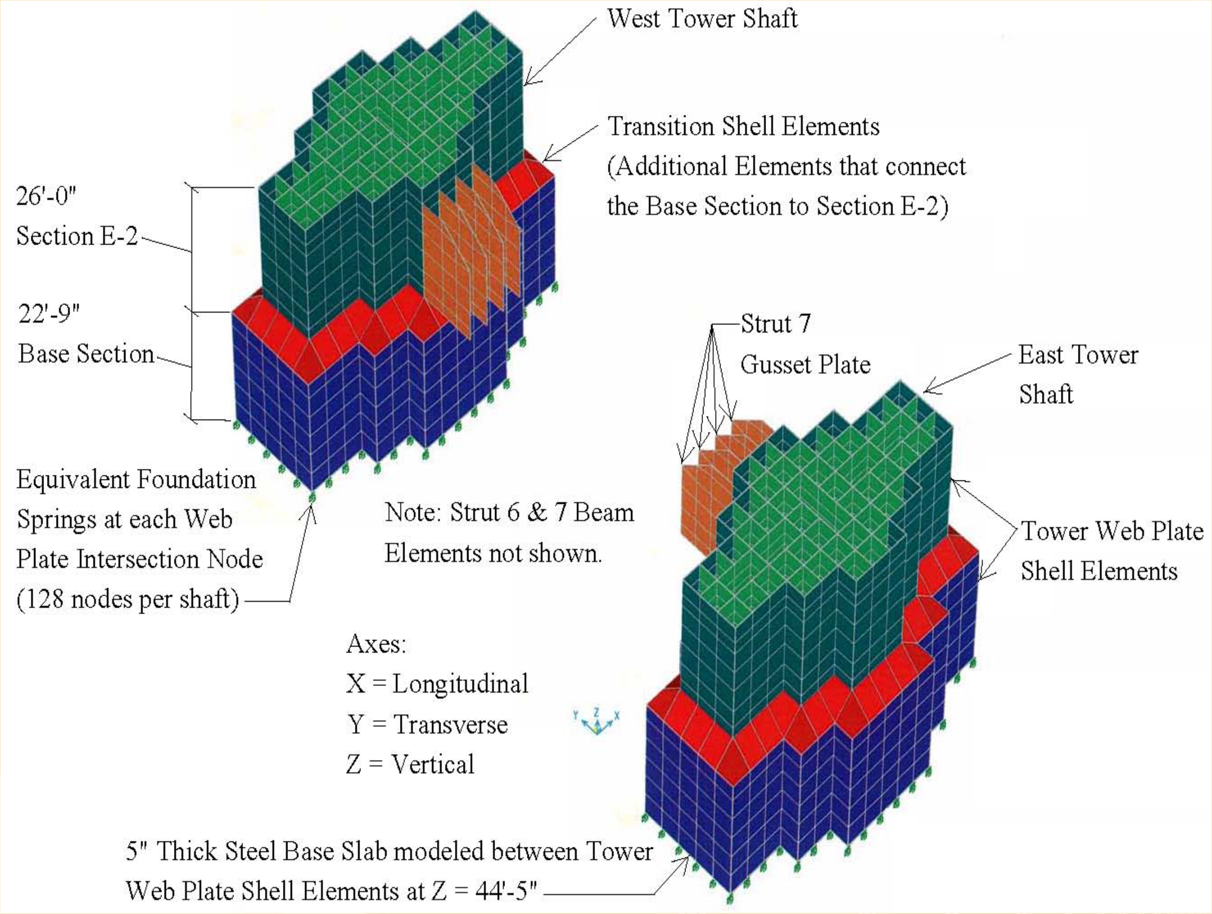
- Compression Only Vertical Springs
- Anchorage Posts
  - tension only rupture truss elements
- Base Plates & Transition Plates
- Lower Strut Gussets Explicitly Modeled



3D Isometric View

Tower Base Modeling

- Refined modeling
- Improved stress distribution
  - base
  - transition
- Directly capture nonlinearities
  - transverse & longitudinal uplift
  - plasticity (accumulated plastic strain)



3D Isometric View

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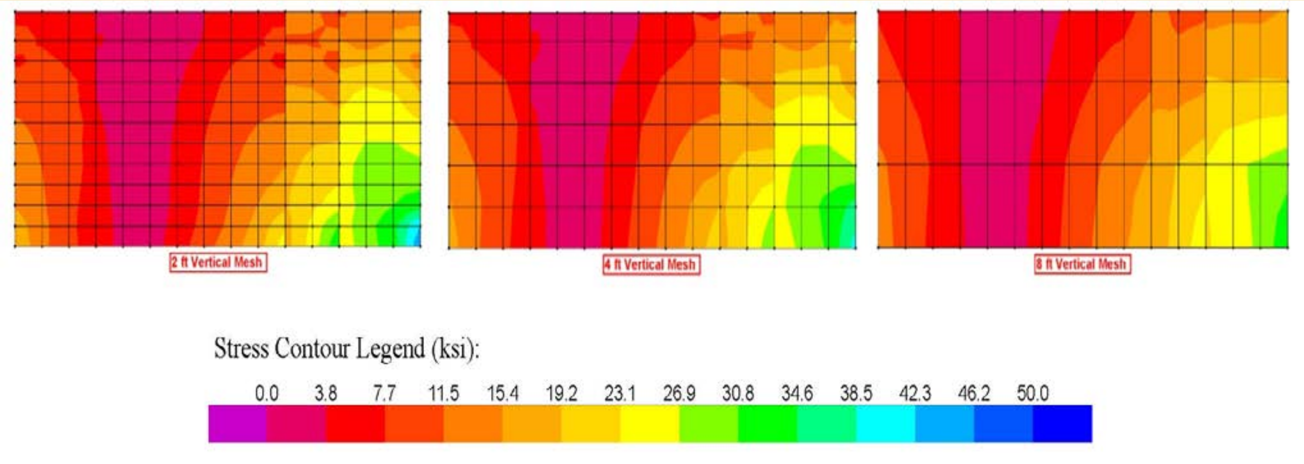
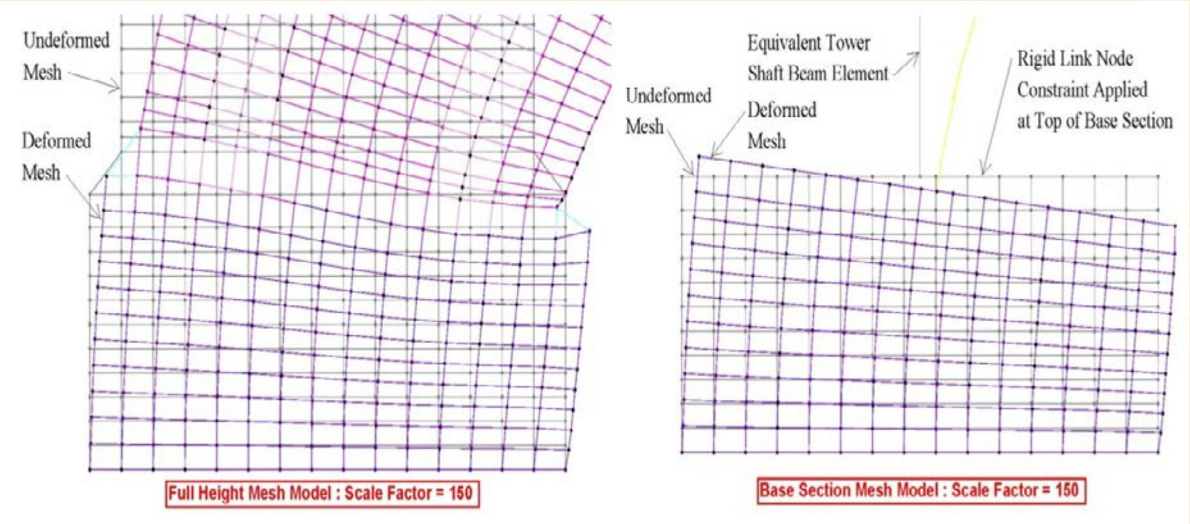
Tower Parametric Studies

- Vertical Mesh Distribution



Developed Longitudinal Elevations

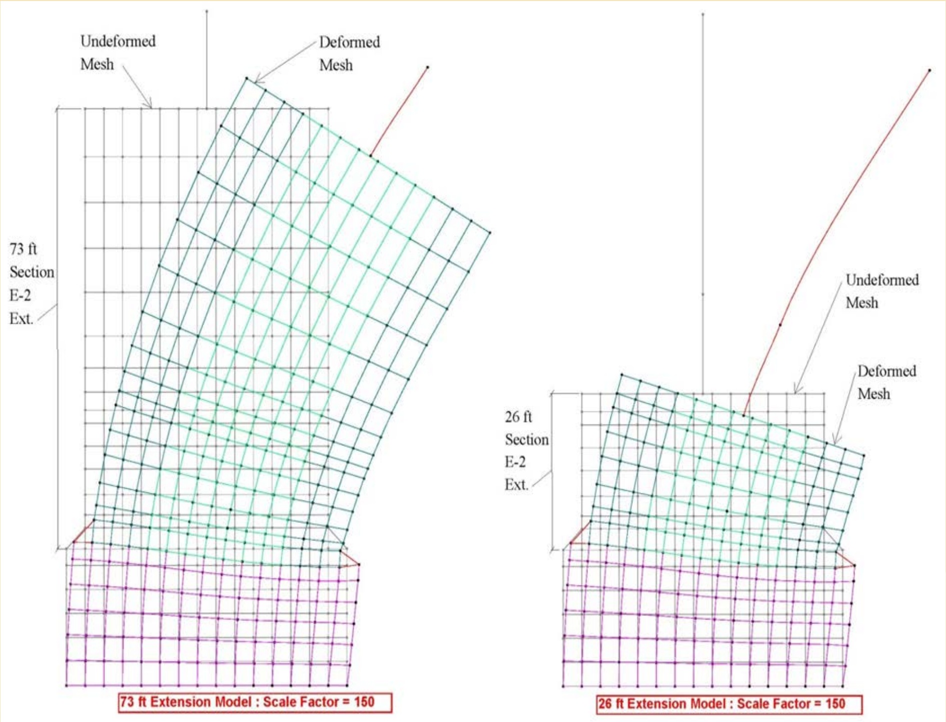
- Base Transition
  - plane sections do not remain plane at transition



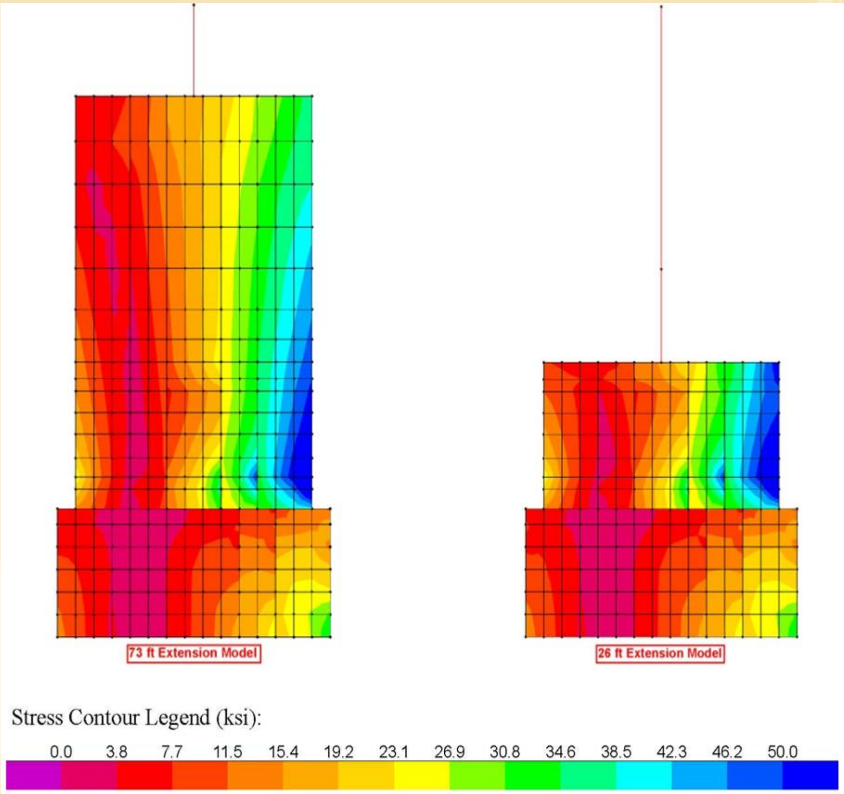
Longitudinal Sections

Tower Parametric Studies

- Base Transition (cont'd)
  - location selected to control accuracy of displacements & stresses



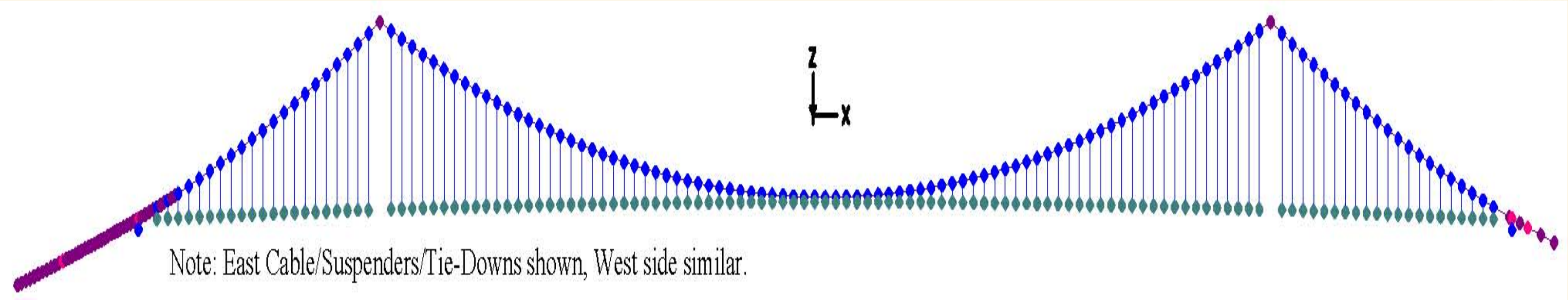
Longitudinal Sections



Developed Longitudinal Elevations

Main Cable & Suspender Modeling

- Cable Elements
- Main Cables – linear elastic material properties
- Suspenders – nonlinear material properties



Longitudinal Elevation

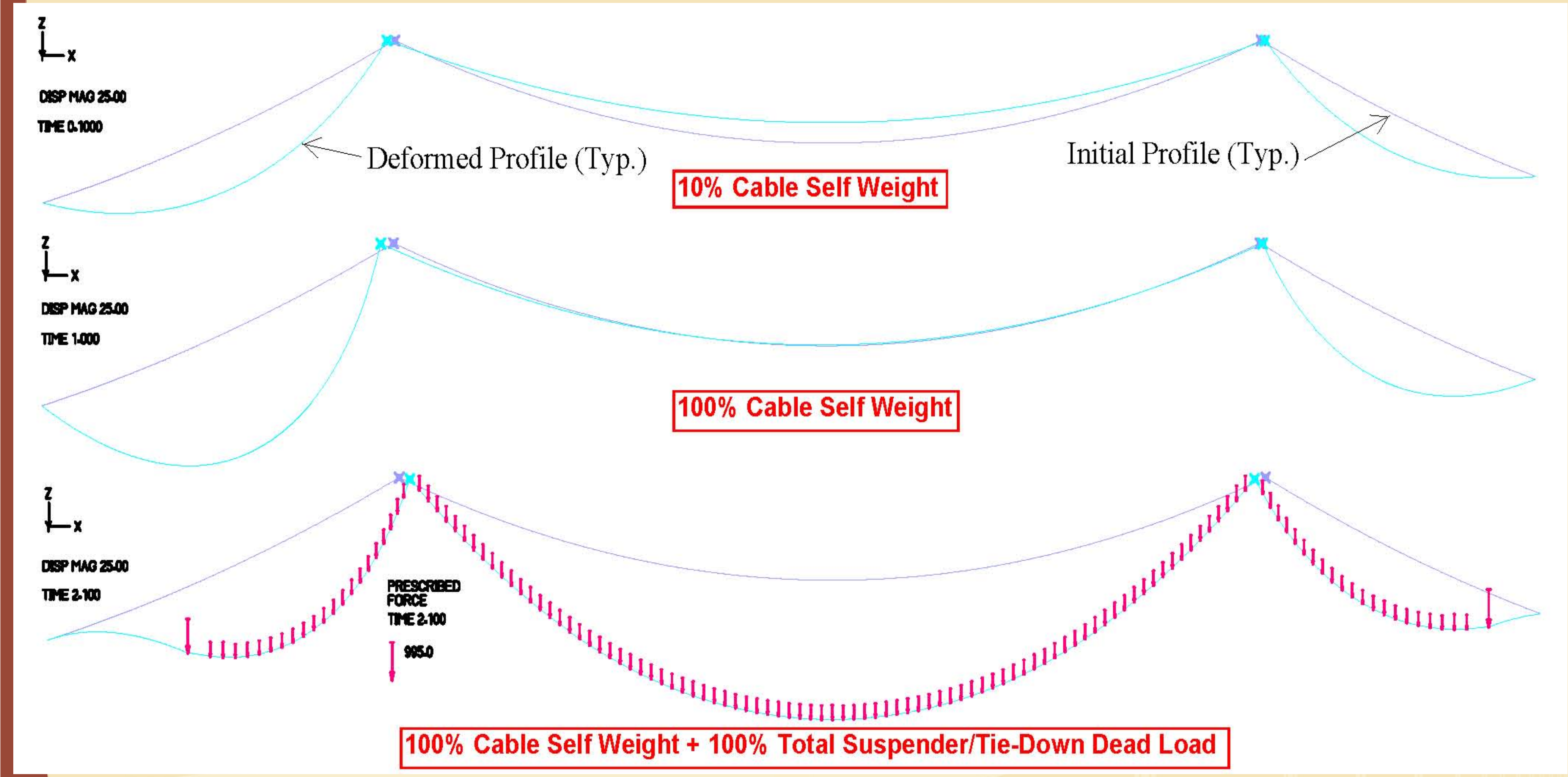
Cable Profile

- Cables Behave Geometrically Nonlinear
  - cable stiffness dependent on deformation (strain)
    - stiffness increases with increase in deformation
  - final profile is dependent on final stress & amount of deformation cable has experienced between 0 and final force

- Global Model Cable Initial Coordinates = Final Displaced Coordinates
  - approximation to eliminate need for complete 3-D model staged construction model

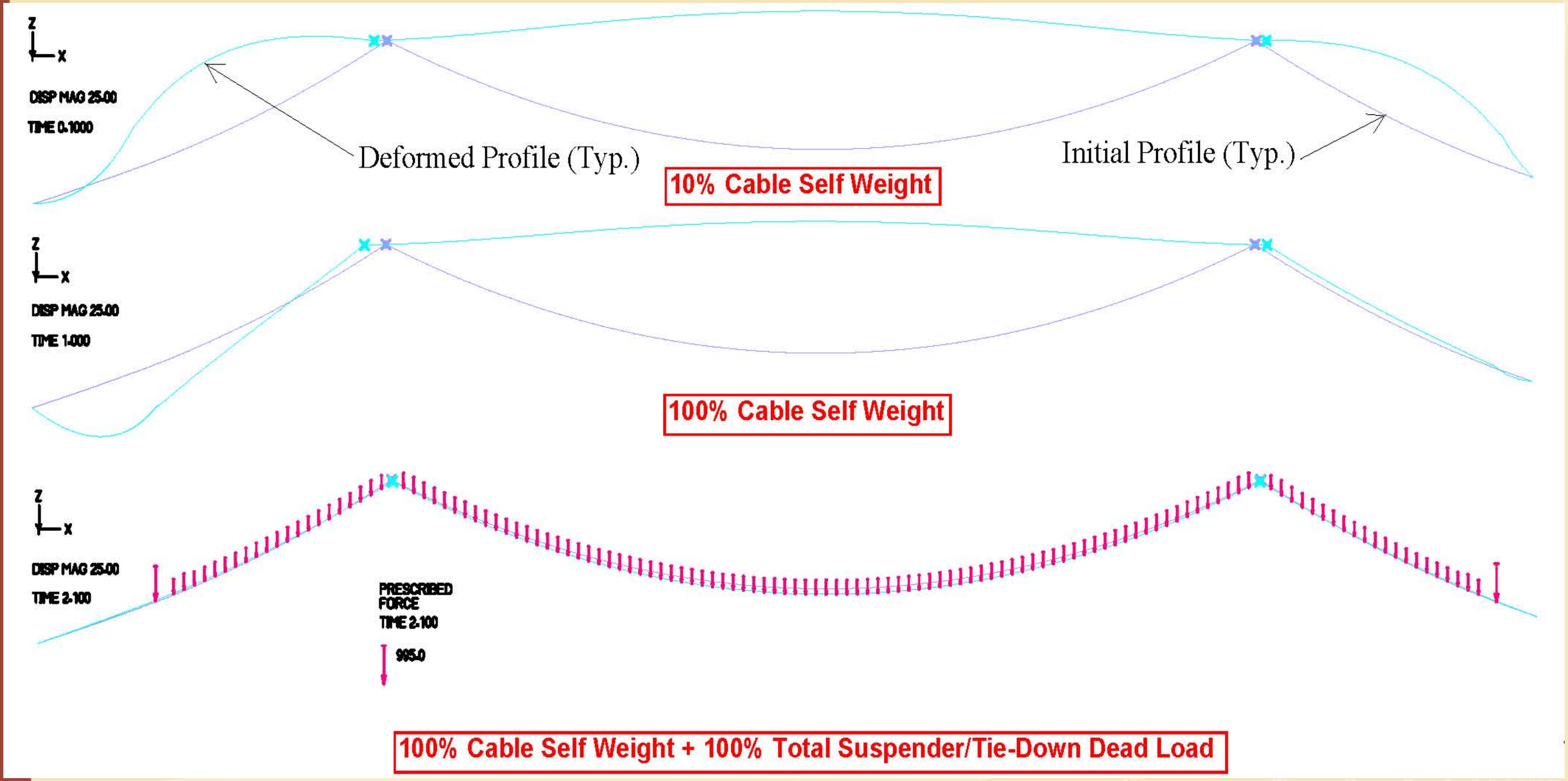
- Required Global Model Cable Input = Coordinates & Initial Strains
  - use 2 simplified stand-alone models to obtain required input:
    - 1. Staged Construction Cable Model
    - 2. Equivalent Initial Coordinates & Initial Strains Cable Model
  - use Original Strauss dead load

Staged Construction Cable Model



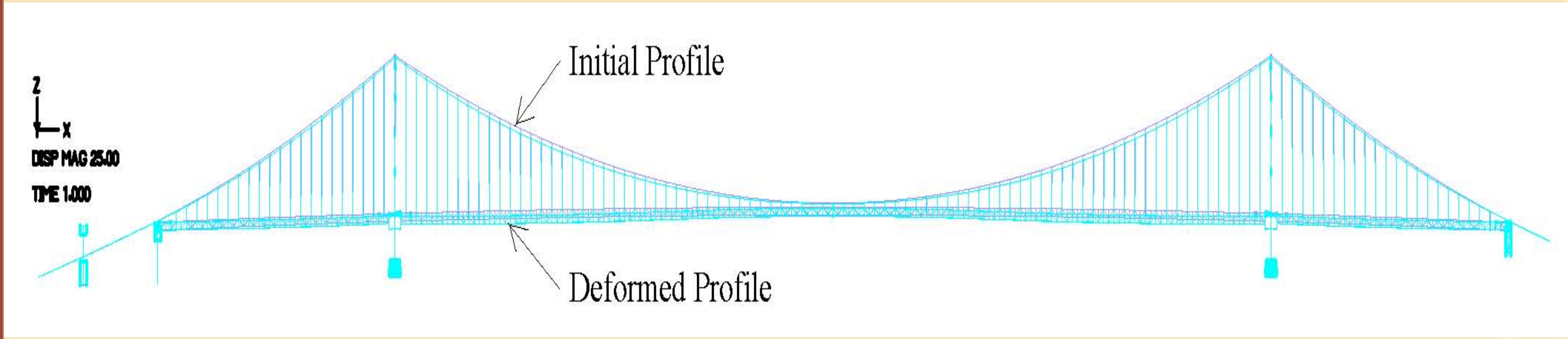
Longitudinal Profiles of Main Cable Staged Construction Dead Load Model

Equivalent Initial Coordinates & Initial Strains Cable Model

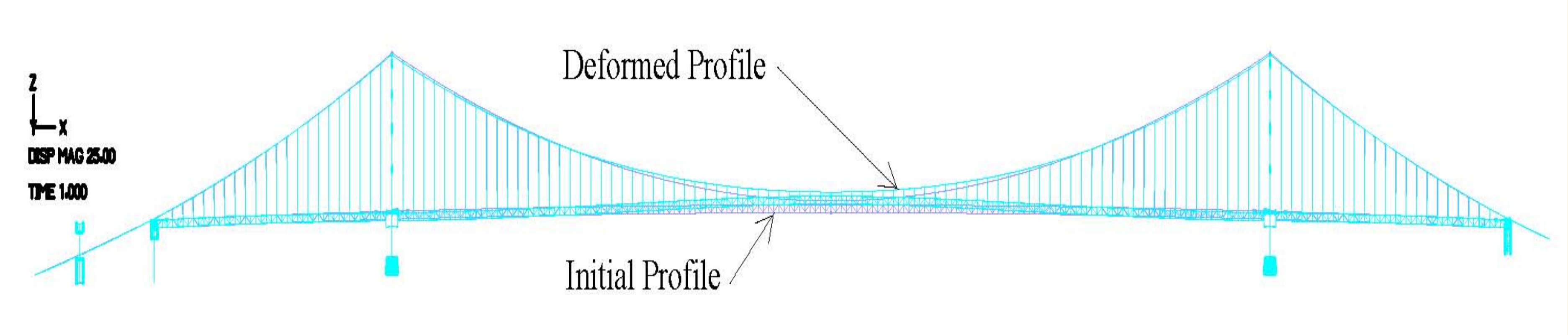


<u>**Longitudinal Profiles of Main Cable Equivalent Initial Conditions Dead Load Model**</u>

Cable Profile – Global Model



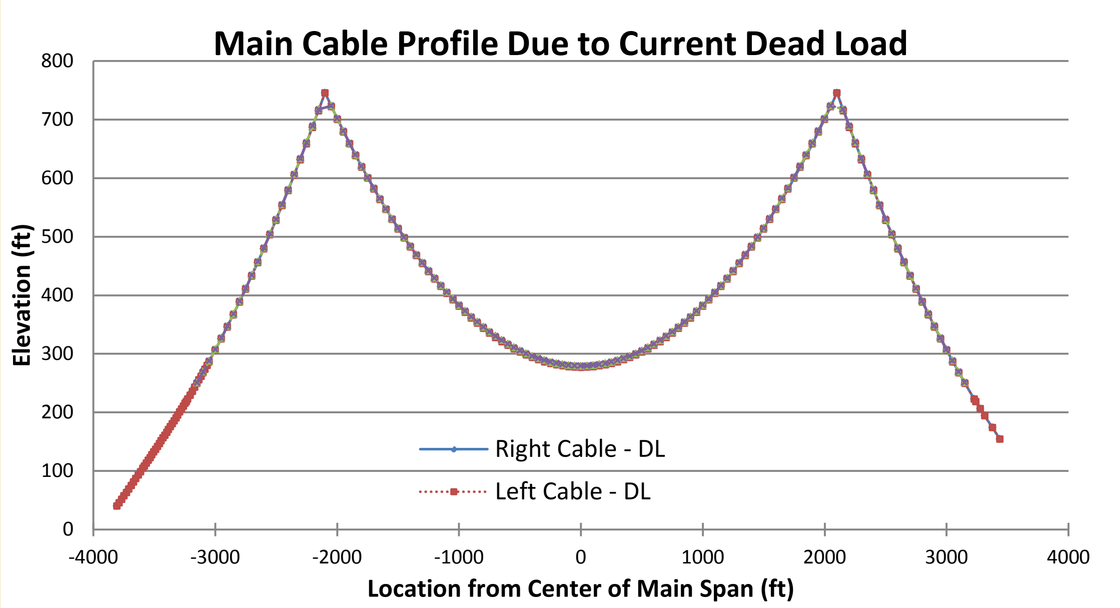
Original Strauss Dead Load Global Model Displaced Shape

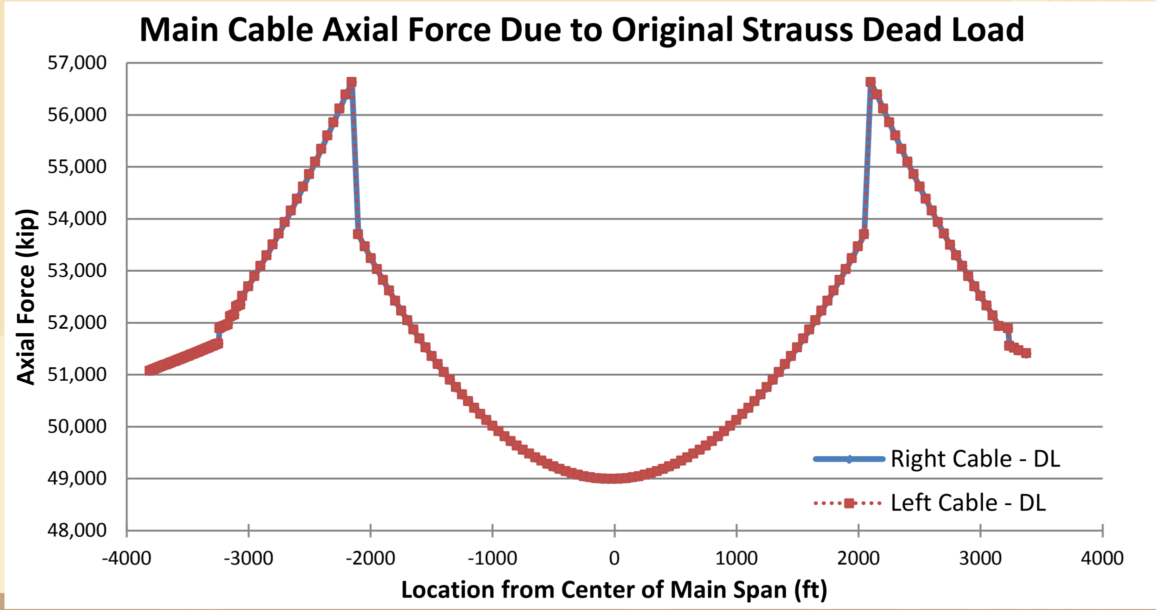


Current Dead Load Global Model Displaced Shape

Cable Profile – Global Model vs. 1992 Survey Comparison

- 1992 Survey
  - excellent correlation
- Main Cable Forces
  - within 3% of Chief Engineer's Report
- Rotations at Anchorages & Towers
  - within 0.3% of Chief Engineer's Report



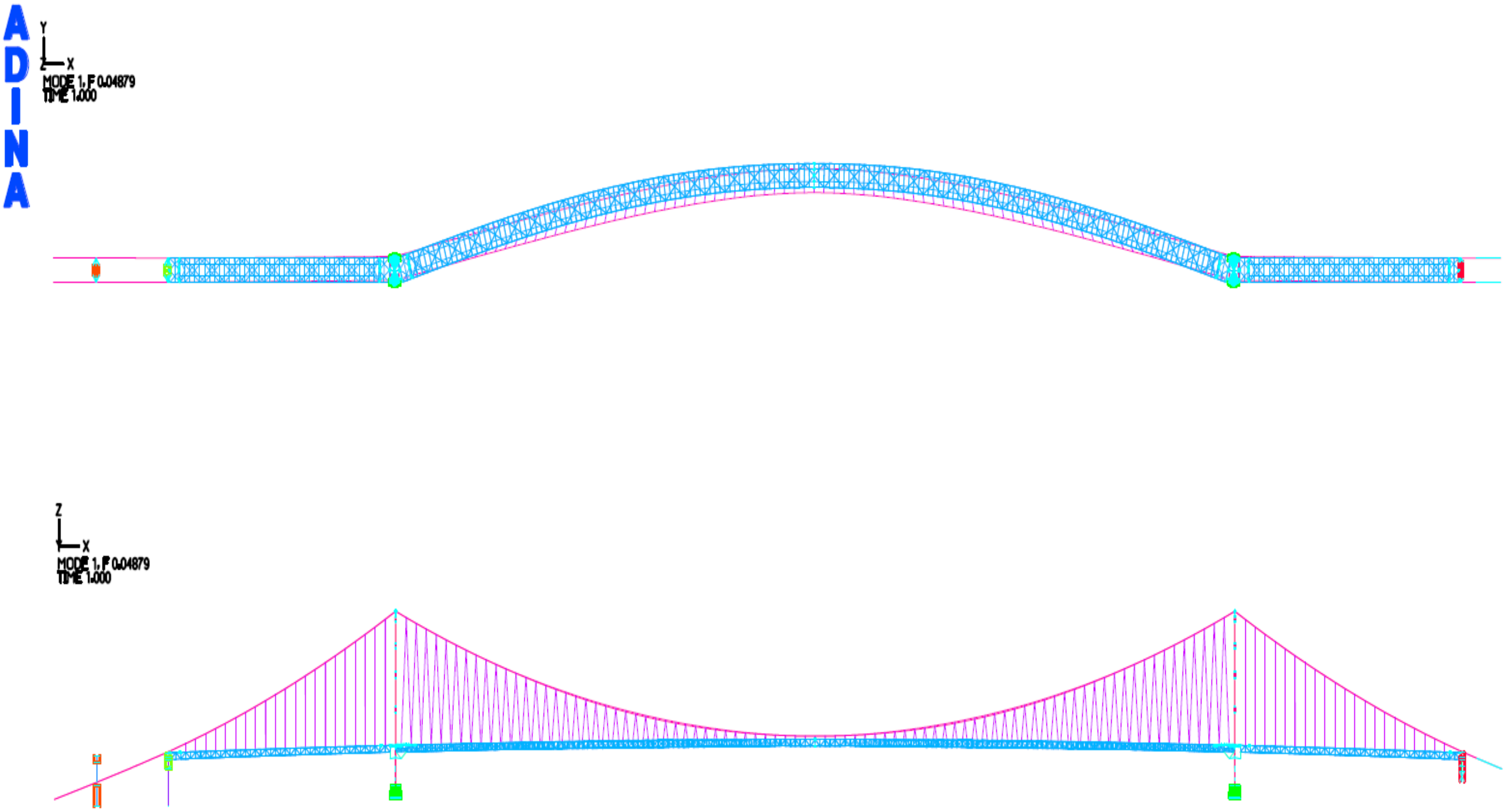


Modal Analysis Results

- 475 Modes Using ADINA's Subspace Iteration Method
- Compared Well with Other Published Studies

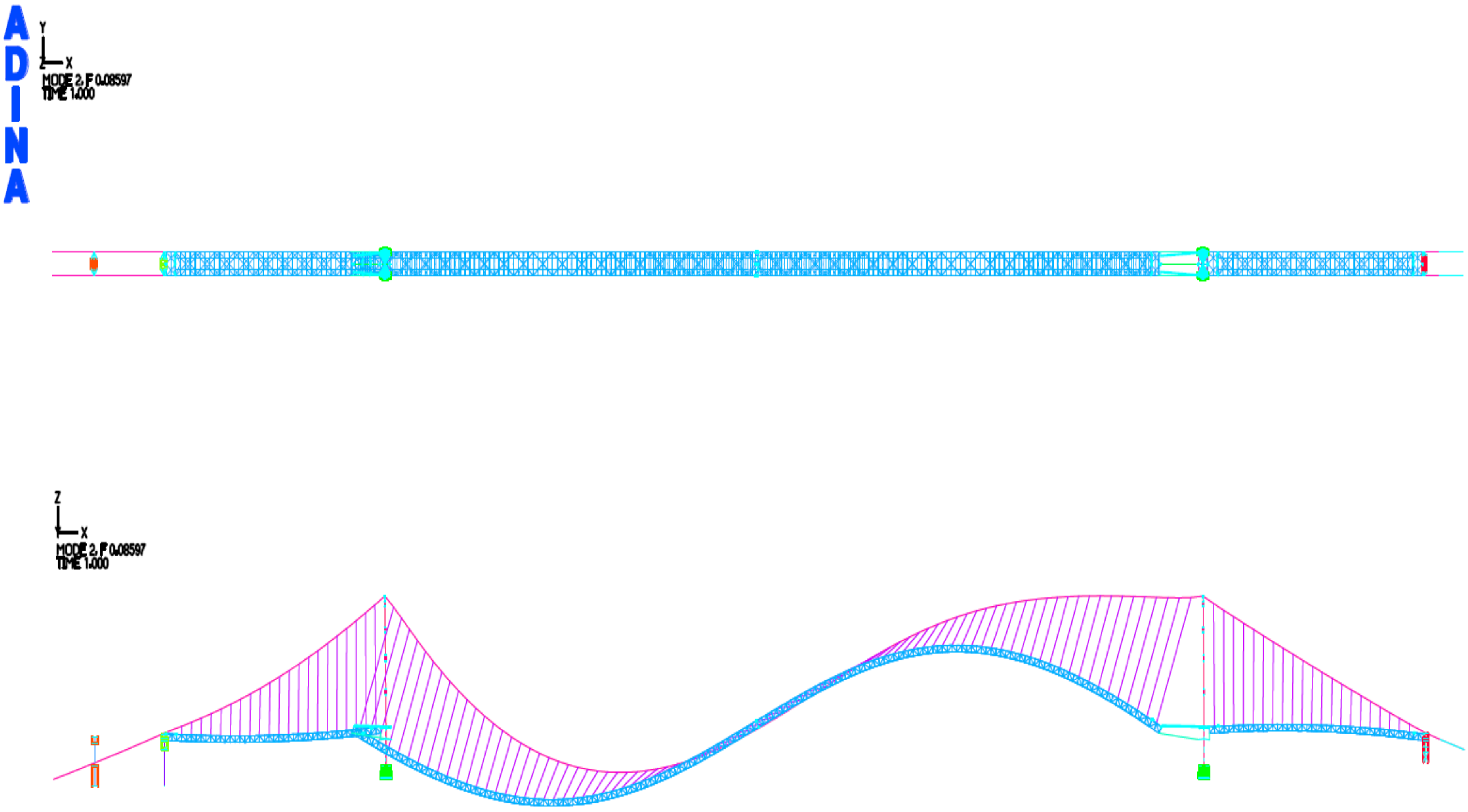
Mode	Frequency (Hz)	Period (sec)	Mass Participation	S_A (g)	S_A (g) * Mass Participation	Mode Description
Predominant Longitudinal Modes						
2	0.0860	11.631	10.0%	0.029	0.3%	Mainspan
5	0.1297	7.713	10.4%	0.068	0.7%	Mainspan
46	0.5568	1.796	30.3%	0.643	19.5%	Sidespans & Towers
64	0.7250	1.379	3.3%	0.851	2.8%	Sidespans & Towers
71	0.7811	1.280	1.4%	0.923	1.3%	Sidespans & Towers
156	1.0133	0.987	1.1%	1.154	1.2%	Sidespans, Mainspan & Towers
207	1.5448	0.647	1.8%	1.588	2.8%	Sidespans & Pylon S1
209	1.5548	0.643	5.3%	1.597	8.4%	Sidespans & Pylon S1
268	2.1258	0.470	4.7%	1.945	9.1%	Pylon S2
272	2.1469	0.466	1.1%	1.957	2.2%	Sidespans & Towers
Predominant Transverse Modes						
1	0.0488	20.495	23.2%	0.008	0.2%	Mainspan
15	0.2218	4.509	3.0%	0.210	0.6%	Mainspan, Coupled With Torsion
17	0.2618	3.820	2.2%	0.278	0.6%	Sidespans
18	0.2619	3.818	9.7%	0.278	2.7%	Sidespans
22	0.3000	3.333	2.3%	0.343	0.8%	Sidespans, Coupled With Torsion
35	0.4243	2.357	1.9%	0.556	1.1%	Mainspan & Towers, Coupled With Torsion
44	0.5280	1.894	4.6%	0.700	3.2%	Mainspan & Towers, Coupled With Torsion
56	0.6493	1.540	4.5%	0.872	3.9%	Sidespans, Mainspan & Towers, Coupled With Torsion
220	1.6539	0.605	1.4%	1.885	2.6%	Sidespans, Mainspan & Towers, Coupled With Torsion
Predominant Vertical Modes						
4	0.1281	7.808	2.1%	0.049	0.1%	Sidespans & Mainspan
6	0.1632	6.128	1.5%	0.078	0.1%	Sidespans & Mainspan
16	0.2583	3.872	14.1%	0.164	2.3%	Sidespans & Mainspan
19	0.2861	3.495	18.2%	0.189	3.4%	Sidespans & Mainspan
65	0.7434	1.345	1.0%	0.619	0.6%	Sidespans

Modal Analysis Results



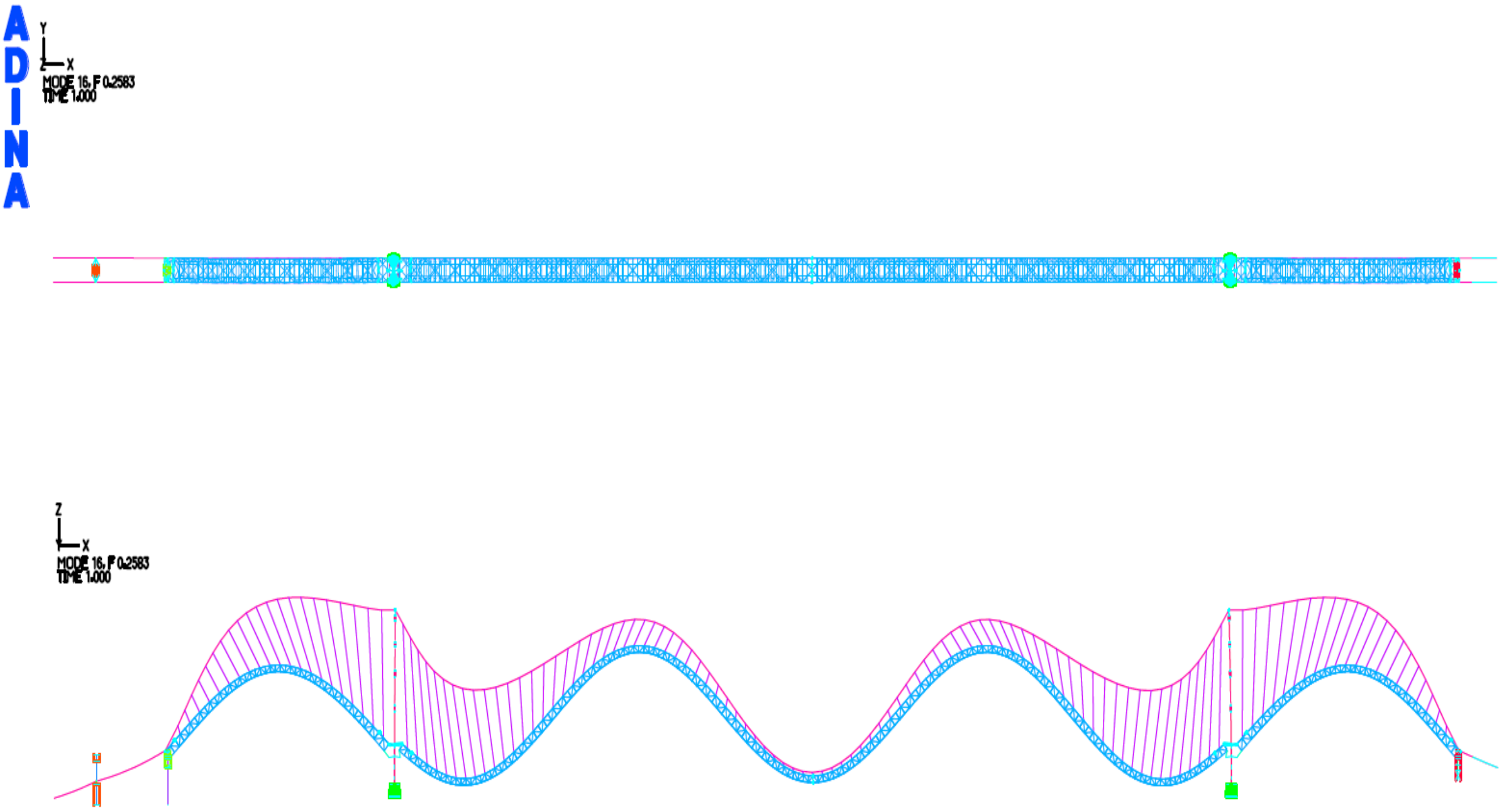
Mode 1: Transverse Mainspan, Period = 20.50 sec, Mass Part. = 23.2%

Modal Analysis Results



Mode 2: Longitudinal Mainspan, Period = 11.63 sec , Mass Part. = 10.0%

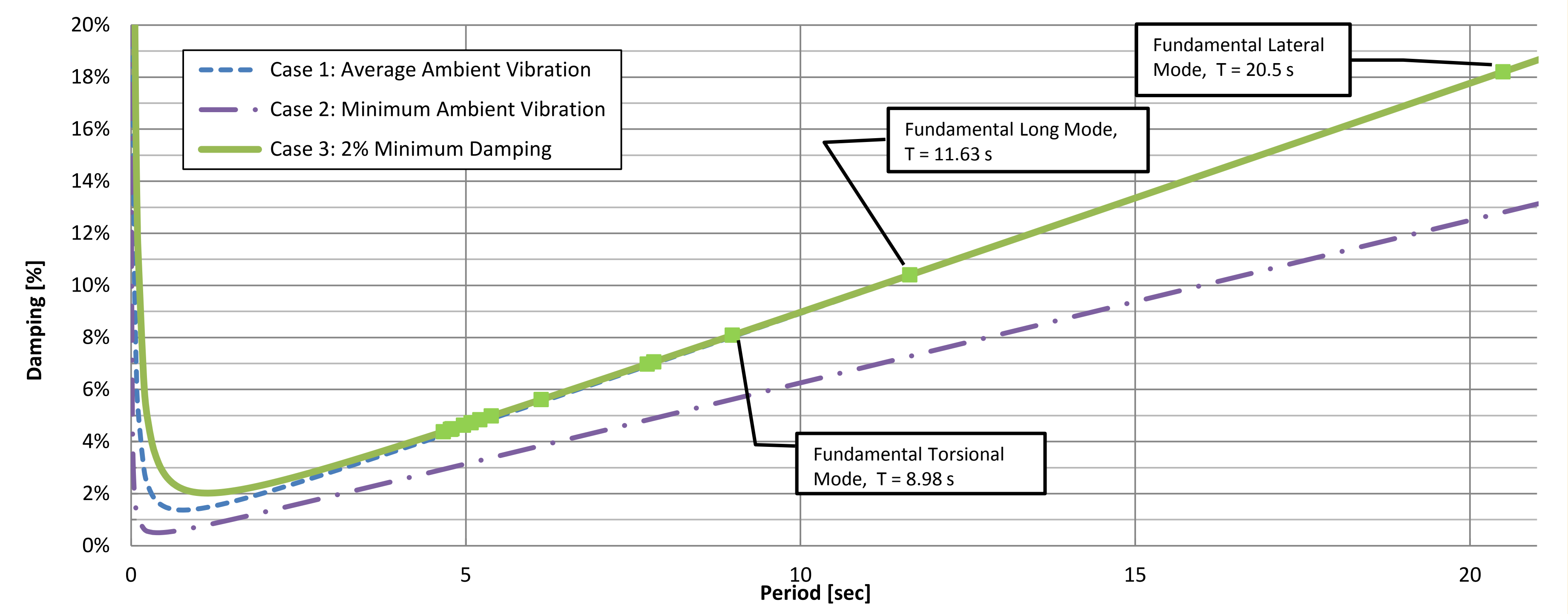
Modal Analysis Results



Mode 16: Vertical Sidespans & Mainspan, Period=3.87 sec , Mass Part.=14.1%

Rayleigh Damping Coefficients – Stiffening Truss, Main Cables & Suspenders

- Coefficients based on average ambient vibration measurements by Abdel-Gaffar, 1982
  - $\alpha = 0.111254$, $\beta = 0.003672$
- Best-fit ambient curves
- 2% min.(2.75% avg.) curve used for comparison for reasonableness
- Conservative estimate of damping



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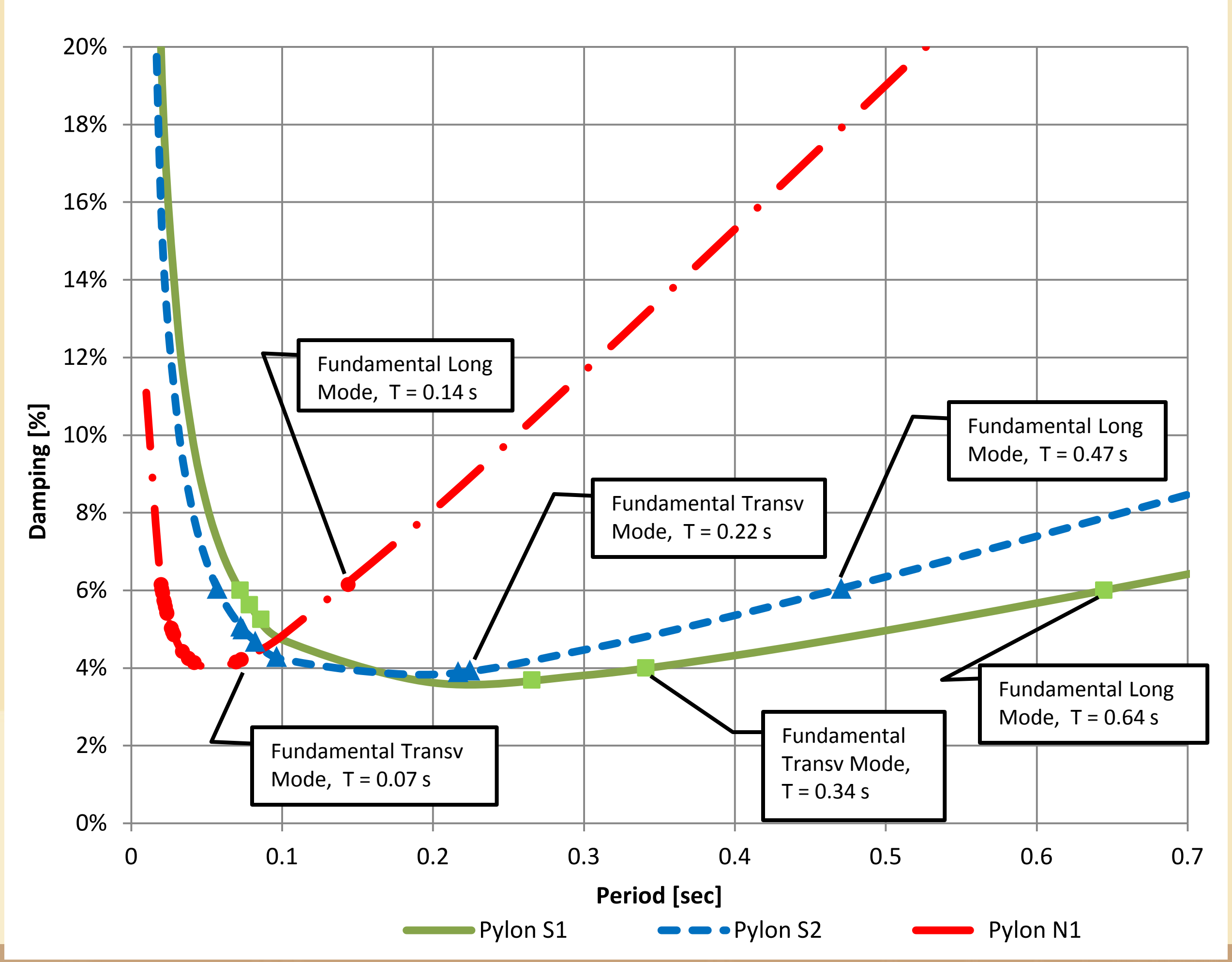
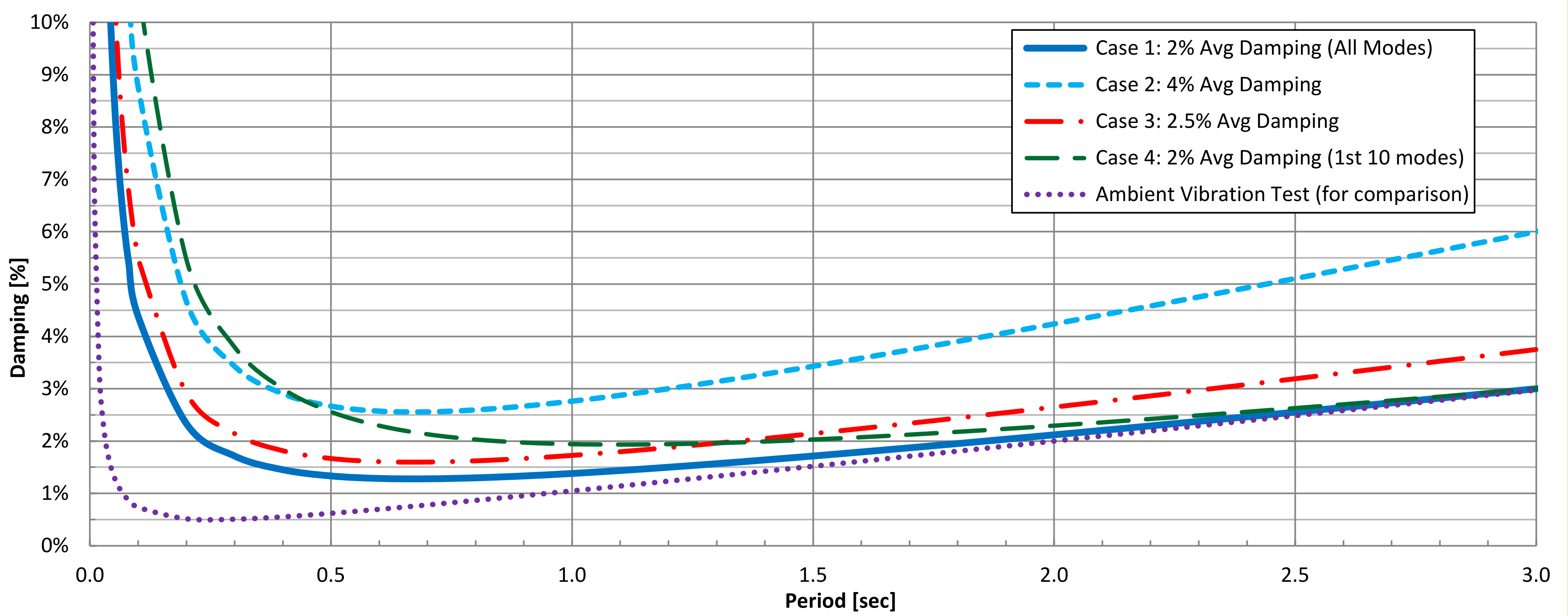
Rayleigh Damping Coefficients – Pylons

- Isolated Pylon Models
- Coefficients selected for each pylon to provide 5% average damping ratio
- Pylon S2
  - $\alpha = 1.440837$
  - $\beta = 0.000980$
- Pylon S1
  - $\alpha = 1.051948$
  - $\beta = 0.001240$
- Pylon N1
  - $\alpha = 4.723483$
  - $\beta = 0.000341$



Rayleigh Damping Coefficients – Towers

- Coefficients selected to provide 2% avg. damping ratio
  - $\alpha = 0.110880$, $\beta = 0.003370$
- Average is over frequencies that can be accurately captured by model (first 10 modes)
- Allow for significant period changes without over-damping
  - Fundamental Transverse Period = 1.8 sec



Additional Damping

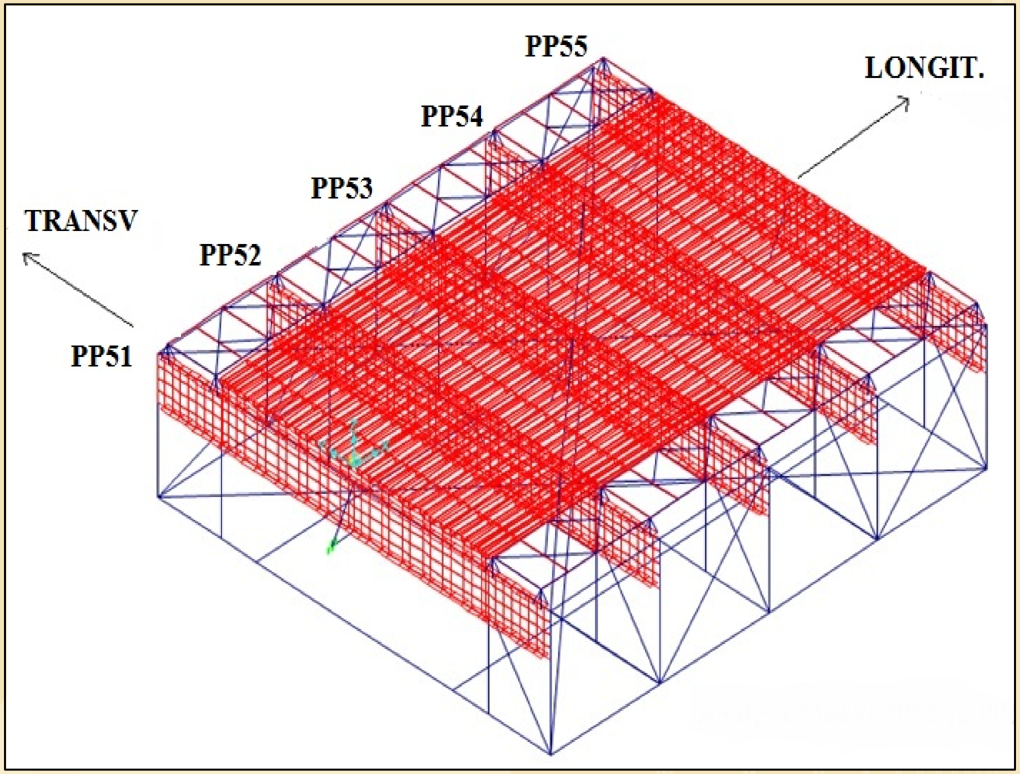
- Tower Bases
  - Additional 5% damping to approximate rocking on concrete pier
  - Vertical dashpots introduced at base of tower
- Main Cables & Suspenders
  - Add perpendicular dashpots with $C = \beta * K_g$ between adjacent cable nodes

Model Verification – Parametric / Sensitivity Studies

- Static Longitudinal & Transverse Pushes
- Isolated Tower Model - compare ADINA & SAP model results
  – dead load, unit push & modal analysis
- Isolated Towers & Pylons Time History Analysis
- *Local Deck & Stiffening Truss Interaction*
- Non-Proportional Rayleigh Damping Verification
- Concrete Pier Influence on Global Behavior
- Tower Shaft Base Spring Constants
- Consistent vs. Lumped Mass
- Iteration Tolerances
- Integration Time Steps
- Wind & Live Load

Local Deck and Stiffening Truss Interaction

- Orthotropic Deck System <u>Stiffness</u> not included in Global Model
- Refined SAP linear elastic Local Model created
- TH Input applied at chord boundaries & suspenders
- Verify Floorbeam & Pedestal demands
- Conclusion:
  - Maximum stiffness contribution approx. 8%
  - Deck system assumption validated



3D Isometric View – SAP Local Model

Assessing Seismic Performance

- Elastic Performance – D/C
  - AASHTO
    - Combined Axial + Flexure
    - Shear & Torsion

- Inelastic Performance – Ductility
  - Global & Local Ductility
  - Cumulative Plastic Displacement Index (CPDI)
    - Number of Equiv. Inelastic Cycles
      $N = CPDI / (\mu_c + \mu_t - 2)$
  - Local Rotational Ductility
  - Cumulative Plastic Rotational Index (CPRI)
  - Ductility Levels Specified by Project Specific Design Criteria

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SA1 – Disp. / Reactions

Model Description: As-Built ADINA Global Model
Model File Name: GGSB_Rev_02_20120505

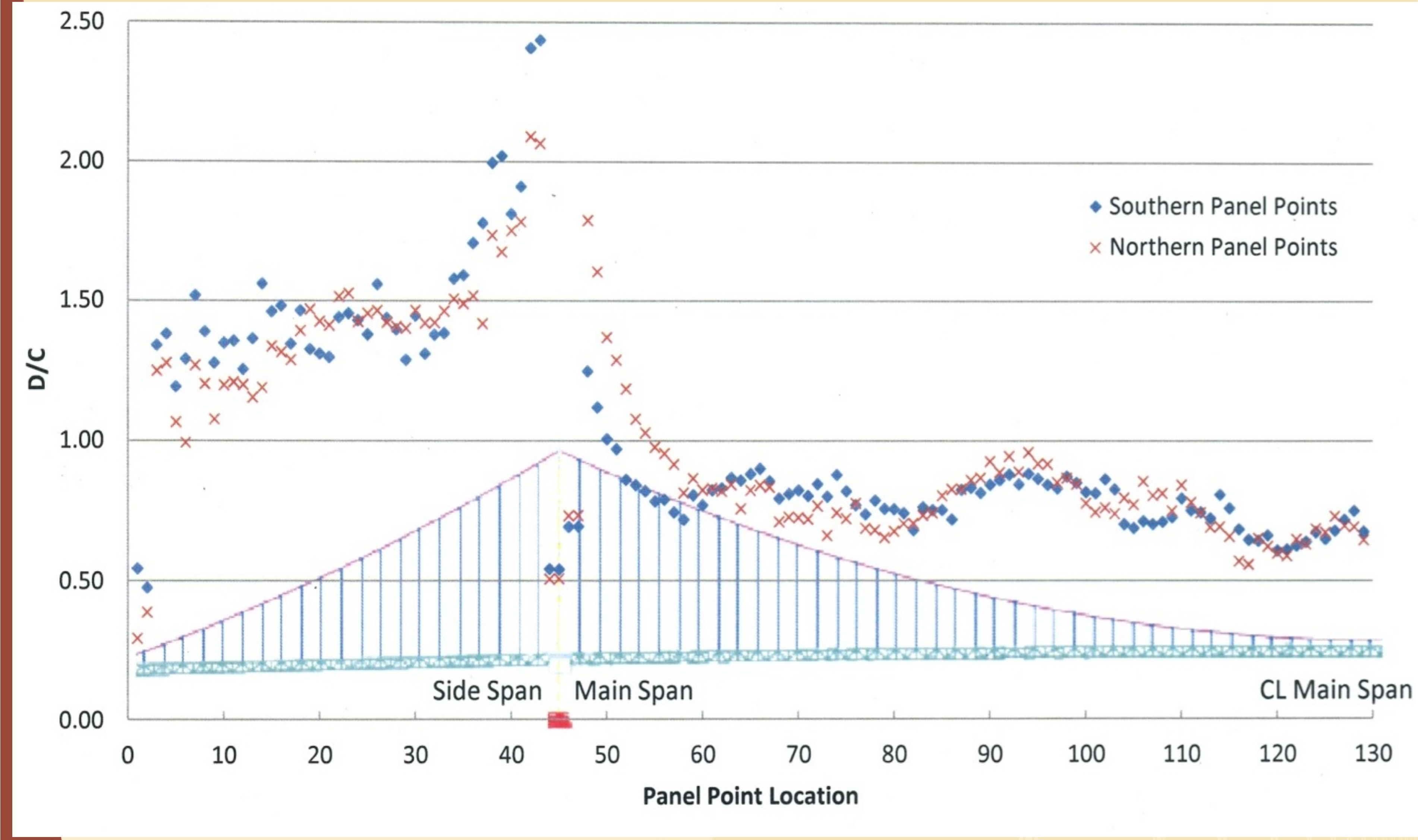
Tower and Truss Displacements (inch)		Relative Displacements: Longitudinal (X) Max.	Longitudinal (X) Min.	Transverse (Y) Max.	Transverse (Y) Min.	Vertical (Z) Max.	Vertical (Z) Min.
South Tower	Top (Cable)	11.2	-12.8	23.7	-24.0	-1.2	-4.3
	Strut 2	23.4	-21.6	17.8	-19.3	-0.6	-3.6
	Strut 3	28.1	-25.1	13.1	-14.8	-0.1	-3.0
	Strut 4	24.6	-21.8	9.0	-9.9	0.2	-2.3
	Strut 5 (Deck)	13.5	-11.4	3.2	-3.3	0.5	-1.3
	Shaft Base (Neg. Z = Uplift)	0.1	-0.1	0.1	-0.1	0.2	-2.1
North Tower	Top (Cable)	11.8	-11.8	26.5	-25.3	-0.9	-4.2
	Strut 2	21.0	-20.6	20.8	-20.2	-0.3	-3.5
	Strut 3	25.3	-26.5	16.5	-15.7	0.1	-2.9
	Strut 4	21.9	-23.7	11.3	-10.3	0.4	-2.2
	Strut 5 (Deck)	12.2	-12.4	4.1	-3.7	0.7	-1.3
	Shaft Base (Neg. Z = Uplift)	0.1	-0.1	0.1	-0.1	0.1	-2.1
Truss	South Sidespan	26.2	-23.4	59.3	-60.9	54.1	-45.2
	Mainspan	34.9	-33.2	31.5	-30.2	57.6	-42.5
	North Sidespan	21.4	-21.3	60.4	-56.8	70.0	-67.3

Reactions (kip, kip-ft)		Longitudinal (FX, MY) Max.	Longitudinal (FX, MY) Min.	Transverse (FY, MX) Max.	Transverse (FY, MX) Min.	Vertical (FZ, MZ) Max.	Vertical (FZ, MZ) Min.	Note
South Anchorage	Base Force (Axial/Shear)	-36,654	-59,682	670	-617	-10,757	-17,702	per cable
South Tower	Top Force (Axial/Shear)	6,428	-6,936	1,996	-1,890	58,731	40,926	per cable
	Base Force (Axial/Shear)	21,604	-24,639	21,092	-21,570	193,764	90,883	total
	Base Moment	3.121E+06	-3.327E+06	5.587E+06	-6.591E+06	2.670E+05	-3.010E+05	reaction
North Tower	Top Force (Axial/Shear)	6,189	-6,530	2,102	-2,425	57,533	39,399	per cable
	Base Force (Axial/Shear)	22,760	-20,750	25,172	-24,475	189,772	86,929	total
	Base Moment	3.372E+06	-3.015E+06	6.840E+06	-6.458E+06	2.126E+05	-2.544E+05	reaction
North Anchorage	Base Force (Axial/Shear)	57,480	33,686	1,779	-2,343	-10,619	-18,615	per cable

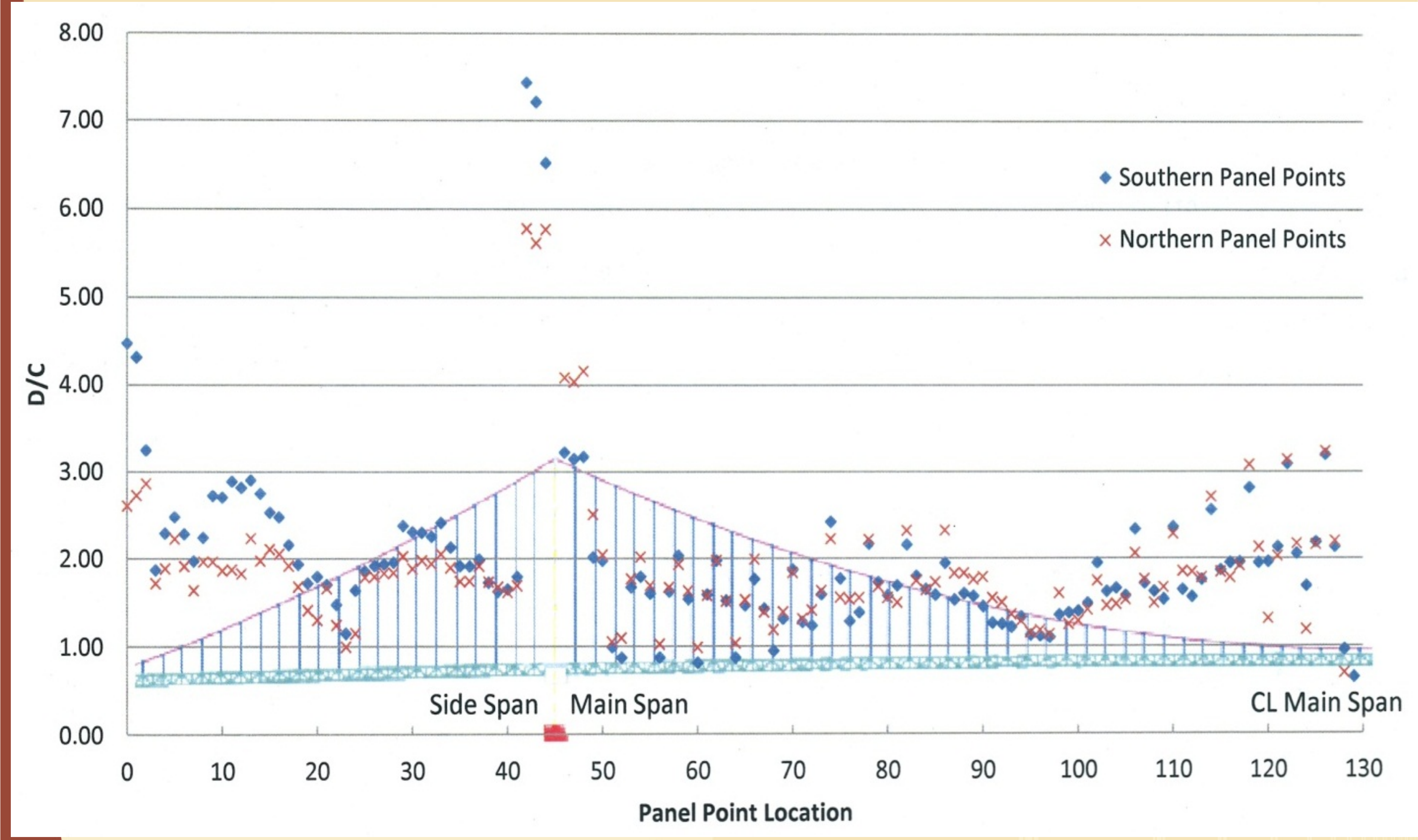
Expansion Joints and Windlocks
(underlined values indicate closing relative disp.)

		Relative Disp. (inch) Longitudinal (X) Max.	Relative Disp. (inch) Longitudinal (X) Min.	Shear Force (kip) Longitudinal (X) Max.	Shear Force (kip) Longitudinal (X) Min.	Shear Force (kip) Transverse (Y) Max.	Shear Force (kip) Transverse (Y) Min.	Shear Force (kip) Vertical (Z) Max.	Shear Force (kip) Vertical (Z) Min.
Expansion Joint - South Sidespan	South Pylon S1 (U0)	20.6	-23.2	–	–	–	–	–	–
	South Tower (U44)	8.5	-11.6	–	–	–	–	–	–
Expansion Joint - Mainspan	South Tower (U46)	23.7	-29.0	–	–	–	–	–	–
	North Tower (U46')	26.7	-26.7	–	–	–	–	–	–
Expansion Joint - North Sidespan	North Tower (U44')	10.1	-8.9	–	–	–	–	–	–
	North Pylon N1 (U0')	21.1	-20.5	–	–	–	–	–	–
Windlock - South Sidespan	South Pylon S1 (U0)	16.1	-17.6	6269	-8694	3913	-3495		
	South Tower (U44)	0.1	-0.1	10348	-13811	3255	-2909	214	-271
Windlock - Mainspan	South Tower (U46)	18.2	-21.2	16582	-17055	1836	-2630		
	North Tower (U46')	21.1	-18.2	18842	-11362	1998	-1869		
Windlock - North Sidespan	North Tower (U44')	0.1	-0.1	11080	-8926	3226	-2769	186	-224
	North Pylon N1 (U0')	17.6	-16.0	4711	-5807	3667	-2862		

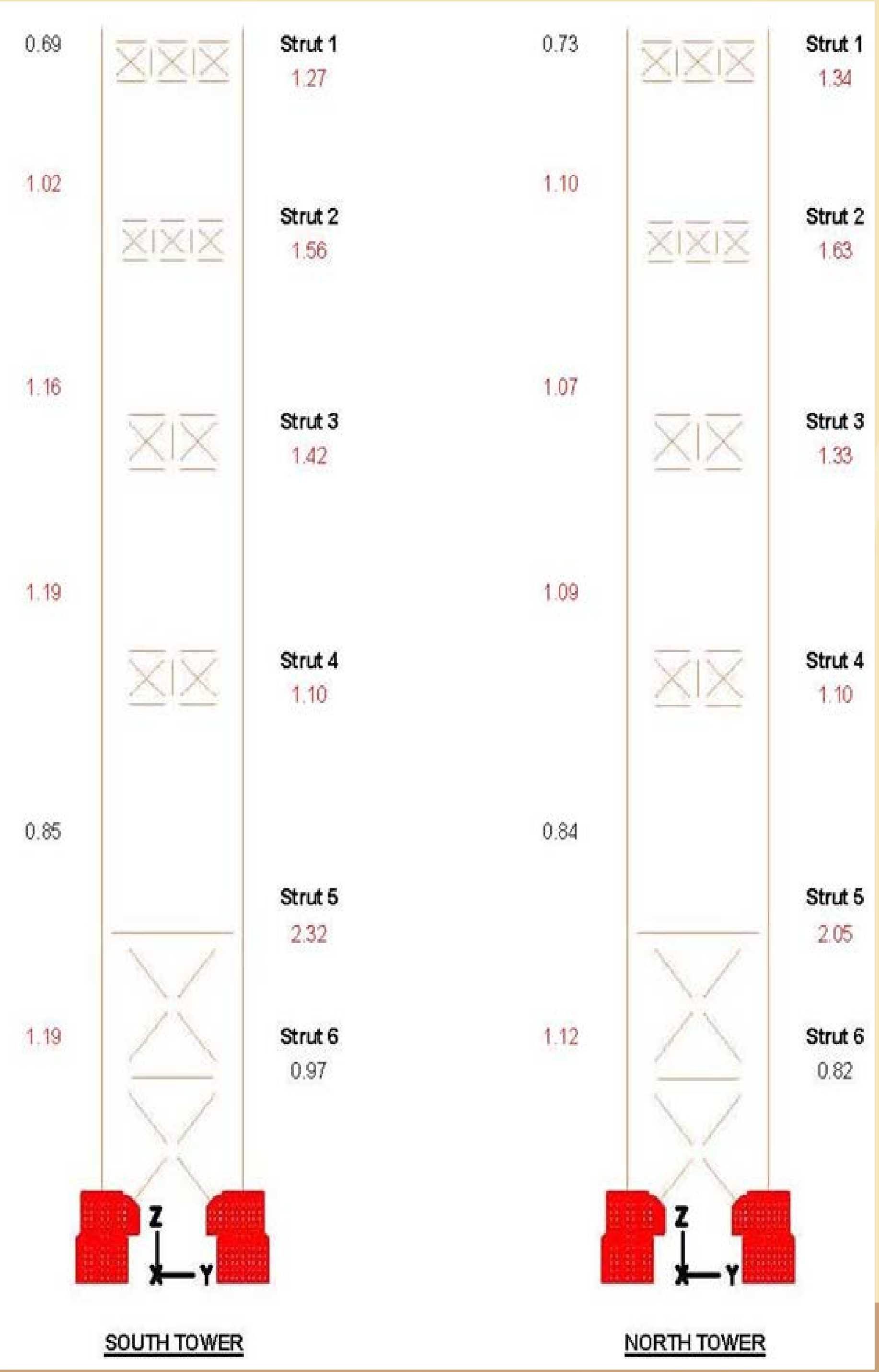
SA1 – Stiffening Truss Top Chord D/C Ratios



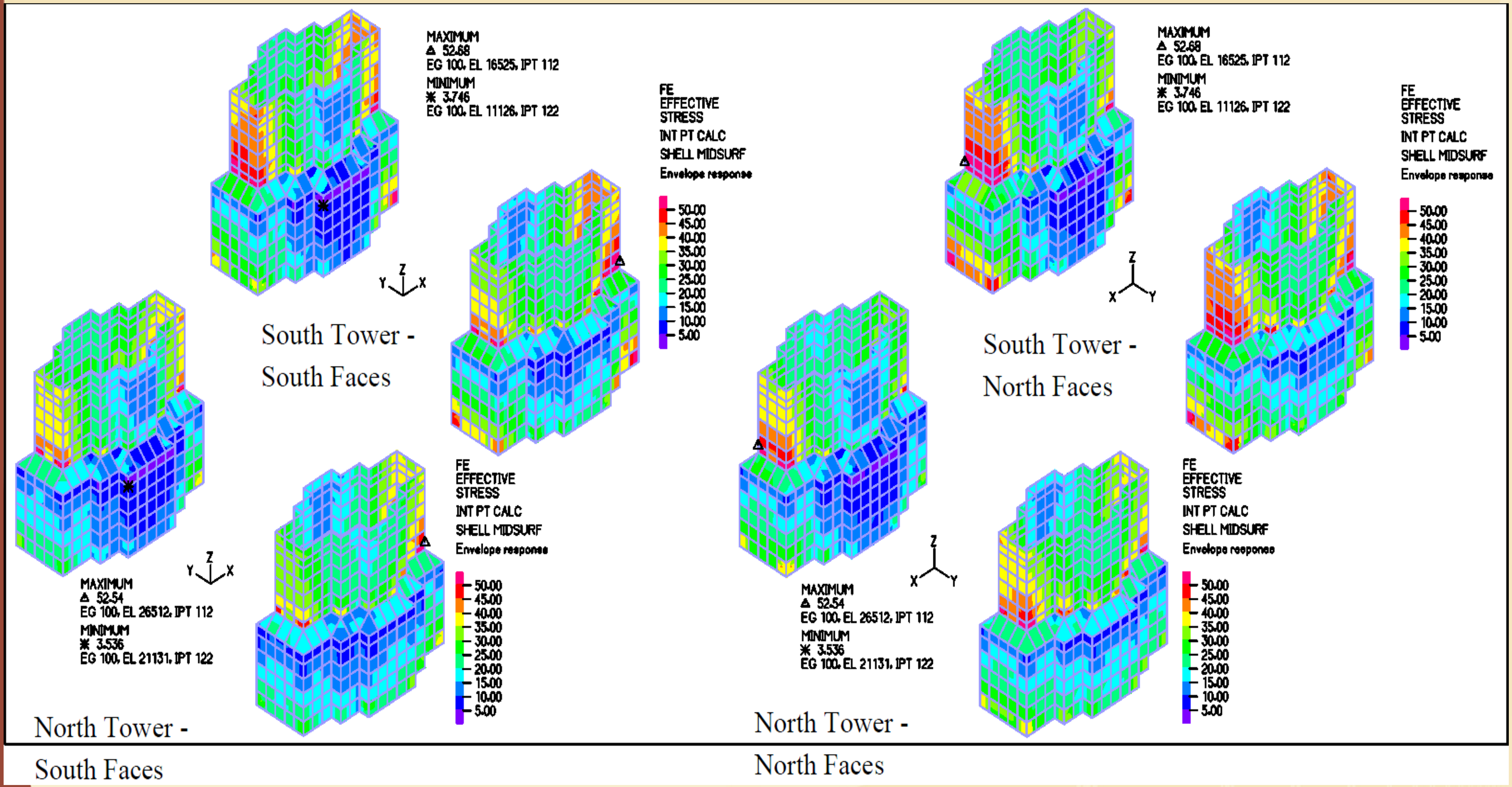
SA1 – Stiffening Truss Top Lateral D/C Ratios



SA1 – Tower D/C Ratios



SA1 – Tower Base Max. Von Mises Stress (Yield = 52.4 ksi)



Thank You! Questions?