Seismic Strengthening of Bridge Columns with FRP in lieu of Steel Jacketing

structural TECHNOLOGIES

2023
Western Bridge Engineers

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Mohammad Jalalpour
Structural Technologies

Making Structures Stronger & Last Longer

structural group

structural TECHNOLOGIES

Condition Assessment & Design	State-of-the-Art Products
▪ Inspections and Condition Assessment for Existing Structures ▪ Durability Modeling ▪ Repair Design ▪ Turnkey Solutions	▪ Post-Tensioning Systems ▪ Strengthening Systems ▪ Cathodic Protection Systems ▪ Moisture Control & Waterproofing Systems ▪ Force Protection

PULLMAN

Repair & Maintenance Services

- Repair, strengthening & protection of civil / structural infrastructure
- Offices throughout the US and in Canada
- Design Build/ IDB focus
- Creative solutions that optimize cost, reduce schedule and improve performance based on sound value engineering
- Commercial & Public, Industrial, Power/Energy, Water & Wastewater, Transportation
- Union craftsmen

Solutions that integrate products, engineering, and construction

Total Group

- Annual Revenues — **$700 million**
- Offerings — Products – Engineering – Construction
- Employees — **3,500 +**

Products

$150 Million

- Regional Technology Centers — Baltimore, Dallas, & Houston

Construction

- Annual Revenues — **$550 Million**

- Projects — Over 22,000 completed since 1976
- Markets Served — 30 offices in US & Middle East
- ENR Ranking — Largest Concrete Repair Contractor
- Typical Range — $2,000 to $30 Million

Specialty Contracting

Diverse Capabilities

Repair & Maintenance Services for Commercial & Public Markets

Project Background

- **Project Background**
- Conforming Design
- FRP Value Engineered Option
- Construction
- Summary

Project Background

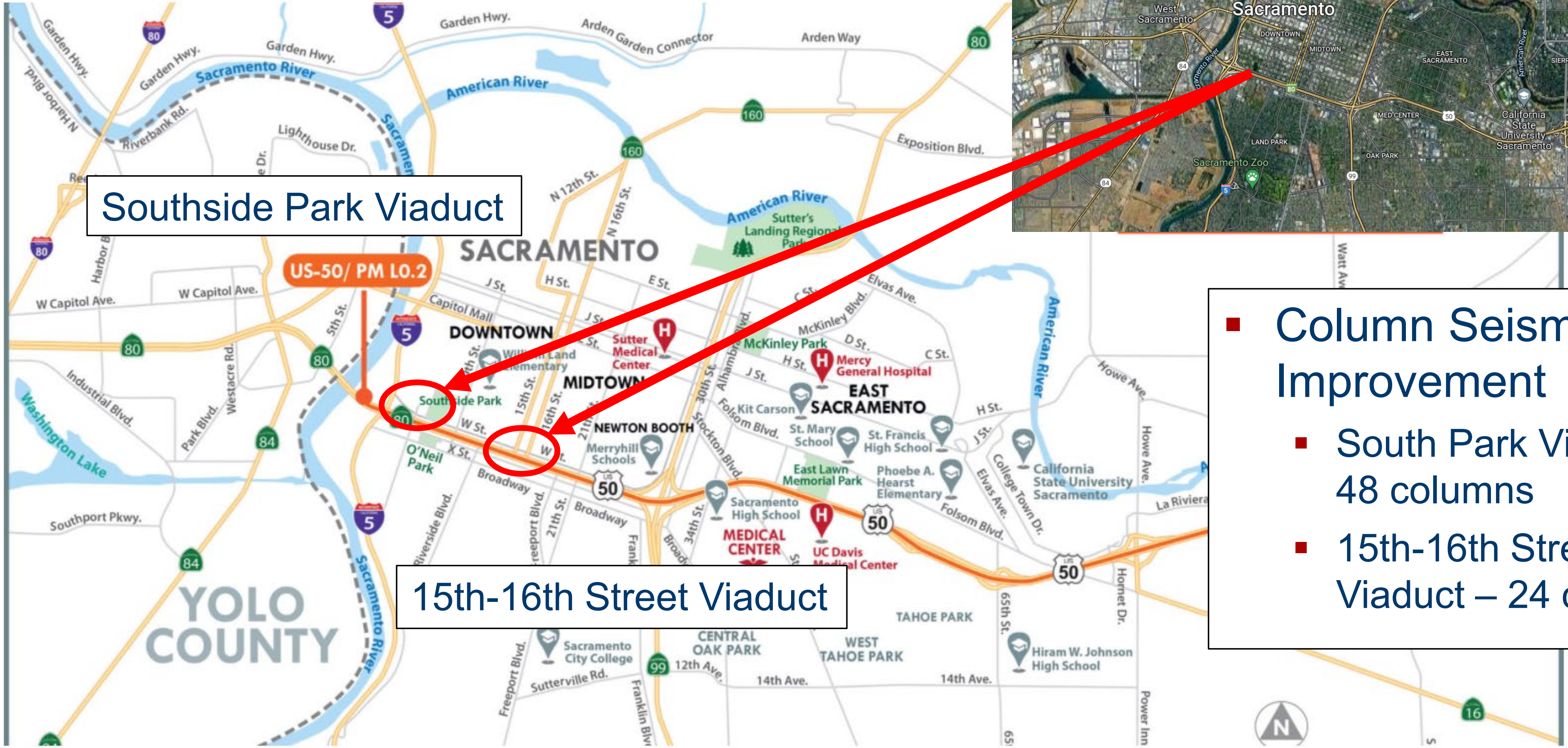
US 50 Multimodal Corridor Enhancement & Rehabilitation Project

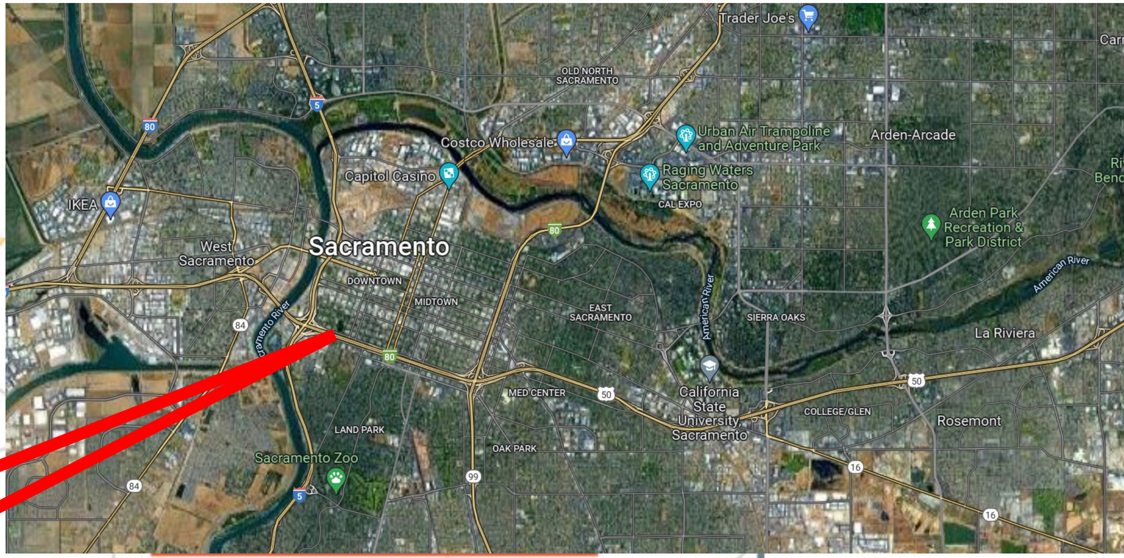
- Highway reconstructed in mid 1960's in Sacramento County
- Enhance Sacramento's multimodal corridor network near downtown
  - Widen 11 bridges and seismic upgrades from I-5 to Watt Avenue
  - 7 miles of carpool lanes and replace all lanes with 100-year pavements and asphalts
  - Rehab 3 stormwater pumping plants
- Owner: Caltrans
- Delivery: DESIGN BUILD
  - Flatiron/WSP JV – awarded at $430M

FLATIRON　　wsp

- Construction Summer 2020 – Spring 2024

Project Location





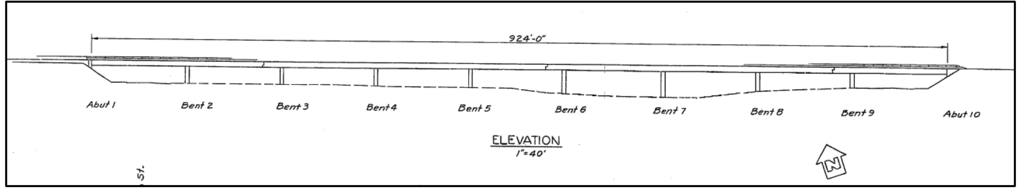
Southside Park Viaduct

15th-16th Street Viaduct

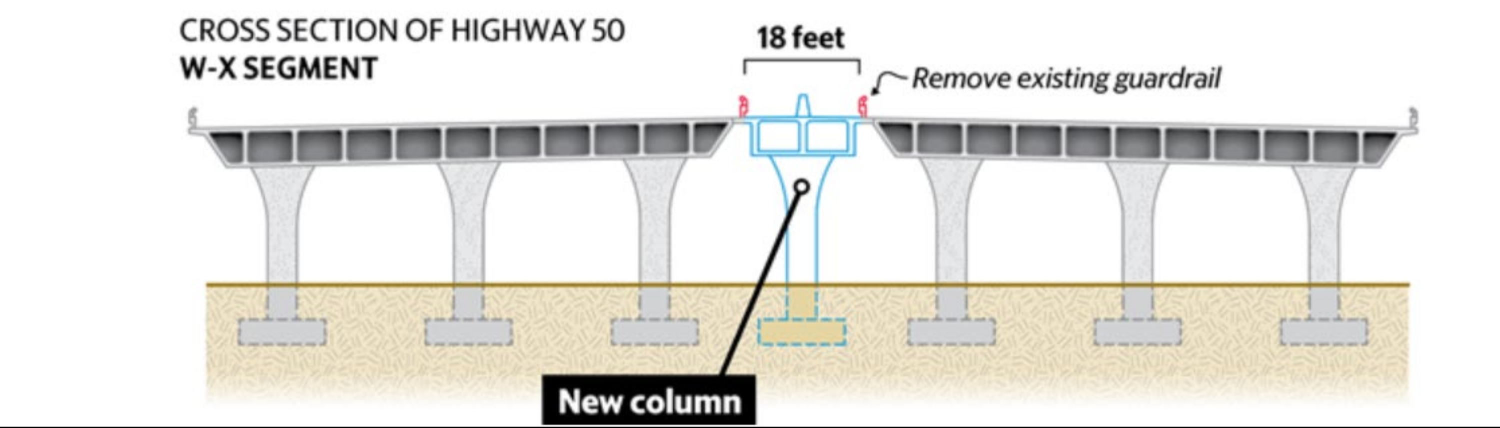
- Column Seismic Improvement
  - South Park Viaduct – 48 columns
  - 15th-16th Street Viaduct – 24 columns

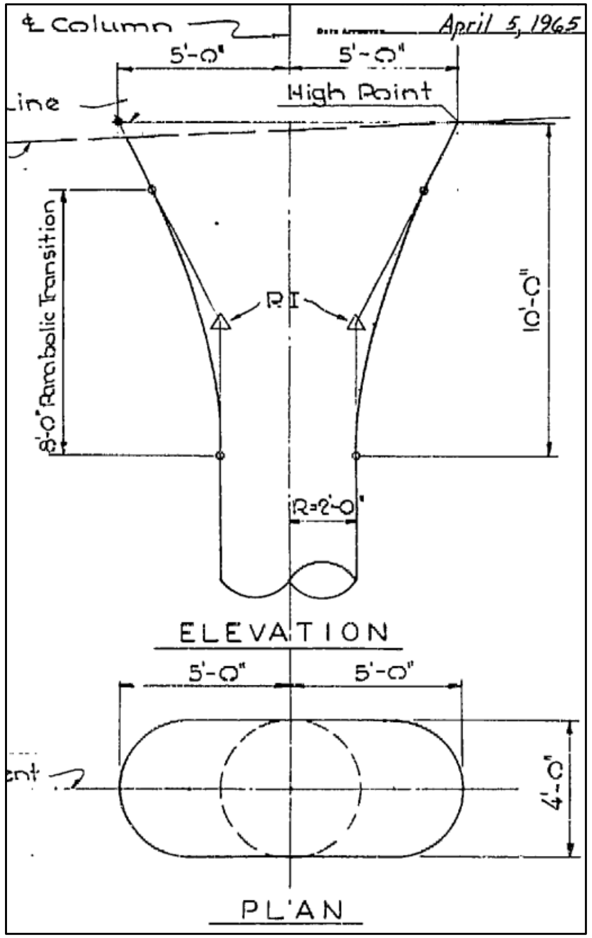
Structure

Southside Park Viaduct (15/16th Street similar)



- Superstructure: CIP box girder
- Substructure: Columns supported by footings & piles
- 42 Columns: 7 bents x 6 cols per bent
- 4' diameter columns with **hyperbolic flare** to 10'
  - Heights range from 19' to 29'





Conforming Design

Project Background

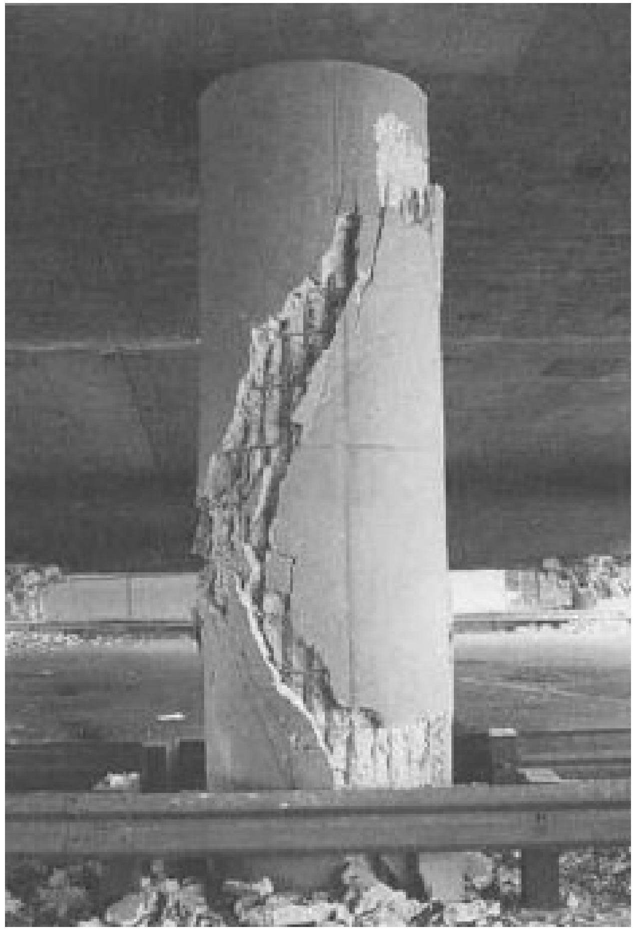
Conforming Design

FRP Value Engineered Option

Construction

Summary

Column Failure Modes



Shear

USGS

Confinement

Kenneth J. Elwood

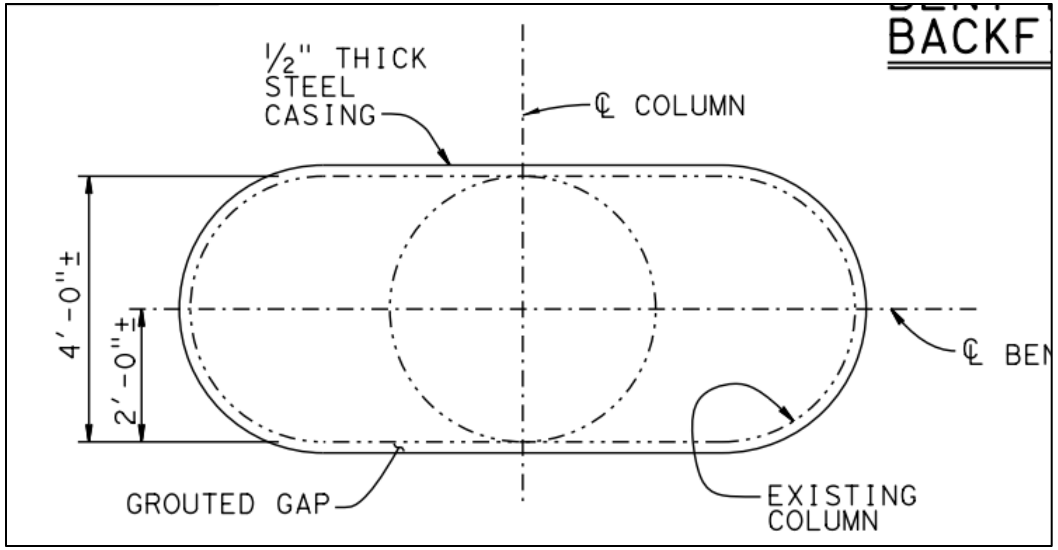
Lap Splice

Column Steel Jacketing

- The columns lacked adequate confining steel that hold the column together during earthquakes
- US 50 columns were determined to be potentially susceptible to Lap Splice, Confinement and Shear Failures.

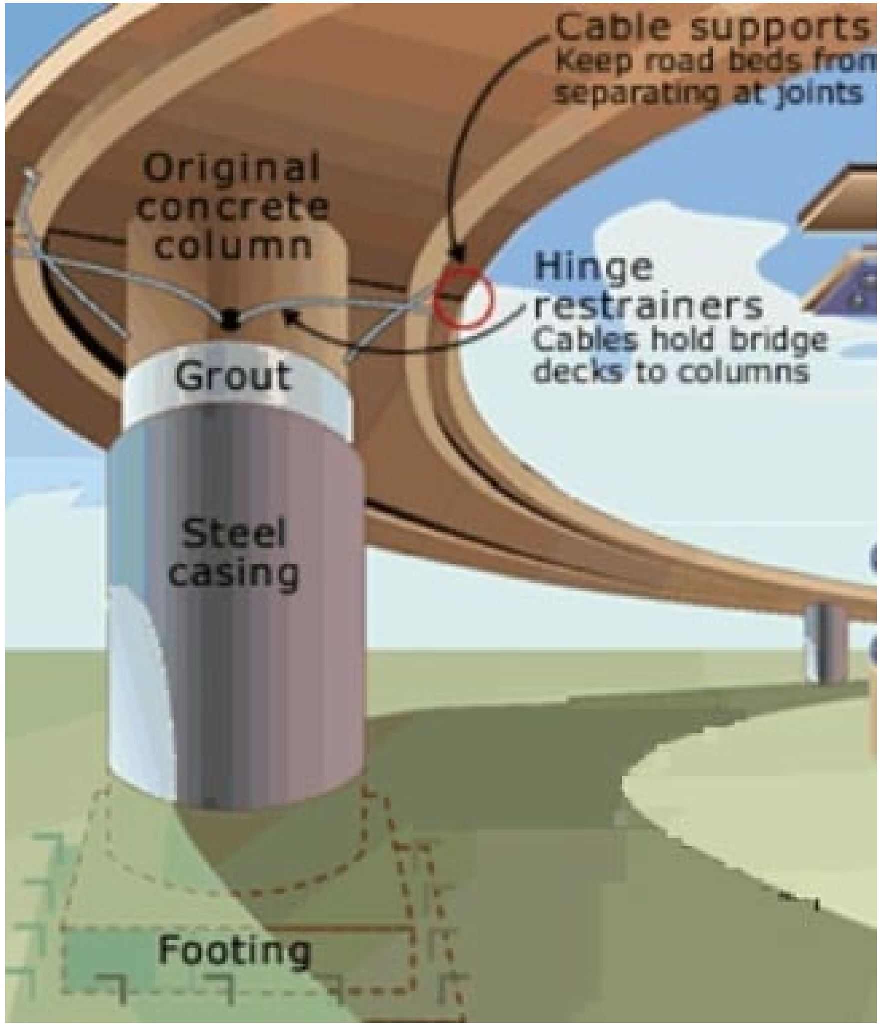
<u>Steel Jacket Design</u>

- Incorporated a continuous ½" thick steel casing **top of the foundation to the top of the column flare**



Column Steel Jacketing

- Steel casing fabricated in 2 halves welded together onsite with horizontal and vertical joints
- Thin layer of concrete grout fills in the interstitial space or “gap” between steel casing and column.



<u>Challenges</u>

- Columns are not uniform - column flare at the top complexity to installation and additional lead time for material fabrication (12 -16 weeks or more)
- Pricing
- Weight / Erection / Safety
- Required Inspections
- Corrosion Concerns

FRP and a true Value Engineered Option

Project Background

Conforming Design

FRP Value Engineered Option

Construction

Summary

Value Engineering with D/B Delivery

- **Design/Build** delivery allows for creativity and optimization through a collaborative effort with all stake holders
- Contractors approached the project looking for technology that would set them apart from the competition while providing a cost advantage
- Conversations with Caltrans was positive when asking their appetite for alternative solutions
- FRP wrapping of columns was born from these conversations with the next steps being to evaluate the cost-benefits of an **ATC (Alternative Technical Concept)**

FRP Design Criteria

Design Approaches:

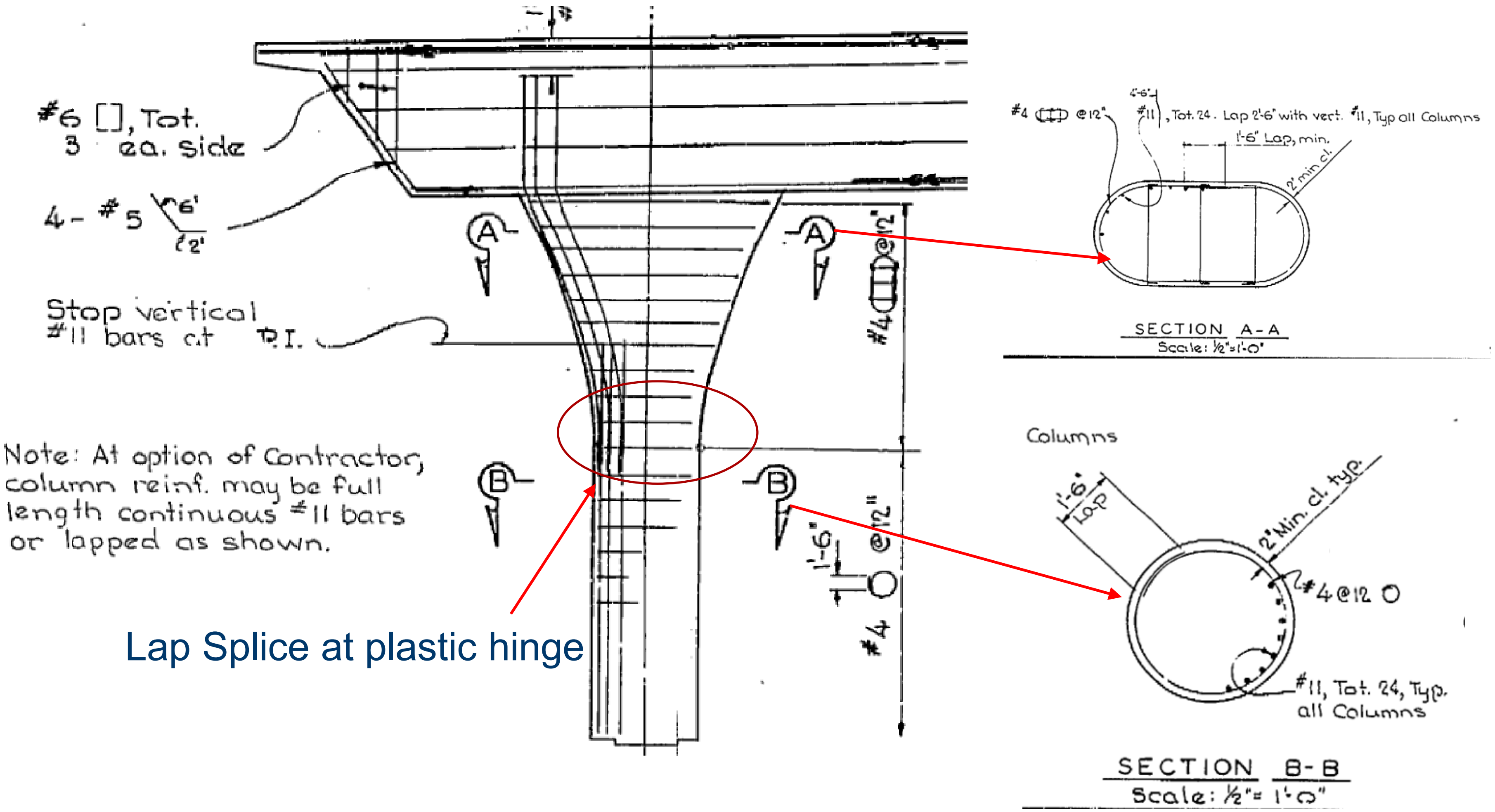
- *Option 1: Steel Equivalency (1/2”)*
- *Option 2: Performance Criteria*

Performance Criteria provided by WSP

- Drift in Longitudinal Direction: 6.5 in.
- Drift in Transverse Direction: 5.0 in.
- Column Average Height: 22 ft
- Column Axial Force: 1100 kips
- Column fixed at the top and pinned at the bottom

Performance Base Design

Existing Columns



Provided Design Criteria by WSP USA

Performance Base Design Criteria

Displacement Demands

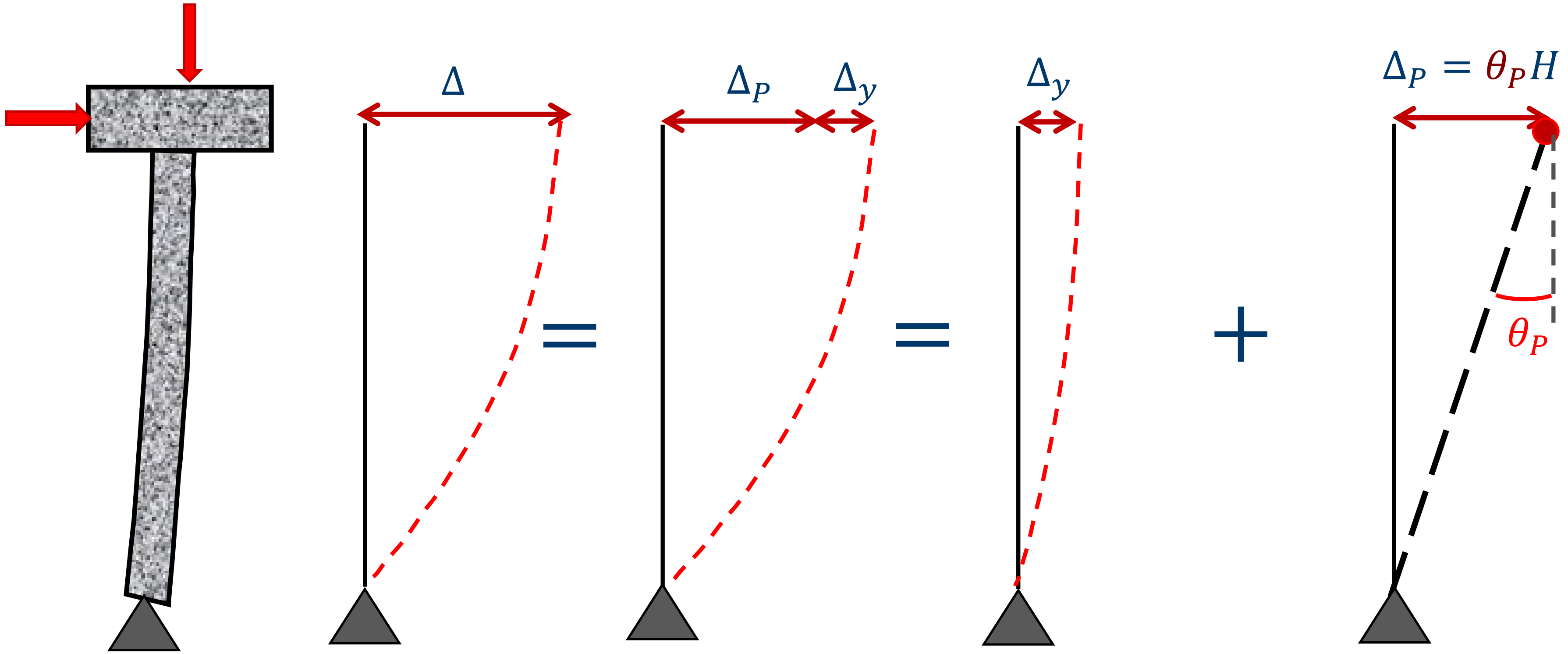
- Longitudinal Direction: 6.5 in.
- Transverse Direction: 5.0 in.

Geometry, Loads, and Material Properties

- Column Average Height: 22 ft
- Column Axial Force: 1100 kips at top of column
- Column End Conditions: Fixed at the top and pinned at the bottom
- Concrete Expected Compressive Strength: 5 ksi
- Steel Expected Yield Strength: 48 ksi
- Steel Expected Yield Strain: 0.00166 in/in
- Steel Reduced Ultimate Tensile Strain: 0.06 in/in
- Required Column Shear Strength: $V_o = 1.2\ V_p$

Performance Base Design

General Behavior

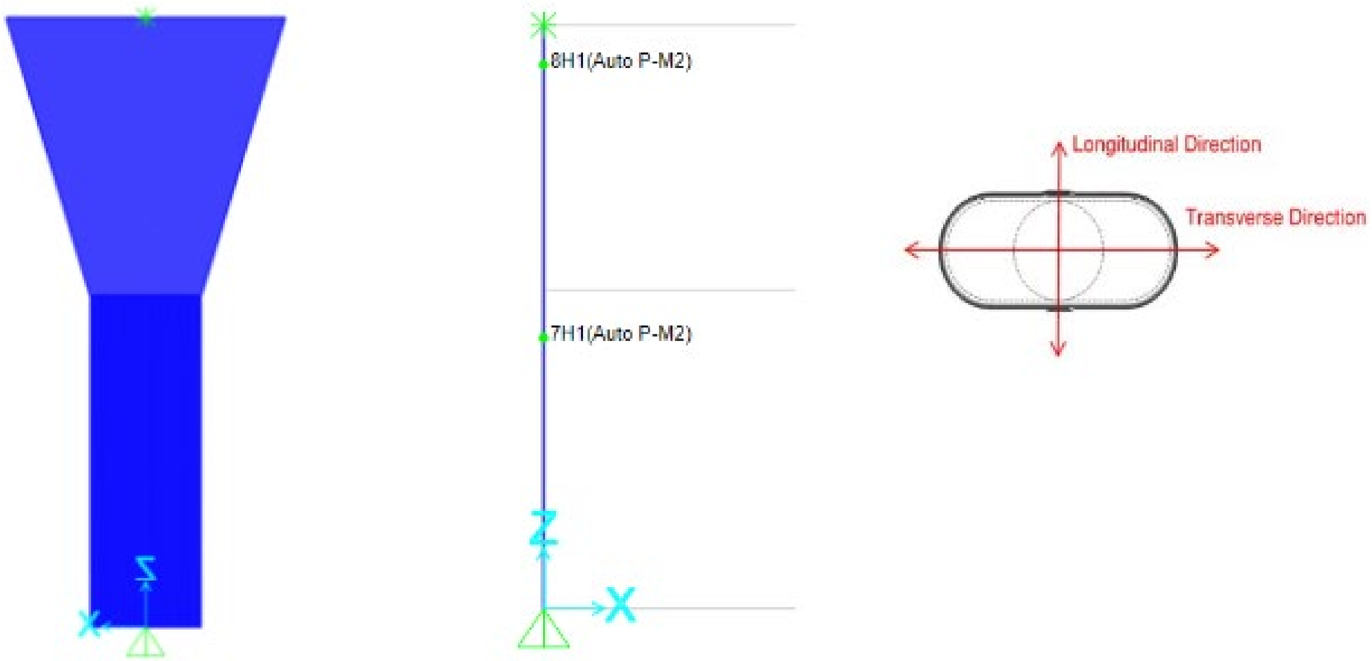


$$\Delta_y = \frac{M_y H^2}{3EI}$$

$$\Delta_P = \theta_P H = \phi_P L_P H$$

Plastic Hinge Confinement and Backbone Curves

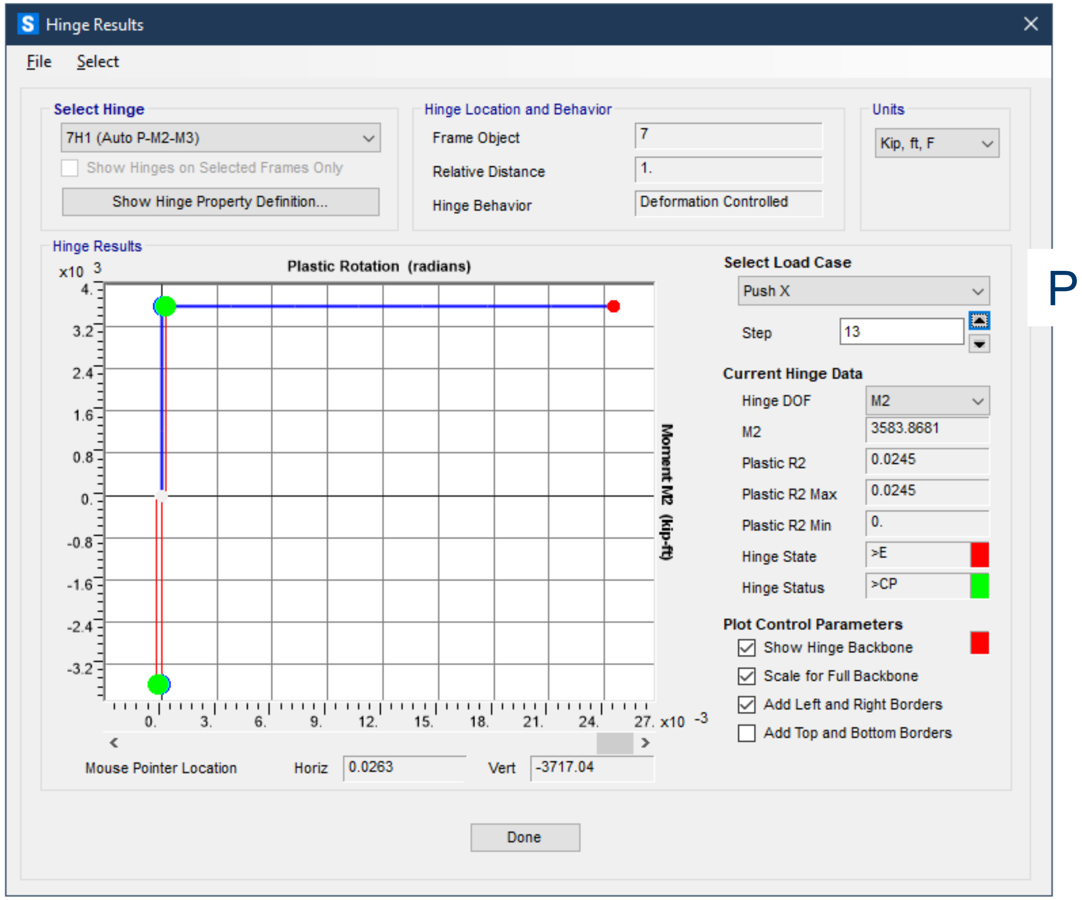
Non-linear Modeling

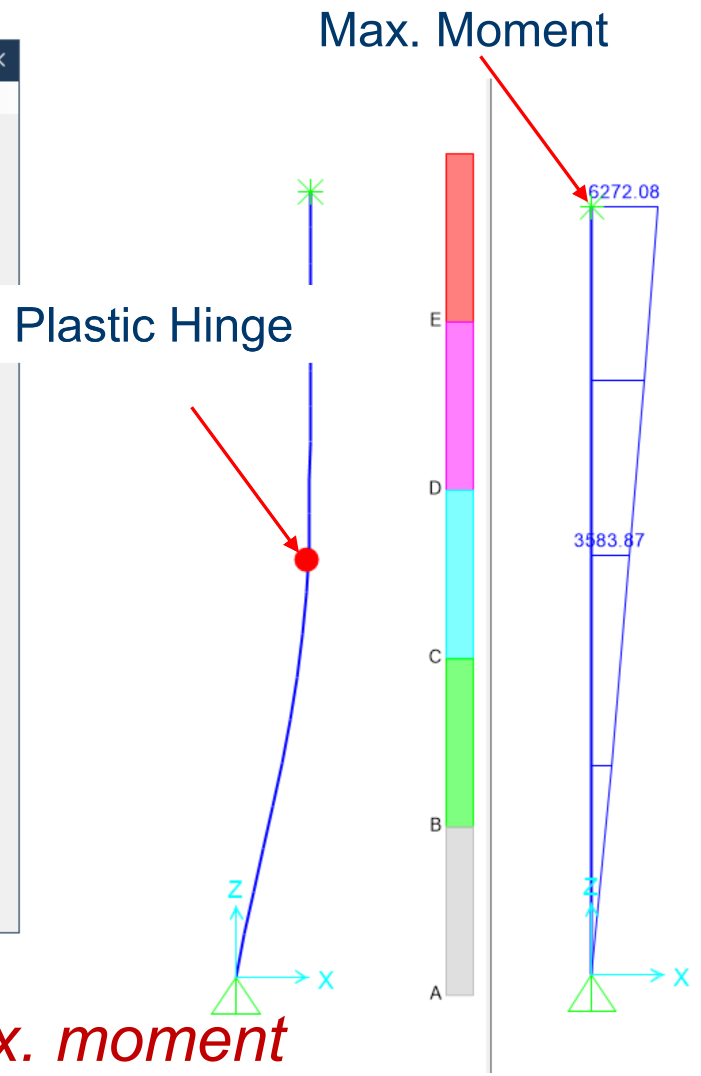


Modeling of columns in SAP 2000

Plastic Hinge Confinement and Backbone Curves

Plastic Hinge Rotation





*Plastic hinge **does not** occur at max. moment*

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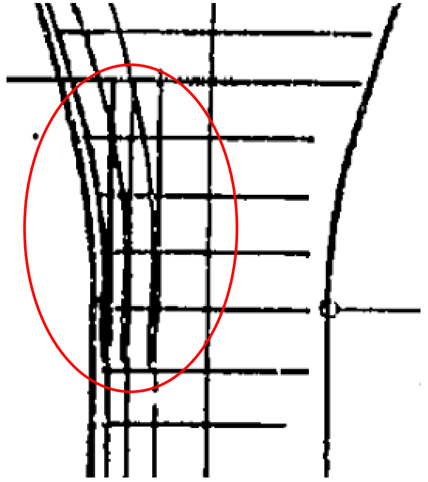
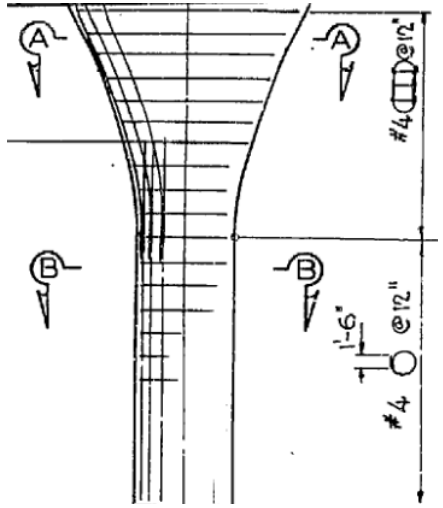
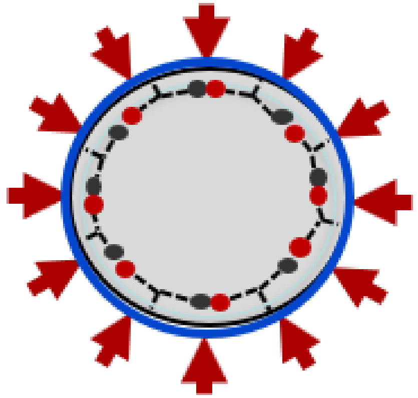
Backbone Curve of FRP Confined Hinge







$$l_d := \frac{3}{40} \cdot \frac{f_{ye}}{\sqrt{psi \cdot f'_{ce}}} \cdot \frac{1}{\left[\frac{c_c}{d_b} + \frac{40 \cdot (A_{st})}{d_b \cdot s_{st} \cdot n}\right]} \cdot d_b$$

Required development length

$$l_d = 40 \cdot in$$

$$Check\_development := \begin{cases} \text{"OK"} & \text{if } L_s \geq l_d \\ \text{"FRP Jacket Required"} & \end{cases}$$

$$L_{s\_min} := \frac{0.025 \cdot d_b \cdot f_{ye}}{\sqrt{psi \cdot f'_{ce}}}$$

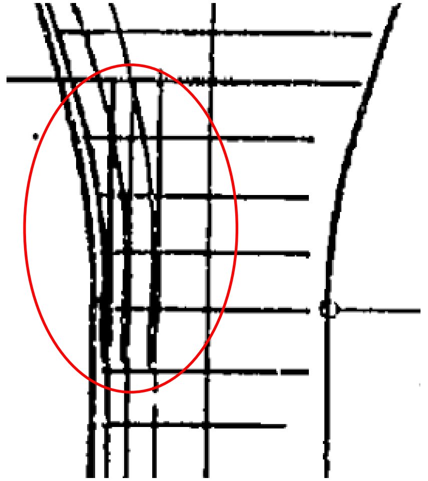
$$L_{s\_min} = 23.9 \cdot in$$

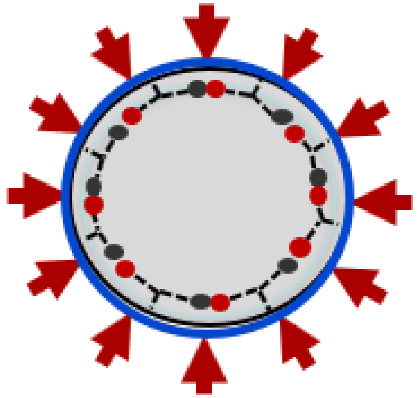
$$L_s := 30 \cdot in$$

$$Check\_Min\_splice\_length := \begin{cases} \text{"OK"} & \text{if } L_s \geq L_{s\_min} \\ \text{"NOT OK"} & \text{otherwise} \end{cases}$$

$$Check\_Min\_splice\_length = \text{"OK"}$$

Backbone Curve of FRP Confined Hinge





Seible, et al. (1997). Seismic Retrofit of RC Columns with Continuous Carbon Fiber Jackets, (Eq. 9)

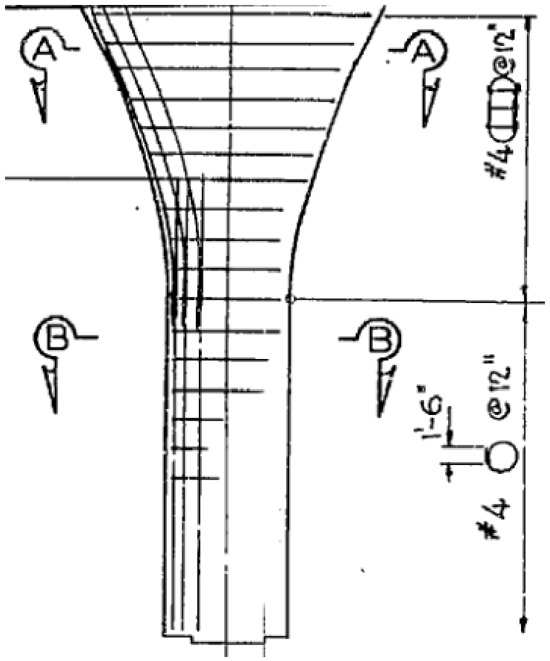
$$t_{jacket} := 500 \cdot \frac{D \cdot \left(f_l - f_h\right)}{\psi_f \cdot E_f}$$ Required FRP jacket thickness (Eq. 9)

$$t_{jacket} = 0.39 \cdot in$$

$$n_f := \frac{t_{jacket}}{t_f}$$ Required layers of FRP

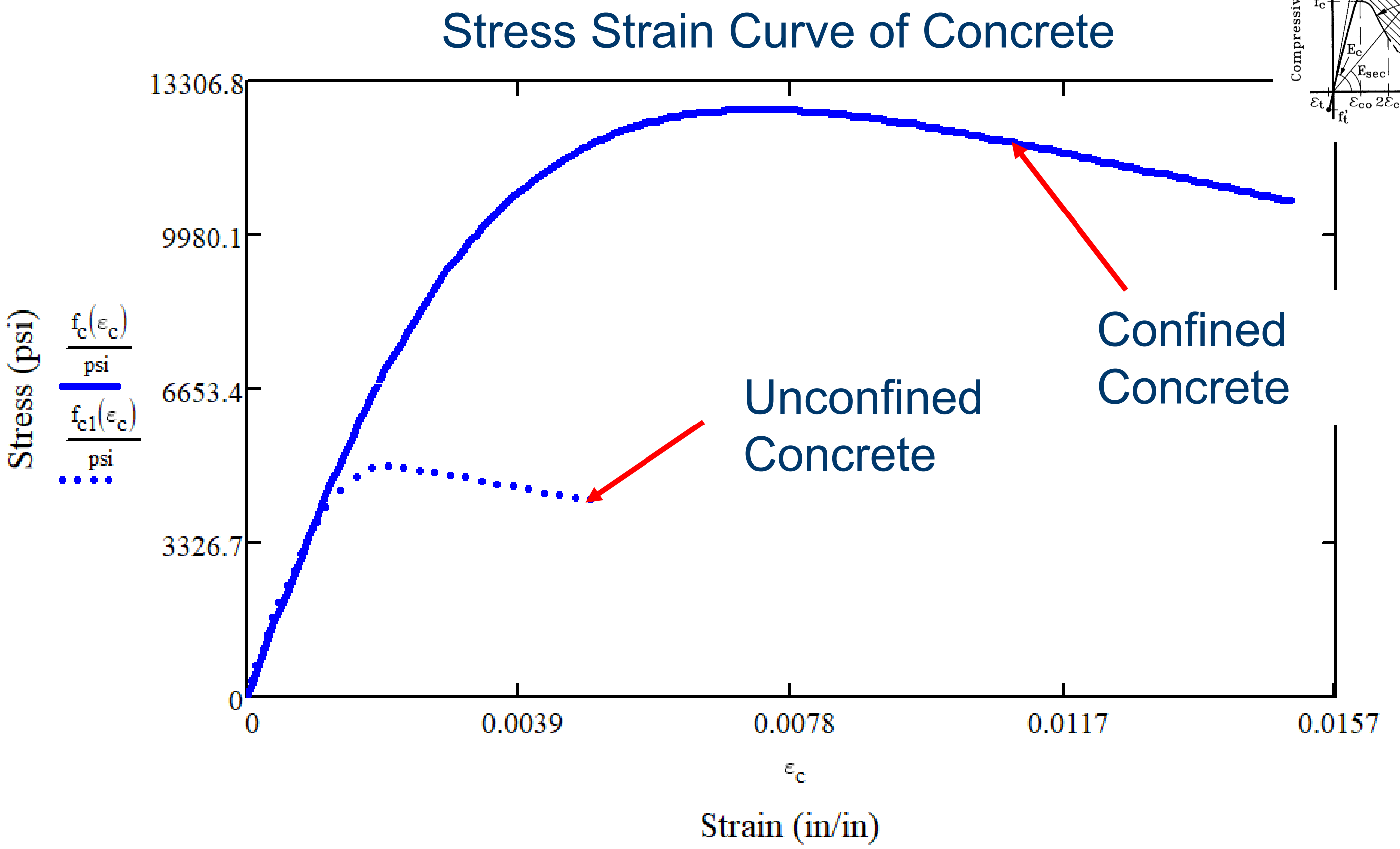
$$n_f = 4.85$$

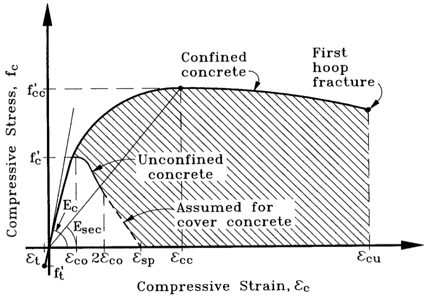
Use 5 plies of V-Wrap C400HM for clamping pressure at lap-splice



Plastic Hinge Confinement and Backbone Curves

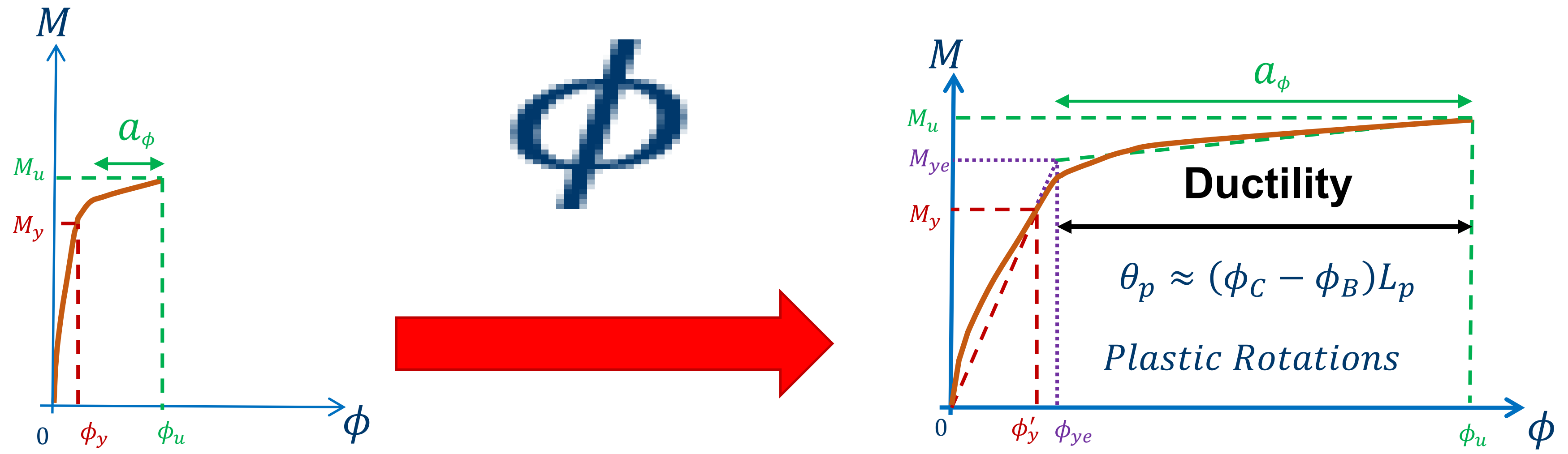
FRP Confined Concrete Vs Unconfined Concrete





Plastic Hinge Confinement and Backbone Curves

Development of Backbone Curve



Backbone Curve of FRP Confined Hinge

Moment-Curvature Analysis (CALTRANS SEISMIC DESIGN CRITERIA VERSION 2.0)

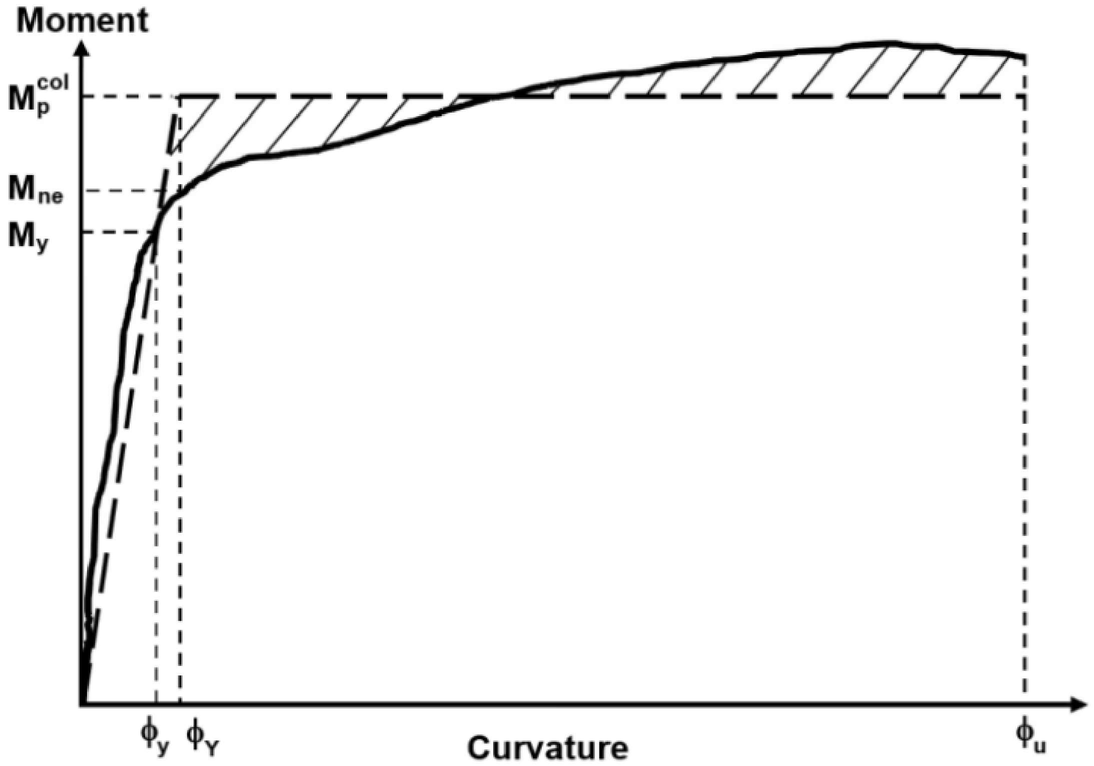
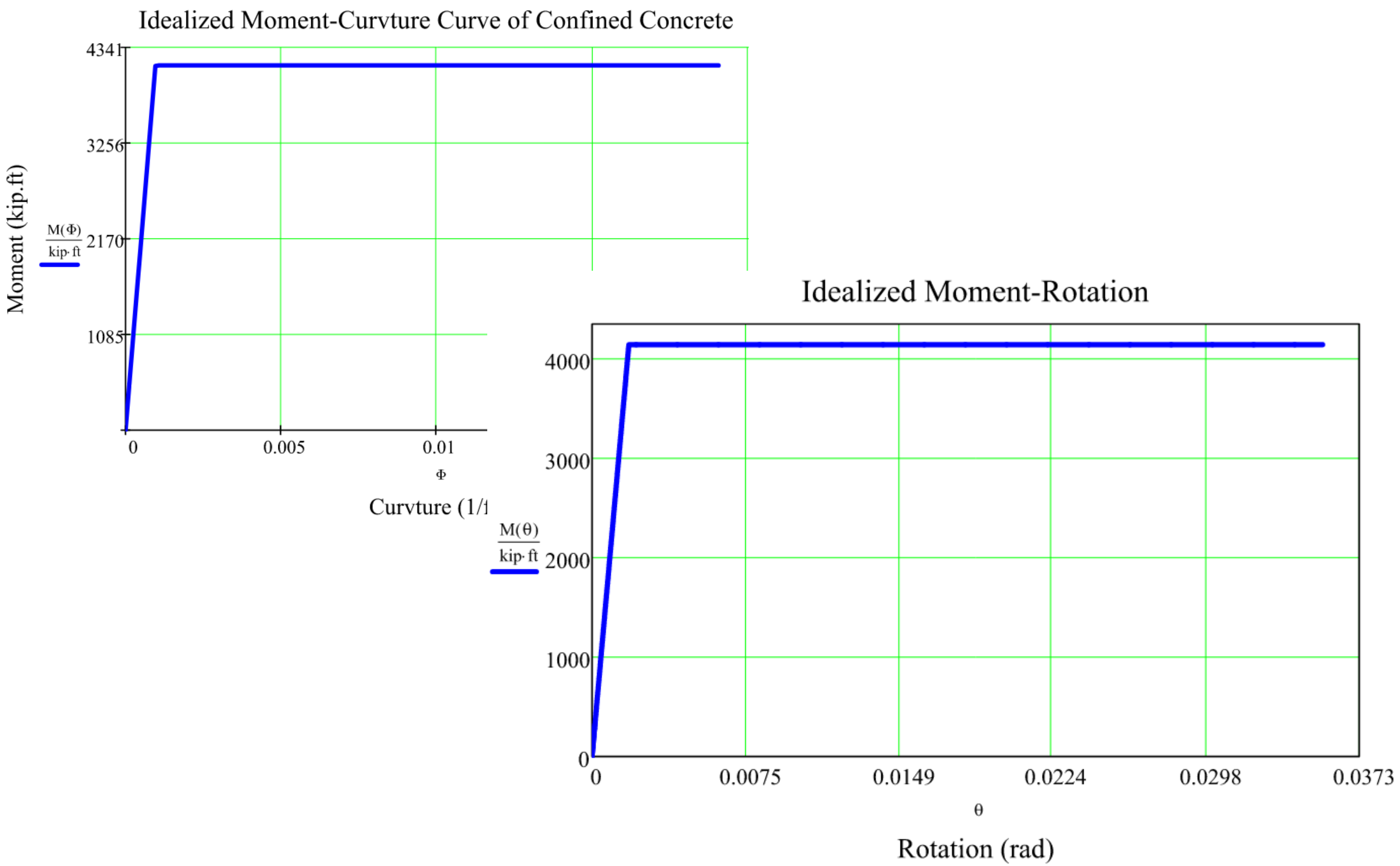


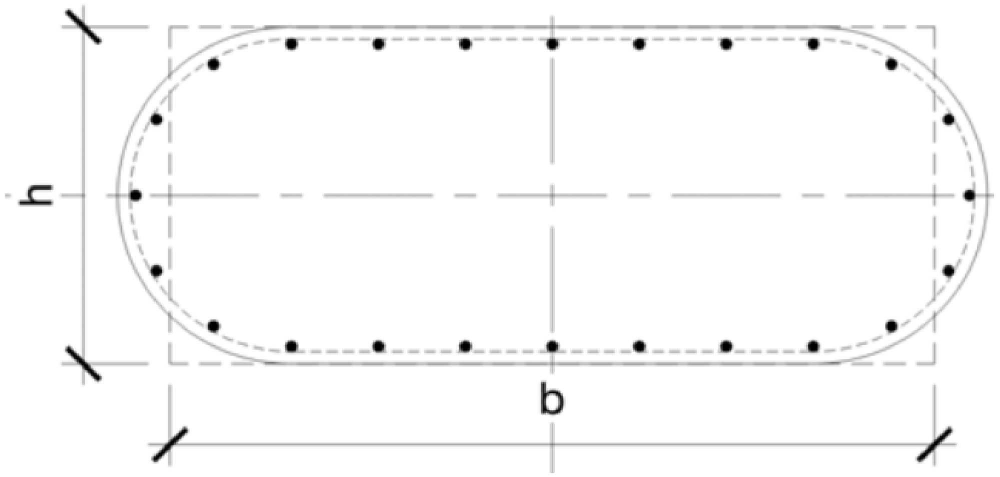
Figure 5.3.6.2-1 Moment - Curvature Curve

Backbone Curve of FRP Confined Hinge

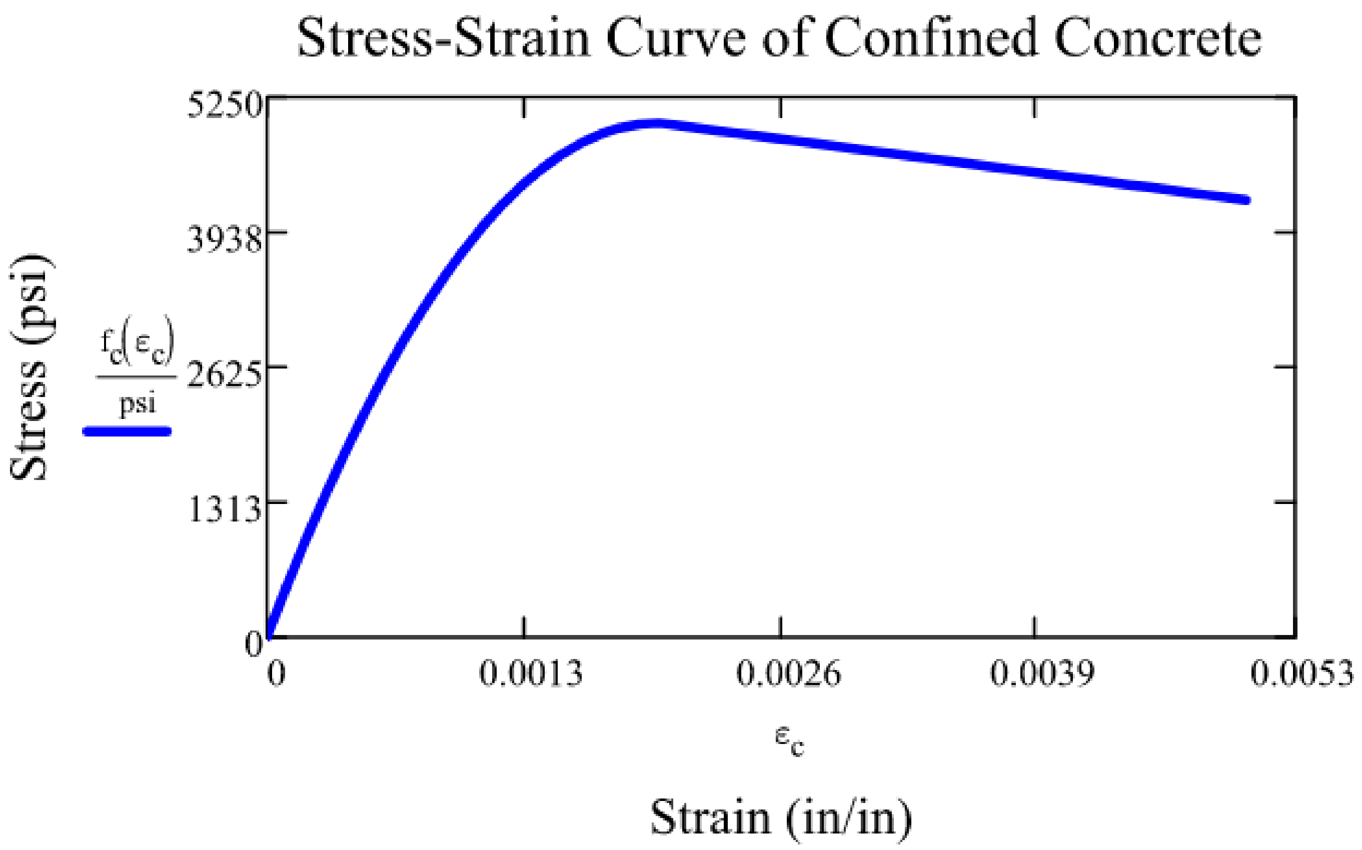


Backbone Curve of FRP Confined Hinge

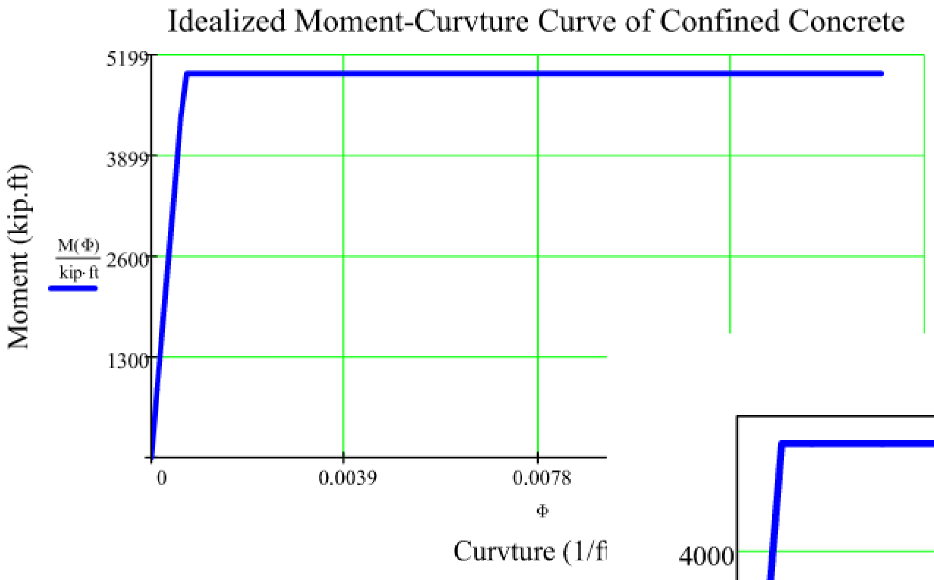
The elliptical shape at the top of the column was conservatively modeled using equivalent rectangular section

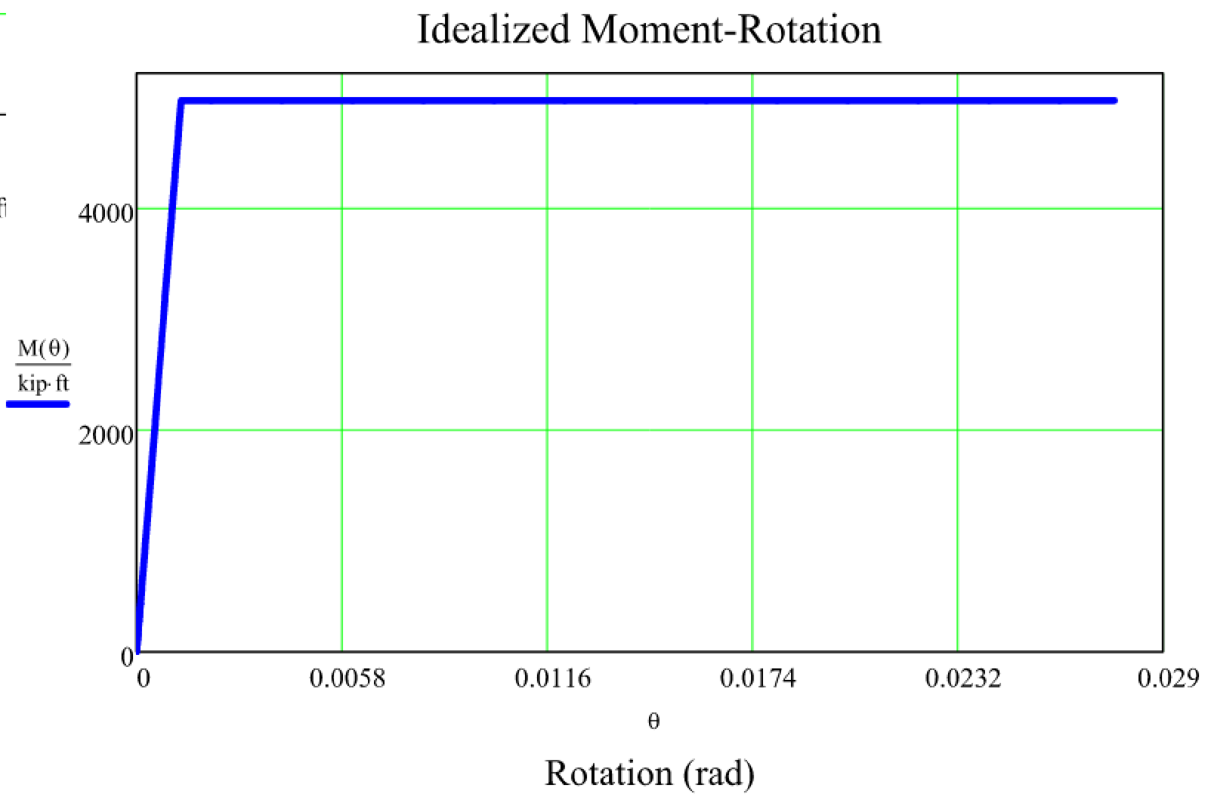


Backbone Curve of FRP Confined Hinge



Backbone Curve of FRP Confined Hinge



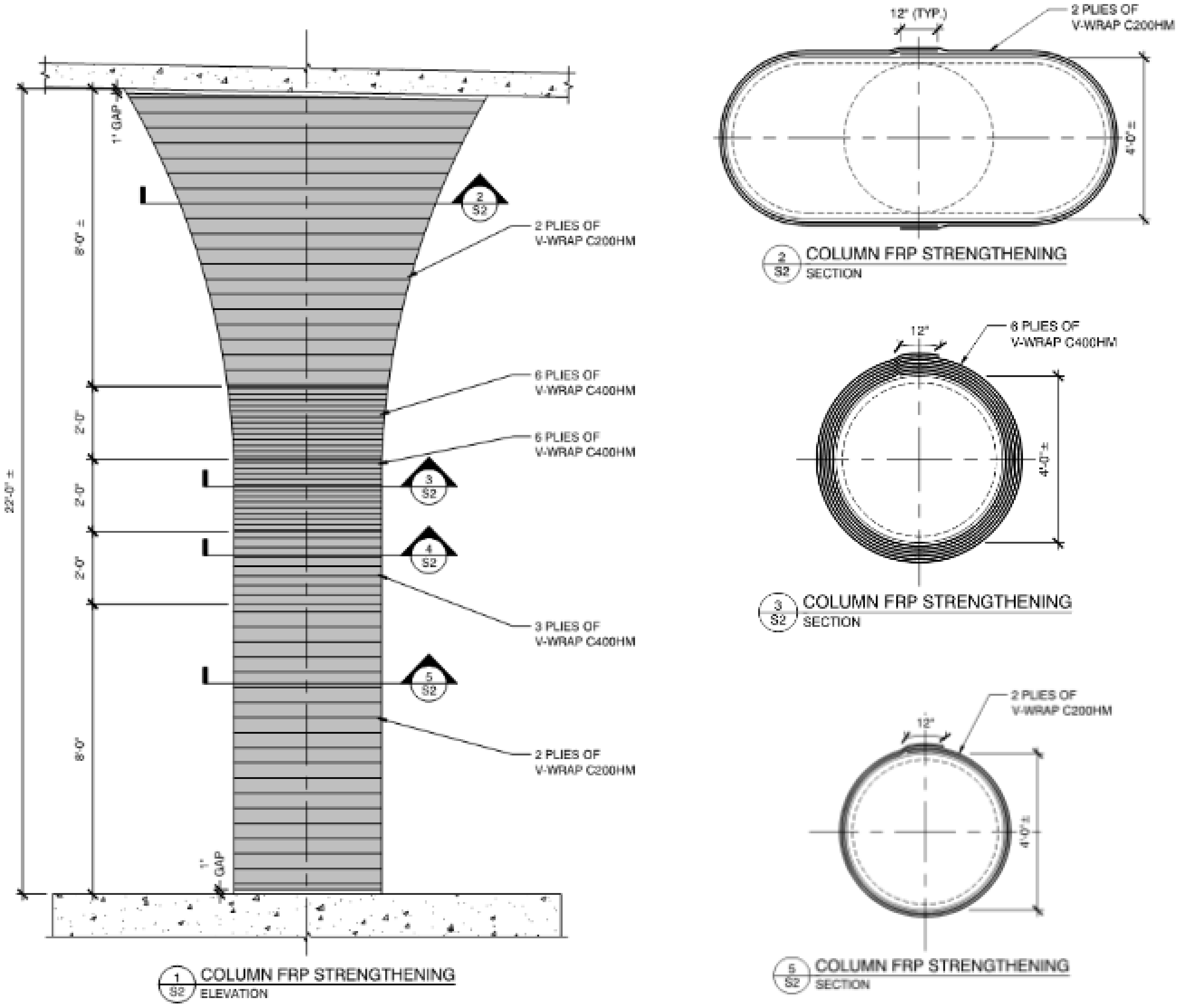


Backbone Curve of FRP Confined Hinge

FRP Design Summary

Item	Existing Capacity	Demand	FRP Layout	FRP Strengthened	M_p Exist. (k-ft)	M_p FRP (k-ft)	Δ_{yi} (in)	Δ_D (in)	μ_D
Plastic Rotation at Bottom of Flare (Transverse)	0 rad	0.024 rad	6 Plies C400HM	0.034 rad	3791	4134	1.48	5	3.4
Plastic Rotation at the Top of Flare (Longitudinal)	0.026 rad	0.016 rad	2 Plies C200HM	0.03 rad	4952	4973	2.31	6.5	2.8
Shear Strength	301 kip	413 kip	2 Plies C200HM	558 kip					
Bar Lap Splice Capacity	36 ksi	48 ksi	5 Plies C400HM	48 ksi					

FRP Jacket Layout



FRP VE Option - Benefits

- Lightweight and much easier to install
- Eliminates welding
- Access issues / concerns are addressed
- Schedule and cost advantage (10-15% cheaper)
- Installed without cranes (Safety)
- Flexible installation of FRP on columns with complex geometry

Long Term Durability

- FRP does not corrode / degrade and therefore offers a much longer duty life than steel

Construction

Project Background

Conforming Design

FRP Value Engineered Option

Construction

Summary

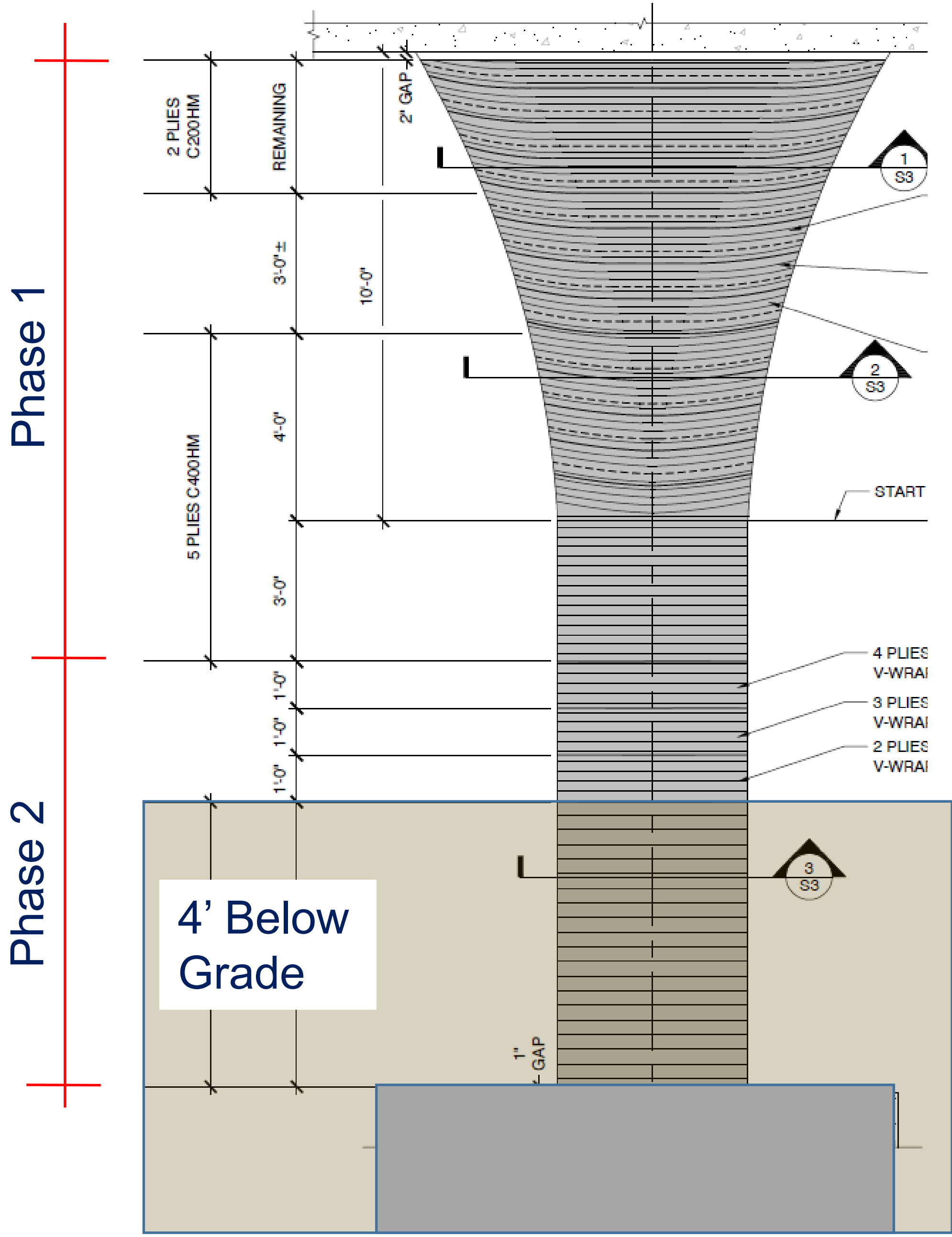
Construction Sequence

Technical Objective

- Full height column wrapping
- FRP placement that keeps fibers oriented horizontally
  - Difficult at hyperbolic flare
  - Mockup to confirm placement technique

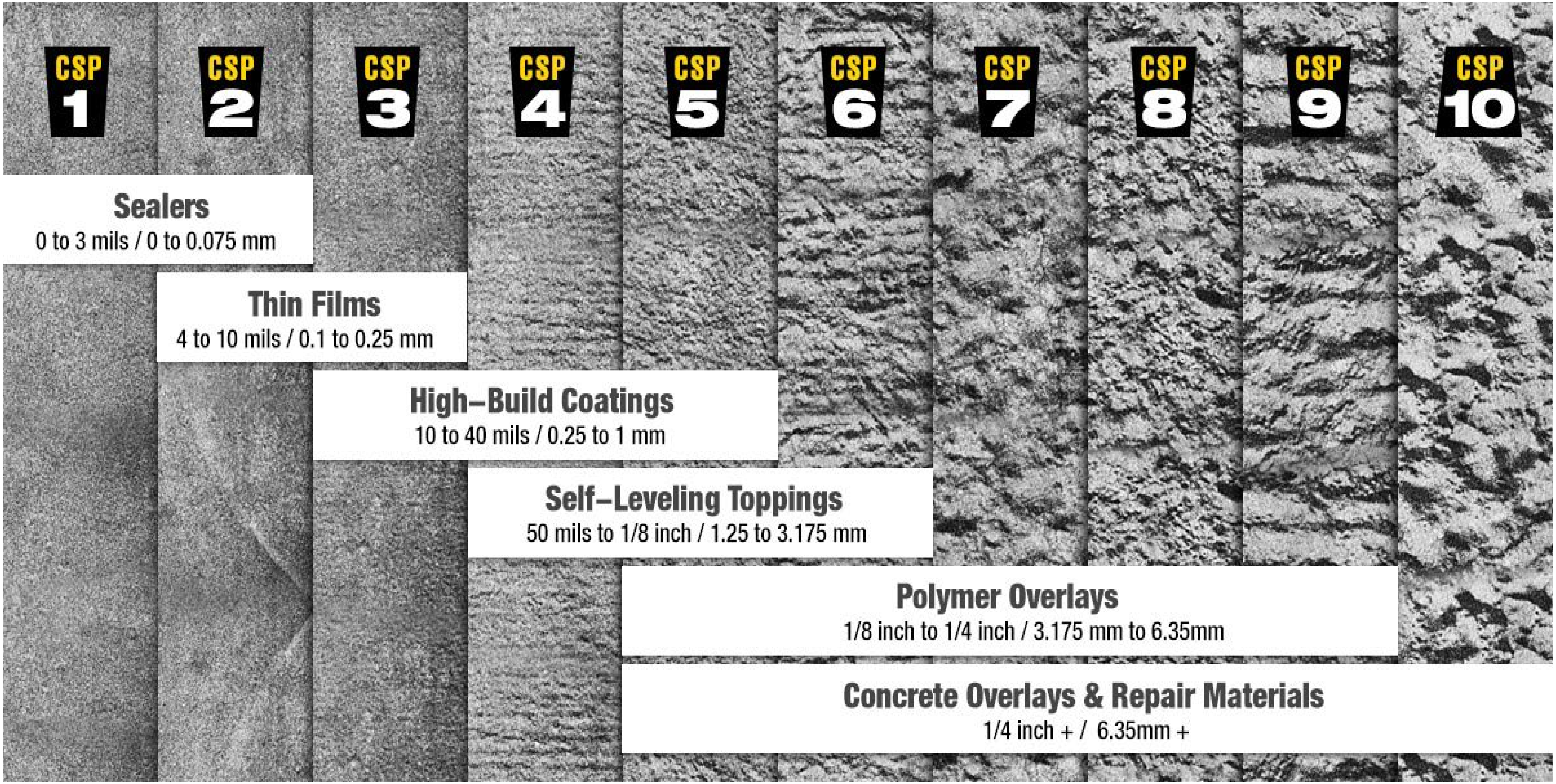
Production Objective

- Separate column wrapping into 2 phases
  - Phase 1: Start work ahead of GC excavating
  - Phase 2: No special access equipment required



FRP Installation Process – Substrate Preparation

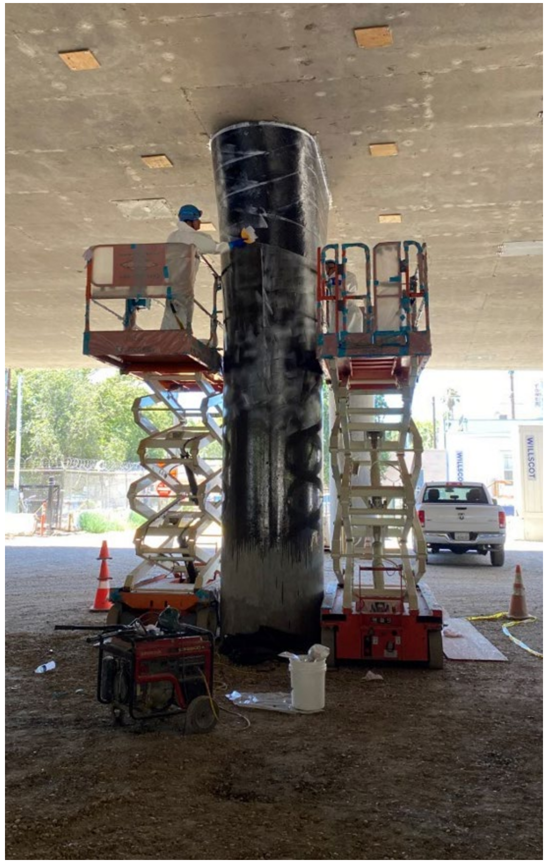
- Use mechanical grinder to open concrete pores and grind any concrete form lines
- Required surface profile, CSP3

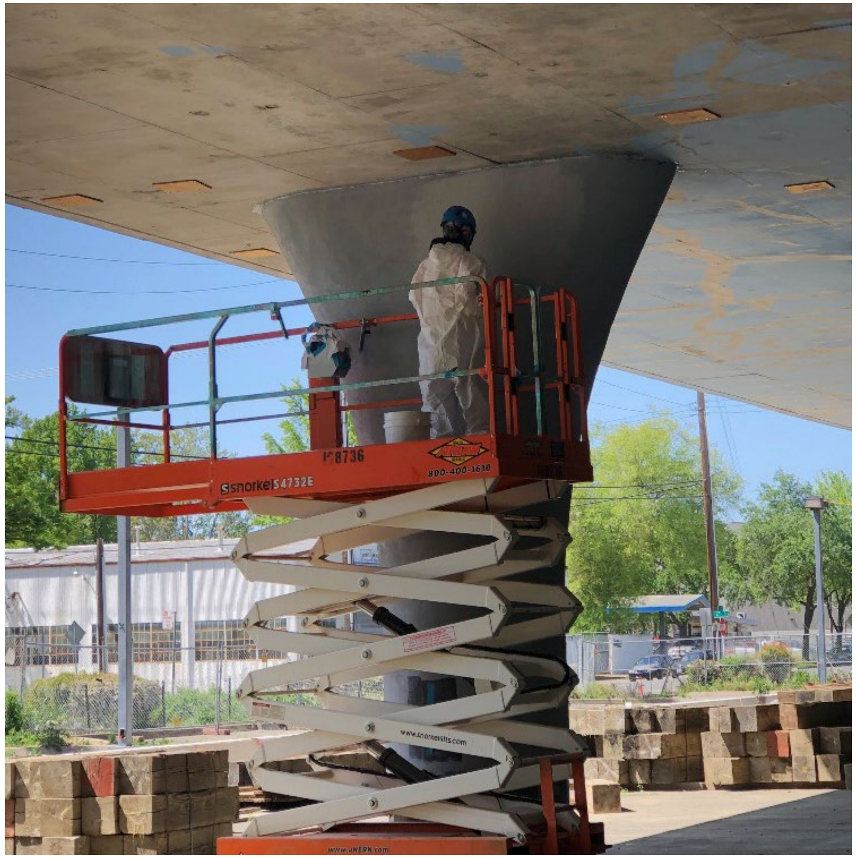

CSP 1
CSP 2
CSP 3
CSP 4
CSP 5
CSP 6
CSP 7
CSP 8
CSP 9
CSP 10
Sealers
0 to 3 mils / 0 to 0.075 mm
Thin Films
4 to 10 mils / 0.1 to 0.25 mm
High–Build Coatings
10 to 40 mils / 0.25 to 1 mm
Self–Leveling Toppings
50 mils to 1/8 inch / 1.25 to 3.175 mm
Polymer Overlays
1/8 inch to 1/4 inch / 3.175 mm to 6.35mm
Concrete Overlays & Repair Materials
1/4 inch + / 6.35mm +

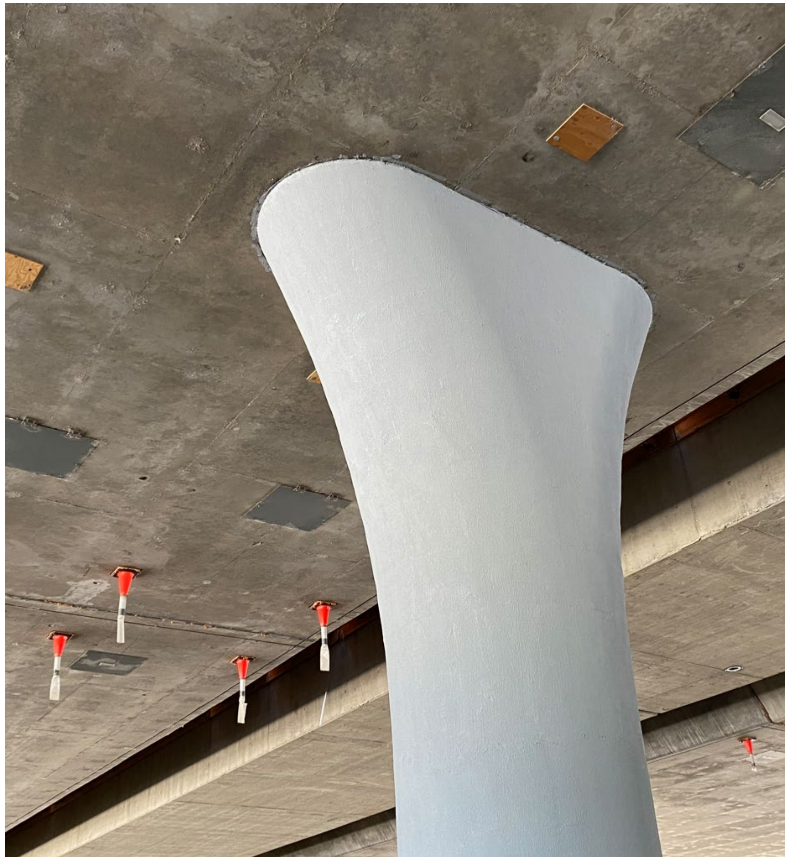
FRP Installation Process

- Apply primer coating and epoxy putty to fill bug holes and form lines
- Use mechanical saturator to impregnate dry FRP fabric, FRP placement

FRP Installation Process







- Complete FRP wrapping and use rib roller to remove air bubbles
- Apply topcoat for long term protection

FRP Installation Process




- Excavate to top of footing
- Repeat steps for FRP installation

Summary

Project Background

Conforming Design

FRP Value Engineered Option

Construction

Summary

Summary

- Worked collaboratively with D/B team to explain FRP proof of concept & initial design for Caltrans approval
- Provided input for FRP optimization and specifications
- Supplied/installed a carbon fiber strengthening system
- We are a resource for your next project!

Performance Factors	Steel Jacket	FRP Wrapping
Cost	$23,900 / col	$20,800 / col
Quality Assurance	Verify Welds ($$)	Direct Tension Tests ($)
Durability	Periodic maintenance	Non corrosive
Flexibility for Odd Shapes	Moderate	High
Fabrication Lead Time	12 – 16 weeks	2 – 3 weeks

We thank you for your time and consideration and welcome any questions

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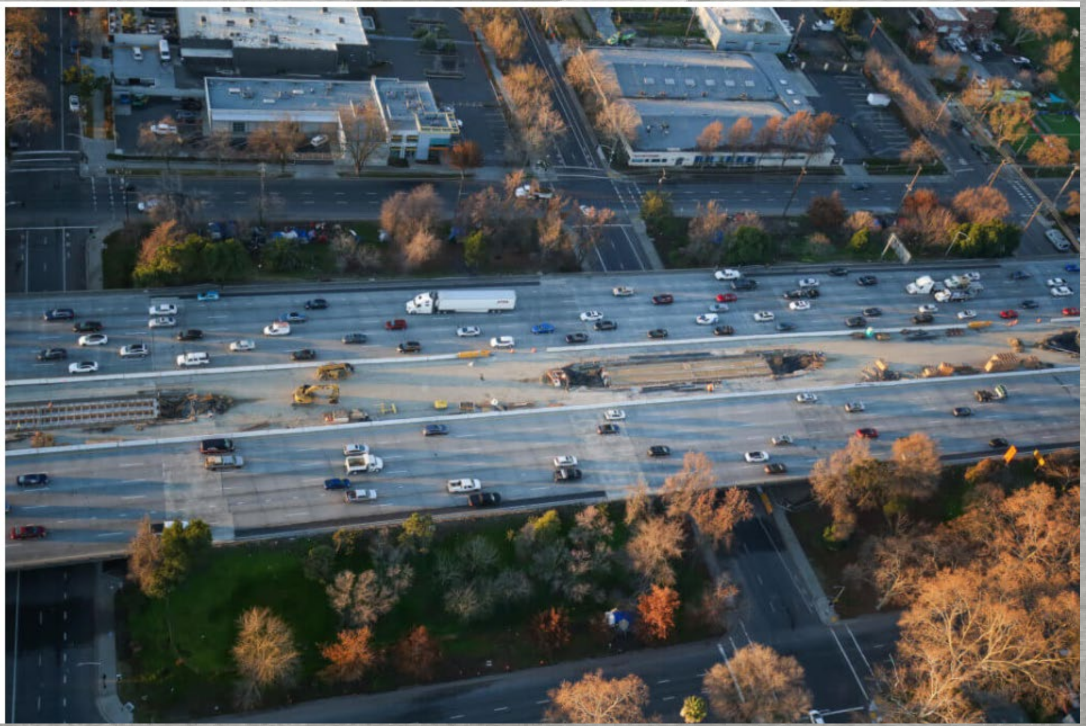

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