A New Type of EDD for the Seismic Retrofit of the Golden Gate Bridge Main Suspension Spans

Western Bridge Engineers' Seminar

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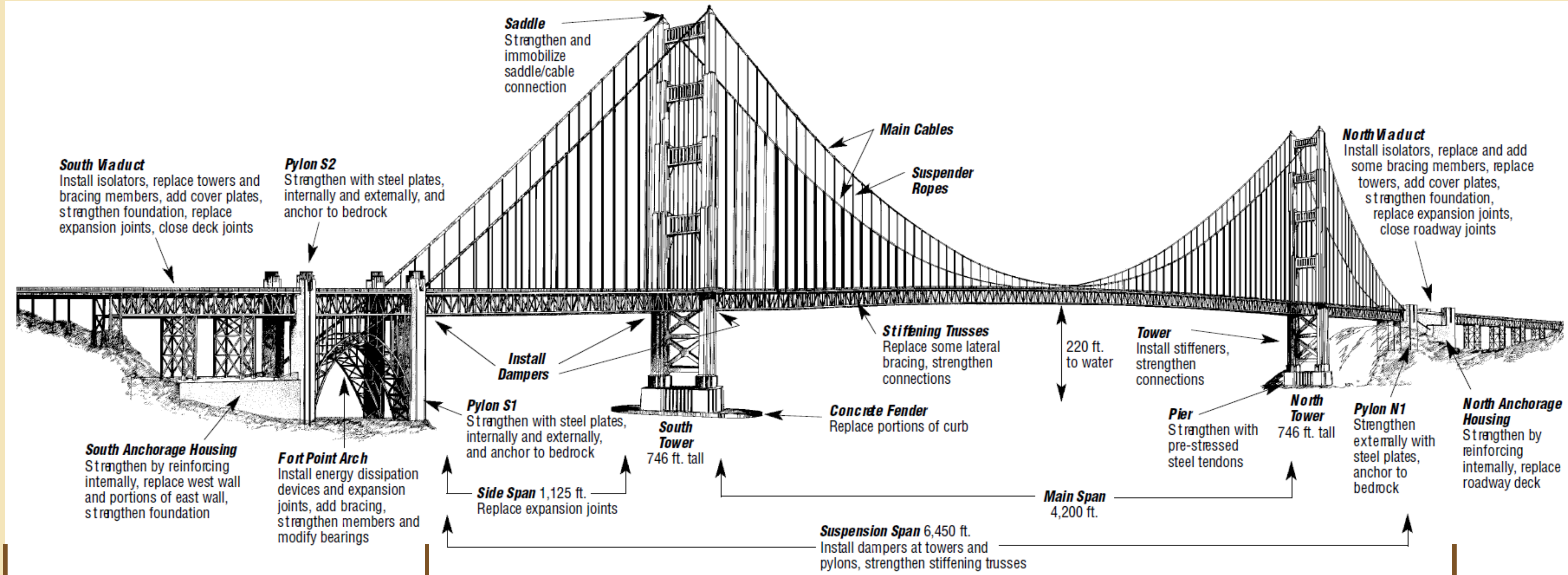
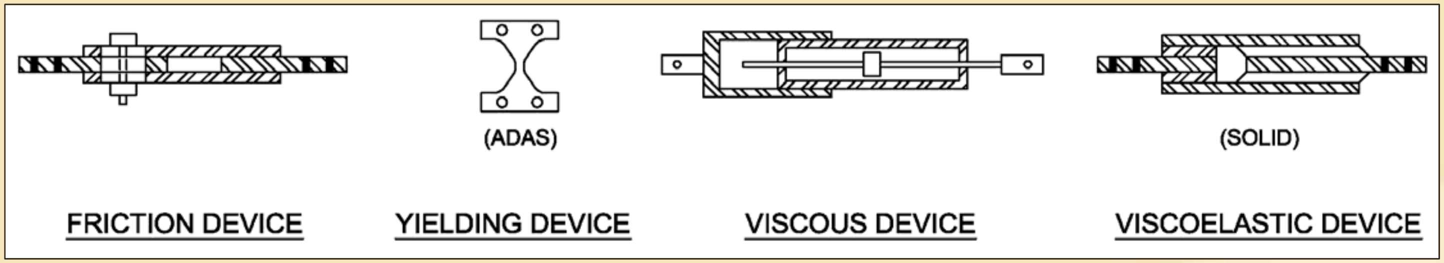
Golden Gate Bridge – Seismic Retrofit Program



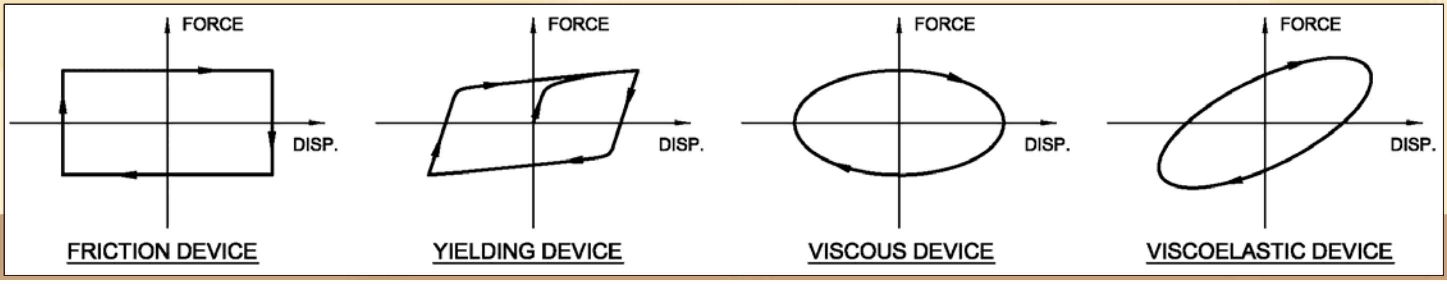
Phase II | **Phase IIIA and IIIB** | **Phase I**

What are Energy Dissipation Devices (EDDs)?

- EDDs:
  - Dissipate energy created by EQ
  - Provide additional physical damping
  - Strategically placed & designed to obtain optimal seismic performance
- Most Common EDD Types:



- Force-Displacement Behavior:



Why are EDDs needed for GGB?

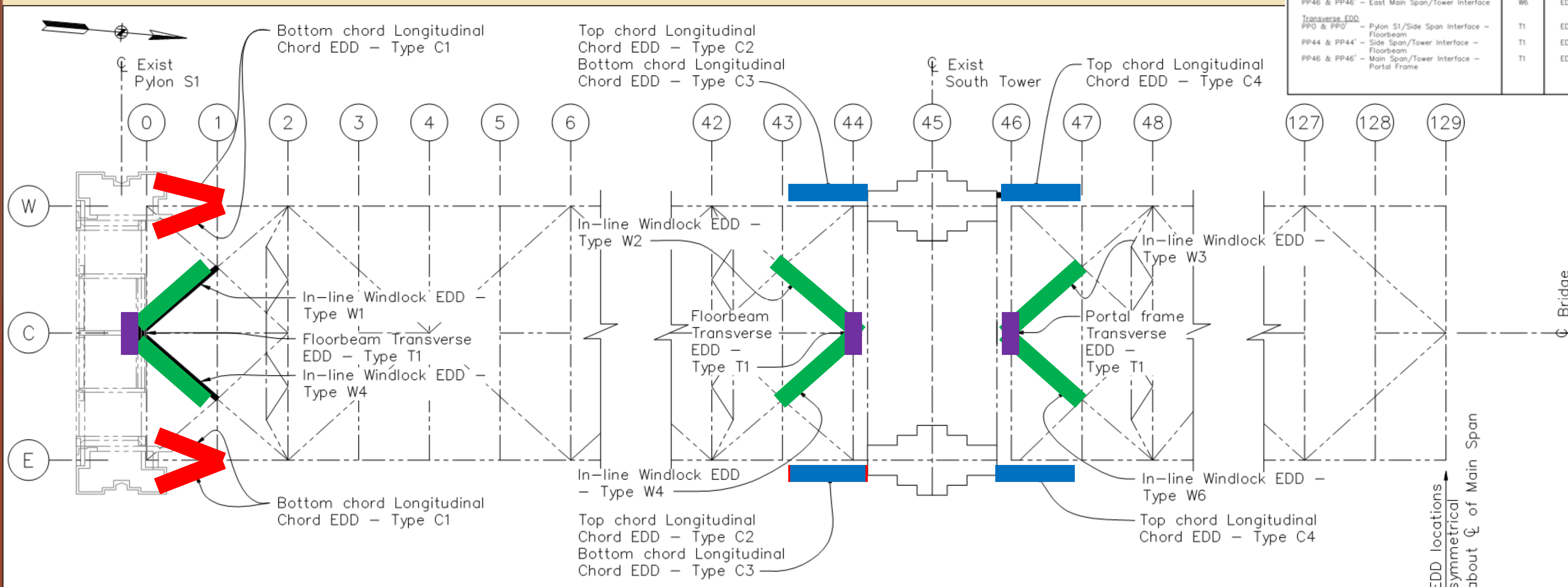
- Selected Based on Results of Numerous Retrofit Strategy Analyses

- Energy Dissipation reduces Seismic Demands
  - Reduction in force near Pylon & Tower Interfaces
    - both stiffening truss & interface components
  - Minimize relative displacements between stiffening truss & interfaces

Where are EDDs going to be located?

EDD TYPE DESIGNATION TABLE		
LOCATION	TYPE	DRAWING
Longitudinal Chord EDD		
PP0 – Pylon S1/Side Span Interface – Bottom Chord	C1	ED010
PP44 & PP44' – Side Span/Tower Interface – Top Chord	C2	ED010
PP44 & PP44' – Side Span/Tower Interface – Bottom Chord	C3	ED010
PP46 & PP46' – Main Span/Tower Interface – Top Chord	C4	ED010
PP0 – Pylon N1/Side Span Interface – Bottom Chord	C5	ED010
In-Line Windlock EDD		
PP0 & PP0' – West Pylon/Side Span Interface	W1	ED050
PP44 & PP44' – West Side Span/Tower Interface	W2	ED050
PP46 & PP46' – West Main Span/Tower Interface	W3	ED050
PP0 & PP0' – East Pylon/Side Span Interface	W4	ED060
PP44 & PP44' – East Side Span/Tower Interface	W5	ED060
PP46 & PP46' – East Main Span/Tower Interface	W6	ED060
Transverse EDD		
PP0 & PP0' – Pylon S1/Side Span Interface – Floorbeam	T1	ED100
PP44 & PP44' – Side Span/Tower Interface – Floorbeam	T1	ED100
PP46 & PP46' – Main Span/Tower Interface – Portal Frame	T1	ED100

External – Bottom Chord   External – Top Chord   Internal – Windlock   External – Transv.



GGB EDD Selection Criteria

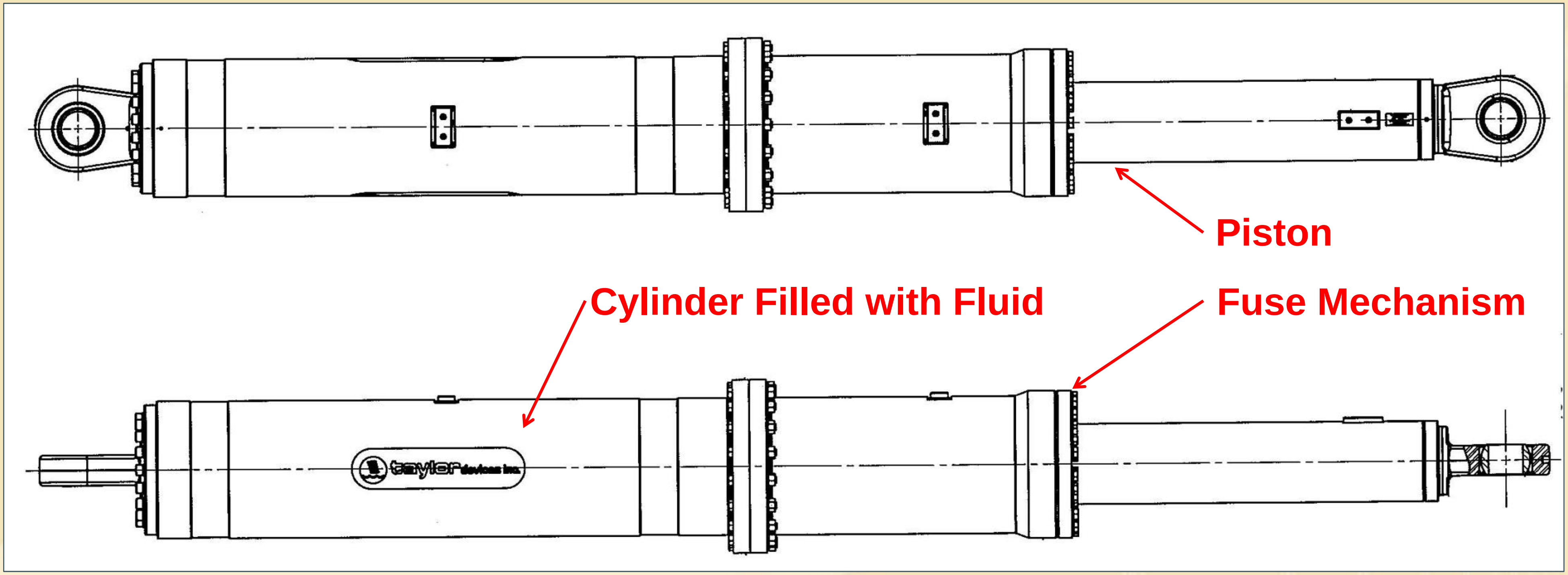
- Analysis: TH required
- Design/Detailing: Engineer or Manufacturer
- Loading: needed for EQ only, or EQ & wind
- Constructability: size constraints
- Maintenance: leaking fluid due to seal failures, material type, corrosion
- Performance: which F-Δ curve is best suited for application
- Dependability/Durability: number of internal components that can have issues, redundancy
- Anticipated Post-Seismic Repair: re-centering capabilities, total replacement required
- Cost
- Client Familiarity

EDD Types Selected for Retrofit Scheme Development

- EDD Types Selected Based on Previously Discussed Selection & Design Considerations
- Types Narrowed Down to:
  - Viscous Dampers
    - popular in past several decades for bridge seismic retrofits
    - additional design enhancements considered to minimize potential seal failures
  - Abrasive Friction Dampers
    - similar concept to that used on previous GGB Phase II retrofit project
    - elongated holes provided for thermal movements

Conceptual Details Specific for GGB – Viscous EDD

- Internal EDD shown, External EDDs similar (require gap mechanism)

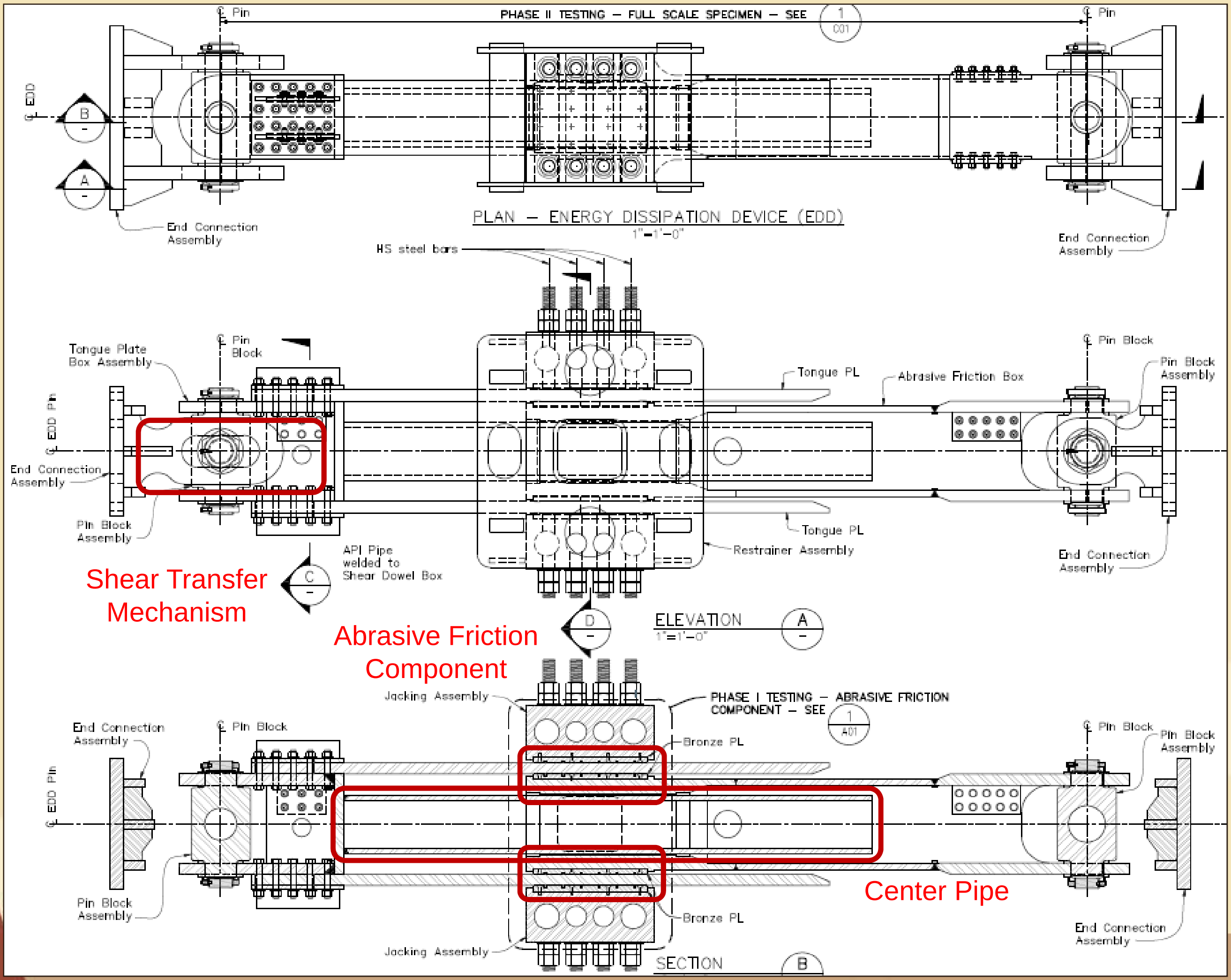


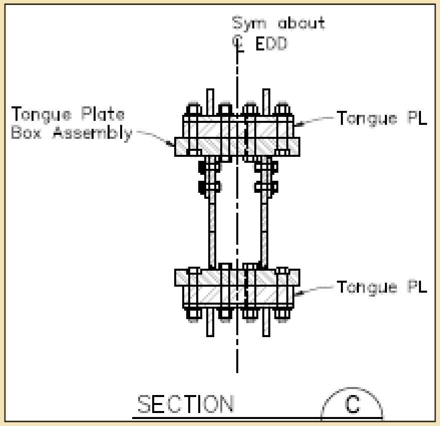
Example Viscous Damper Plan and Elevation (Courtesy of Taylor Devices, Inc.)

Abrasive Friction EDD – Details

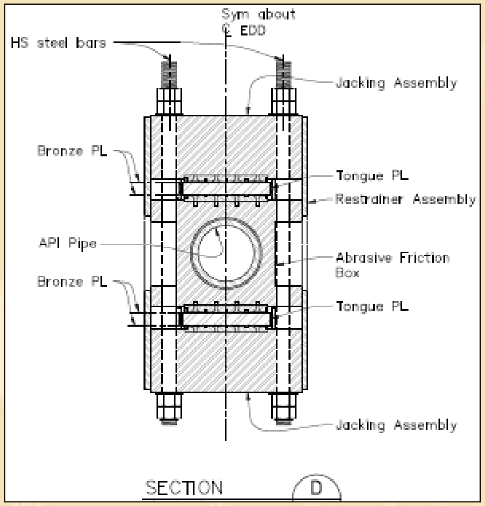
- 3 Main Internal Components:
  - Abrasive Friction Component
    - required for all EDDs
    - leaded tin bronze plates internally compressed using PT rods
  - Shear Transfer Mechanism
    - required for External EDDs only
    - pins provided within elongated holes
  - Center Pipe
    - connects Abrasive Friction & Shear Transfer Mechanism components together
    - provides flexural continuity
      - global compression capacity achieved with center pipe

Abrasive Friction EDD





Tongue Plate Box

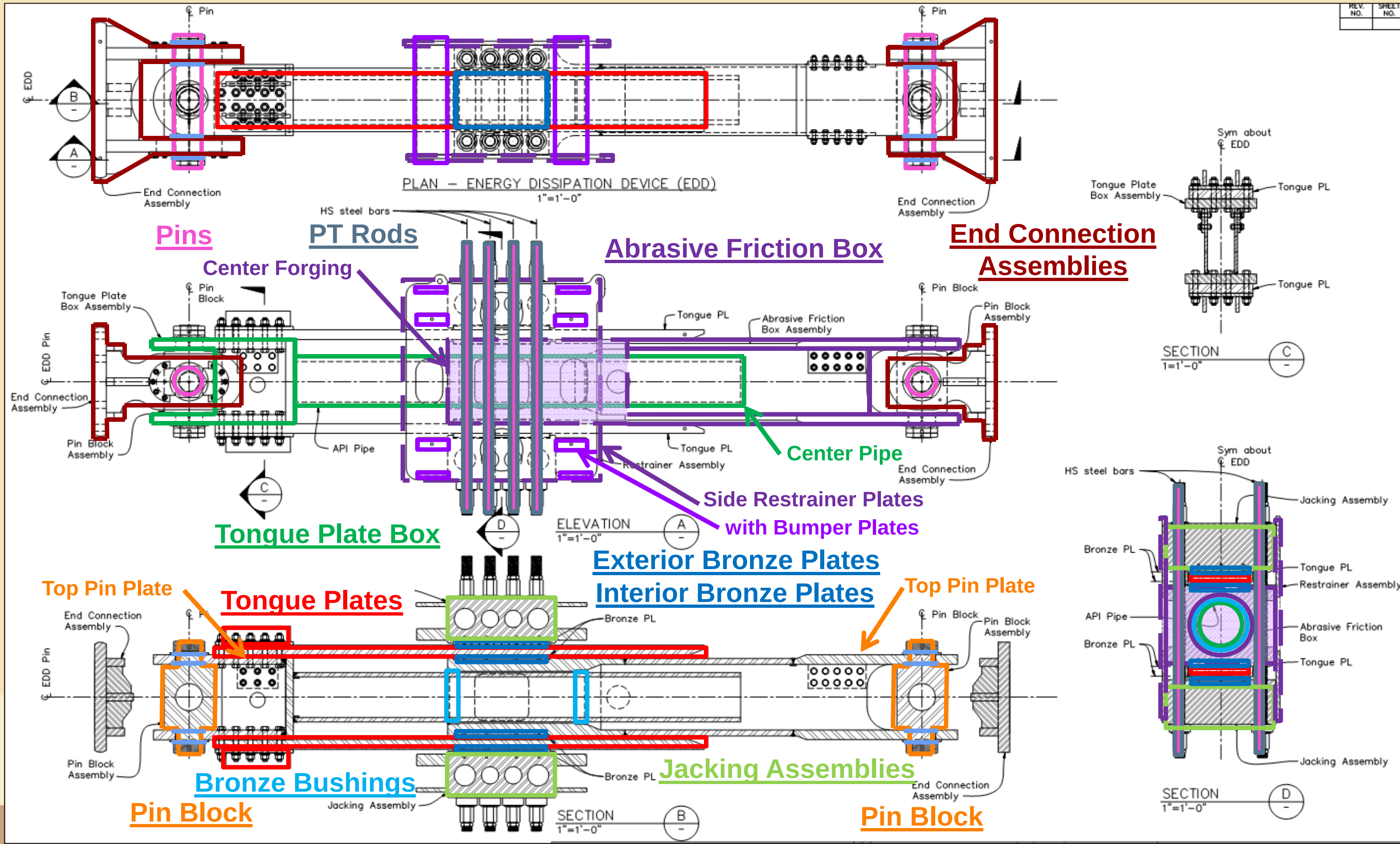


Jacking Assembly & Abrasive Friction Box

Selected EDD Type – Abrasive Friction EDD

- Similar Concept successfully implemented during previous Phase II retrofit project
  - performing well - no maintenance issues
- Friction plates provide predictable, consistent & reliable behavior
  - sacrificial - spare plates will be fabricated during construction
- Excellent Energy Dissipation
  - nearly elastic-perfectly-plastic hysteretic loop
- Mechanical Behavior - no fluid present (no potential leaking issues)
- Minimal Post-EQ Repairs
- Design includes Detailed Analytical Modeling & Physical Testing Programs

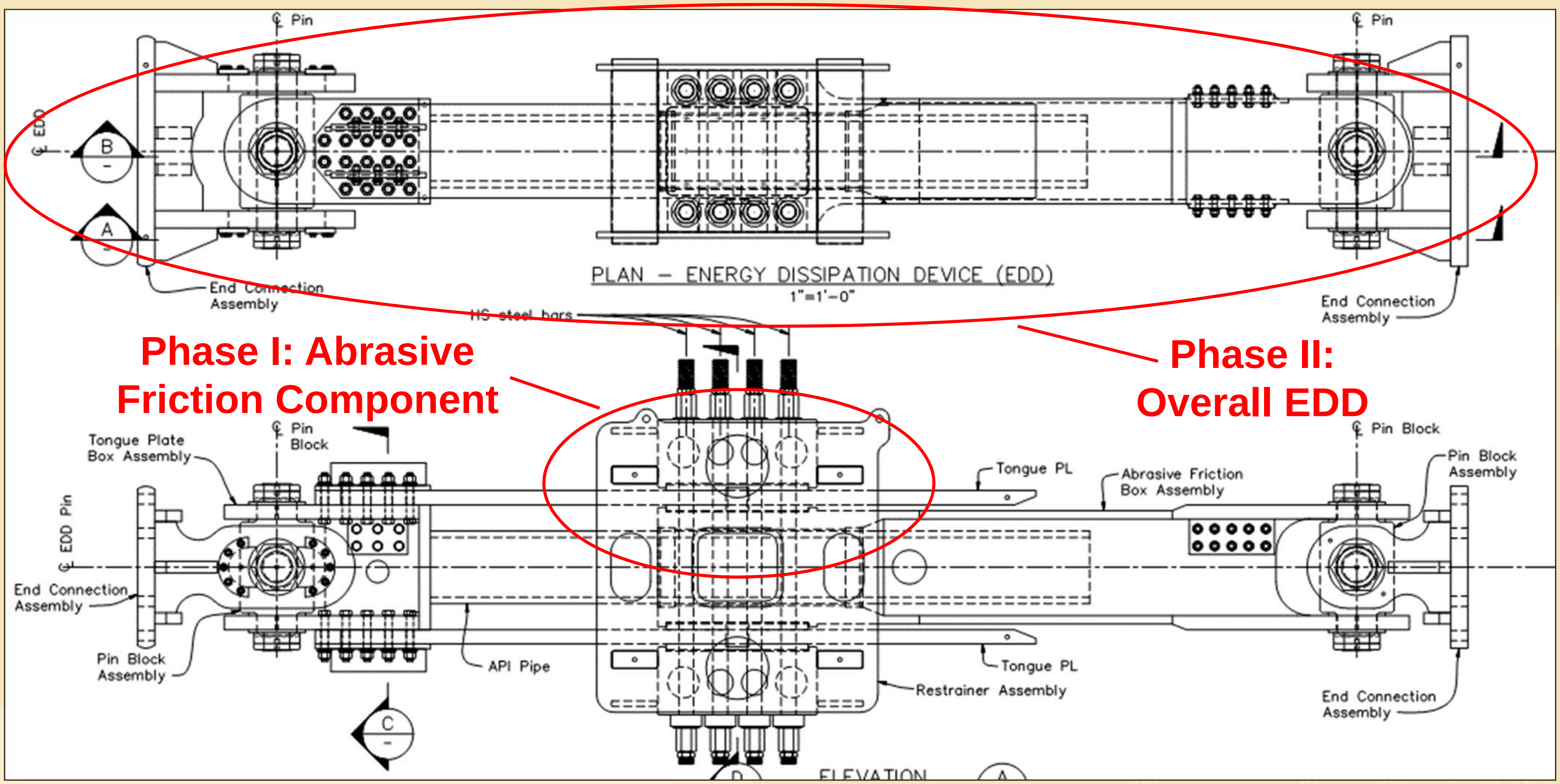
Abrasive Friction EDD – Plan & Elevation



EDD Testing Program

- Phase I Testing Program at University of Buffalo (UB)
  - 0.4 Scale (based on Similitude) established by UB Laboratory Equipment Constraints
- Phase I Testing Objectives:
  - Verify abrasive friction hysteretic behavior & energy dissipation characteristics for dynamic loading
  - Provide conclusions for implementation into Phase II Testing (refine full-scale design)
- Phase II Testing Program at University of California at San Diego (UCSD)
  - Full Scale Unit
- Phase II Testing Objectives:
  - Confirm EDD's ability to reliably dissipate the required amount of energy

EDD Testing Program



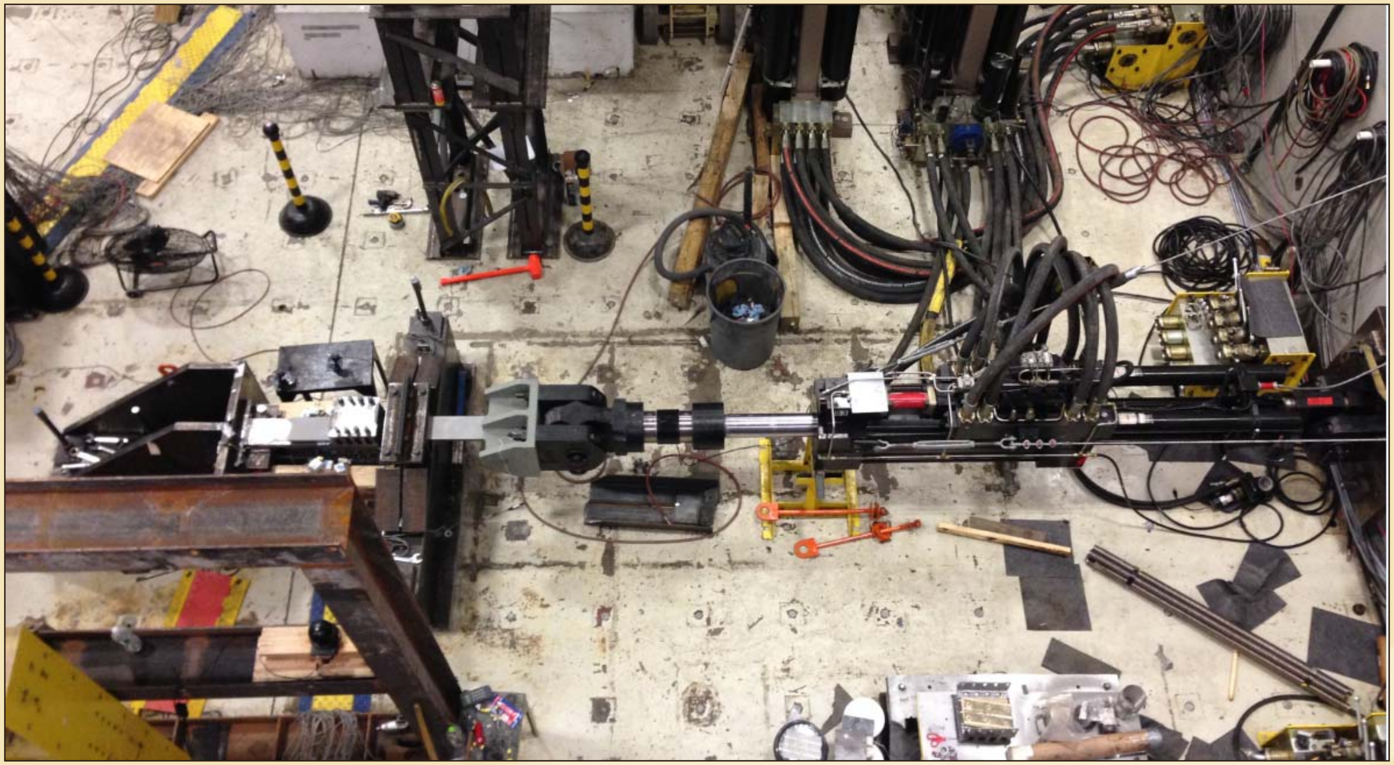
Golden Gate Bridge Phase IIIB

Phase I Testing
UB

Phase I Testing

- Parameters Investigated in Phase I Tests:
  - Velocity Effects
  - Contact Pressure Effects
  - Seismic Time History Loading
  - Thermal / Energy Effects
  - Surface Roughness Effects
  - Friction Materials (aluminum bronze, brake pads, leaded tin bronze)
  - Protective Coatings / Corrosion Potential

UB Phase I Test Setup



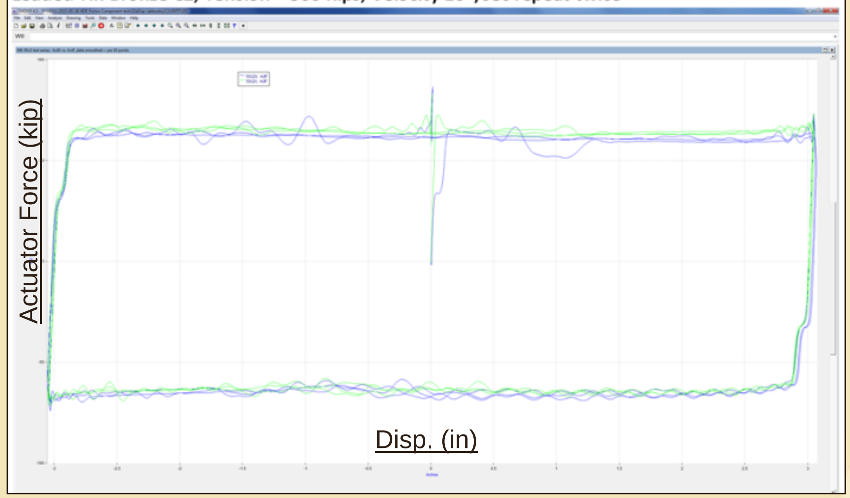
Aerial View of Test Setup

Tongue Plate

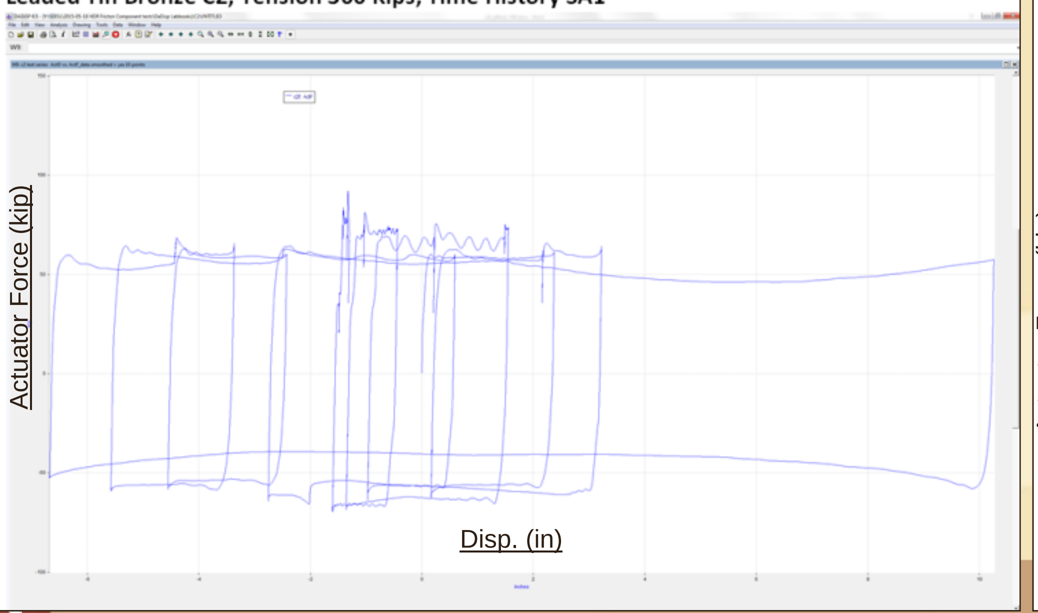
Phase I Testing Results

- Satisfactory Repeatability Results from:
  - Varying Velocity Tests
  - Varying Clamping Force Tests
  - Time History Dynamic Tests

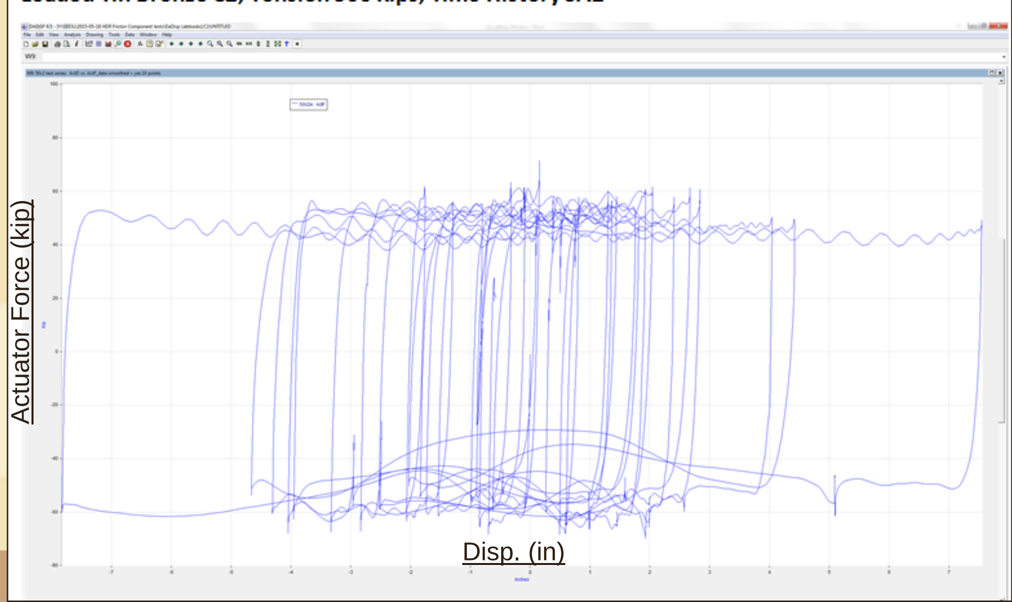
Leaded Tin Bronze C2, Tension = 300 Kips, Velocity 10"/sec repeat twice



Leaded Tin Bronze C2, Tension 300 Kips, Time History SA1

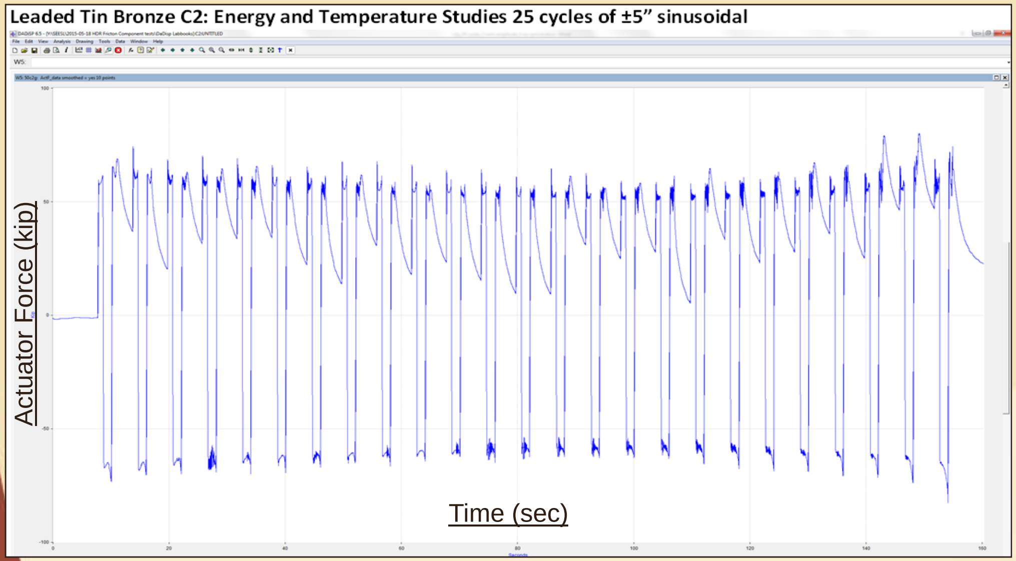


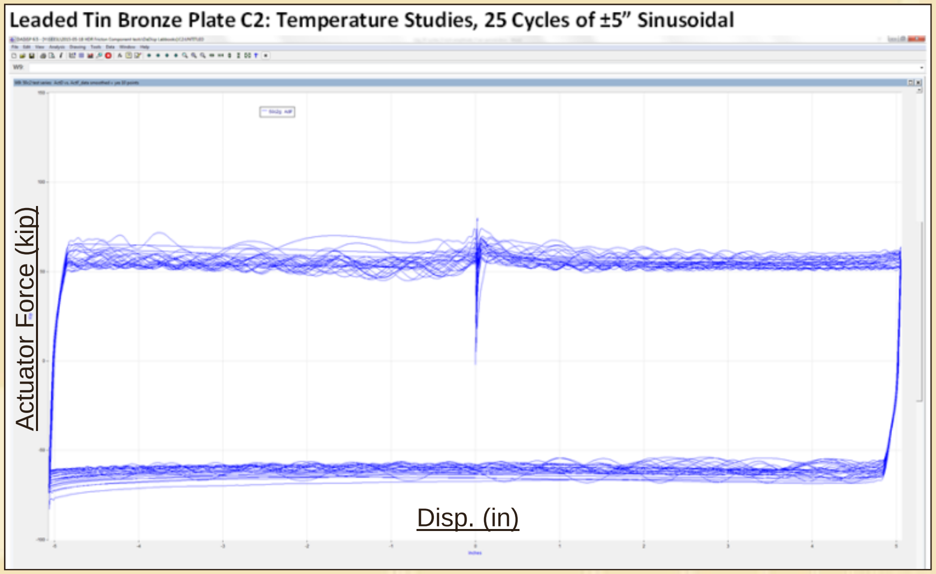
Leaded Tin Bronze C2, Tension 300 Kips, Time History SA2



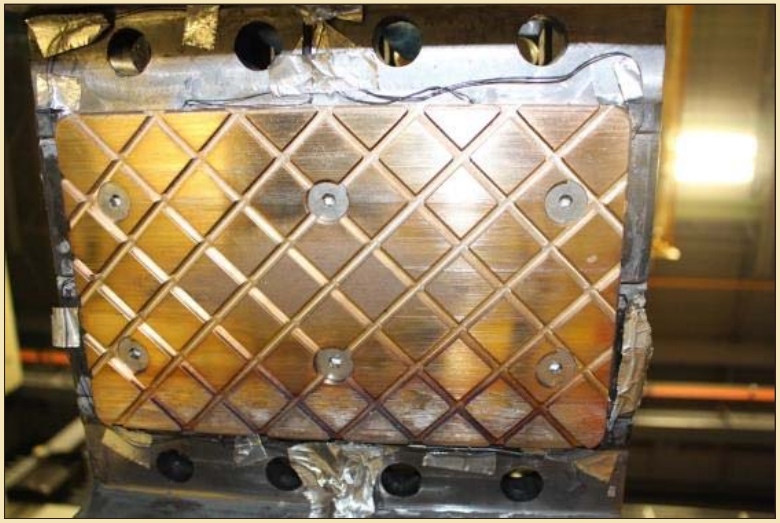
Phase I Testing Results

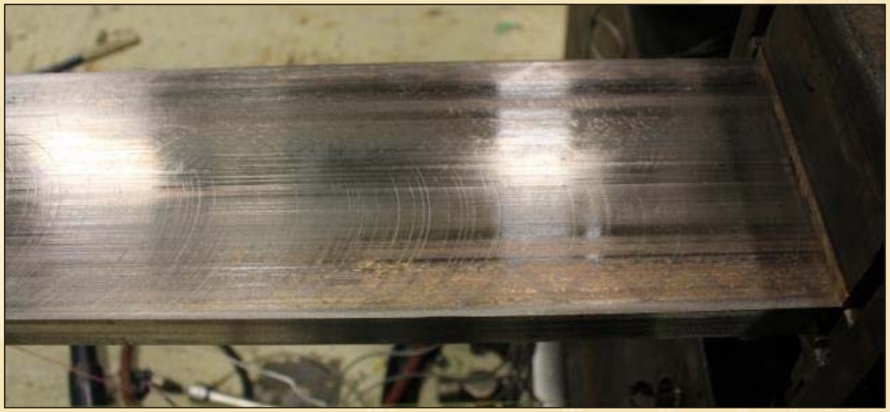
- Satisfactory Repeatability Results from:
  - Energy / Thermal Tests





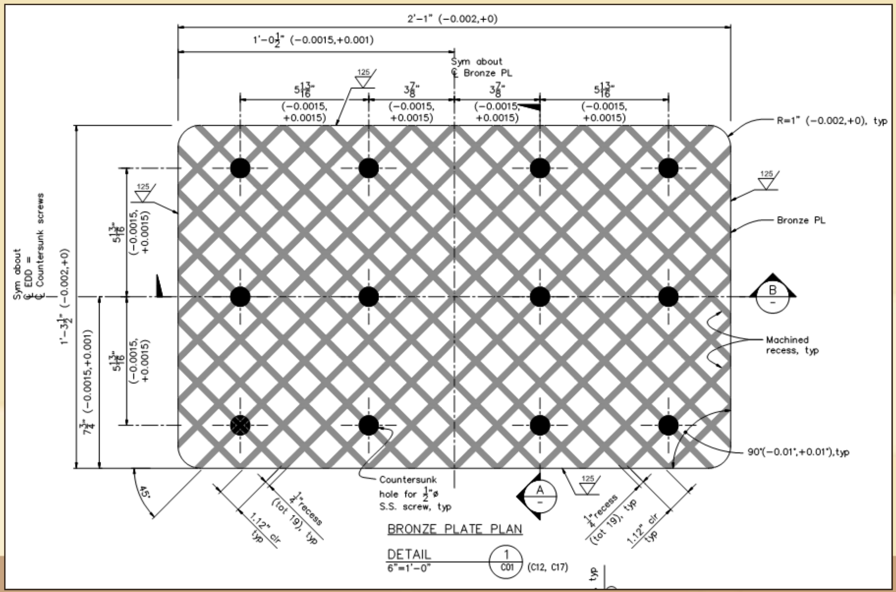
Phase I Testing - Post Test Photos

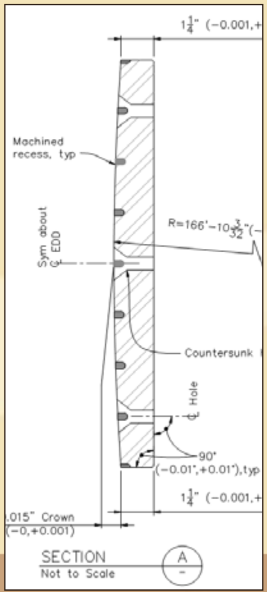




Phase I Testing Conclusions

- Reliable and Repeatable results Confirmed with use of following materials
  - Tongue Plate
    - Smooth 17-4 PH Stainless Steel
  - Friction Plate
    - Smooth Leaded Tin Bronze Plate with “Waffle” Machined Groove Pattern





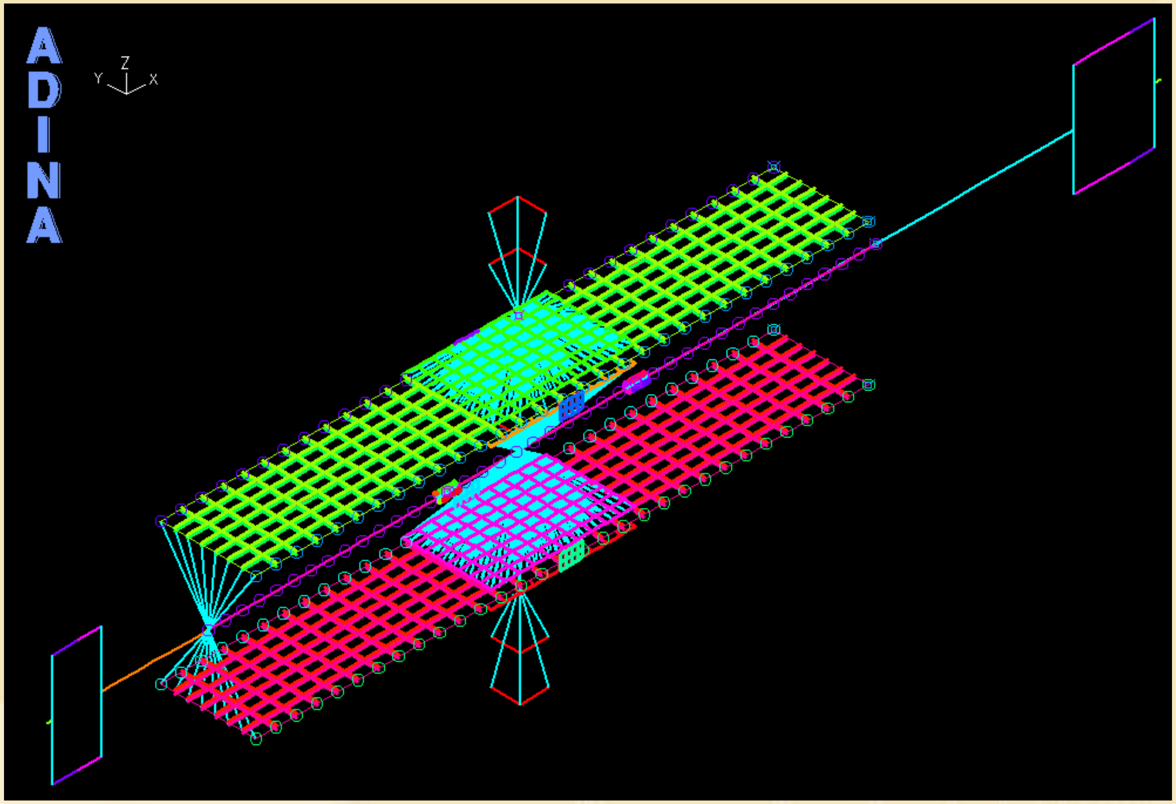
Golden Gate Bridge Phase IIIB

Full Size Specimen Design

Global EDD Modeling

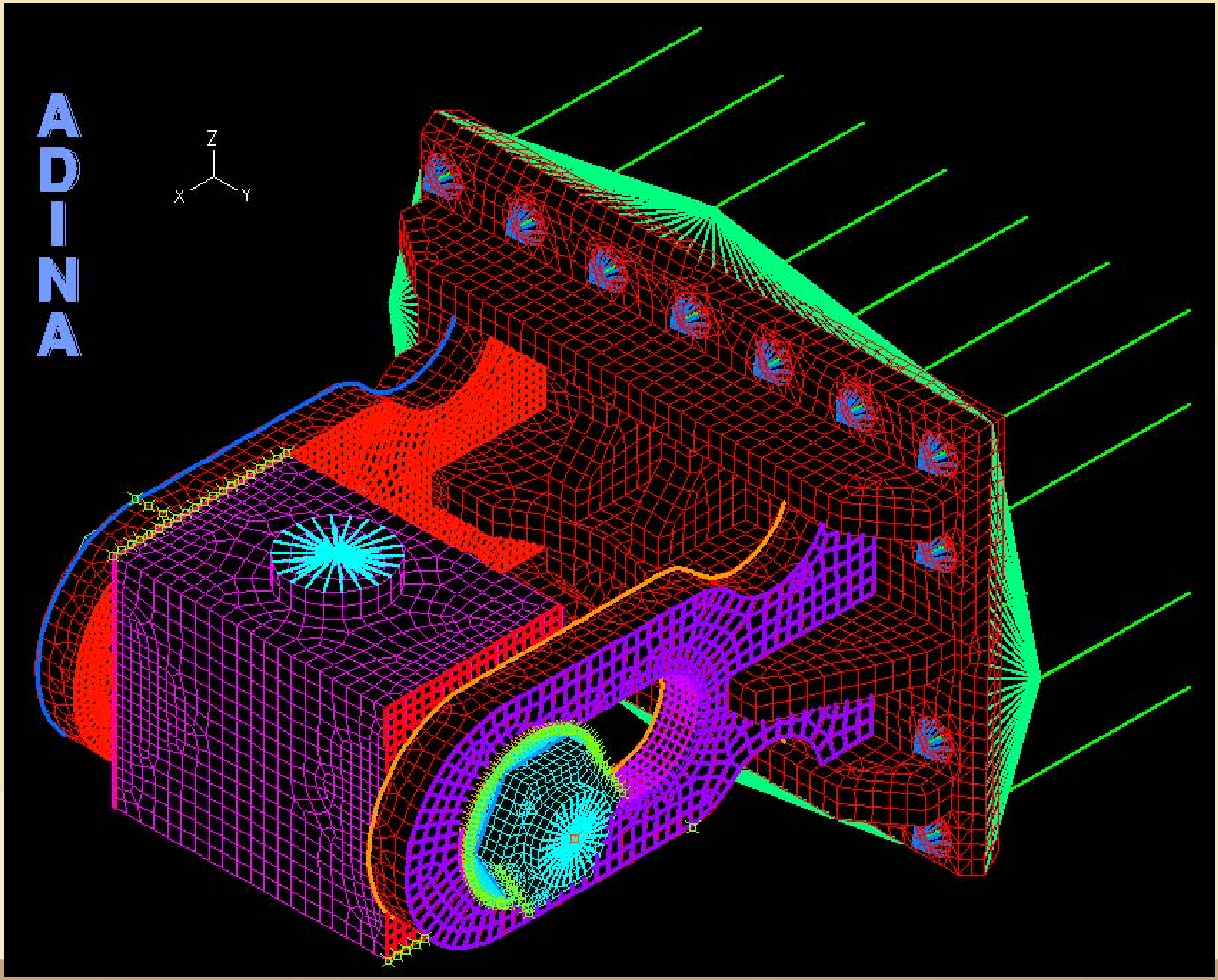
- Nonlinear FEM of Entire EDD:
  - Material Nonlinearity
  - Tongue Plate & Pipe Contact
  - Elongated Hole Gap
  - Jacking Assembly / Bumper Gap
  - Large Displacement

- Used for Estimating:
  - Component Demands
  - Impact
  - Compressive Buckling

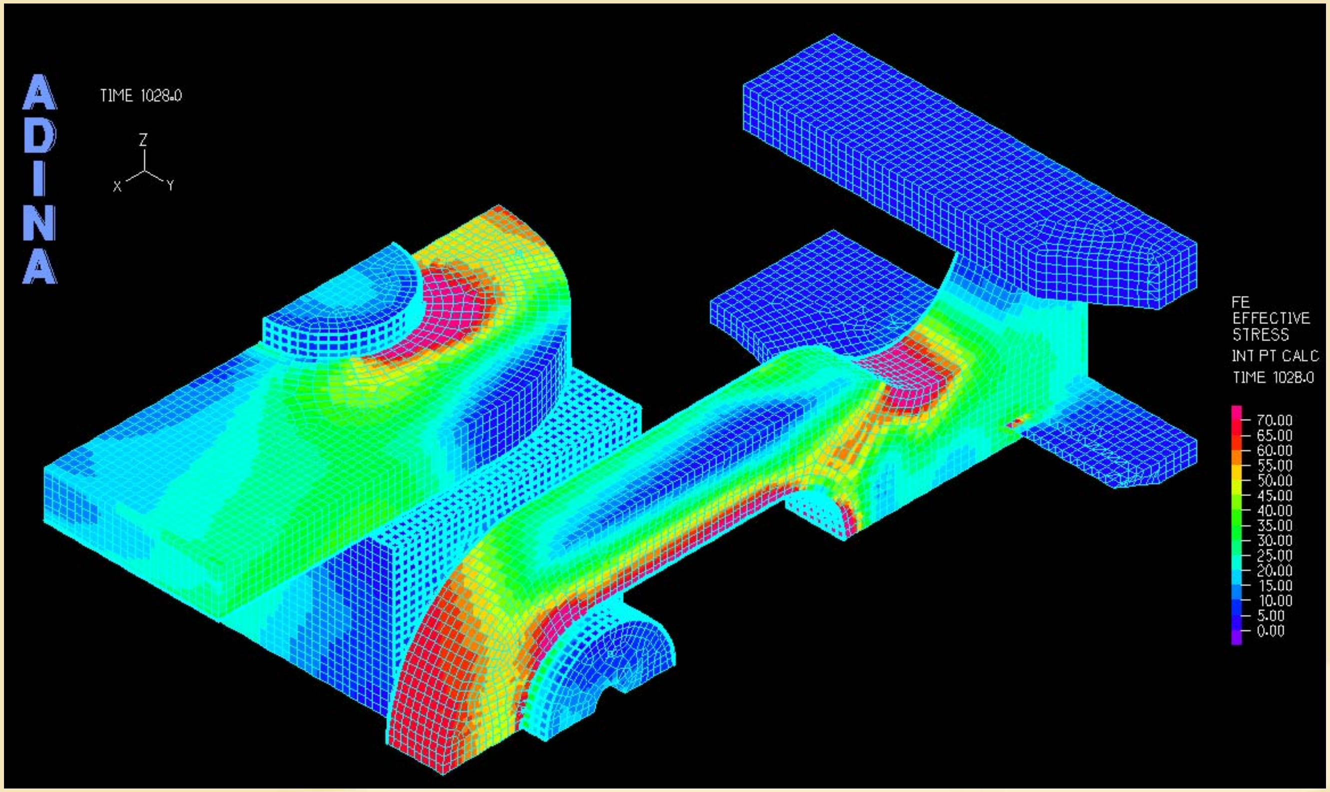


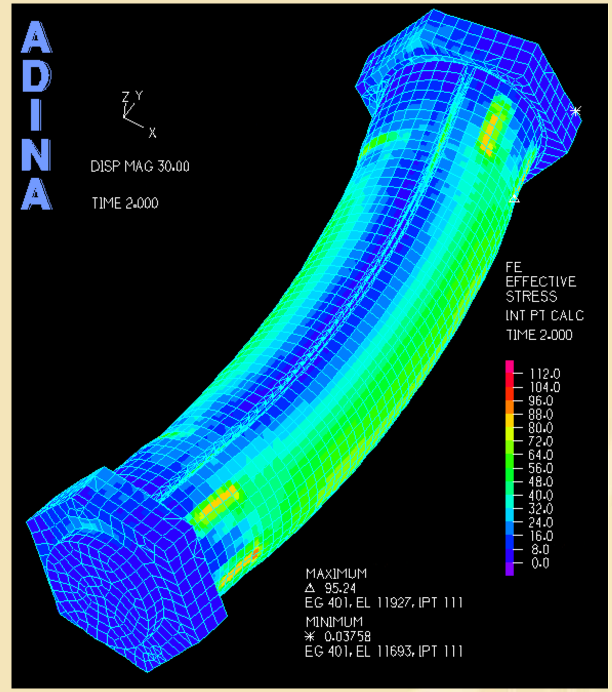
Local EDD Modeling

- Nonlinear Finite Element Modeling:
  - Material Nonlinearity
  - Contact
  - Large Displacement

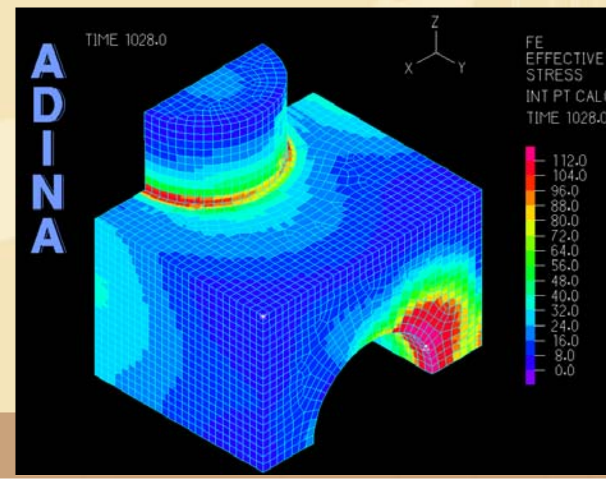


Local EDD Modeling

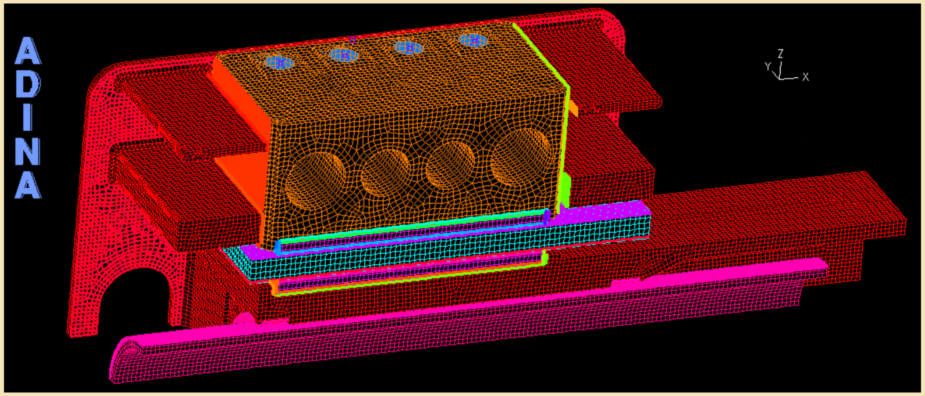


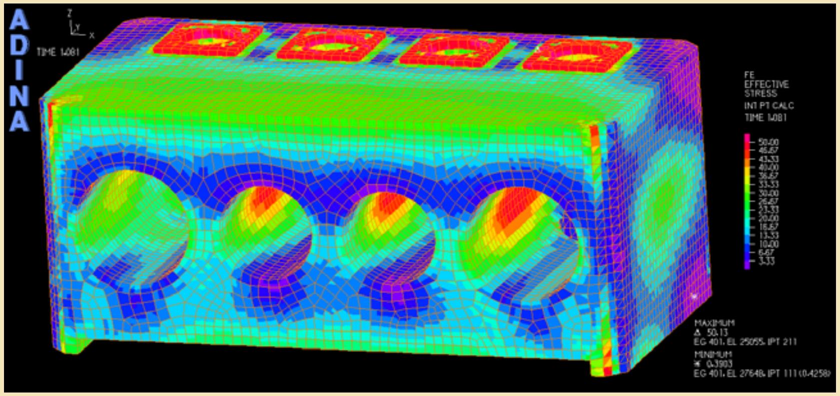


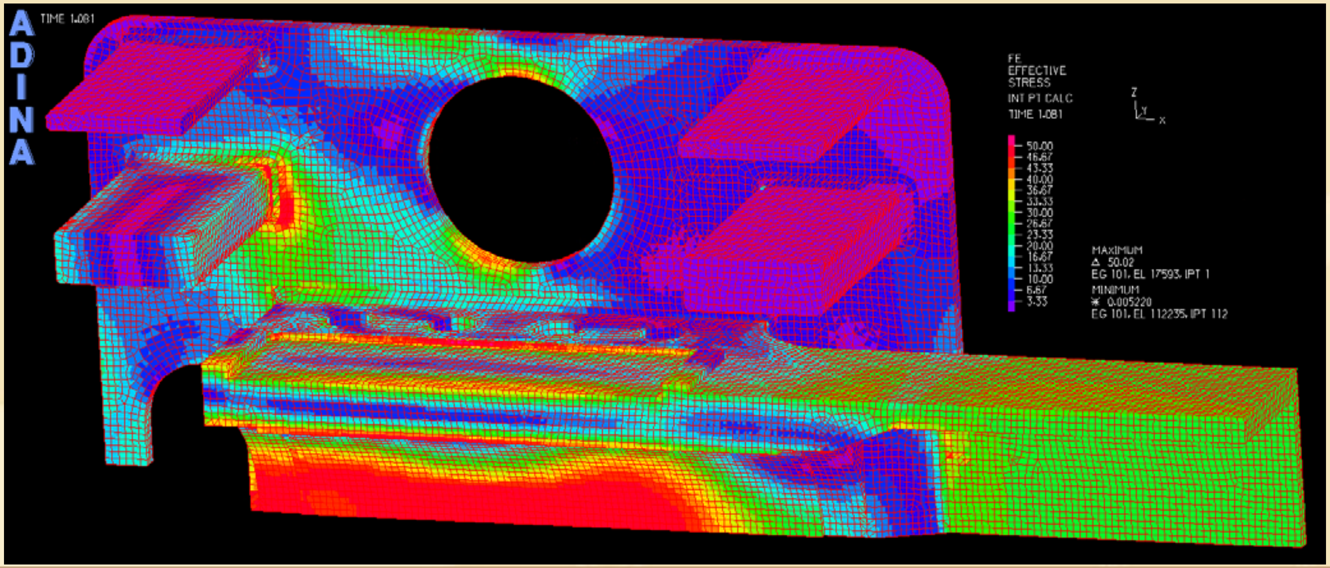
Von Mises Stresses Shown



Local EDD Modeling







Von Mises Stresses Shown

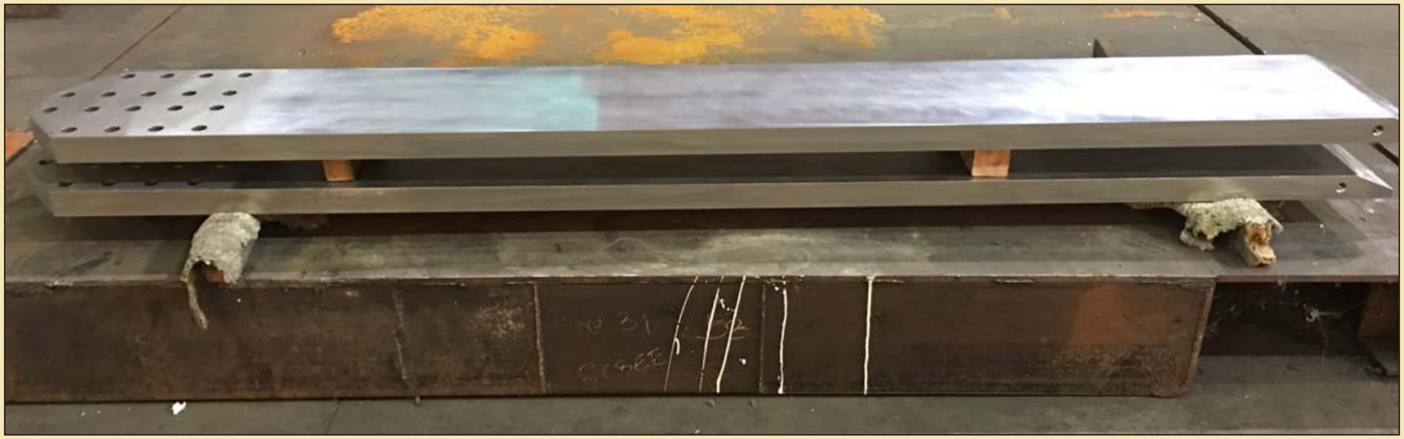
Golden Gate Bridge Phase IIIB

Full Size Specimen Fabrication
G&G Steel

Full Size EDD Specimen

Finished Tongue Plate Box

Tongue Plates, Jacking Assemblies & Bronze Plates



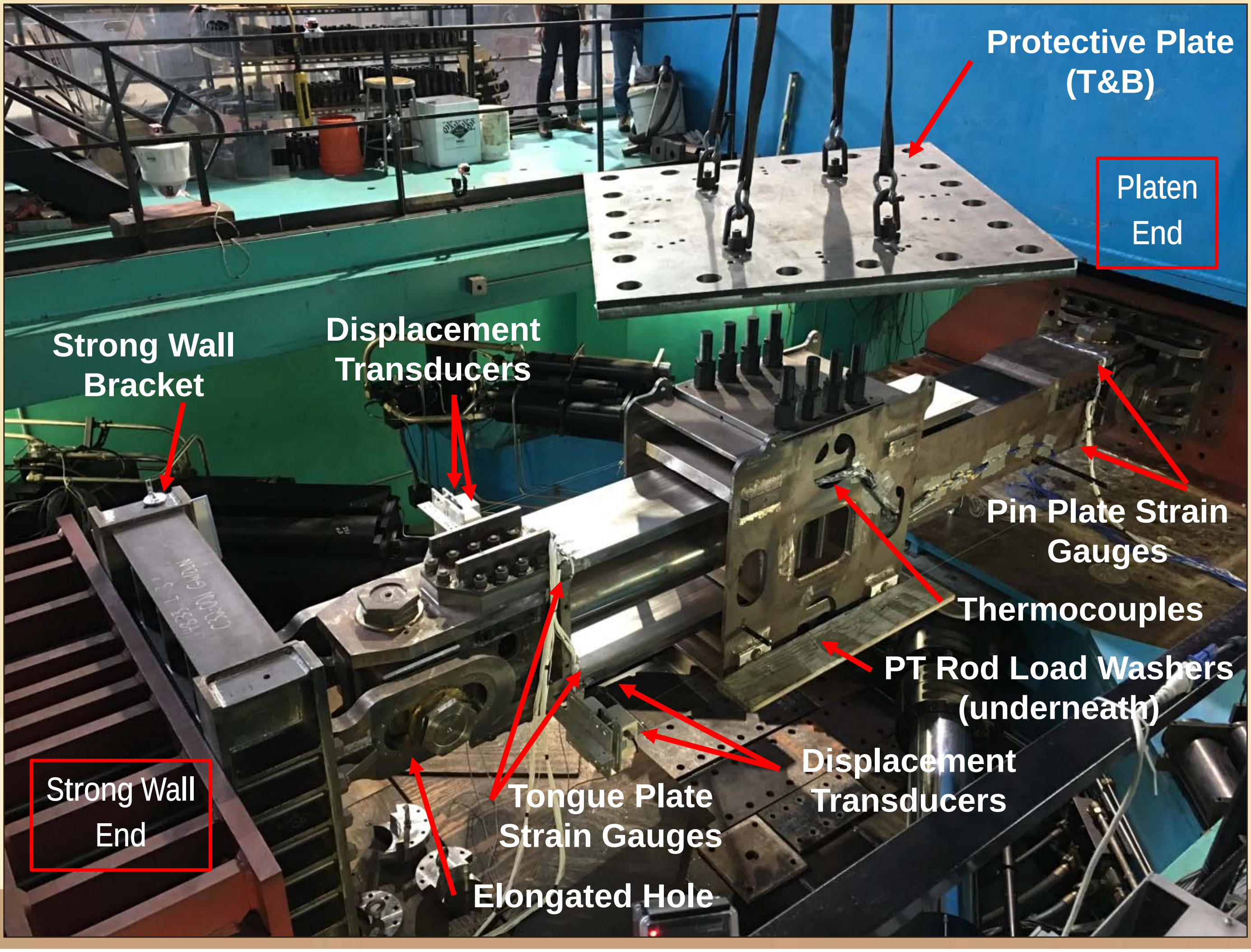
Abrasive Friction Box: Machining

Golden Gate Bridge Phase IIIB

Phase II Testing
UCSD

UCSD Phase II Test Setup

- Strong Wall provides Fixed Point of Support
- Shake Table Displacements Imposed at Platen End

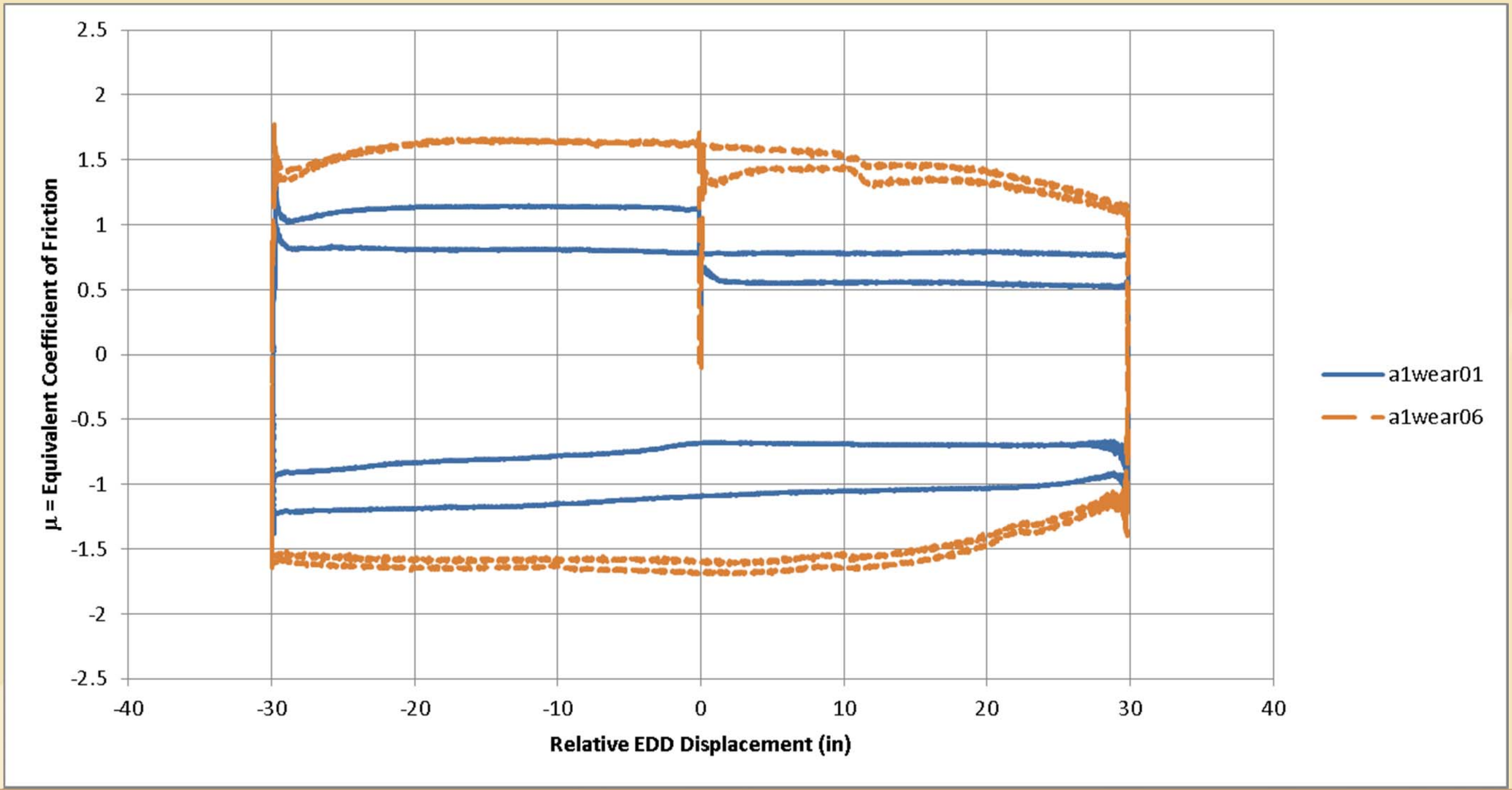


Phase II Testing Protocol Summary

- 27 Tests Performed on Full Size Specimen
- Tests Included:
  - Calibration
  - Pseudo-Static Wear-in
  - Varying Velocity
  - Transitory Service Load Vibration
  - Energy Dissipation & Temperature
  - Seismic Dynamic
    - 1D & 3D
    - with & without elongated hole activated
  - Compression (2000 kip lab capacity)

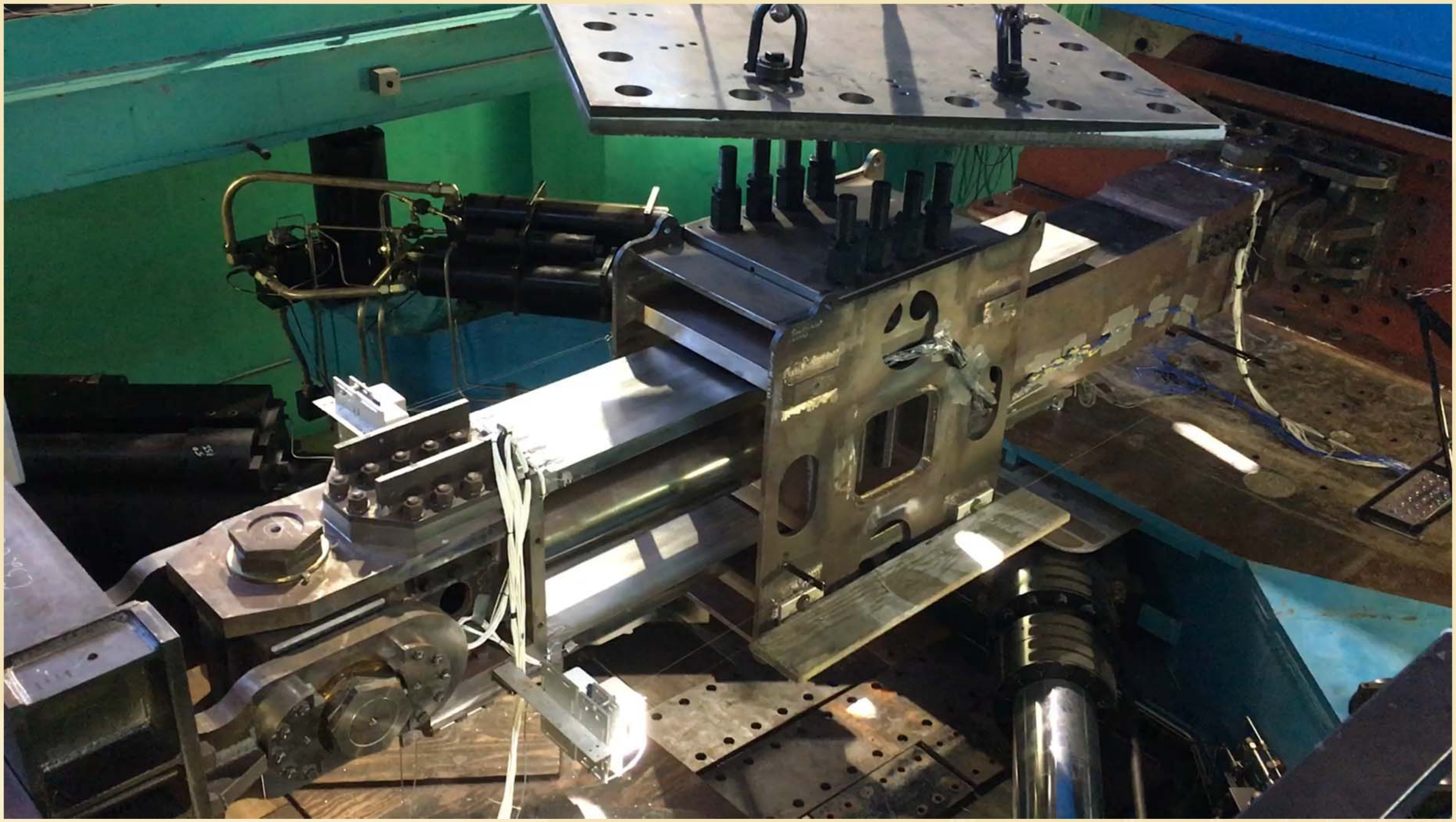
Test No.	Task	File Name	Test Date	Description	No. of Cycles	Direction of Motion	Amplitude (in)	Max. Velocity (in/sec)
1	A1 Series	A1cal1run01	9/9/2016	Calibration	1	Long.	± 2	1
2		A1wear01	9/12/2016	Wear-in	2	Long.	± 30	2
3		A1wear02	9/12/2016		2	Long.	± 30	2
4		A1wear03	9/12/2016		2	Long.	± 30	2
5		A1wear04	9/12/2016		2	Long.	± 30	2
6		A1wear05	9/12/2016		2	Long.	± 30	2
7		A1wear06	9/12/2016		2	Long.	± 30	2
8	A2 Series	A2cal01	9/13/2016	Calibration	1	Long.	± 2	1
9		A2cal02	9/13/2016		2	Long.	± 2	1
10		A2Ai46SA1r01	9/13/2016	Internal Windlock EDD @ PP46	Seismic	Long.	± 10.47	37.6
11	A5 Series	A5v10r01	9/14/2016	Various velocity	1	Long.	± 21"	10
12		A5v40r01	9/14/2016		1	Long.	± 21"	40
13		A5v70r01	9/14/2016		1	Long.	± 21"	70
14	A7 Series	A7cal01	9/14/2016	Calibration	1	Long.	± 2	1
15		A7Ai46SA1r01	9/14/2016	Internal Windlock EDD @ PP46	Seismic	Long.	± 10.321	32.96
16	A2V Series	A2v01	9/15/2016	vibration "walk" test	sine	Lat	± 0.125	0.44
17		A2v02	9/15/2016		random	Lat	± 0.125	var.
18	A3 Series	A3e44SA1r01	9/15/2016	External EDD @ PP44	Seismic 3D	Long.	8.63	25.7
						Lat	11.02	14.62
						Vert.	2.94	6.84
19		A3cal01	9/15/2016	Calibration	1	Long.	± 2	1
20		A3e44SA1r02	9/16/2016	External EDD @ PP44	Seismic 3D	Long.	8.63	25.7
						Lat	11.02	14.62
						Vert.	2.94	6.84
21	A2 Series	A2Ai46SA101r	9/16/2016	Internal Windlock EDD @ PP46	Seismic	Long.	± 10.321	32.96
22	A5 Series	A5v20r01	9/16/2016	Energy Dissipation Run	5	Long.	± 21"	20
23	A4 Series	A4v20r01	9/19/2016	Various velocity, pin plugs removed	1	Long.	± 21"	20
24		A4v40r01	9/19/2016		1	Long.	± 21"	40
25	A4 Series	A4e46SA1t20	9/20/2016	External EDD @ PP46, pin plugs removed	Seismic 3D	Long.	31.23	20
						Lat	7.93	19.94
						Vert.	3.13	6.63
26		A4e46SA1t30	9/20/2016		Seismic 3D	Long.	31.17	30
						Lat	7.93	23.4
						Vert.	3.13	6.63
27	A6 Series	A6comp1r01	9/28/2016	Compression	1/4	Long.	/	/

Phase II Test Results – Pseudo-Static Wear-in



Phase II Test Results – Variable Velocity

- 1 Cycle of ±21-inch Sinusoidal Disp.
- Max. Input Velocity = 10, 40 & 70 in/sec



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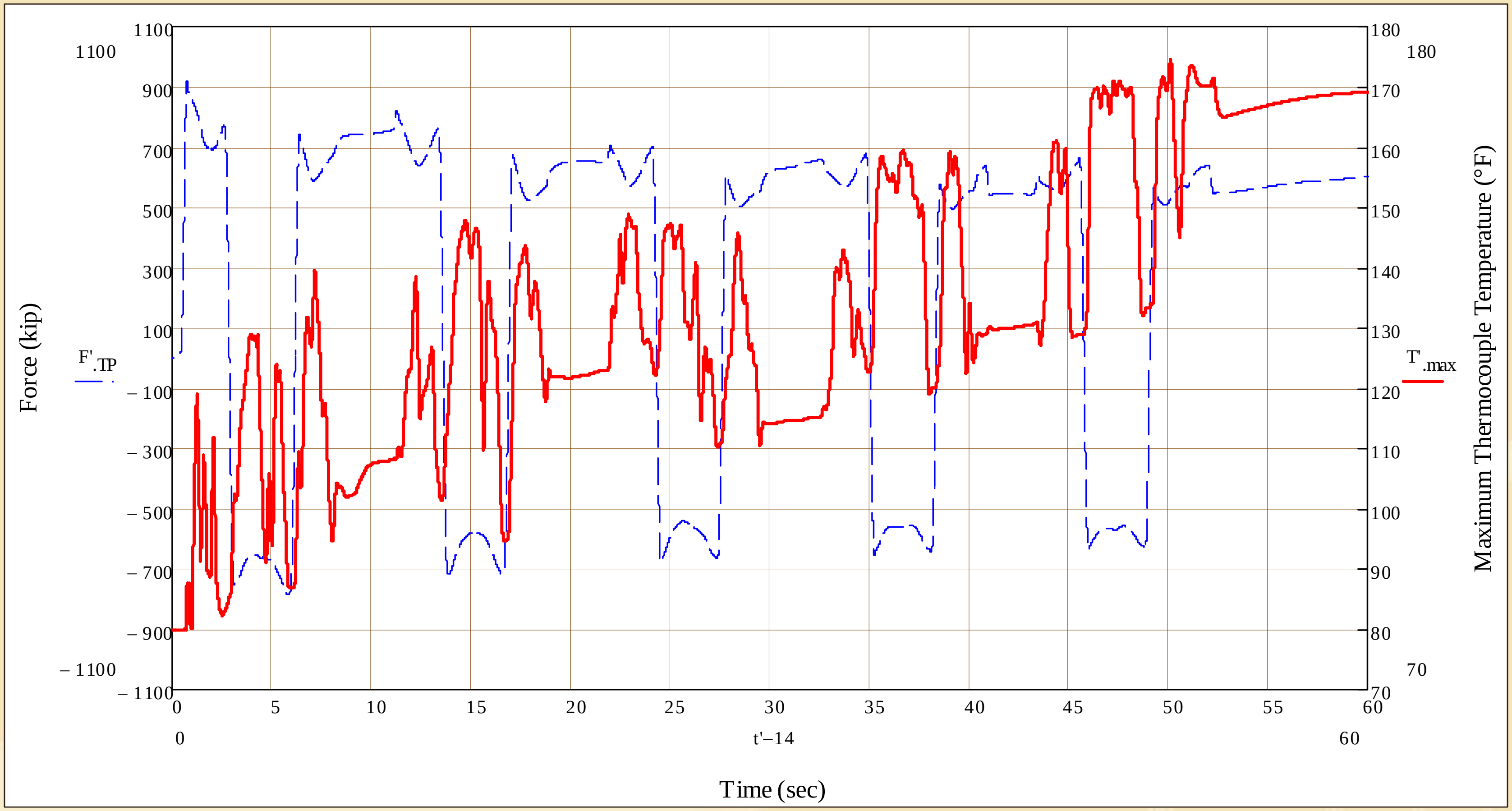
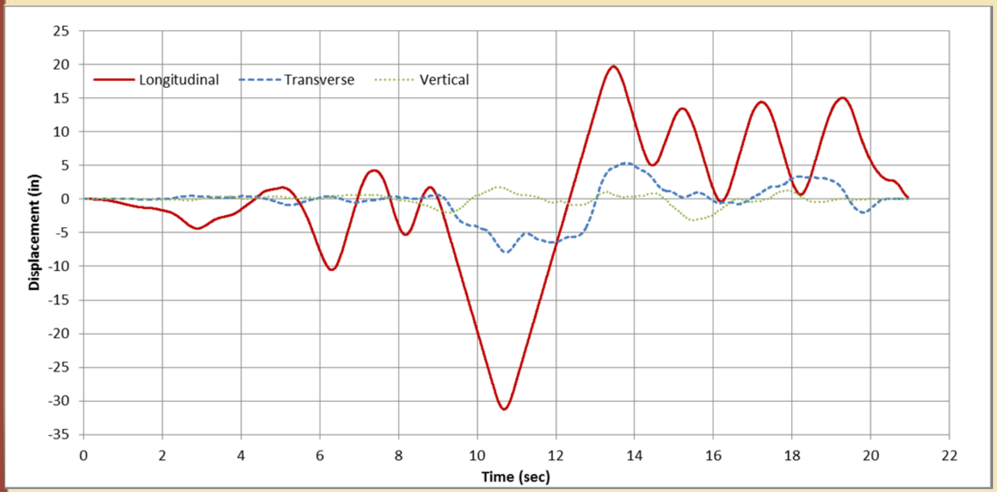
Phase II Test Results – Energy Dissipation &Temperature

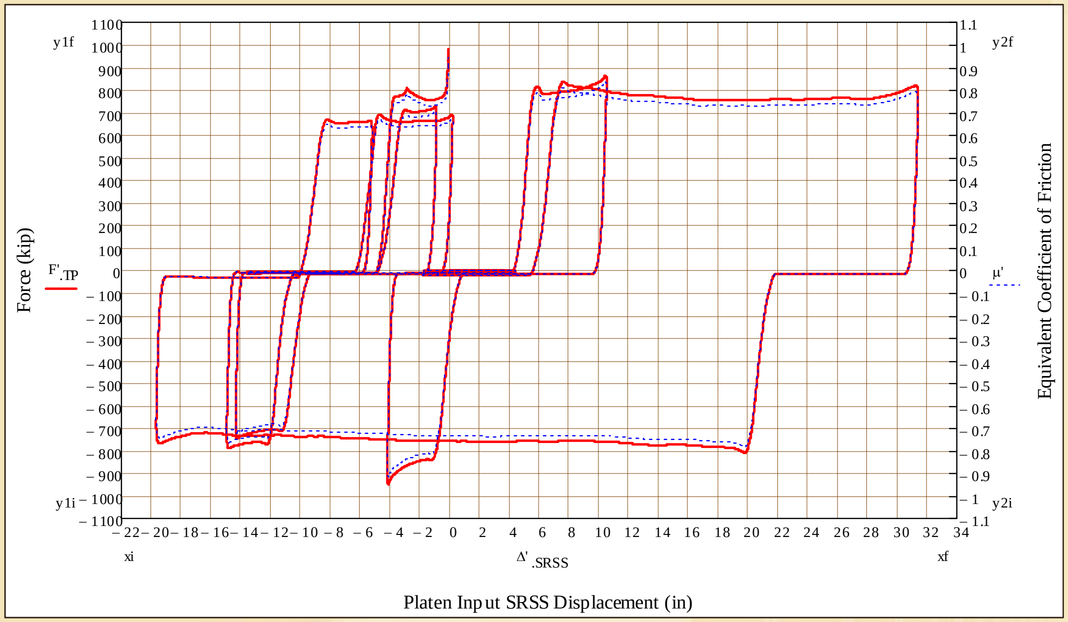


Energy Test 22 – Force and maximum bronze plate thermocouple temperature response history

Phase II Test Results – 3D Seismic Dynamic with Elongated Holes



3D Seismic Impact Test 25 – Input displacement



3D Seismic Impact Test 25 – Force & μ vs. **Platen** disp. (1034 kip clamping force, **21.3** in/sec peak velocity)

Phase II Test Results – 3D Seismic Dynamic with Elongated Holes

Link

Phase II Post-Test Photos

- Bronze Friction Plates
  - Material fusing / plastic flow not observed

Figure 3 –Lower Bronze Plate

Phase II Testing Summary

- Material fusing / plastic flow not observed with C93700 friction plates
  - combination of alloy with 17-4 PH SS tongue plates demonstrates excellent wear resistance, repeatability & energy dissipation
- EDD force (coeff of friction) is a function of input velocity
- Confirmed ability of EDD to dissipate required amount of energy
- No concern of friction material thermal effects
- Force-displacement hysteresis loops demonstrate excellent repeatability characteristics
- For axial & 3D input motion, bi-directional pins at each end functioned satisfactory

Phase II Testing Summary

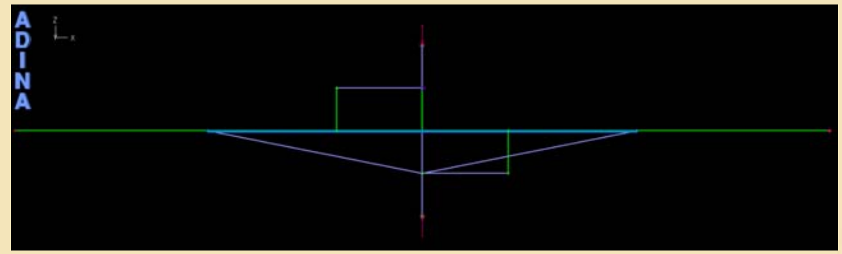
- Impact - no concern of:
  - localized yielding or damage of elongated holes or bi-directional pins
  - local tongue plate or global EDD buckling

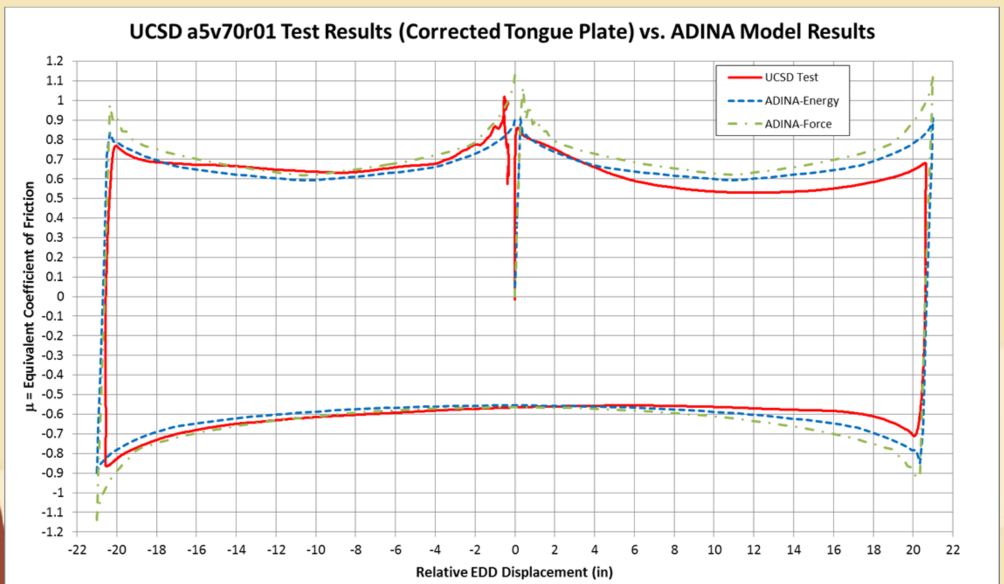
- EDD successfully sustained 2000 kip compressive load (max. facility capacity)

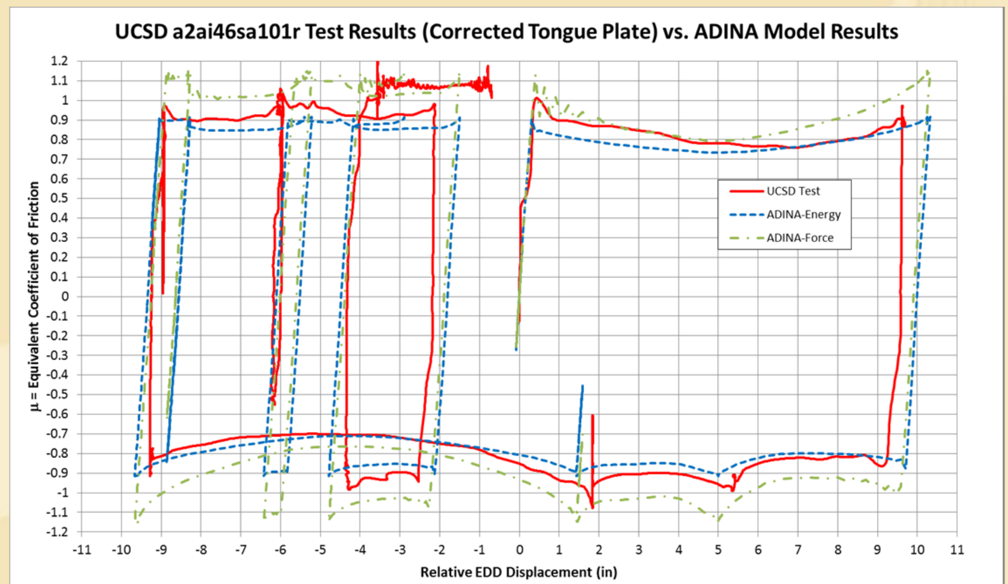
- Based on number of tests performed, total accumulative displacement & energy delivered, it is anticipated that:
  - EDDs will provide dependable performance for aftershocks that may occur after MCE
  - friction plates will not need to be replaced after MCE
    - locations that require replacement based on post-EQ inspection of each EDD

Implementation of Test Results

- Equivalent Friction Coefficient
  - Varies with sliding velocity
  - Varies with clamping force
  - Consider Upper & Lower Bound







Thank you!

Questions?