

---

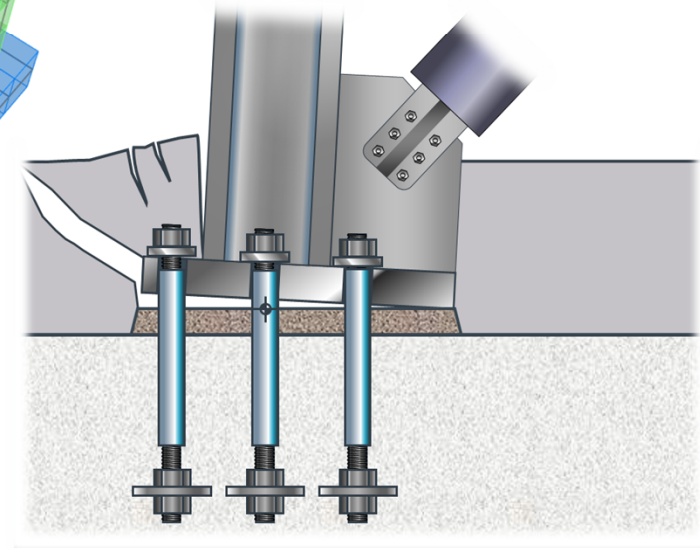
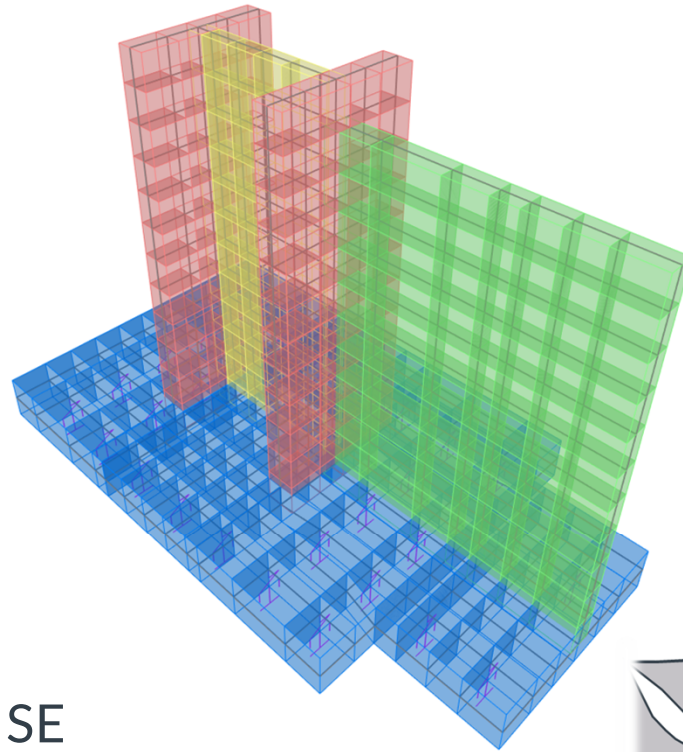
# Design method for rotational ductility of braced-frame base-plate connections in tension

Rafael Sabelli, SE

Walter P Moore

Rupa Garai, SE

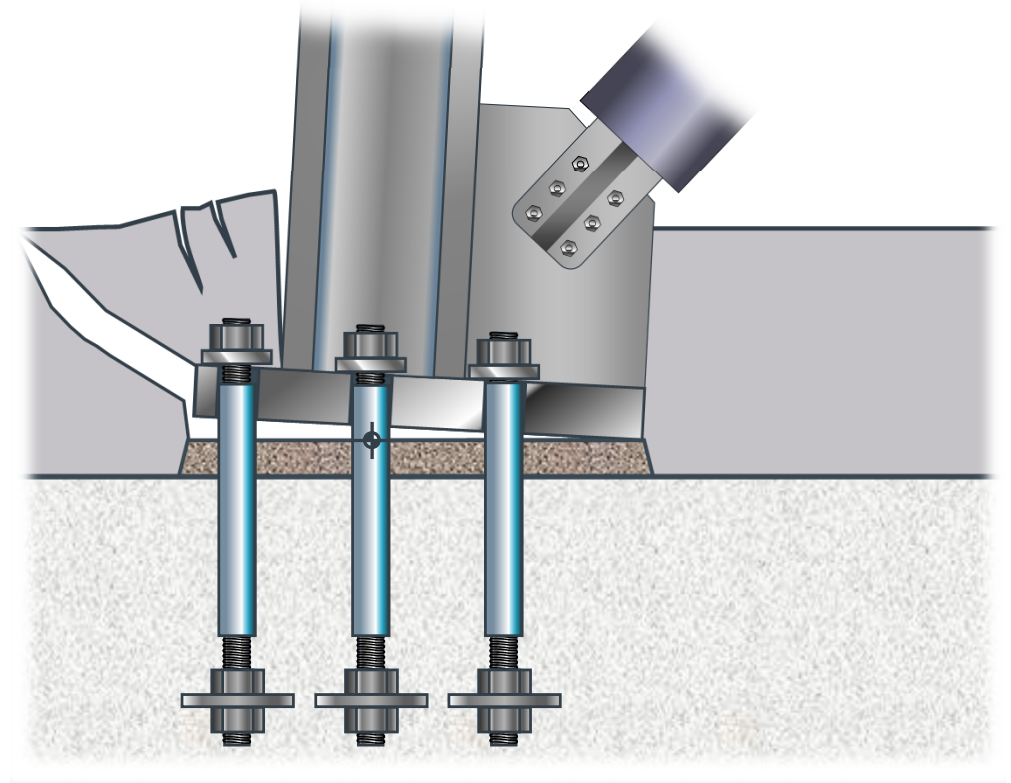
SKIDMORE, OWINGS & MERRILL



---

## Outline

- Generic Approach
- Project-Specific Approach

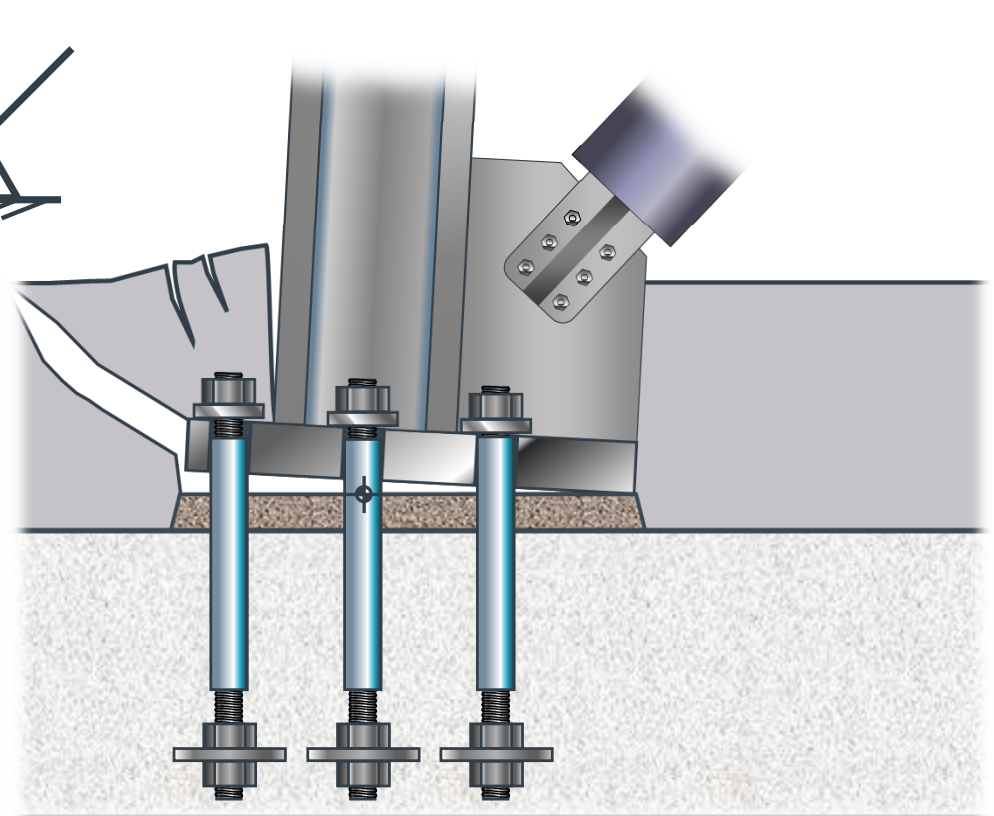
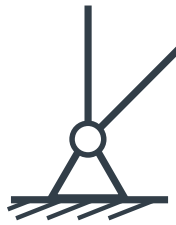


---

## Can we treat CBF base connections as pinned?

### Typical design rationale

- Model as pinned
  - Conservative for brace required strength
  - Moments relieved by uplift
  - Plastic hinges implicitly allowed for columns
    - Connections behave as fixed for high column compression

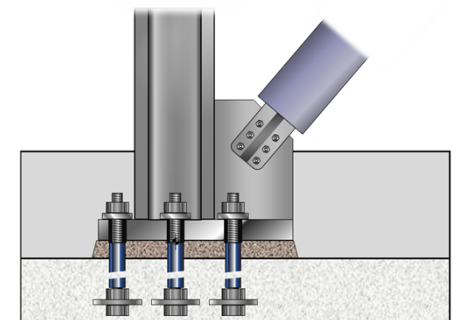


## Design method for rotational ductility of braced-frame base-plate connections in tension

- Ductile braced frames are expected to undergo significant lateral drift
  - $1\% \leq \Delta \leq 3\%$
- Anchor rods for ductile braced frame are required to be designed for the full uplift capacity corresponding to yielding and strain hardening at all levels (potentially unrealistic demand)
  - No prescriptive flexural requirement
  - Pin-base analysis permitted
- Gusseted base-plate connections can be very stiff in flexure
- Questions:
  - Should flexural demands be added to uplift demands on anchors?
  - Can gusseted base-plate connections be modeled as pins?



$$P_{u_{col}} = 0.9D - 0.2S_{DS}D - \sum \left( \frac{\beta+1}{2} \right) \omega R_y F_y A_{sc} \sin(\gamma)$$



---

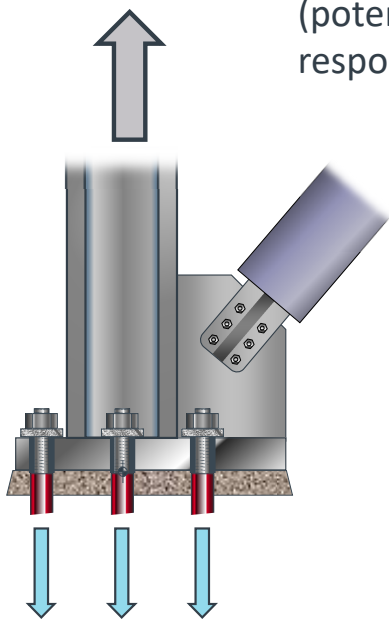
## Design method for rotational ductility of braced-frame base-plate connections in tension

1. Establish drift (rotation) demand
  - 2.5% rotation deemed to be adequate rotation requirement for gusseted connections in AISC 341
  - Additional investigation outside of the scope of this study
2. Develop method to convert base rotation into element deformation demand
  - Proposed mechanism: 100% of rotation from anchor elongation to simplify design
    - Neglect base-plate flexibility
    - Neglect grout compression
    - Neglect foundation flexibility
  - Method confirmed by frame analysis with hook and gap elements
3. Quantify deformation capacity of elements with ductility demand
  - Outside of the scope of this investigation
  - (a few remarks at the end)

## Design idealizations

$$P_u = \sum \left( \frac{\beta+1}{2} \right) \omega R_y F_y A_{sc} \sin(\gamma) + 0.2 S_{DS} D - 0.9 D$$

(potentially reduced using response-history analysis)



Equal forces

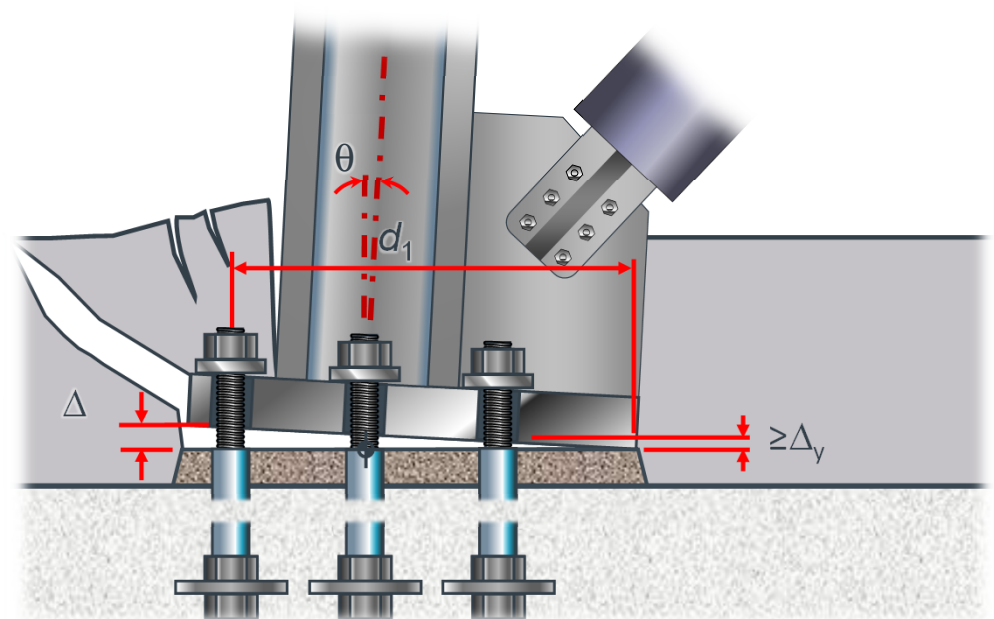
$$T_u = \frac{P_u}{n}$$

Design idealization used for anchor-rod sizing

$$\Delta = \theta d_1$$

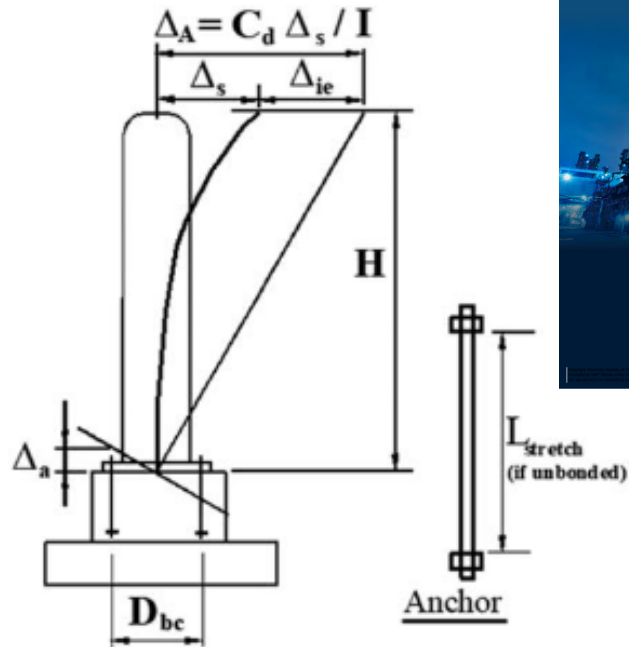
$$\Delta \leq \epsilon_{\max} L_y$$

- Ensure required rotation can be reached



Design idealization used for verifying anchor-rod ductility

# Design idealizations



$\Delta_s = \text{deflection from elastic analysis}$   
 $\Delta_{ie} = \Delta_s [(C_d / I) - 1]$   
 $\Delta_a = (\Delta_{ie}) (D_{bc}) / H = (e_a) L_{stretch}$   
 $L_{stretch} \geq \Delta_a / e_a$ , Where  $e_a$  is approx. 5%

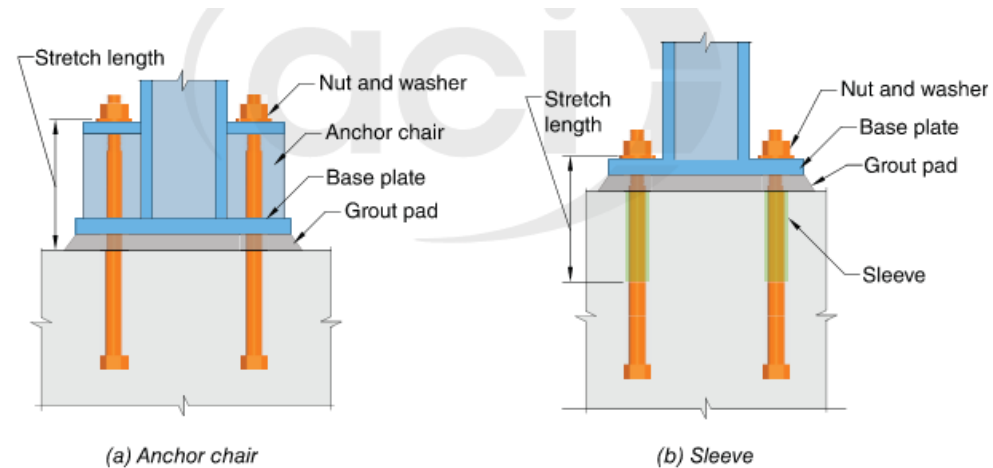
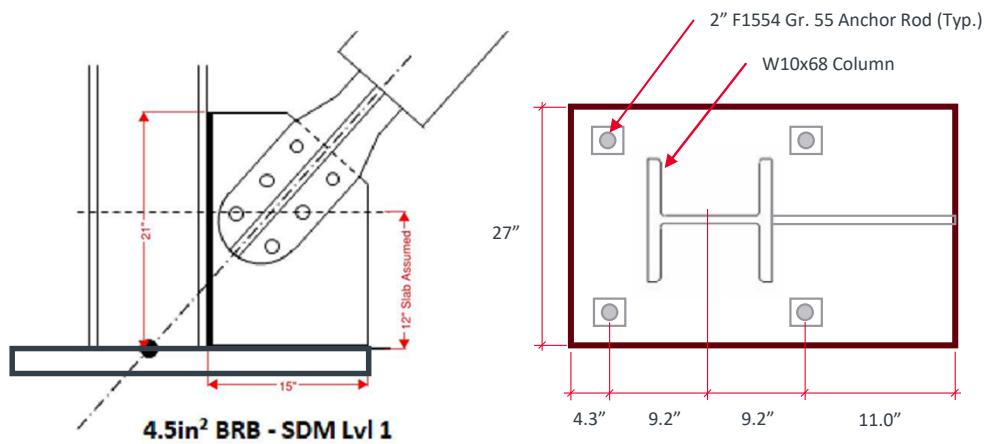


Fig. R17.10.5.3—Illustrations of stretch length.

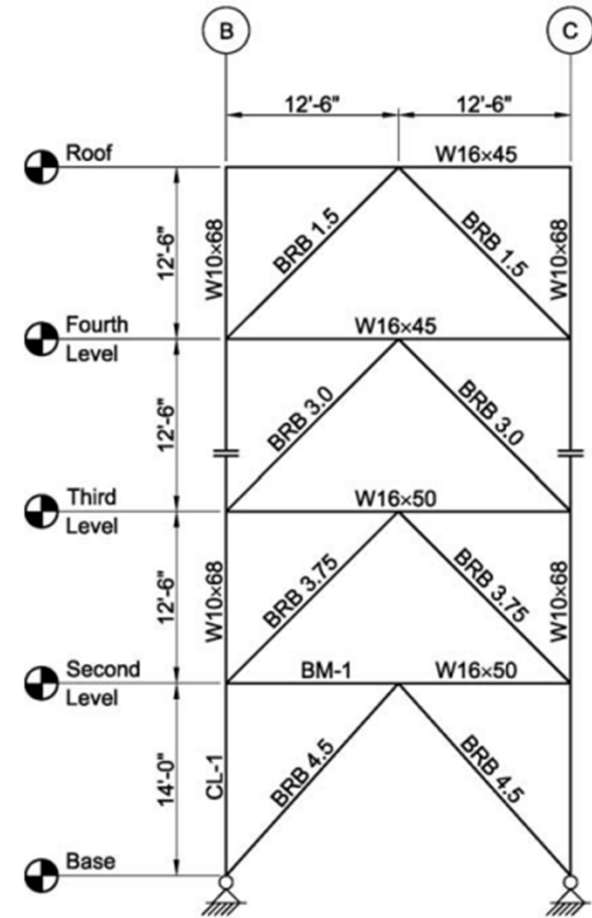
Figure 3-26. Determining the minimum stretch length of vertical vessel anchors.

# Design

- ASIC *Seismic Design Manual* example for Buckling-Restrained Braced Frame
- Connection design completed as required



Gusset Geometry per Brandt Saxey of Corebrace



Example BRBF from AISC SDM

---

# Anchor Bolt Selection

## Design

Anchor Bolt Design:

$$P_u = \sum \left( \frac{\beta + 1}{2} \right) \omega R_y F_y A_{sc} \sin(\gamma) + 0.2 S_{DS} D - 0.9 D$$
$$= 500 \text{ kips}$$

$$T_u = \frac{500 \text{ kips}}{4 \text{ bolts}} = 125 \text{ kips/bolt}$$

2" Diameter Grade 55 Anchors  
(rolled threads, smooth shank)

$$\phi T_n = 0.9 F_y A_g = 133 \text{ kips}$$

$$\sum \phi T_n = 532 \text{ kips}$$

$$\phi T_n = 0.9 F_y A_g = 133 \text{ kips/bolt} > T_u = 125 \text{ kips/bolt}$$

$$\frac{T_u}{\phi T_n} = 1.06$$

## Analysis

Anchor Bolt Analysis Definition:

$$P_y = F_y A_{se} R_y = 55 \text{ ksi} (2.7 \text{ in}^2) 1.1$$

$$= 163.5 \text{ kips/bolt}$$

$$\frac{P_y}{\phi T_n} = 1.31$$

$$2P_y = 327 \text{ kips}/(2 \text{ bolts})$$

*Stiffness per Row of Anchor Rods*

$$\frac{EA}{L} = \frac{29000 \text{ ksi} (5.4 \text{ in}^2)}{30 \text{ in}} = 5223 \text{ kip/in}$$

# Base Plate Modeling

W10x68 column with P-M interacting hinge

Column is rigid where stiffened by gusset

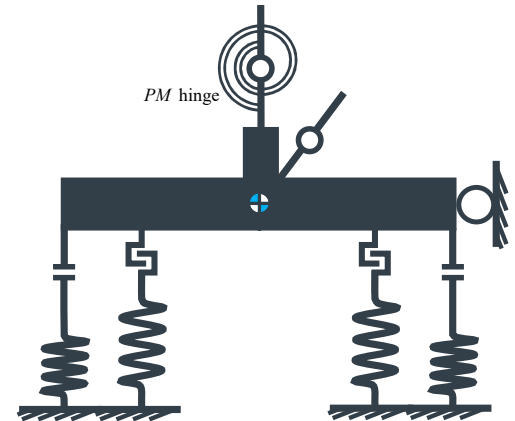
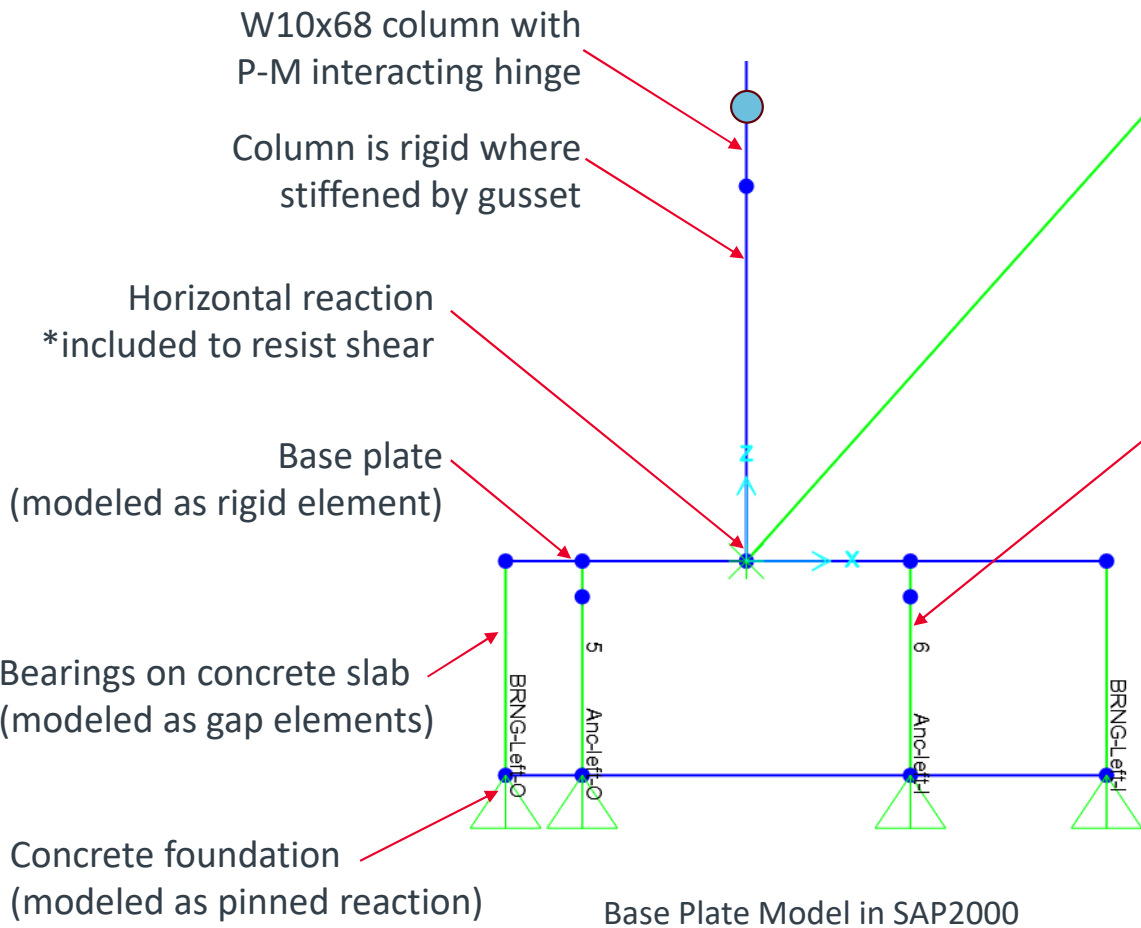
Horizontal reaction  
\*included to resist shear

Base plate  
(modeled as rigid element)

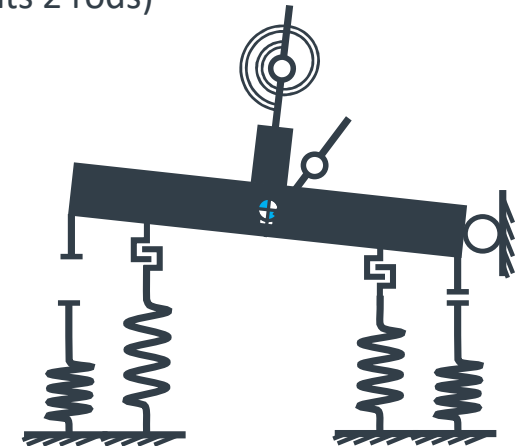
Bearings on concrete slab  
(modeled as gap elements)

Concrete foundation  
(modeled as pinned reaction)

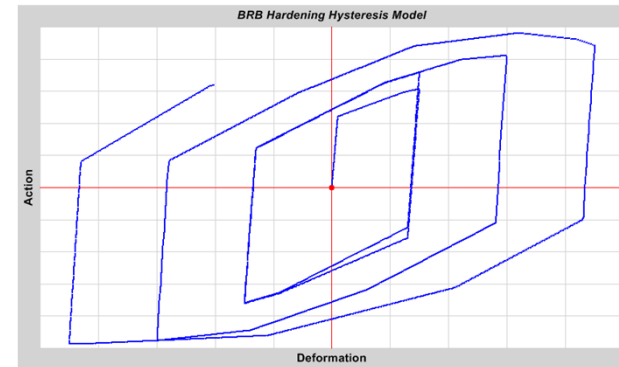
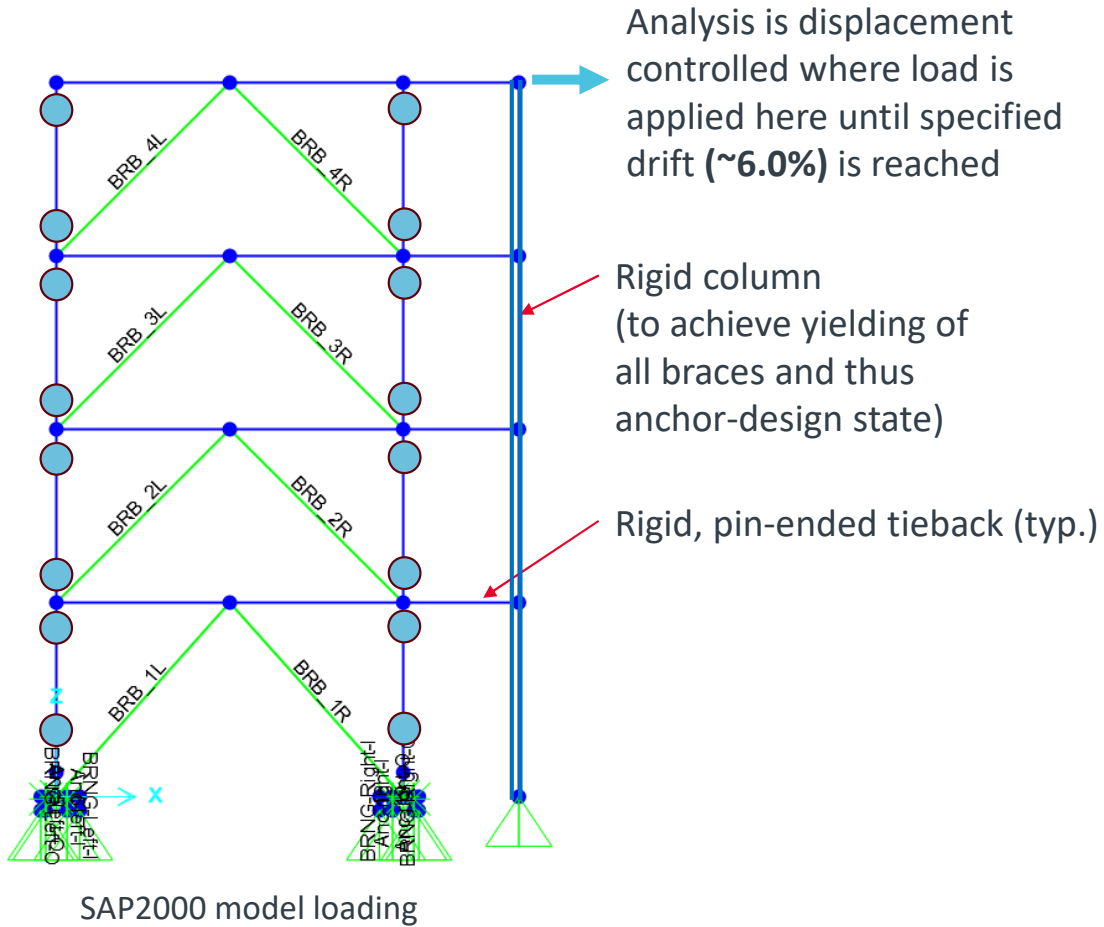
Level 1 BRB



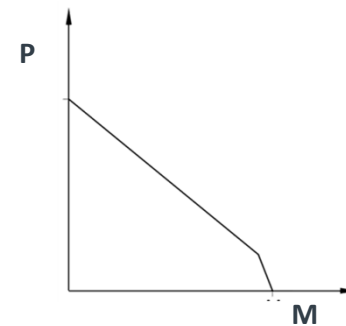
Anchor rods with bi-linear stiffness  
(modeled as hook elements)  
(Represents 2 rods)



# BRBF modeling



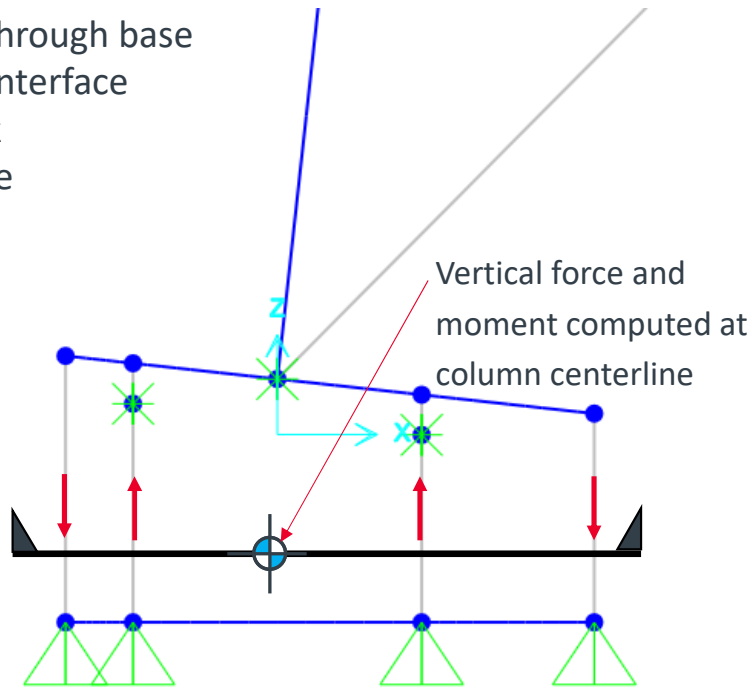
BRB modeling



Column PM hinge  
Per AISC Chapter H

# Run Analysis

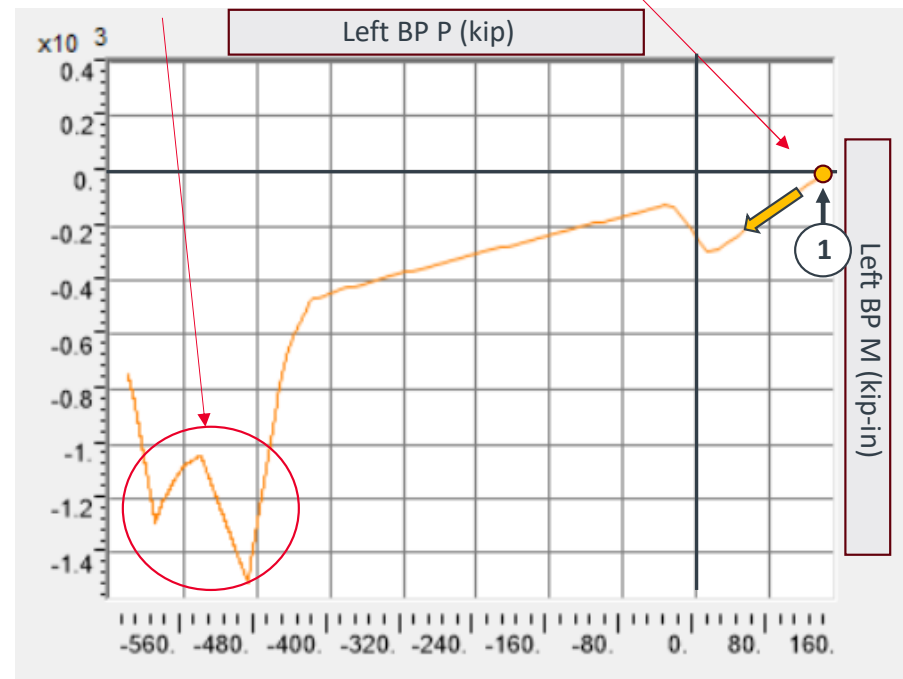
Section cut through base plate – slab interface used to track  
-vertical force  
-moment



Base plate model in SAP2000- post analysis

Note peaks-  
Behavior not as  
originally expected

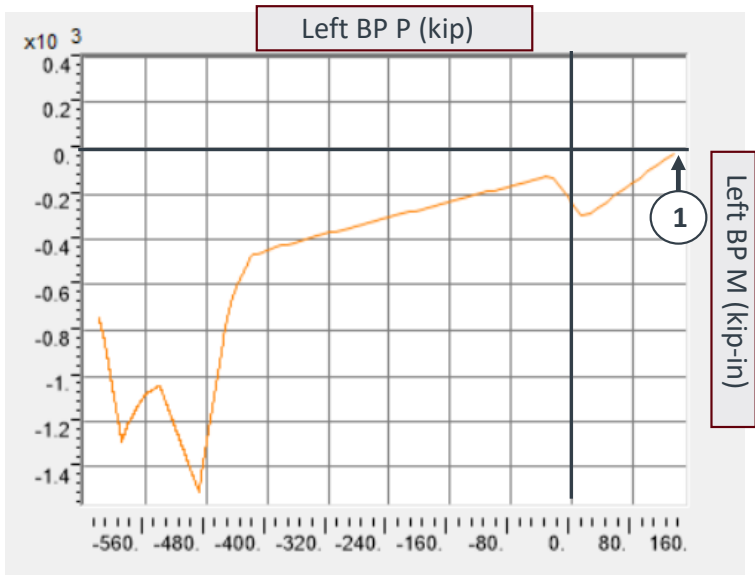
Start here-  
Gravity loads only on column



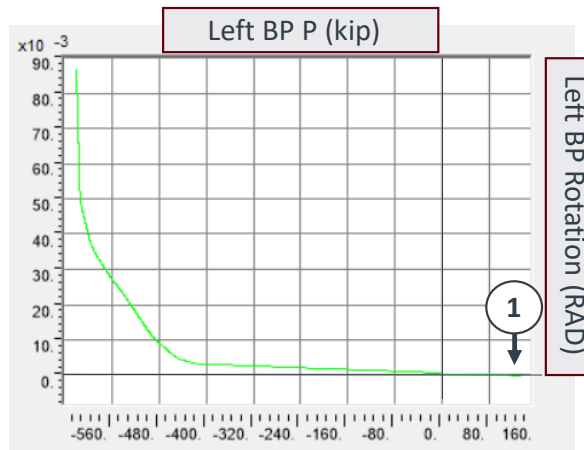
P-M Diagram for Base Plate Experiencing Uplift

# Understanding Behavior- Tension Side

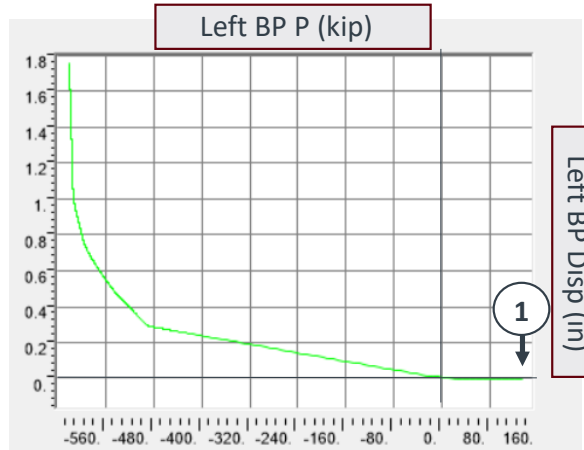
## 1. Gravity Loads Only on BP



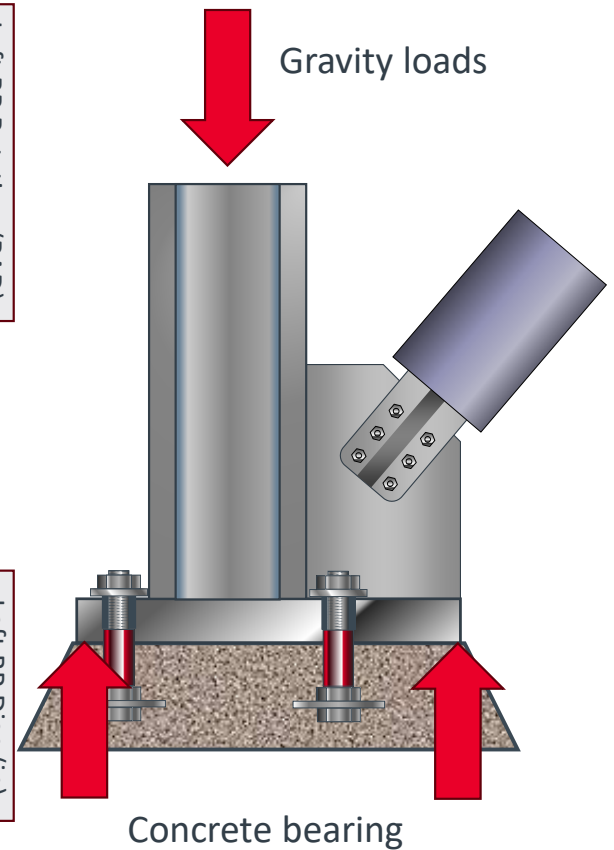
P-M Diagram for Base Plate Experiencing Uplift



BP Rotation vs Axial Load

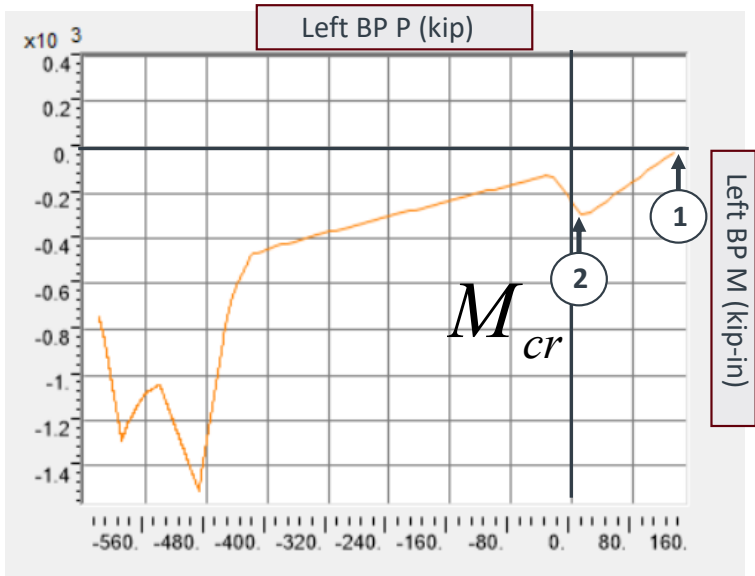


BP Uplift vs Axial Load

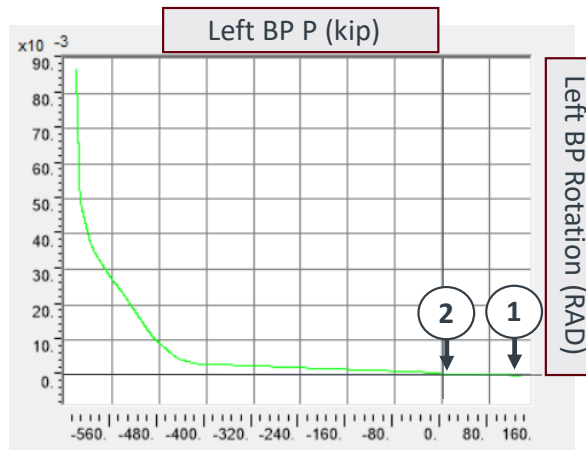


# Understanding Behavior- Tension Side

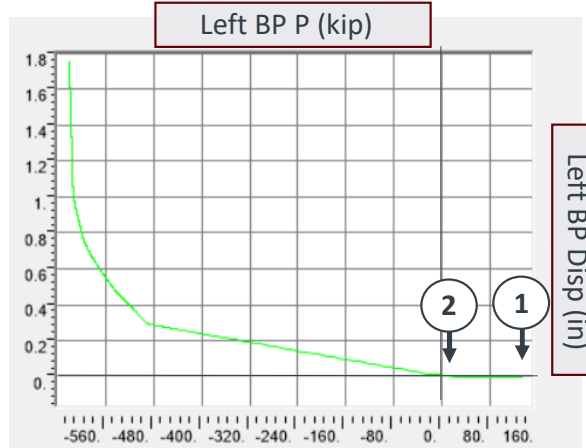
## 2. BP Lifts Off of Outside Edge



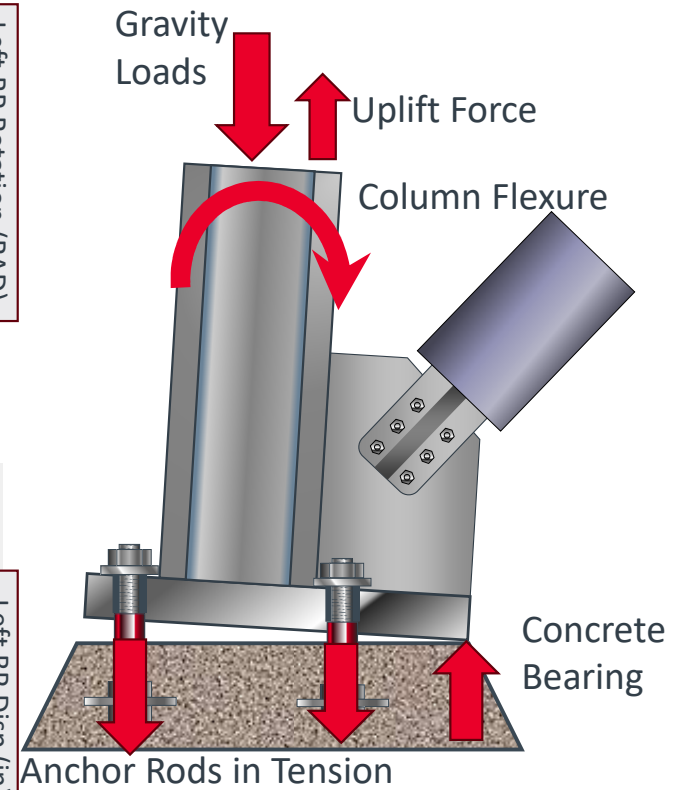
P-M Diagram for Base Plate Experiencing Uplift



BP Rotation vs Axial Load



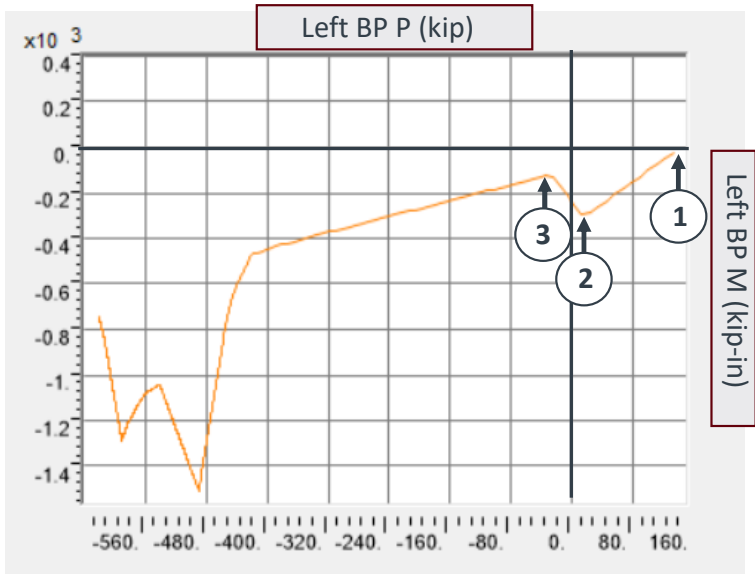
BP Uplift vs Axial Load



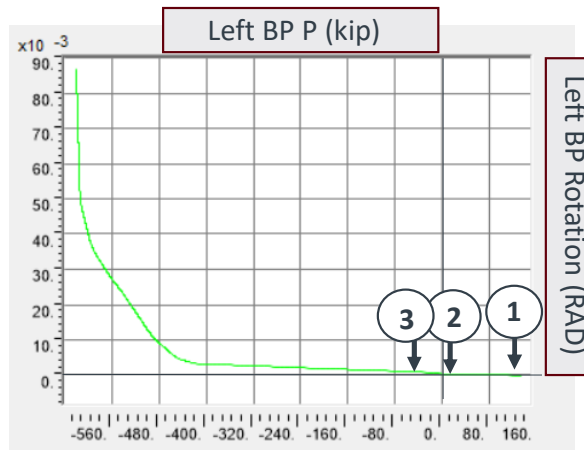
# Understanding Behavior- Tension Side

Elastic uplift

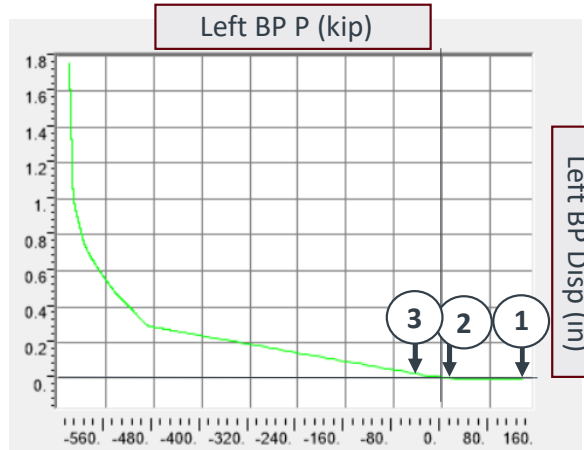
## 3. BP Lifts Off Bearing Completely



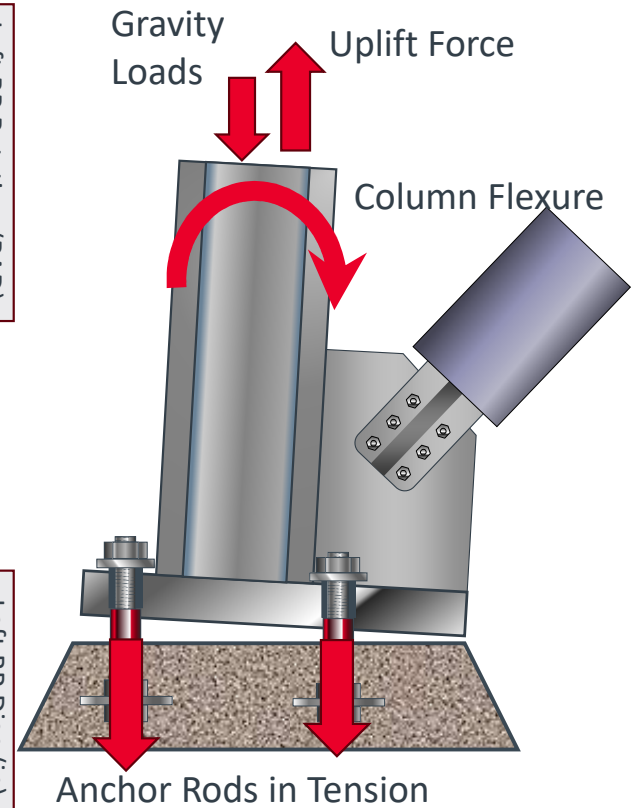
P-M Diagram for Base Plate Experiencing Uplift



BP Rotation vs Axial Load

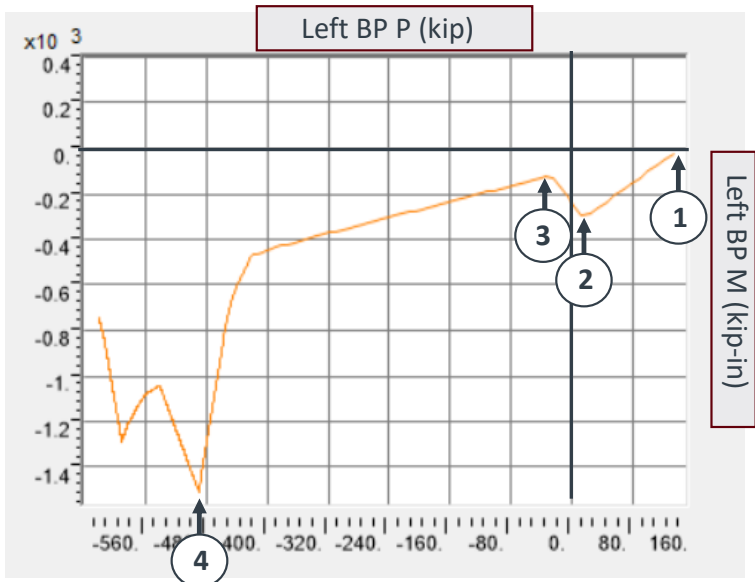


BP Uplift vs Axial Load

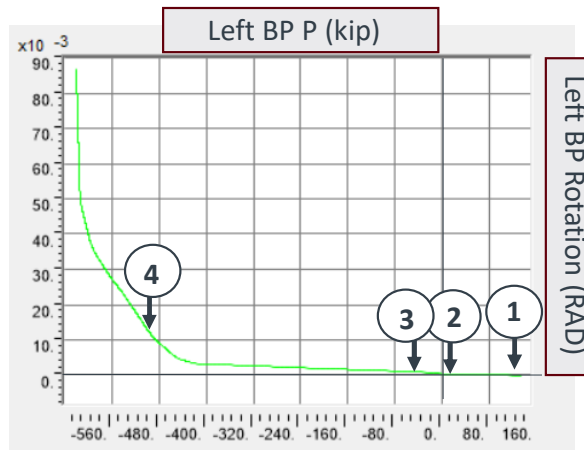


# Understanding Behavior- Tension Side

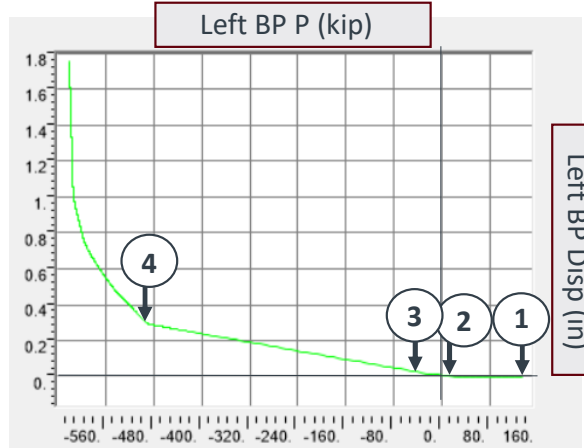
## 4. Outer Anchor Yields



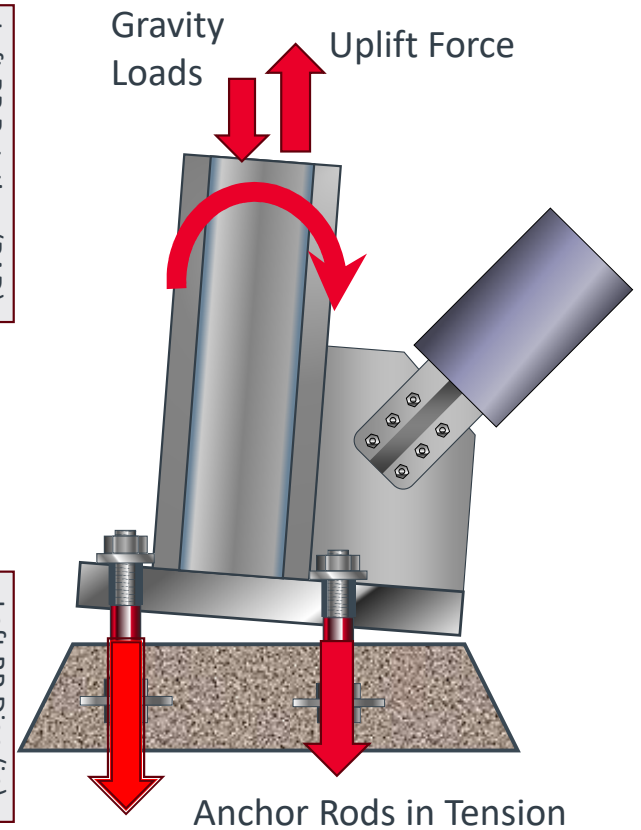
P-M Diagram for Base Plate Experiencing Uplift



BP Rotation vs Axial Load

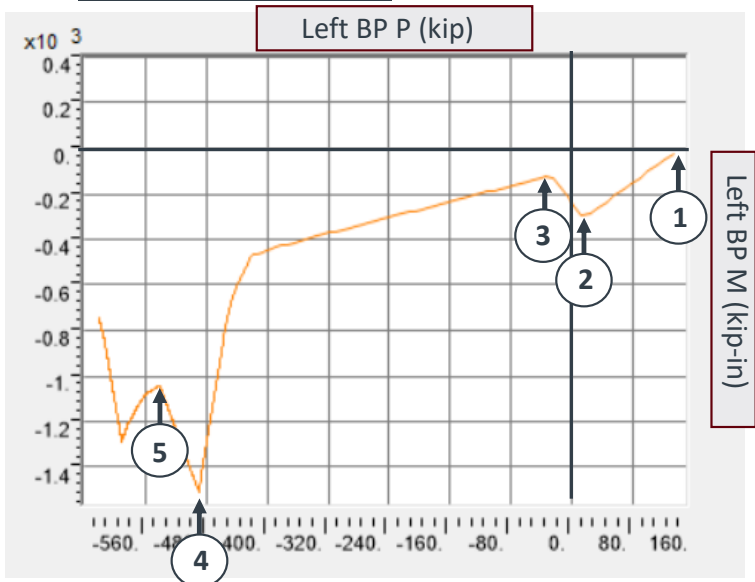


BP Uplift vs Axial Load

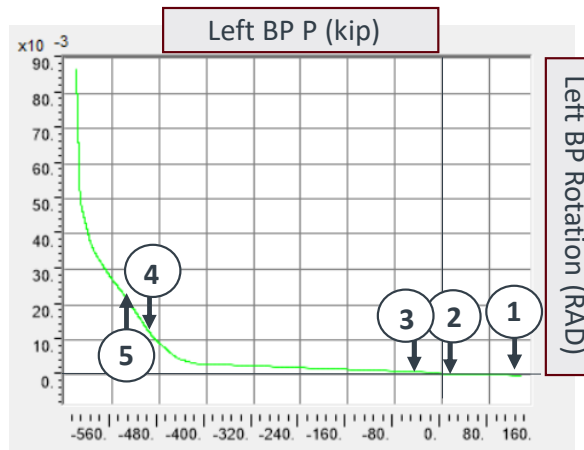


# Understanding Behavior- Tension Side

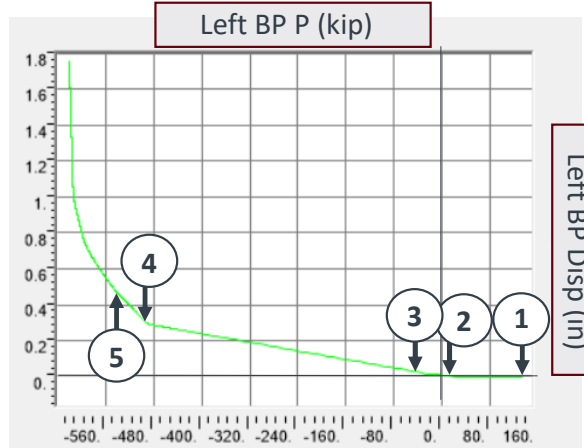
## 5. Rotation Brings Inside Bearing Back Into Contact



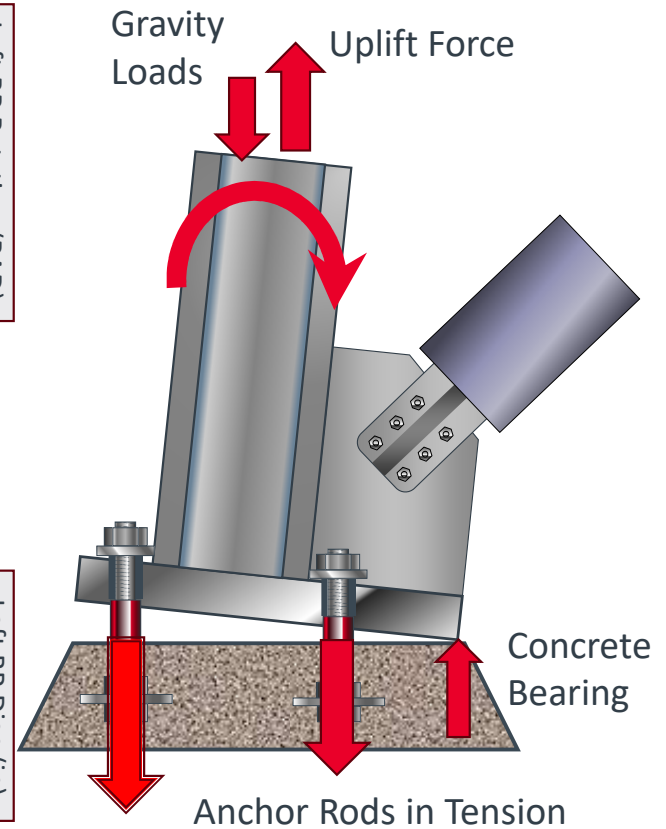
P-M Diagram for Base Plate Experiencing Uplift



BP Rotation vs Axial Load

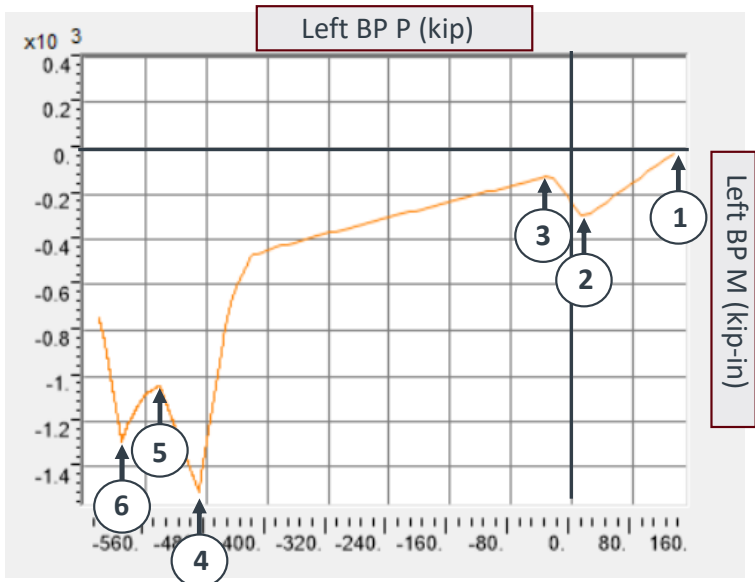


BP Uplift vs Axial Load

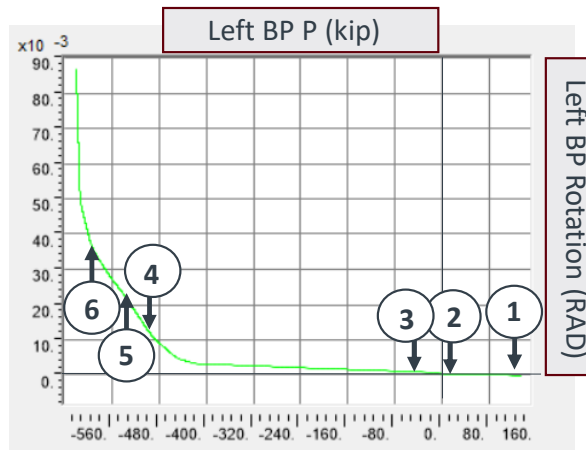


# Understanding Behavior- Tension Side

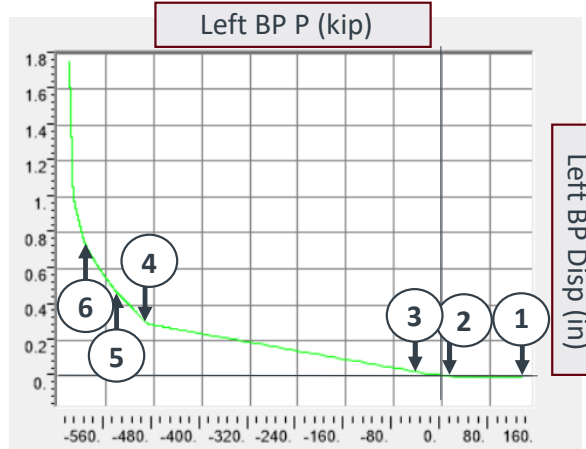
## 6. Inside Anchor Yields



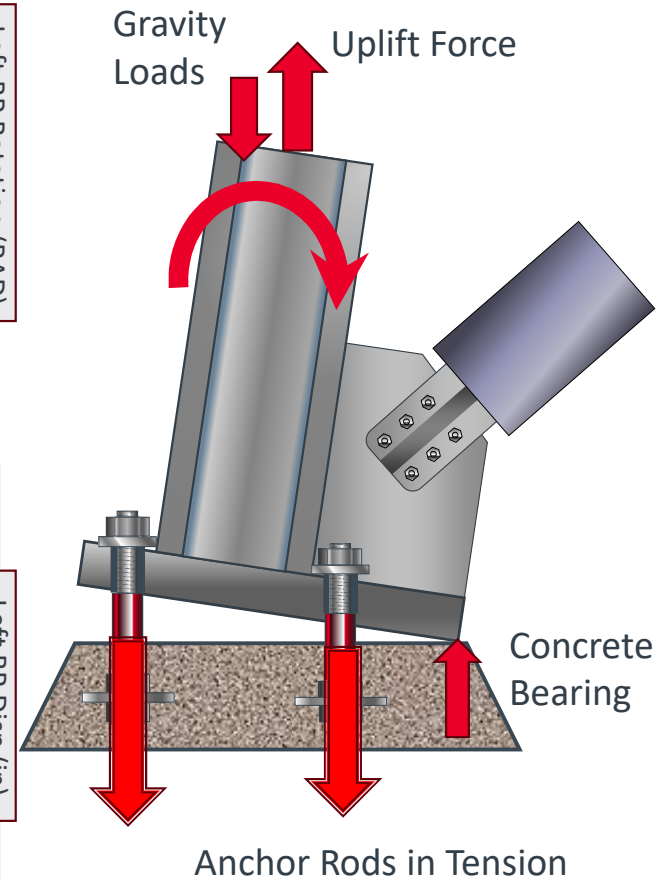
P-M Diagram for Base Plate Experiencing Uplift



BP Rotation vs Axial Load



BP Uplift vs Axial Load

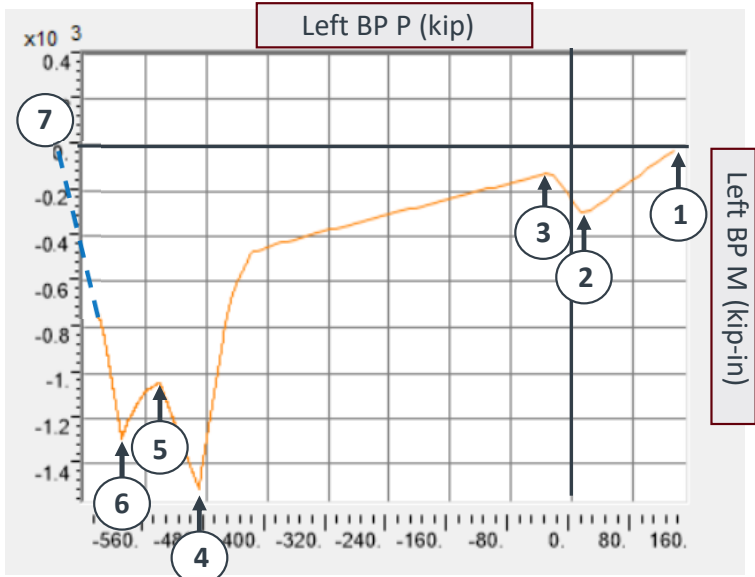


Anchor Rods in Tension

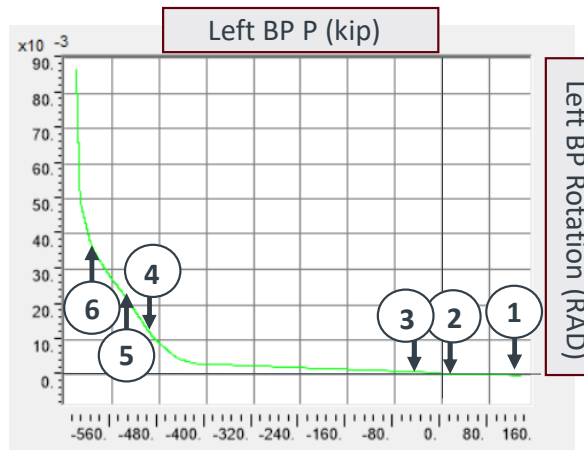
# Understanding Behavior- Tension Side

Inelastic uplift mechanism

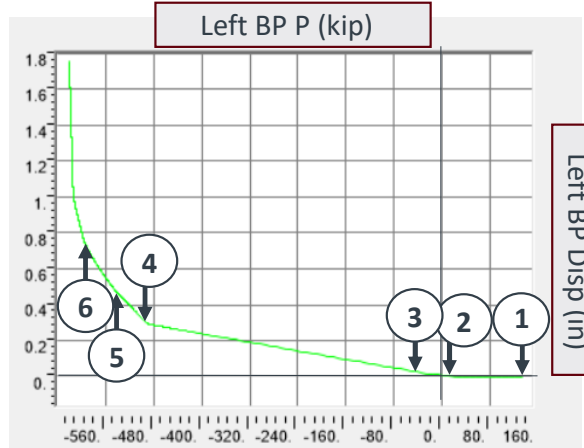
7. Base plate lifts off  
**(POINT NOT BE REACHED)**



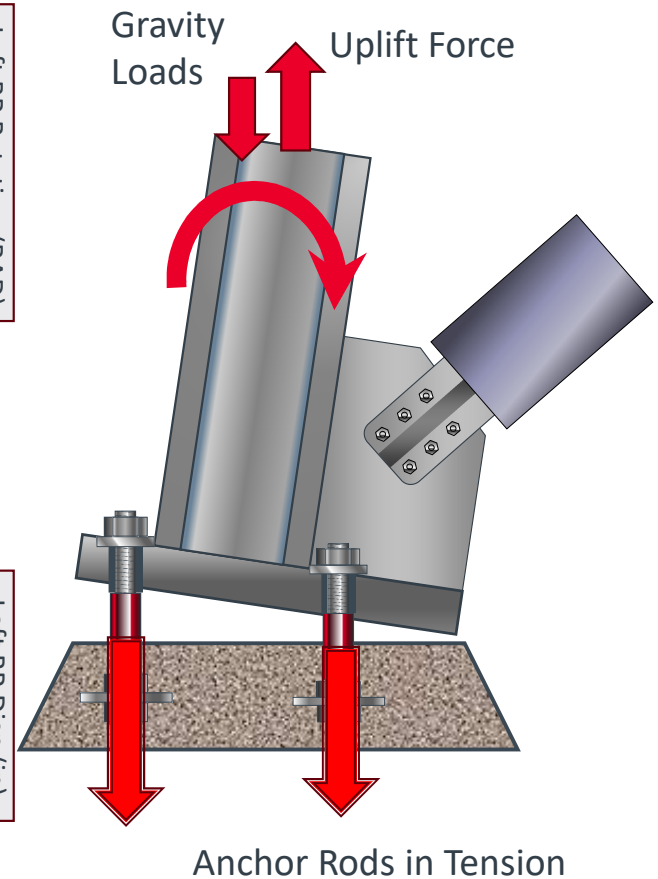
P-M Diagram for Base Plate Experiencing Uplift  
Frame does not have sufficient uplift capacity to yield all rods without additional prying (bearing) force (result of AISC 341 capacity design)



BP Rotation vs Axial Load

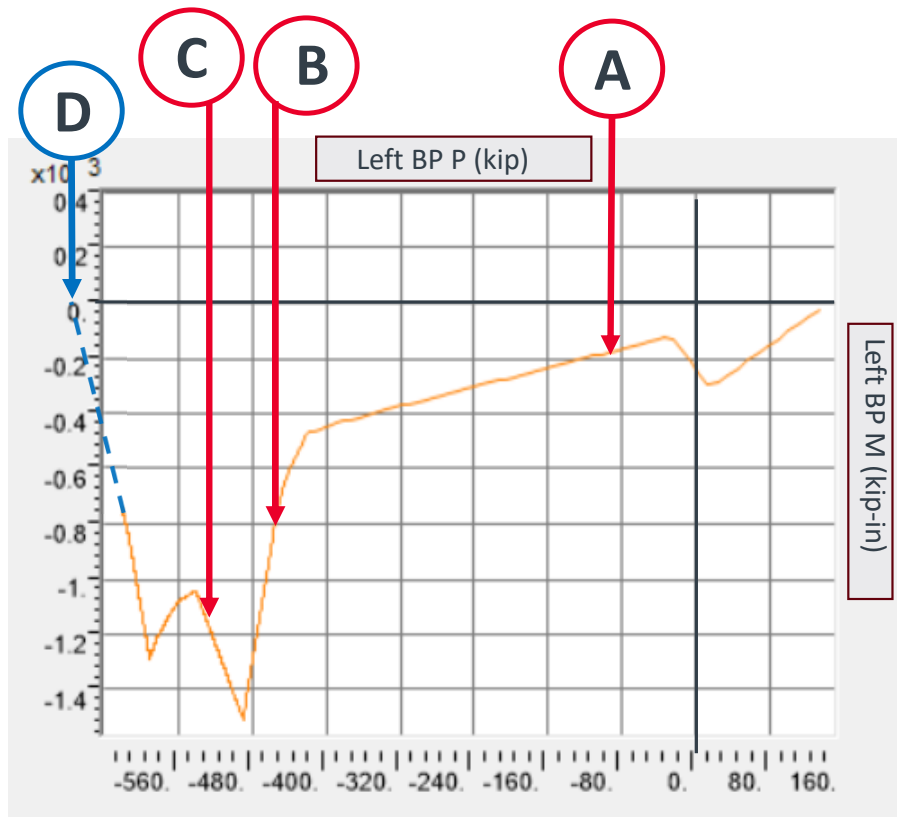


BP Uplift vs Axial Load



Anchor Rods in Tension

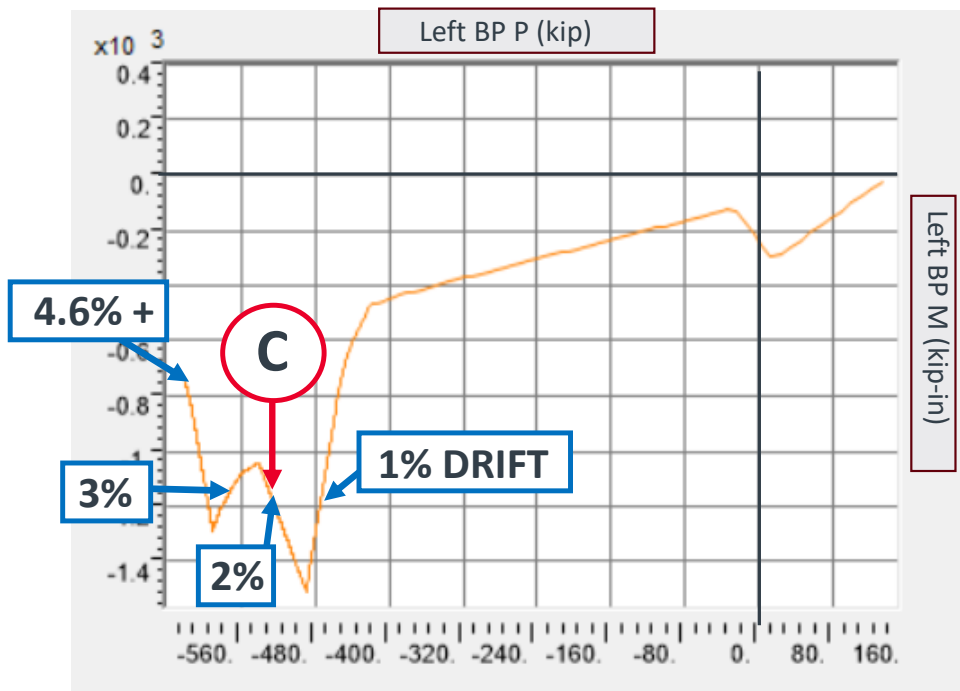
## Understanding Behavior- Tension Side



P-M Diagram for Base Plate Experiencing Uplift

- A. Design Overturning Moment (5760 k-ft)  
(base shear forces)
- B. Overstrength Overturning Moment (15,100 k-ft)  
(all braces yield and strain harden)  
(frame action not included)
- C. Overturning Moment Corresponding to Anchor Rod Design Capacity (16,900 k-ft)
- D. Overturning Moment For Full Expected Yield of Rods (20,700 k-ft)  
**-This point is not be reached**  
**-Frame does not have sufficient overturning capacity (even with frame action)**  
(anchors yield in direct tension from frame plus prying due to rotation)

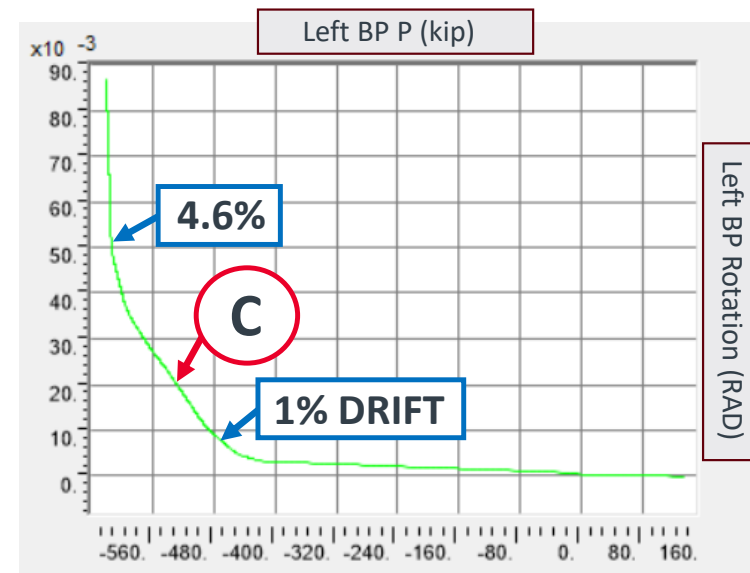
## Understanding Behavior- Tension Side



P-M Diagram for Base Plate Experiencing Uplift

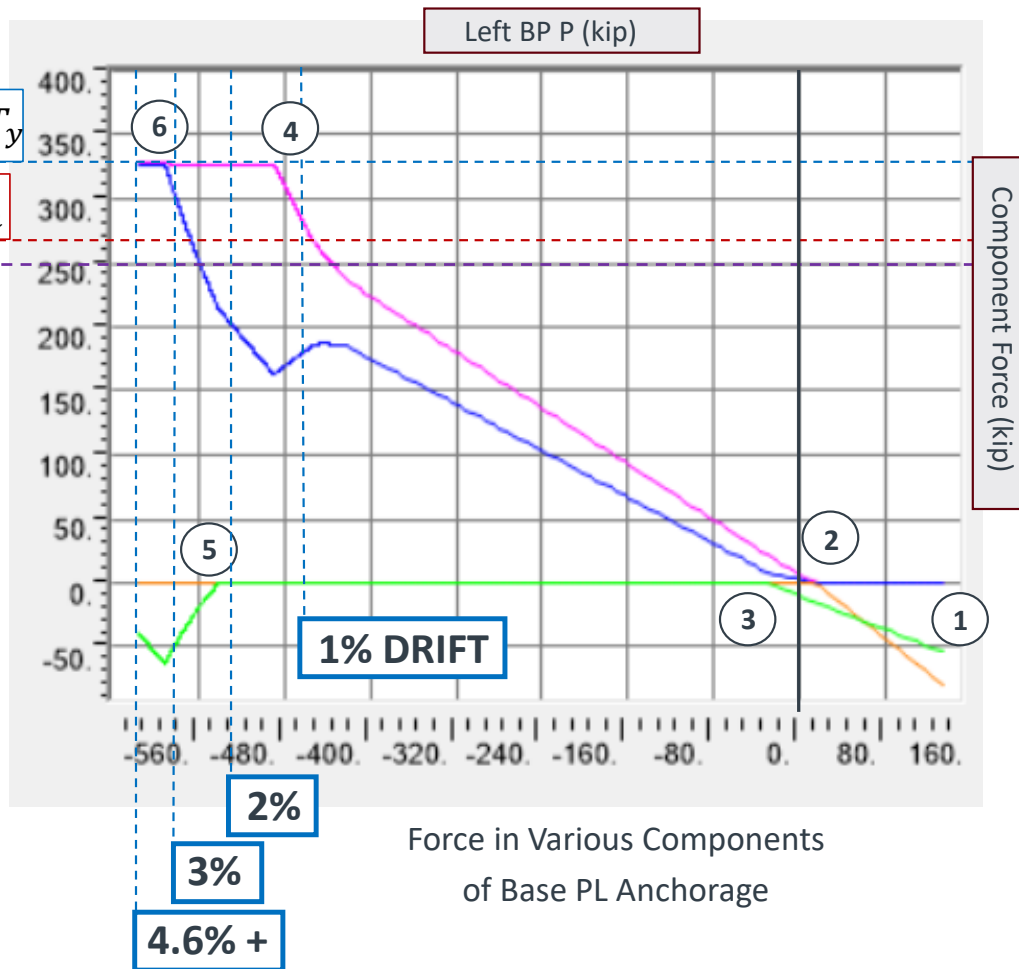
C. Overturning Moment Corresponding to Anchor Rod Design Capacity (16,900 k-ft)

At ~4.6% drift a story mechanism is created at every level



BP Rotation vs Axial Load

# Understanding Behavior- Tension Side



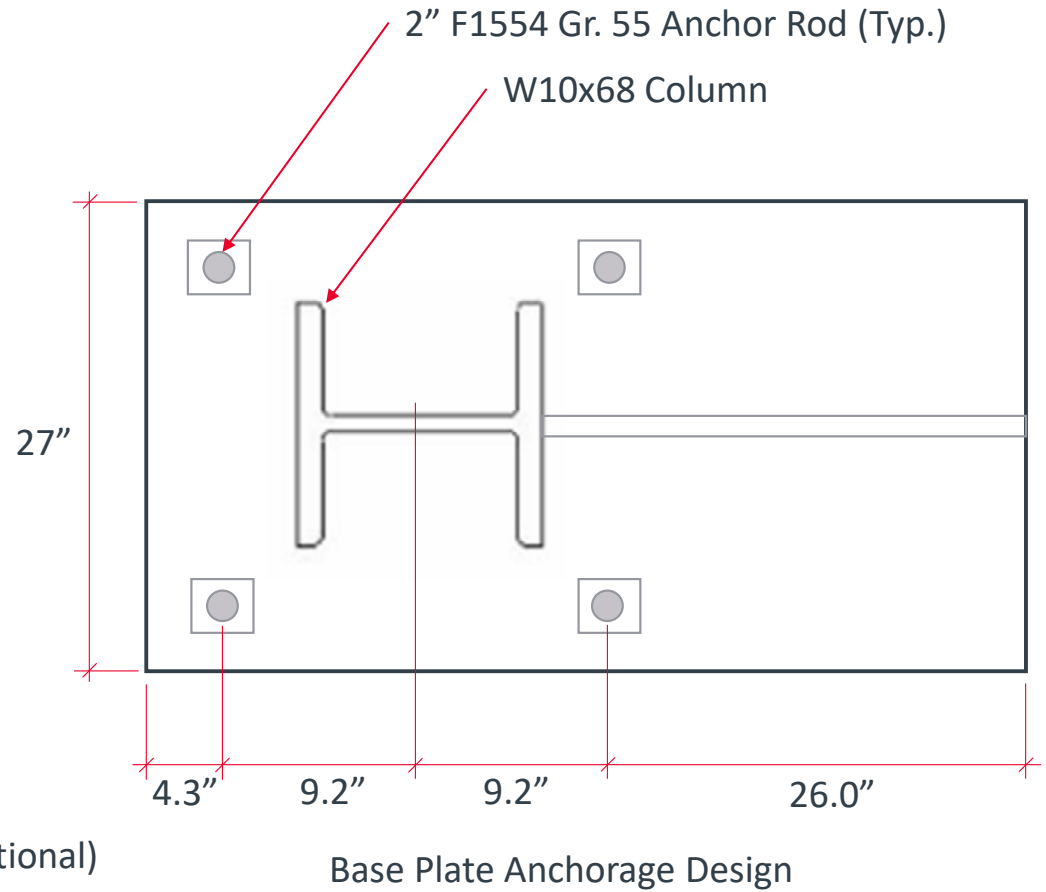
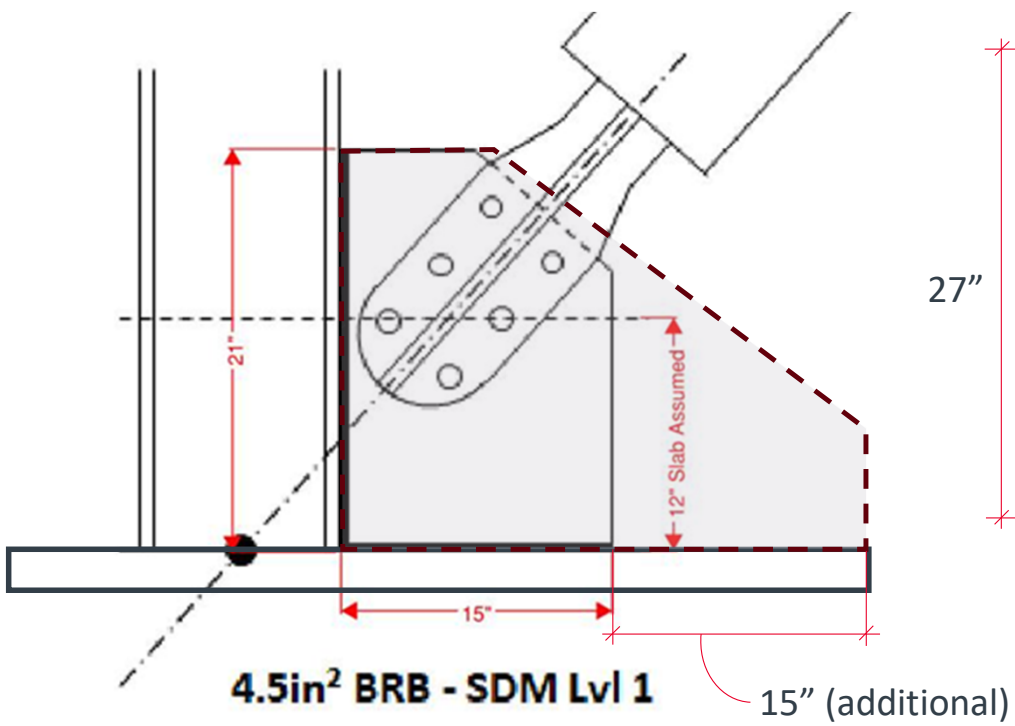
- Outside bearing
- Inside bearing
- Inside anchor
- Outside anchor

1. Gravity loads only on BP
2. BP lifts off outside edge
3. BP lifts off bearing completely
4. Outer Anchor Yields
5. Bearing comes back into contact
6. Inner anchor yields

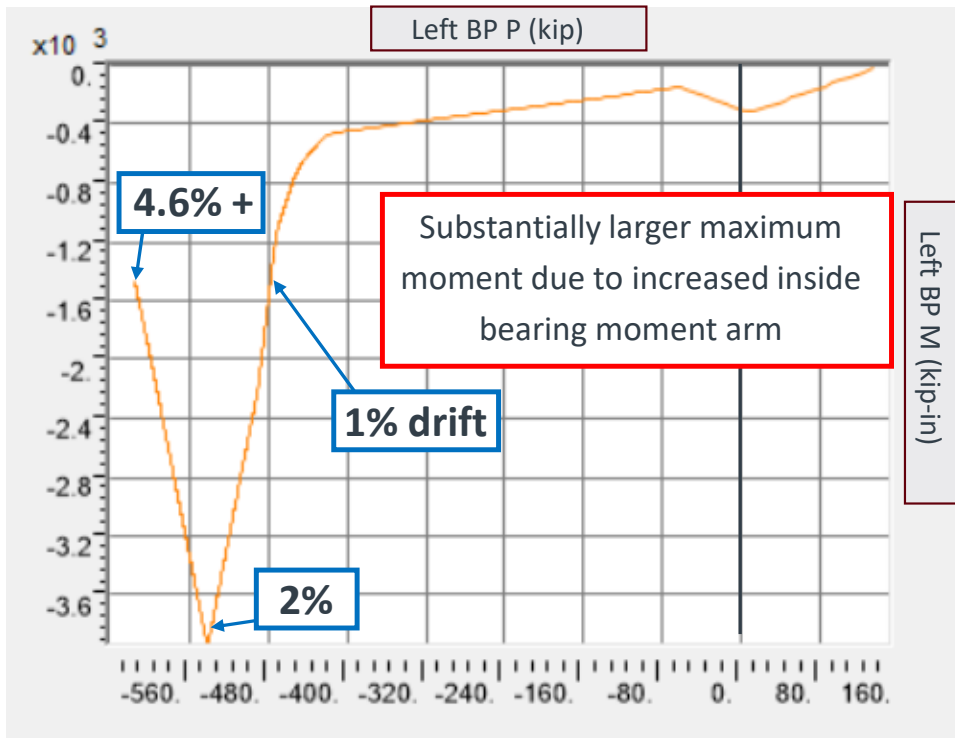
## Determine Required BP Rotation & Rod Elongation

	Event	Column Base Rotation $\theta_{CB}$ (degrees)	Lateral Drift Angle $\theta$ (degrees)	Calculated anchor elongation		Analyzed anchor elongation
				$\Delta = \theta_{CB}d_1$	$\Delta = \theta d_1$	
		(degrees)	(degrees)	(in)	(in)	(in)
1	Gravity Loads Only	0.00	0.00	0.00	0.00	0.00
2	BP Lifts Off Outside Bearing	0.00	0.047	0.00	0.024	0.00
3	BP Lifts Off Bearing Completely	0.050	0.070	0.026	0.036	0.026
A	<u>Design Overturning Moment</u>	0.073	0.10	0.037	0.053	0.067
B	<u>Overstrength Overturning Moment</u>	0.36	0.46	0.18	0.24	0.33
4	Outer Anchor Yields	0.61	0.76	0.31	0.39	0.39
C	<u>Anchor Rod Design Capacity</u>	1.2	1.2	0.61	0.61	0.62
5	Inside Bearing Back in Contact	1.3	1.3	0.68	0.67	0.68
6	Inner Anchor Yields	2.0	2.0	1.0	1.0	1.0
	Final	3.7	3.4	1.9	1.8	1.9

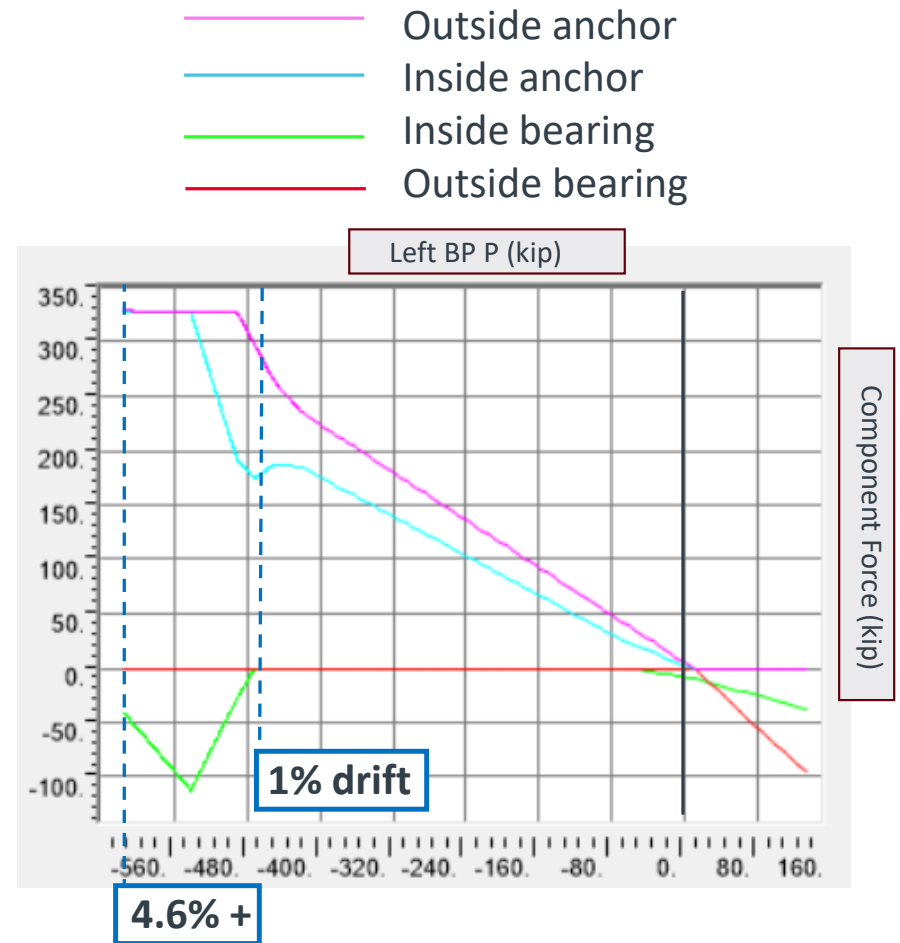
# Long Gusset Plate Variant



# Longer Gusset Plate Variant



P-M Diagram for Base Plate Experiencing Uplift  
(Long BP Variant)



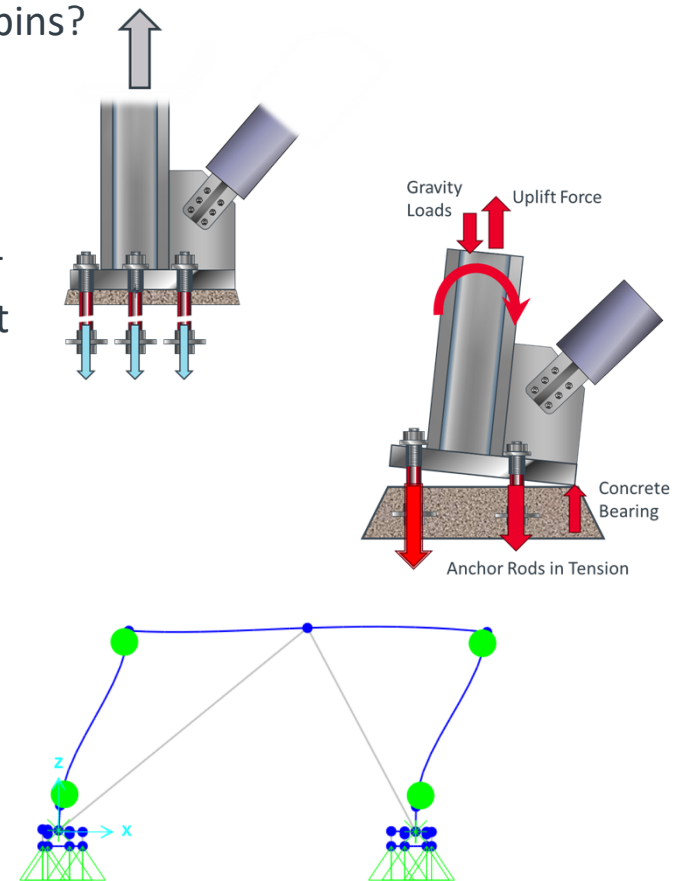
Force in Various Components of Base PL Anchorage  
(Long BP Variant)

## Base PL Connection Pin Model

Original Question: Can gusseted base-plate connections be modeled as pins?

Answer: Yes & No

- Forces in anchor rods **are not directly captured**
  - Full frame uplift strength < anchor design strength per AISC 341
  - Anchors nevertheless yield due to combined uplift and moment
- Rotations at base plates **are captured**
  - These can be used to establish anchor-rod elongation
- Moment demands on columns and foundations **are not captured**
  - AISC 341 allows the engineer to neglect the column moment
    - Not an issue specific to base-plate design
  - Foundation moments should be considered
    - Capacity design or ductile detailing may be used



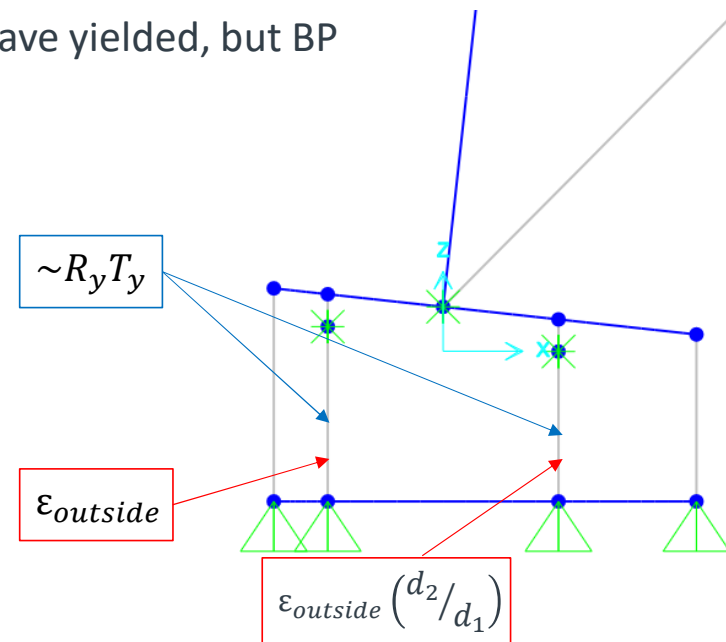
---

## Base Connection Flexural Demands

Original Question: Should flexural demands be added to uplift on anchors?

Answer: Yes (For Deformations) & No (For Forces)

- Force is very similar in all anchors once they have yielded, but BP rotation causes differing strain in anchor rods



---

## Summary

- Anchors yield regardless of design calculation
  - Anchor forces equalize after base-plate lift-off and yield of anchors
- Gap-and-hook model results consistent with limit-state models
  - Anchor elongation
    - 0% difference for 2% drift
    - 9% difference for 3.4% drift
- Gap history events interesting, but not consequential
- Design method appears to be validated
- Future research may allow reduced anchor demands at the expense of modeling complexity
  - Base plate flexural deformation reduces anchor elongation
  - Grout deformation or crushing reduces anchor elongation and connection moment

# Rocky Mountain Power

RMP HQ Base Plate Design (SEAU)  
2026.02.12

ROCKY MOUNTAIN POWER HQ  
PRELIMINARY STRUCTURE  
SKIDMORE, OWINGS & MERRILL

SOM

# Rocky Mountain Power



# Rocky Mountain Power Project Location



# Rocky Mountain Power Project Location



# Rocky Mountain Power Building Information

- 10-Story Building
- 169' Tall
- Risk Category: III
- Typical Floor-to-Floor Height: 14'-0"
- Lateral Force-Resisting System: Steel BRB Frames
- Gravity Force-Resisting System: Steel Composite Framing
- Foundation System: Auger Cast-In Place Piles

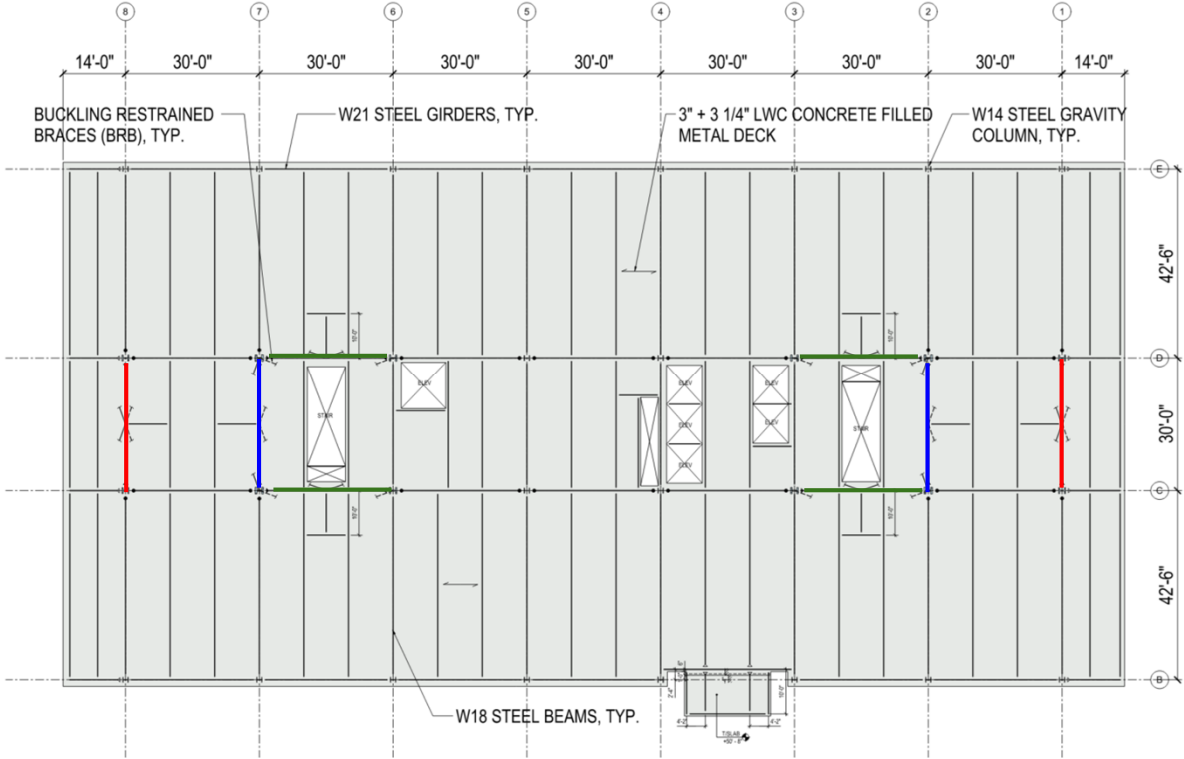
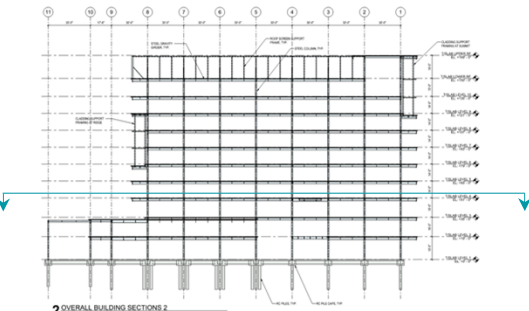
Project Status: In Construction



# Structural Framing Plan

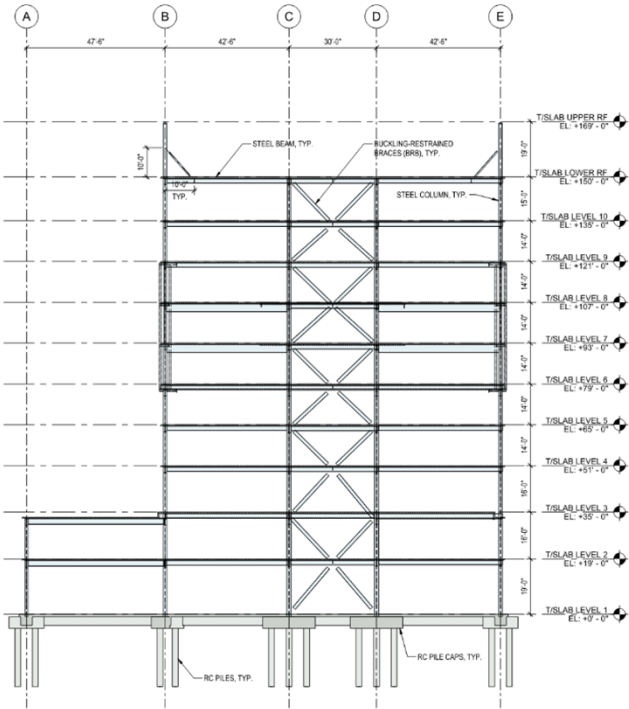
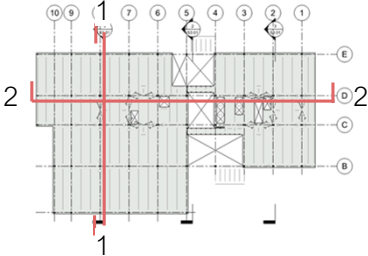
## Typical Tower Framing Plan

- Cross (X)
- Inverted Chevron (Λ)
- Chevron (V)

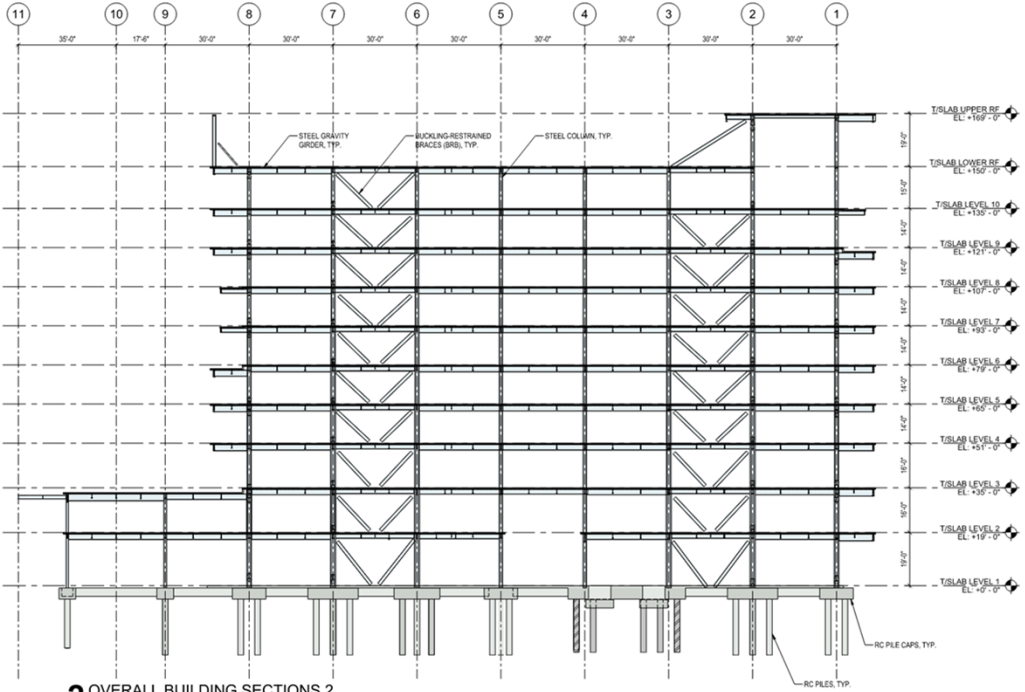


# Structural Section

## Transverse Direction



**1** OVERALL BUILDING SECTIONS 3  
SCALE: 1/16" = 1'-0"



**2** OVERALL BUILDING SECTIONS 2  
SCALE: 1/16" = 1'-0"

# Structural Analysis

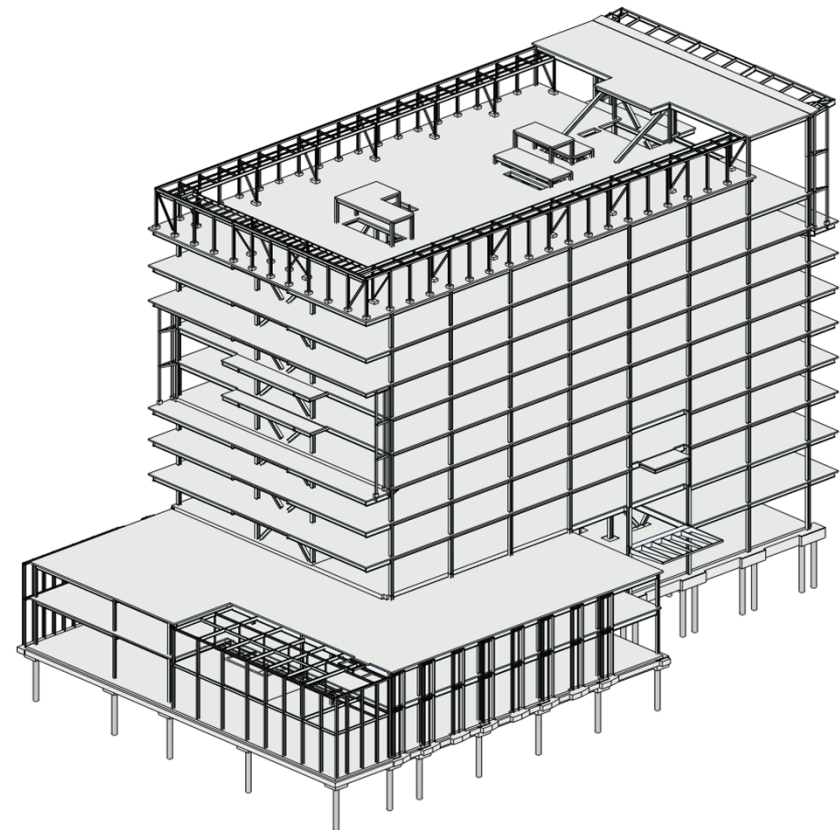
## Design Criteria (Code-Based)

- Building Code:
- Seismic Force-Resisting System:
- Gravity Force-Resisting System:
- Risk Category:
- Seismic Design Category
- Site Class:
- Importance Factor:
- Allowable Drift Ratio
- Seismic Design Parameters:
- Surface Roughness Category:
- Exposure Category:
- Mean Recurrence Interval:
- Equivalent Basic Wind Speed:
- Service Wind Speed:

Steel BRB Fra  
 $R = 8, C_d = 5, \Omega_o = 2.5$

Steel Compos

$S_{DS} = 0.82G, \rho$



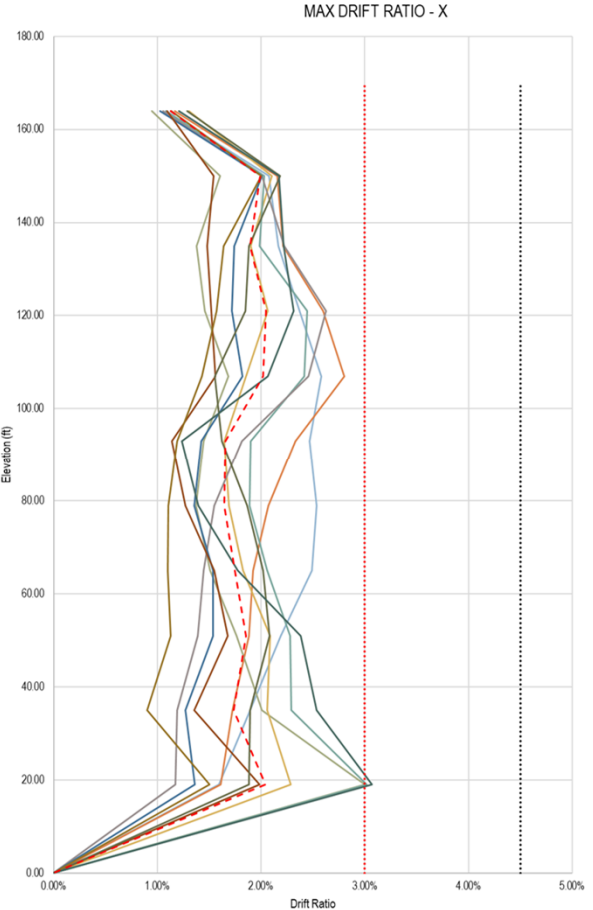
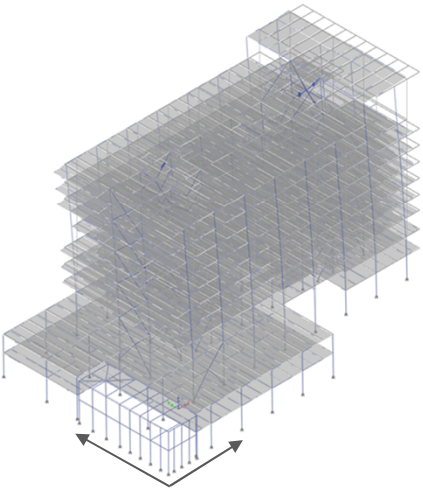
109 mph

84 mph (50 years)

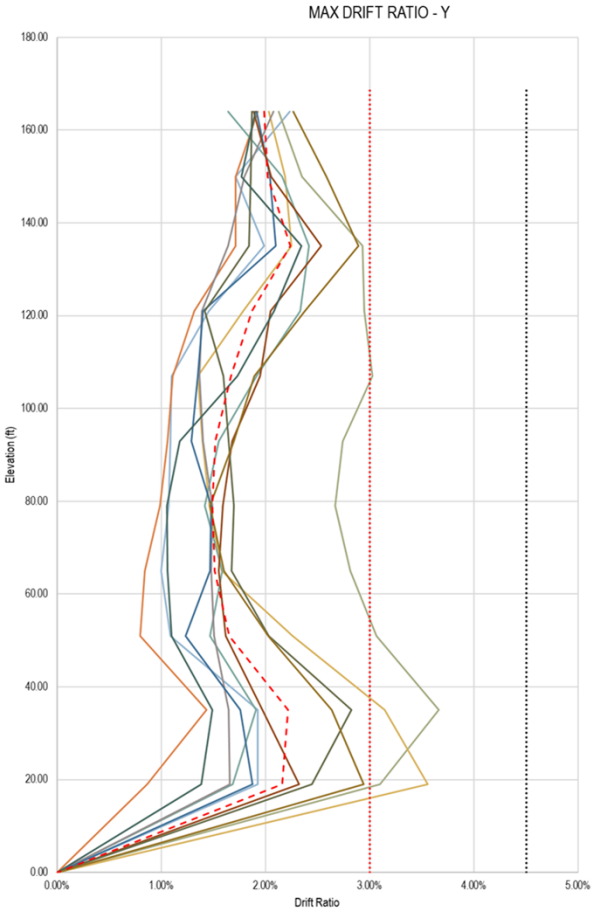
# Nonlinear Response History Analysis

## Story Drifts

### Nonlinear Response History Analysis per ASCE 7-22 Ch. 16



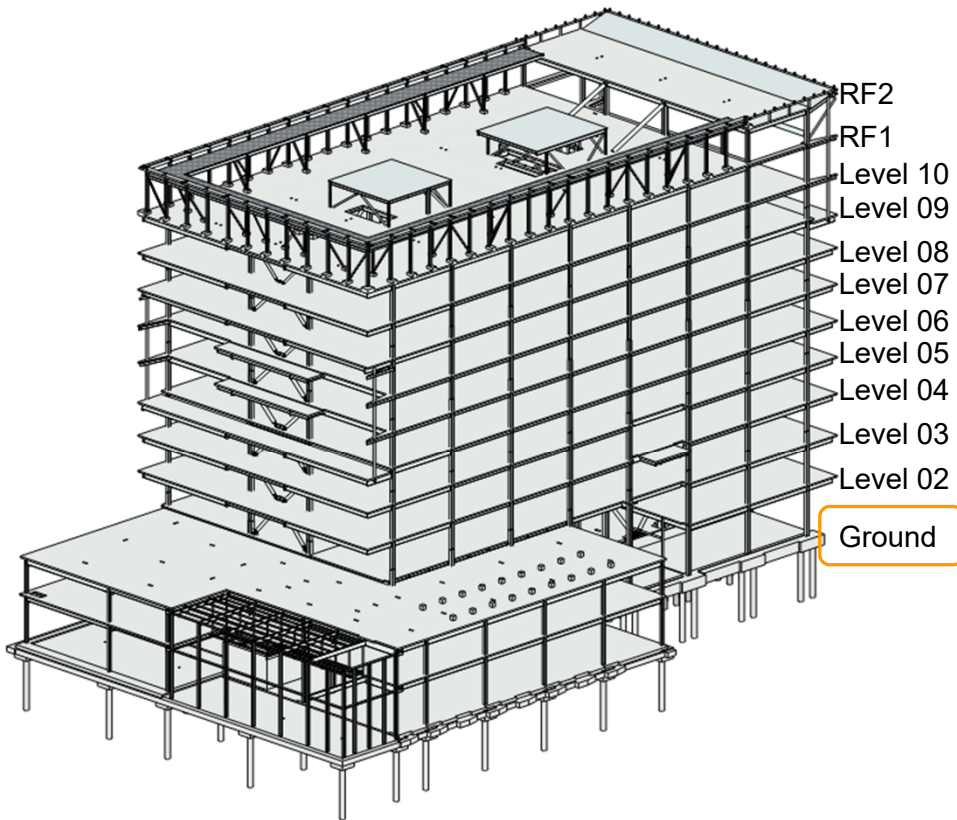
- NTH01 KOBE AMA
- NTH02 KOBE TAK
- NTH03 ITALY A-BAG
- NTH04 SMART\_4511
- NTH05 CHUJETSU
- NTH06 IWATE
- NTH07 SMART\_4501
- NTH08 DARFIELD\_DSLCN
- NTH09 DARFIELD\_HORCN
- NTH10 LOMAP
- NTH11 LANDERS
- - - AVERAGE
- ..... SINGLE GM LIMIT
- ..... AVG LIMIT



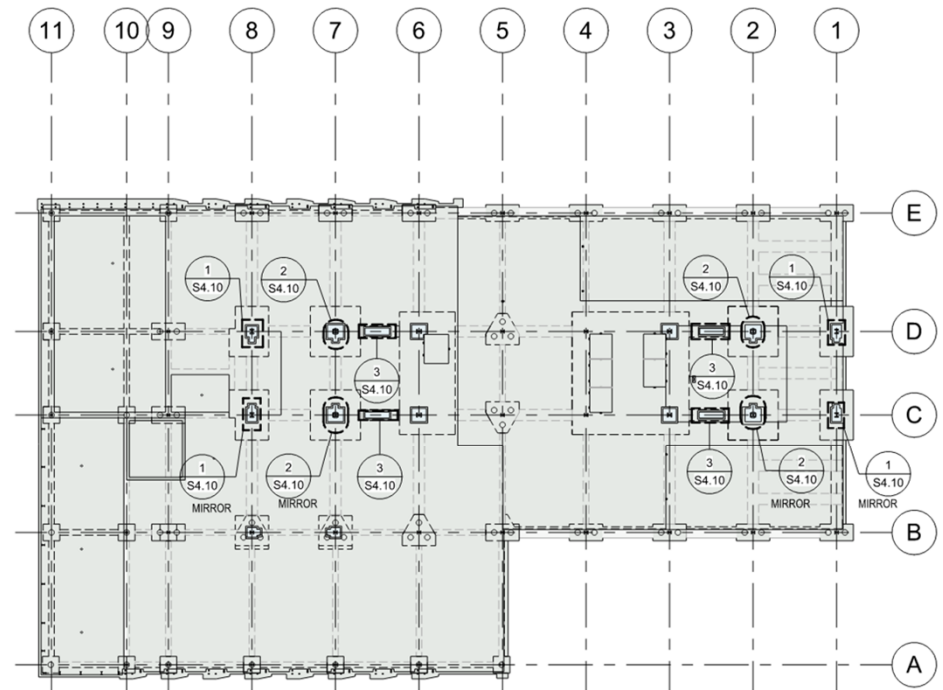
- NTH01 KOBE AMA
- NTH02 KOBE TAK
- NTH03 ITALY A-BAG
- NTH04 SMART\_4511
- NTH05 CHUJETSU
- NTH06 IWATE
- NTH07 SMART\_4501
- NTH08 DARFIELD\_DSLCN
- NTH09 DARFIELD\_HORCN
- NTH10 LOMAP
- NTH11 LANDERS
- - - AVERAGE
- ..... SINGLE GM LIMIT
- ..... AVG LIMIT

# Anchor Plate Design

## BRB Base Key Plan

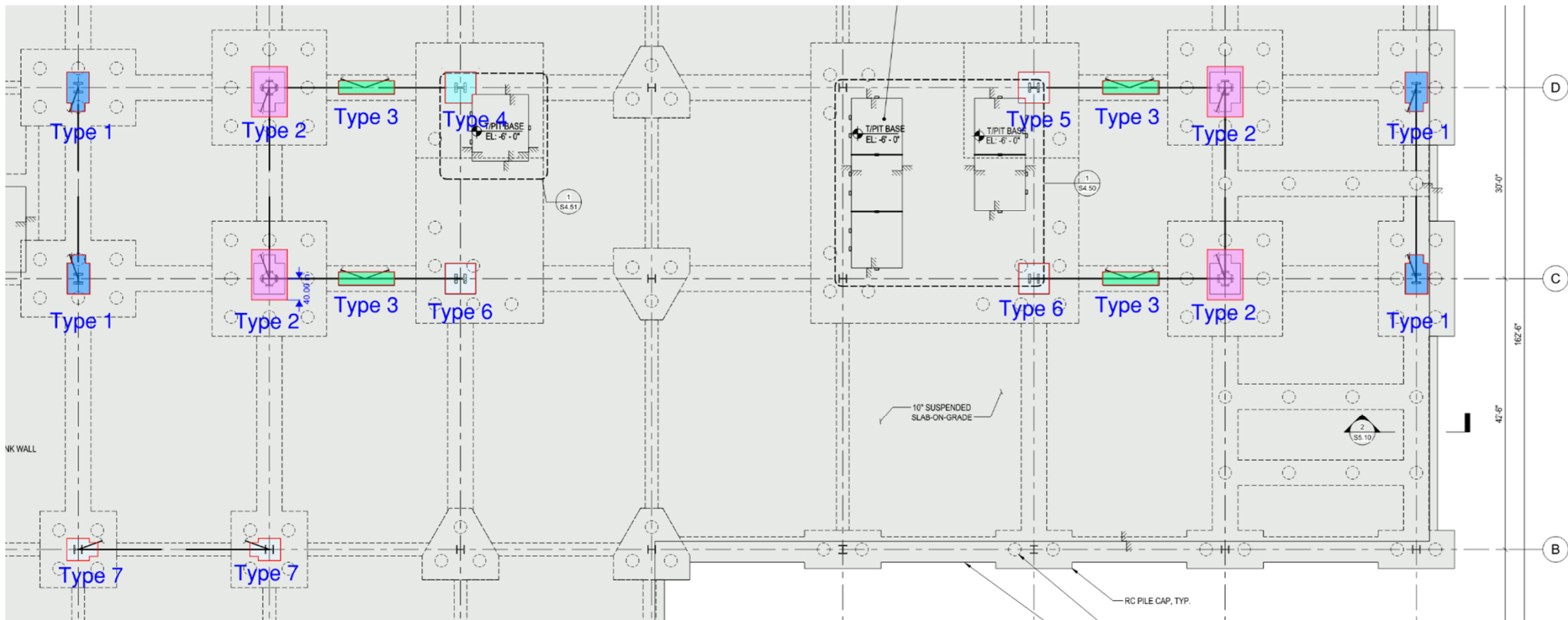


1 OVERALL 3D VIEW  
SCALE:



4 BRB BASE KEY PLAN  
SCALE: 1/32" = 1'-0"

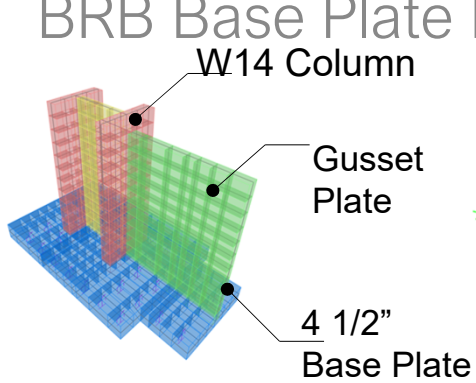
# Anchor Plate Design BRB Base Key Plan



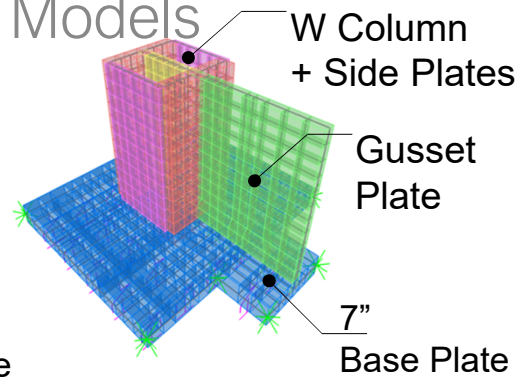
ROCKY MOUNTAIN POWER HQ  
STRUCTURAL PEER REVIEW  
SKIDMORE, OWINGS & MERRILL

# Anchor Plate Design

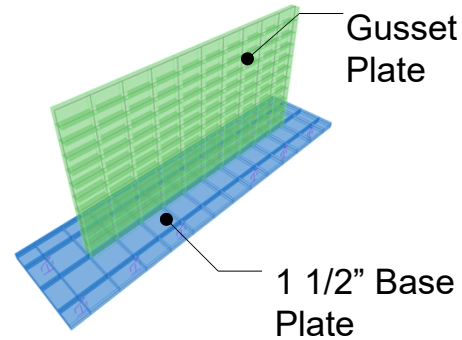
## BRB Base Plate Models



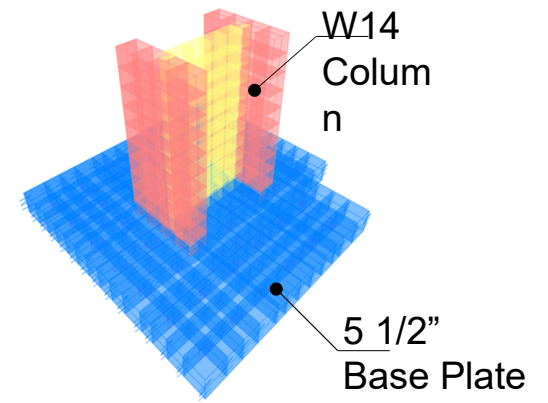
Type 1



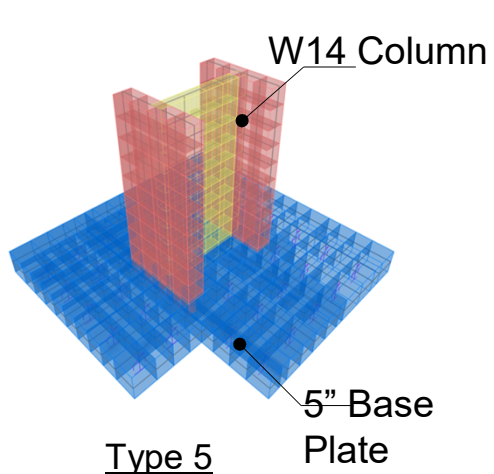
Type 2



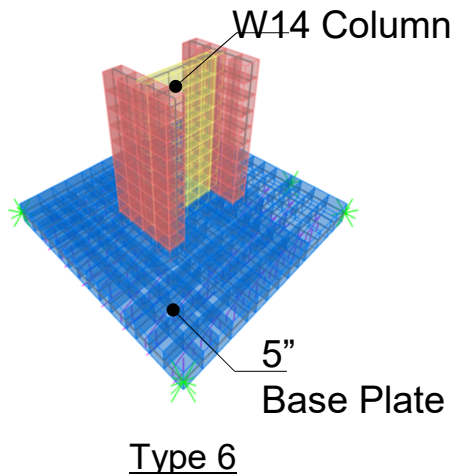
Type 3



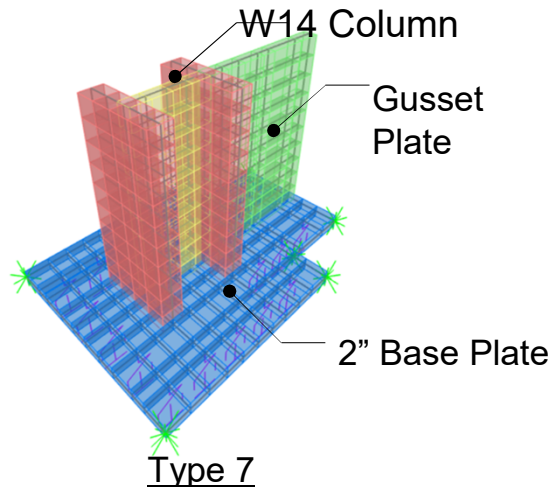
Type 4



Type 5



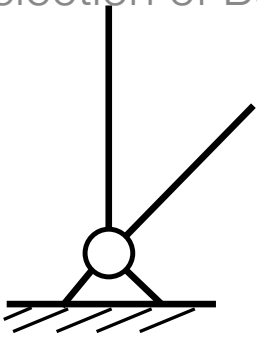
Type 6



Type 7

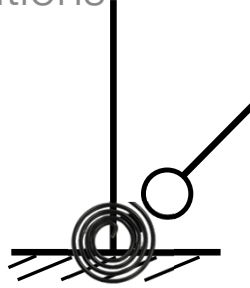
# Anchor Plate Design

## Selection of Base Boundary Conditions



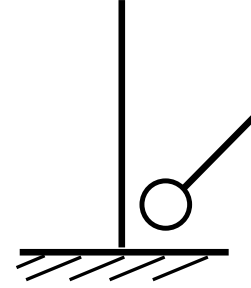
**Pinned Base**

1. Design anchor system to take axial and shear force from load combinations per ACI 318 Chapter 17.
2. Allow yielding of anchor rods and design anchor system to meet ductility criteria per ACI 318 Ch. 17.5.3.
3. Deformation-Controlled Design



**Spring Base**

1. Establish an anchor system model to estimate rotational spring constant
2. Design anchor system to take axial, shear force, and moment from load combinations per ACI 318 Chapter 17.
3. Force-Controlled Design.

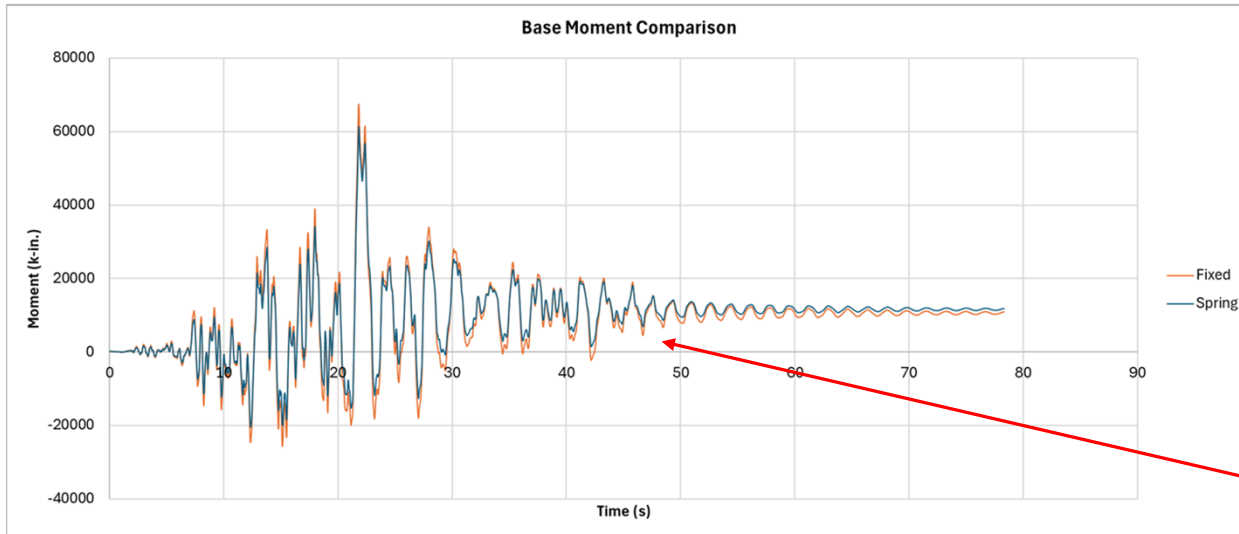
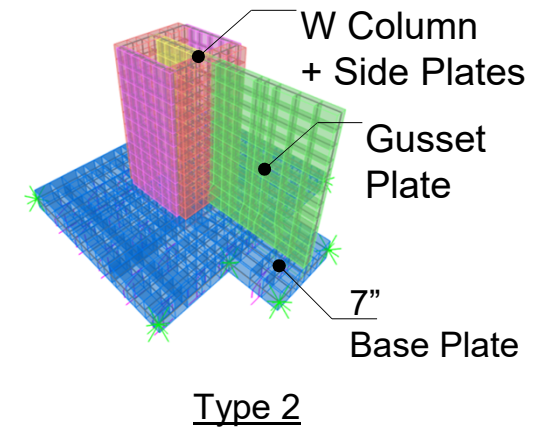
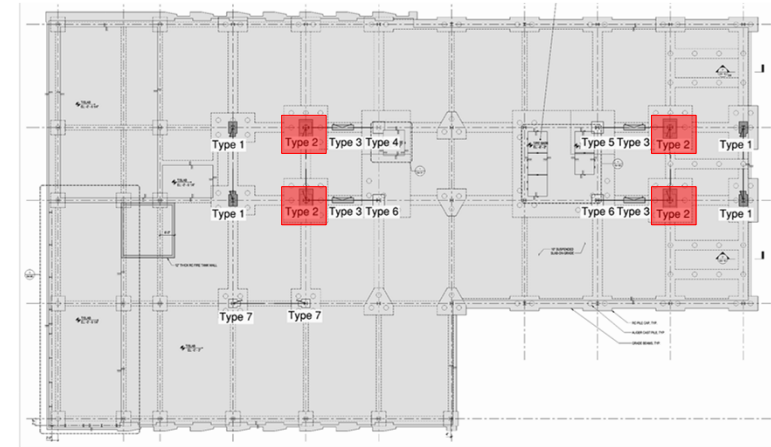
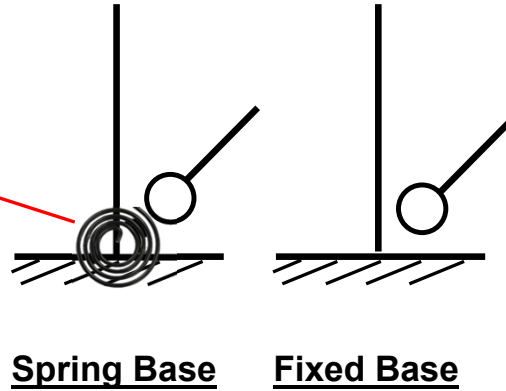
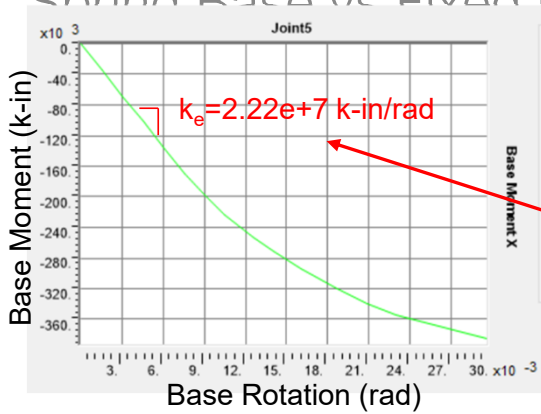


**Fixed Base**

1. Design anchor system to take axial, shear force, and moment from load combinations per ACI 318 Chapter 17.
2. Force-Controlled Design.

# Anchor Plate Design

## Spring Base vs Fixed Base

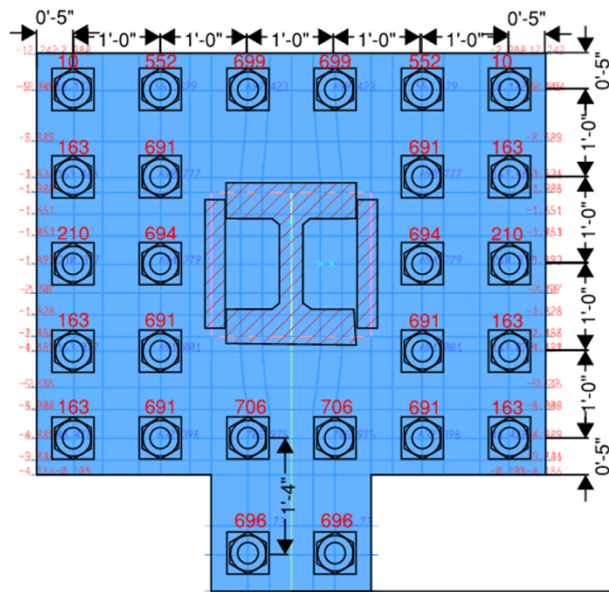


No significant difference for the selected case study.

# Anchor Plate Design

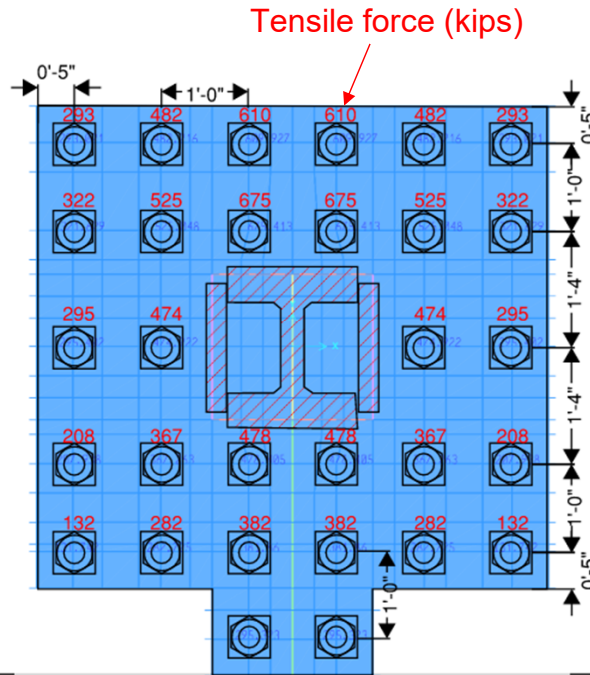
Fixed Base Design

## Tension Forces on Rods



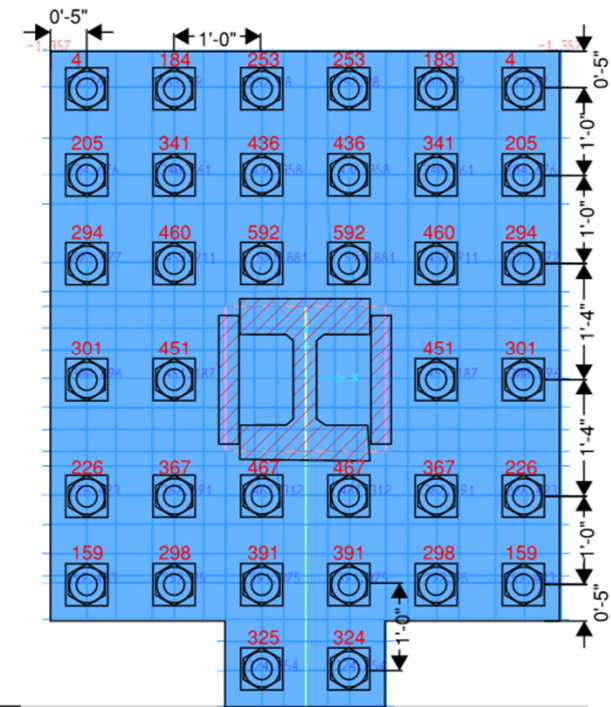
**Iteration 1**

1. Max. Rod Tensile Force (3" Rod) = 706 kips (DCR = 1.20)
2. Base Plate Thickness = 7 in.



**Iteration 2**

1. Max. Rod Tensile Force (3" Rod) = 675 kips (DCR = 1.14)
2. Base Plate Thickness = 12 in.
3. (Or adding stiffeners)



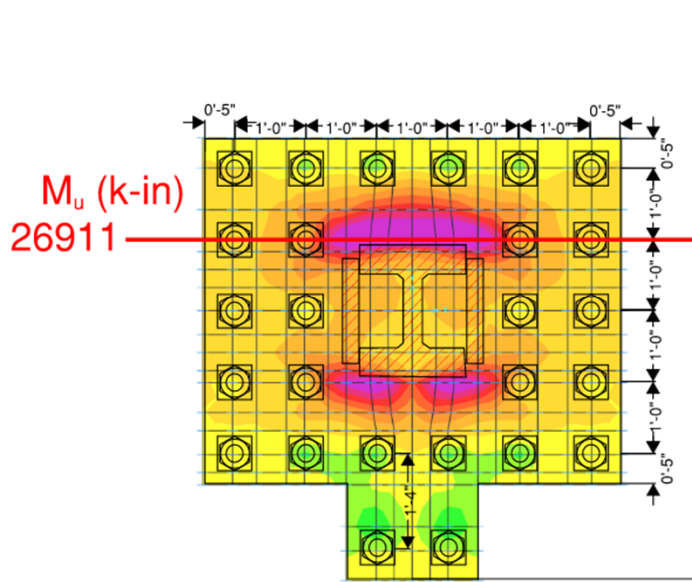
**Final**

1. Max. Rod Tensile Force (3" Rod) = 592 kips (DCR = 1.00)
2. Base Plate Thickness = 12 in.
3. (Or adding stiffeners)

# Anchor Plate Design

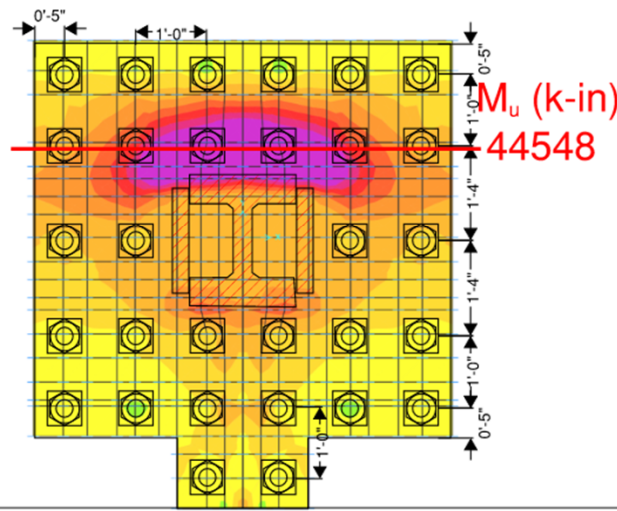
## Fixed Base Design

### Bending Moment on Base Plates



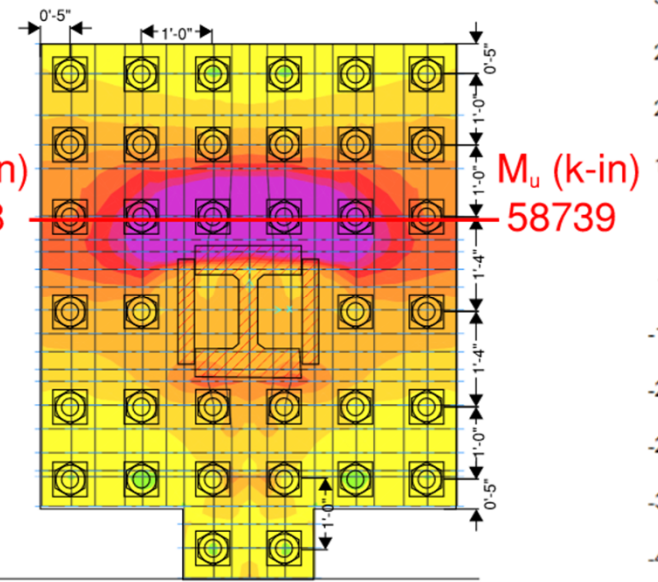
**Iteration 1**

1. Moment DCR = 0.92
2. Base Plate Thickness = 7 in.



**Iteration 2**

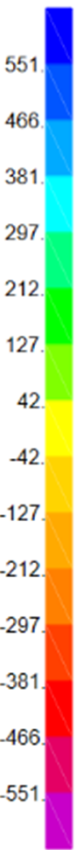
1. Moment DCR = 0.62
2. Base Plate Thickness = 12 in.  
(Or adding stiffeners)



**Final**

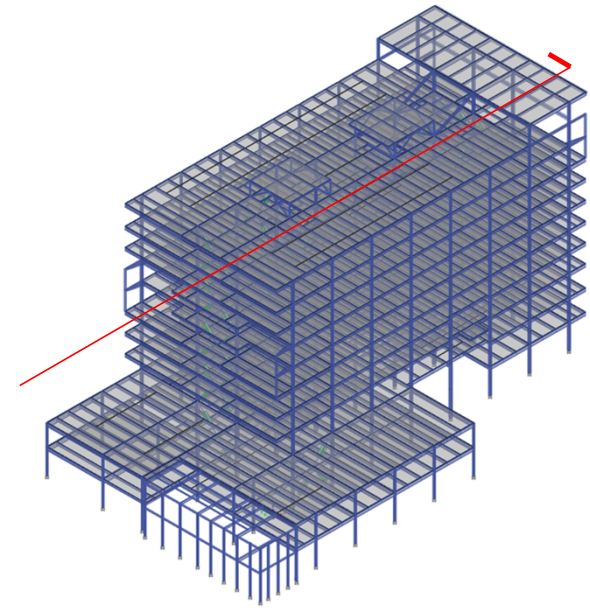
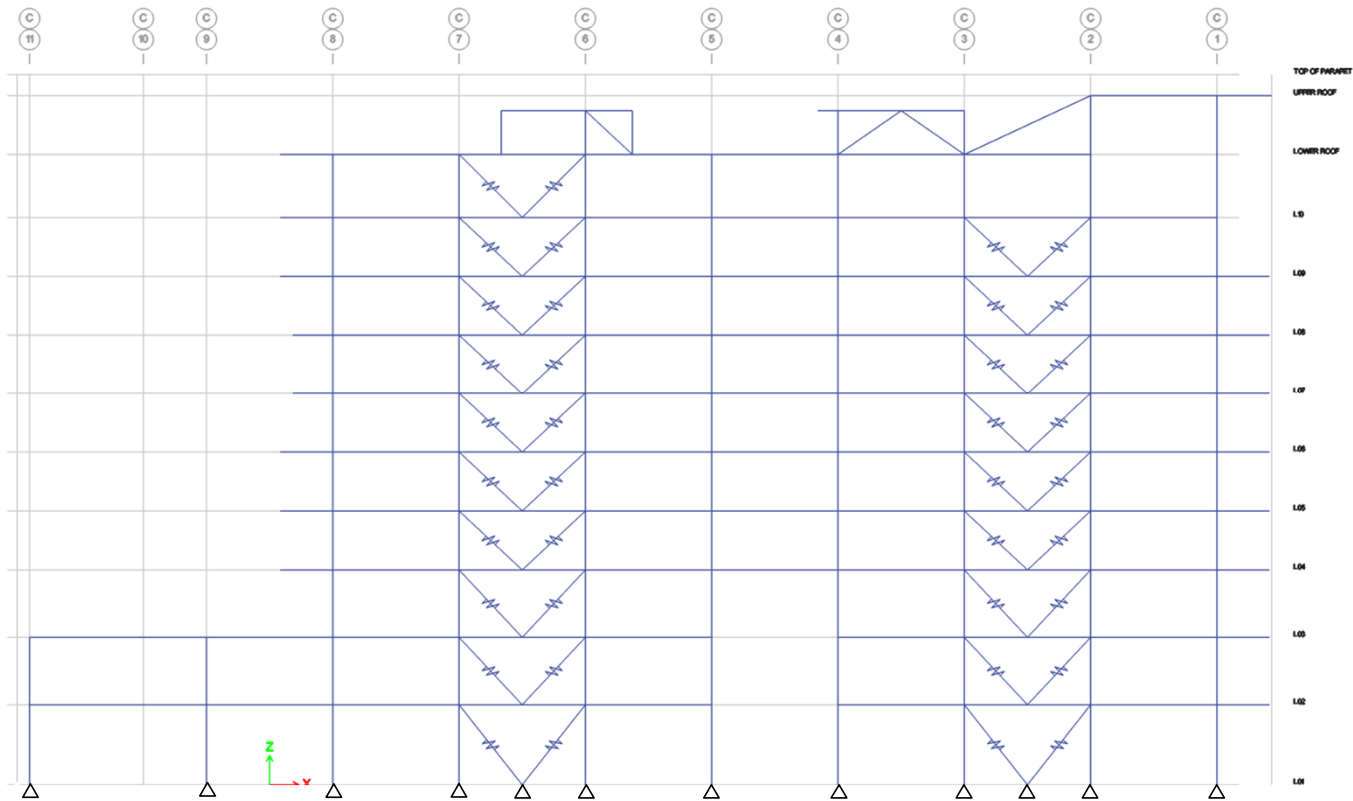
1. Moment DCR = 0.81
2. Base Plate Thickness = 12 in.  
(Or adding stiffeners)

Moment  
(k-ft/ft)



# Anchor Plate Design

## Pinned Base Model Elevation

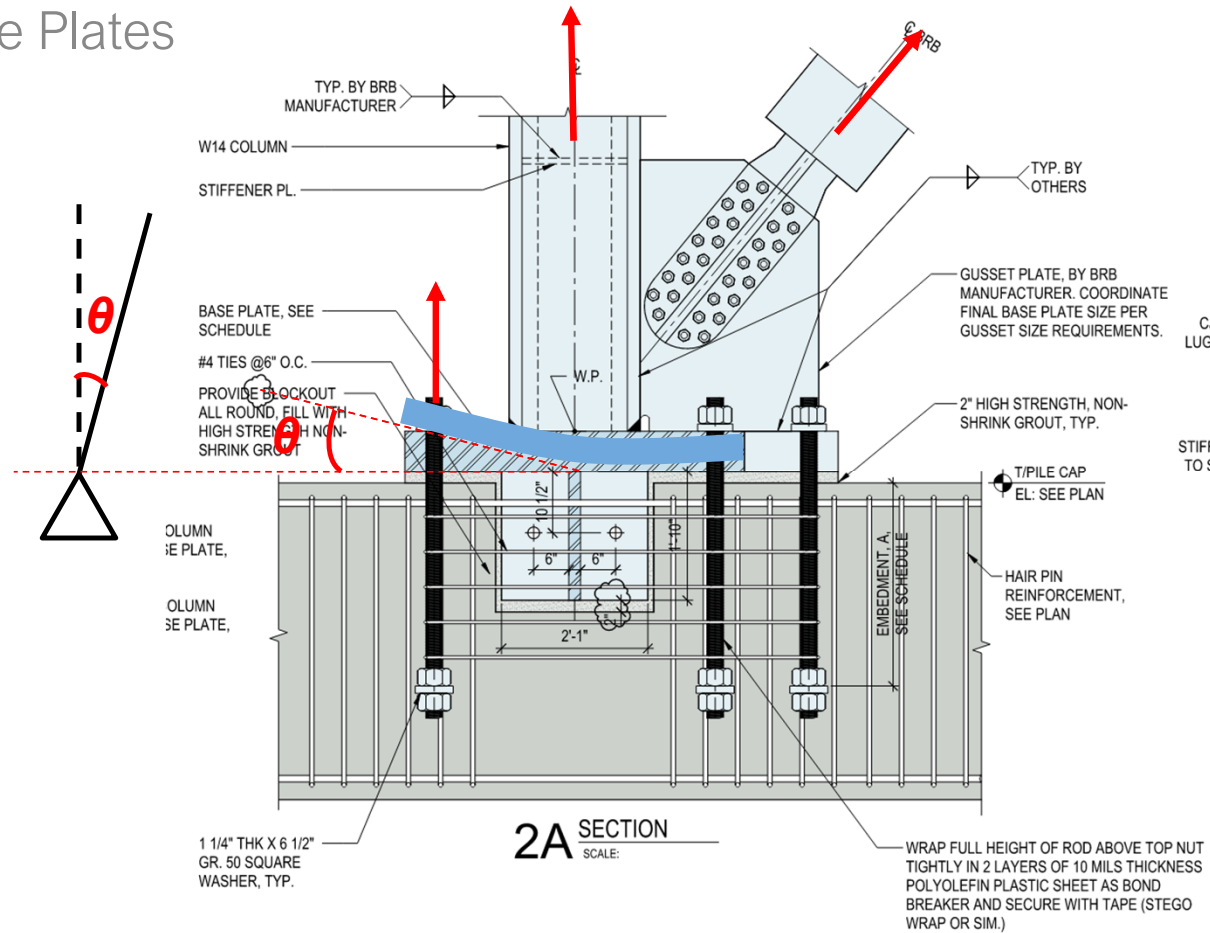


# Anchor Rod Design

## Ductile Demand for Pinned BRB Base Plates

### Design of Pinned Base Plates

1. Establish Target Drift
  - 2% Drift (Average MCE NLRHA)
  - 3% Drift (Max. MCE NLRHA)
1. Design Anchor Plate per ACI 318 Chapter 17
  - Allow Anchor Rod to undergo Yielding
1. Design Rod Axial Deformation
  - Meet Acceptance Axial Deformation Criteria



# Bonded and Unbonded Rods

# Rocky Mountain Power Reference 1 for Bonded Bars

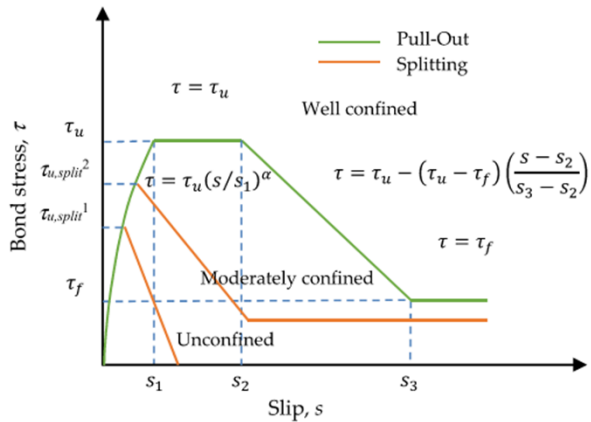


Figure 16. Analytical bond stress-slip relationship (CEB-FIP Model Code 2010).

Table 8. Parameter values of the prediction model for the bond stress-slip relationship.

Parameter	CEB-FIP Model [15]	Huang et al. [37]	Harajli et al. [40]	This Study
	Confined Concrete	Normal Strength Concrete	Concrete	Confined Concrete
$s_1$	1.0 mm	1.0 mm	0.15 Distance bet. ribs	Equation (15)
$s_2$	3.0 mm	3.0 mm	0.35 Distance bet. ribs	3.0 mm
$s_3$	Distance bet. ribs	Distance bet. ribs	Distance bet. ribs	Distance bet. ribs
$\alpha$	0.4	0.4	0.3	0.3
$\tau_u$	$2.5\sqrt{f'_c}$	$0.4f_{cm}$	$2.57\sqrt{f'_c}$	Equation (13)
$\tau_f$	$0.4\tau_u$	$0.4\tau_u$	$0.9\sqrt{f'_c}$	$0.4\tau_u$

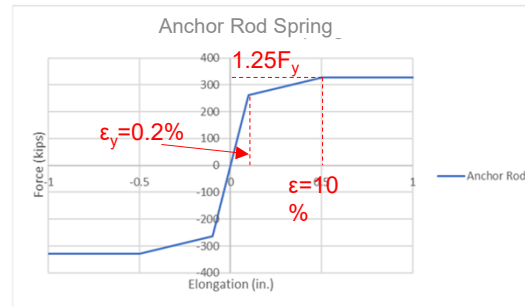
ROCKY MOUNTAIN POWER HQ  
PRELIMINARY STRUCTURE  
SKIDMORE, OWINGS & MERRILL



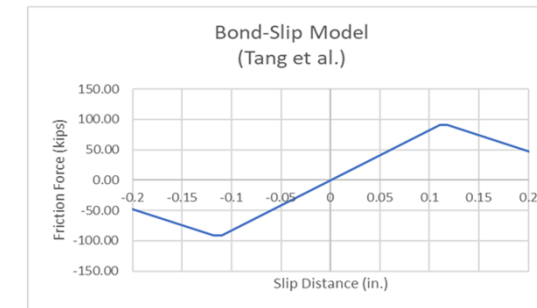
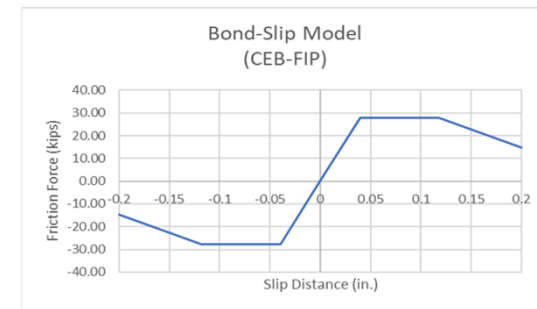
Article

## Modeling Local Bond Stress-Slip Relationships of Reinforcing Bars Embedded in Concrete with Different Strengths

Chao-Wei Tang <sup>1,2,3,\*</sup> and Chiu-Kuei Cheng <sup>4</sup>

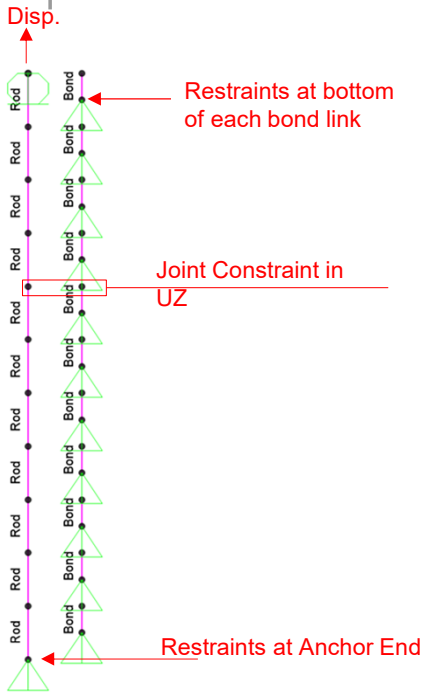


**Rod Model**



**Bond-Slip Model**

# Rocky Mountain Power Simplified Model for Bonded Rod

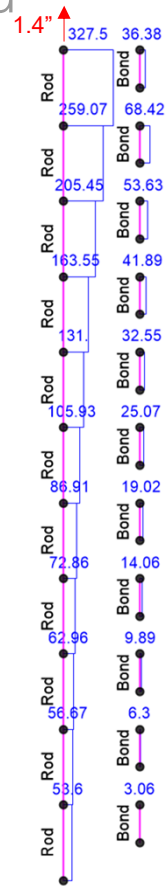


Rod + Bond

**SAP2000  
Model**

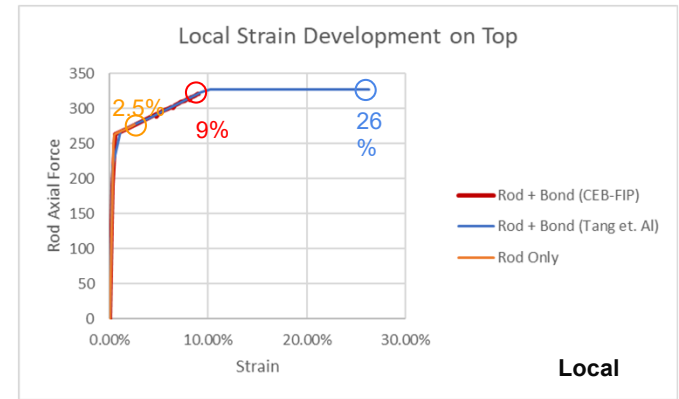
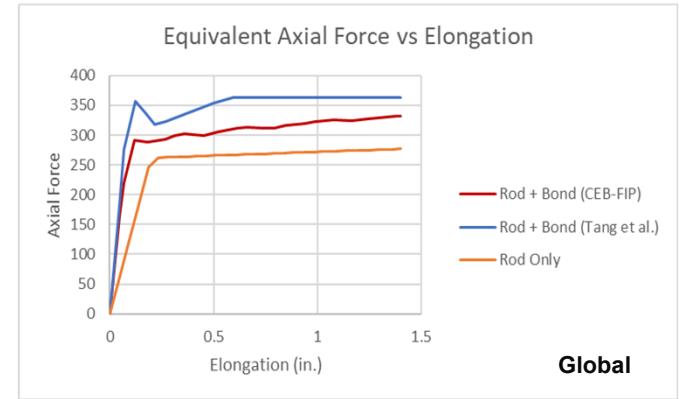


ROCKY MOUNTAIN POWER HQ  
PRELIMINARY STRUCTURE  
SKIDMORE, OWINGS & MERRILL



**Axial Force Distribution at Final Step**

(Tang et al. Model)



**Analysis Results**

# Rocky Mountain Power Reference 2 for Bonded Bars

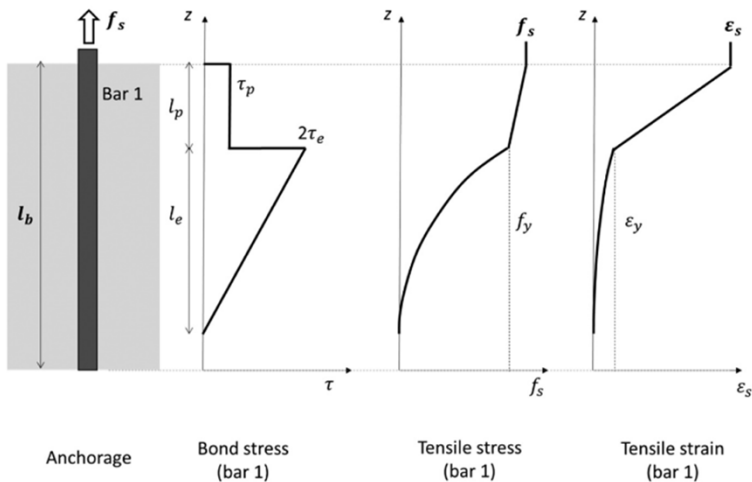


Fig. 2ons for steel bars yielding in tension and no slip at unloaded end.

$$l_p = \frac{(f_s - f_y) d_b}{4\tau_p}$$

$$l_e = \frac{f_y d_b}{4\tau_e}$$



Contents lists available at ScienceDirect

Structures

journal homepage: [www.elsevier.com/locate/structures](http://www.elsevier.com/locate/structures)



Tensile strength and slip model for steel reinforcement anchorages and lap splices

Juan Murcia-Delso <sup>a,\*</sup>, Matias Birrell <sup>b</sup>, Rodrigo Astroza <sup>b</sup>, Julian Carrillo <sup>c,d</sup>

## Mechanical Properties [Bar & Machined Specimen]

Property	Grade 36	Grade 55	Grade 105
<b>Tensile Strength, ksi</b>	<b>58 - 80</b>	<b>75 - 95</b>	<b>125 - 150</b>
Yield Strength, min, ksi (0.2% Offset)	36	55	105
Elongation in 8 inch, min, % [Note A]	20	18	12
Elongation in 2 inch, min, % [Note A]	23	21	15
Reduction of Area, min, %	40	30	45

Note A:

Elongation in 8 Inch applies to bars. Elongation in 2 inch applies to machined specimens.

### CEB-CIP Model

$$L_p = (1.25 - 1) f_y d_b / (4\tau_p) = 0.25 * 105 * 2" / 4 / 0.36 = 36.5"$$

$$L_e = f_y d_b / (4\tau_e) = 105 * 2" / (4 * 0.89 / 2) = 117.97" > (55 - 36.5)"$$

$$\rightarrow L_e = 18.5"$$

### Tang et al. Model

$$L_p = (1.25 - 1) f_y d_b / (4\tau_p) = 0.25 * 105 * 2" / 4 / 1.16 = 11.3"$$

$$L_e = f_y d_b / (4\tau_e) = 105 * 2" / (4 * 2.89 / 2) = 36.3" < (55 - 11.35)"$$

$$\rightarrow L_e = 36.3"$$

Considering all elongation happened at Lp region. Considering all elongation happened at Lp region.

$$\Delta = 1.4" = (\epsilon_y * L_e / 2) + (\epsilon_y + \epsilon_{top}) * L_p / 2$$

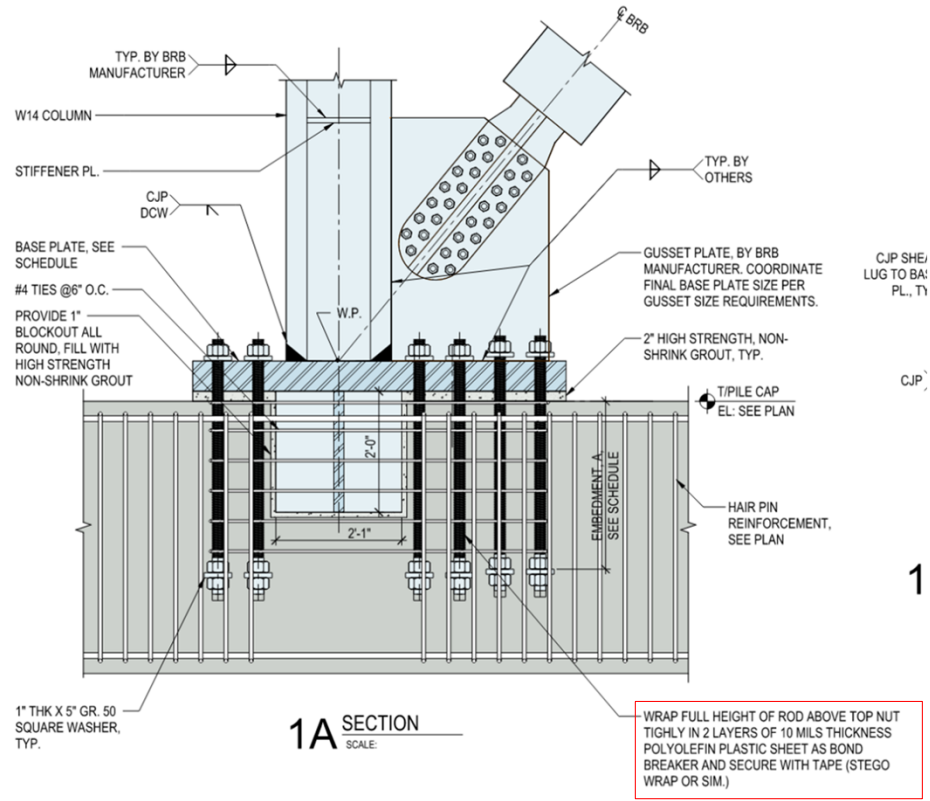
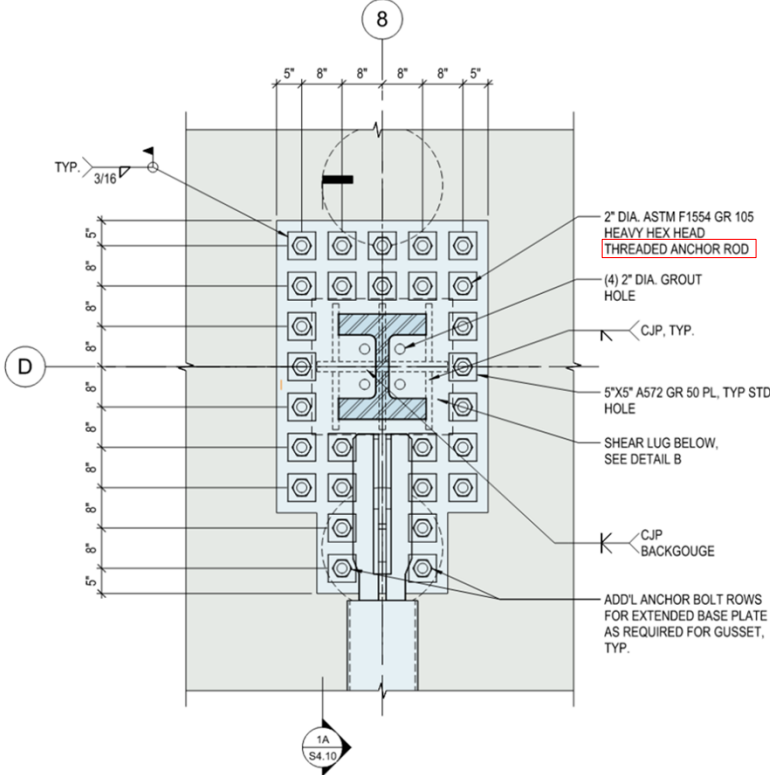
$$\rightarrow \epsilon_{top} = 0.074 = 7.4\%$$

$$\Delta = 1.4" = (\epsilon_y * L_e / 2) + (\epsilon_y + \epsilon_{top}) * L_p / 2$$

$$\rightarrow \epsilon_{top} = 0.239 = 23.9\%$$

ROCKY MOUNTAIN POWER HQ  
PRELIMINARY STRUCTURE  
SKIDMORE, OWINGS & MERRILL

# Rocky Mountain Power Updated Unbonded Rod Detail



**1** TYPICAL SINGLE BRACE COLUMN BASE PLATE DETAIL  
SCALE: 3/4" = 1'-0"

ROCKY MOUNTAIN POWER HQ  
PRELIMINARY STRUCTURE  
SKIDMORE, OWINGS & MERRILL

# Threaded/Unthreaded Length and Rod Axial Deformation Criteria



# Anchor Rod Specification

## ASTM F1554-17

**TABLE 3 Tensile Properties for Bars and Machined Specimens**

	Grade		
	36	55	105
Tensile strength, ksi	58–80	75–95	125–150
Yield strength, min, ksi (0.2 % offset)	36	55	105
Elongation in 8 in. , min, % <sup>A</sup>	20	18	12
Elongation in 2 in. min, % <sup>A</sup>	23	21	15
Reduction of Area, min, %	40	30	45

<sup>A</sup> Elongation in 8 in. applies to bars. Elongation in 2 in. applies to machined specimens.

# Anchor Rod Design

UCSD Report No. SSRP-2014/13 for F1554 A193 B7

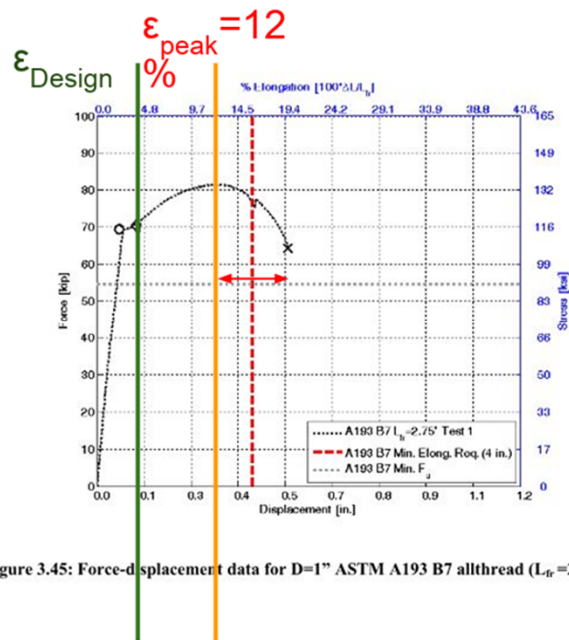


Figure 3.45: Force-displacement data for D=1" ASTM A193 B7 allthread ( $L_{tr}=2.75"$ )

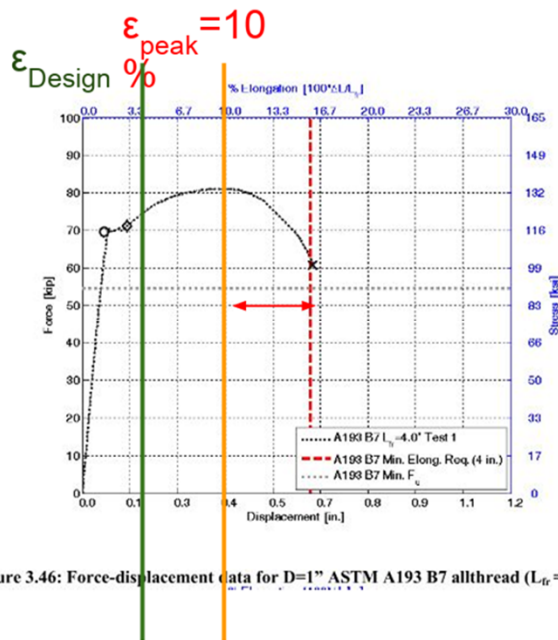


Figure 3.46: Force-displacement data for D=1" ASTM A193 B7 allthread ( $L_{tr}=4.0"$ )

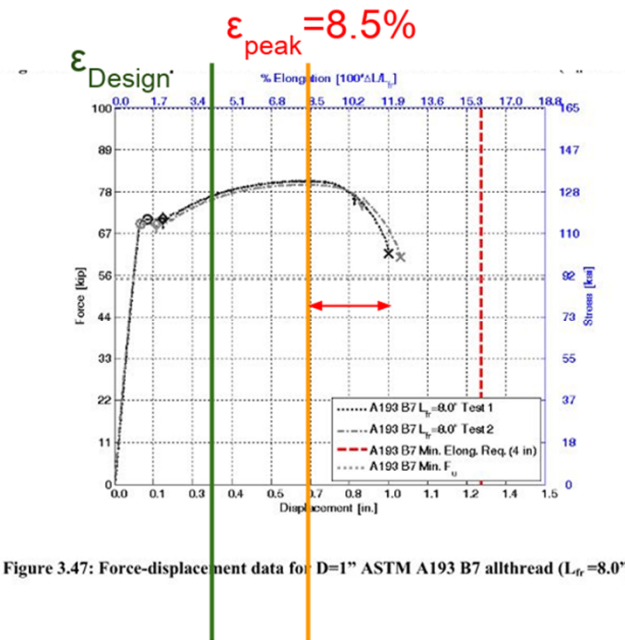


Figure 3.47: Force-displacement data for D=1" ASTM A193 B7 allthread ( $L_{tr}=8.0"$ )

Trautner, C., Copellini, M., & Hutchinson, T. (2015).

# Anchor Rod Design

## Base Plate Rotation Check (Type 2)

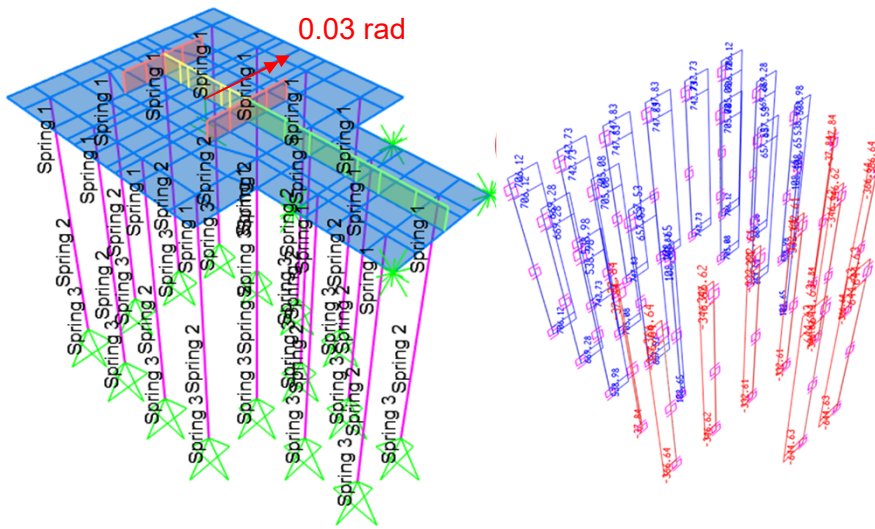
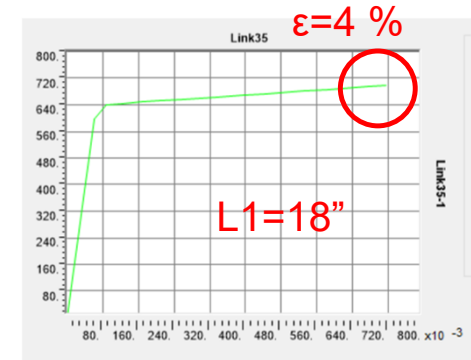
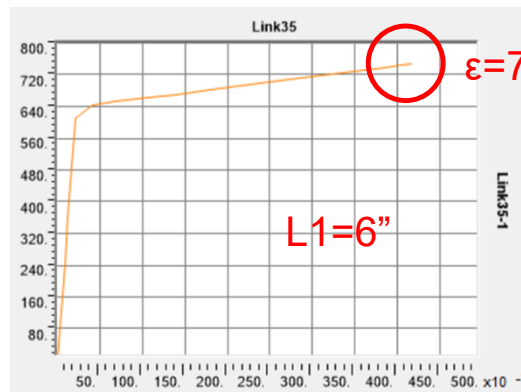
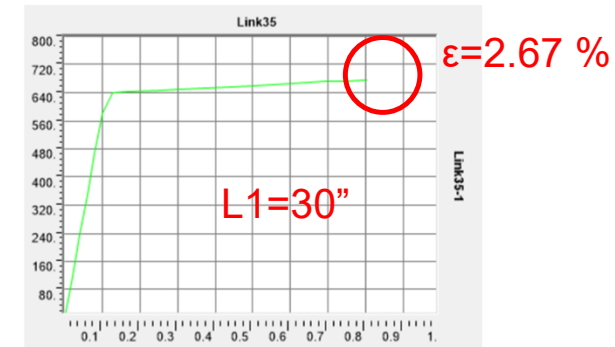
$$\epsilon_y = 105 \text{ ksi} / 290000 \text{ ksi} = 0.36\%$$

### 1. Anchor Rod Springs Considering Threads

Base Type	Diameter	Threads/in	A <sub>se</sub>	A <sub>g</sub>	T <sub>ye</sub>	T <sub>yg</sub>
2	in	4.5	in <sup>2</sup>	in <sup>2</sup>	kips	kips
	3		6.09	7.07	639	742



Base Rotation and Moment



3D Model

Link Axial Forces

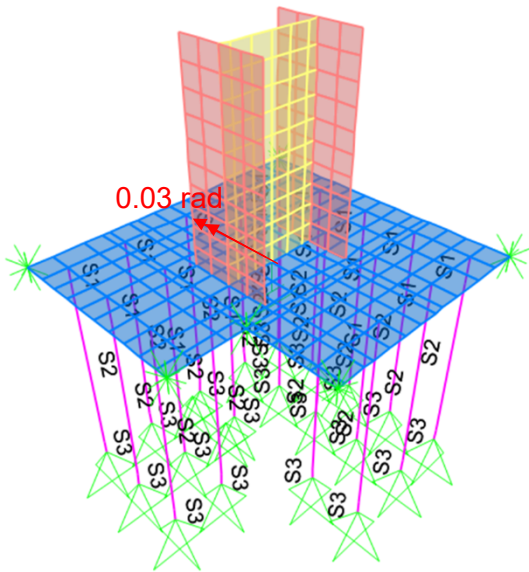
Link Deformation vs Force

# Anchor Rod Design

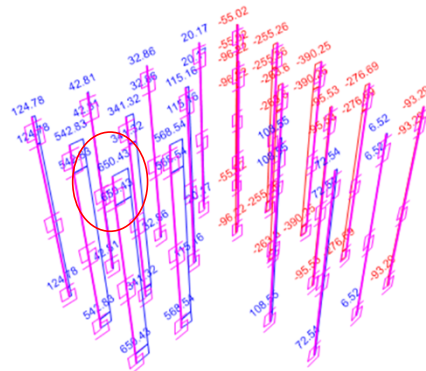
## Base Plate Rotation Check (Type 5)

$$\epsilon_y = 105 \text{ ksi} / 290000 \text{ ksi} = 0.36\%$$

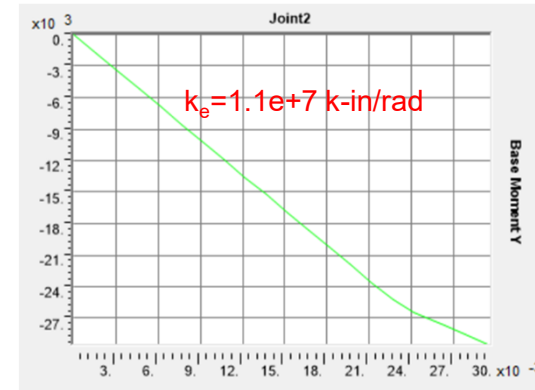
1. Anchor Rod Springs Considering Threads						
Base Type	Diameter	Threads/in	A <sub>se</sub>	A <sub>g</sub>	T <sub>ye</sub>	T <sub>yg</sub>
	in		in <sup>2</sup>	in <sup>2</sup>	kips	kips
4~6	3	4.5	6.09	7.07	639	742



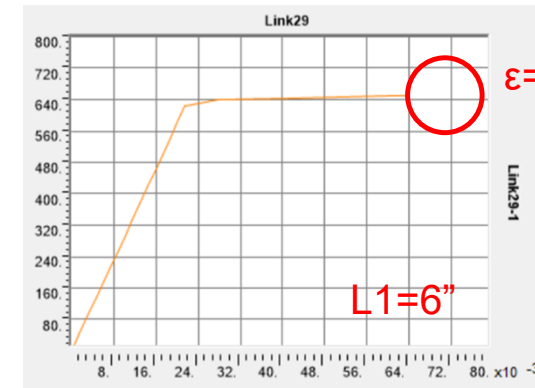
3D Model



Link Axial Forces



Base Rotation and Moment



Link Deformation vs Force

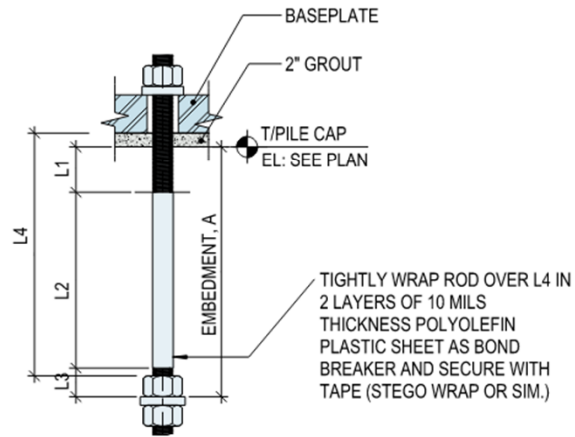
# Anchor Rod Design

## Summary of Max. Strain on Top of Anchor Rods

1. Anchor Rod Springs Considering Threads											
Base Type	Diameter	Threads/ in	A <sub>se</sub>	A <sub>g</sub>	T <sub>ye</sub>	T <sub>yg</sub>	Threaded Length L1	Un-Threaded Length L2	Threaded Length L3	Total Length L	ε <sub>max</sub>
	in		in <sup>2</sup>	in <sup>2</sup>	kips	kips	in	in	in	in	
1	3	4.5	6.09	7.07	639	742	6	45	4	55	4.00%
2	3	4.5	6.09	7.07	639	742	30	21	4	55	3.60%
3	2	4.5	2.50	3.14	262	330	6	32	4	42	0.32%
4	3	4.5	6.09	7.07	639	742	12	32	4	48	3.66%
5	3	4.5	6.09	7.07	639	742	6	38	4	48	2.23%
6	3	4.5	6.09	7.07	639	742	12	32	4	48	3.20%
7	2	4.5	2.50	3.14	262	330	6	38	4	48	0.20%

# Anchor Rod Design

## Threaded Length Detail



NOTE:  
1. SEE S4.10 AND S4.11 FOR BASE PLATE AND WASHER DETAILS.  
2. L4 = A + GROUT THICKNESS

BRB COLUMN BASE ANCHOR ROD SCHEDULE							
BASE PLATE TYPE	BASE PLATE DETAIL	ANCHOR ROD DIAMETER	THREADED LENGTH L1	UN-THREADED LENGTH L2	THREADED LENGTH L3	EMBEDMENT A	REMARKS
1	1/S4.10	3"	9"	3'-9"	4"	4'-7"	
2	2/S4.10	3"	2'-6"	1'-9"	4"	4'-7"	
3	3/S4.10	2"	6"	2'-8"	4"	3'-6"	
4	1/S4.11	3"	1'-0"	2'-8"	4"	4'-0"	
5	2/S4.11	3"	9"	3'-2"	4"	4'-0"	
6	3/S4.11	3"	1'-0"	2'-8"	4"	4'-0"	
7	4/S4.11	2"	6"	3'-2"	4"	4'-0"	

## 5 THREADED LENGTH DETAILS OF BRB COLUMN BASE ANCHOR ROD

SCALE: 3/4" = 1'-0"

## Summary and Conclusion

- Designed pinned base anchor plates and rods to accommodate nonlinear rod deformation, achieving ductility requirements.
- Designed unbonded rod length to meet sufficient elongation capacity.
- Longer threaded length at the top helps reduce axial strain at the top of the rods.

# Recommendations and discussion

# Rod variables

- F1554 Material
  - Grades 36, 55, 105
- Treatment
  - Cold-rolled, annealed, hot-rolled
- Threading
  - Cut thread, rolled thread, upset thread (forged)
  - Fully threaded, partially threaded/smooth shank
- Casting
  - Bonded, debonded
- 3x3x3x2=108 combinations

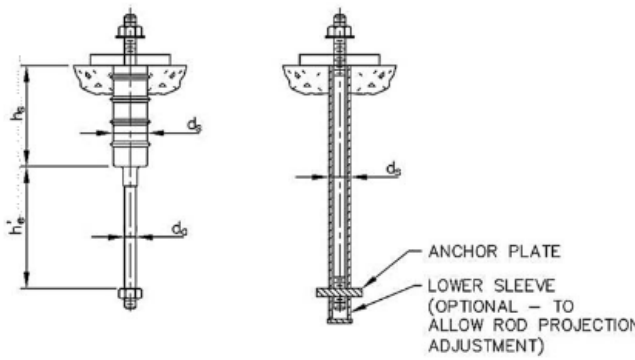
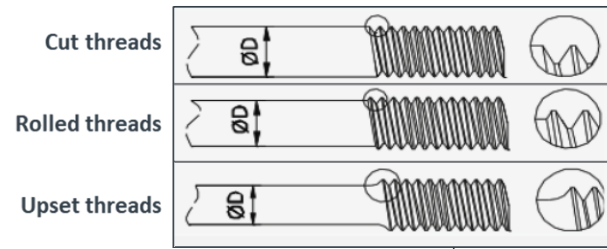
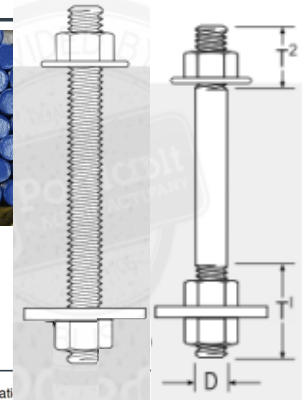
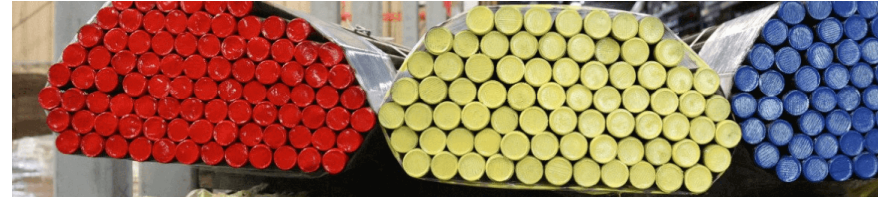
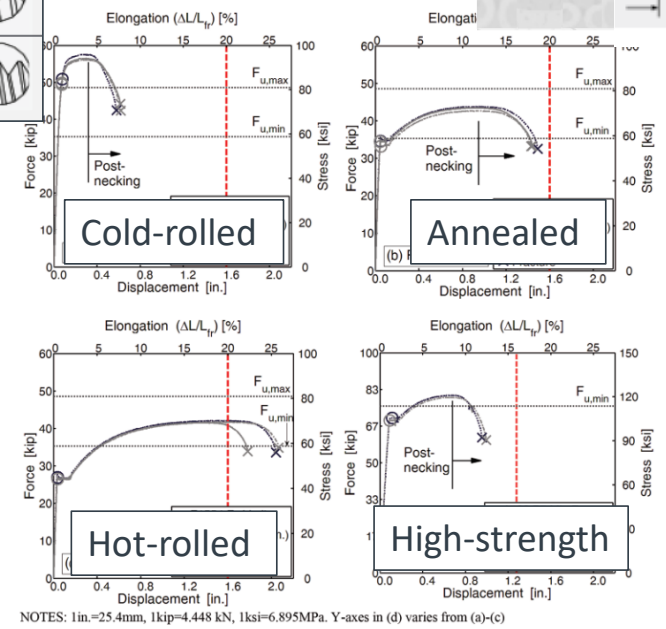


Figure 3-1. Typical anchor sleeves: (a) partial sleeve, (b) full-length sleeve.



NOTES: 1in.=25.4mm, 1kip=4.448 kN, 1ksi=6.895MPa. Y-axes in (d) varies from (a)-(c)  
 Force-displacement and stress elongation response for 1 in. (25 mm) diameter samples,  $L_e = 8$  in. (203 mm):  
 (a) Grade 36 CW; (b) F1554 CW-A; (c) F1554 HR; and (d) A193 B7.

# Rod variables

Δ Elongation of F1554 Anchor Rods		Grade 36			Grade 55			Grade 105
		Cold-worked/ Cold-drawn	Annealed <sup>1</sup>	Hot-rolled <sup>2</sup>	Cold-worked/ Cold-drawn	Annealed <sup>1</sup>	Hot-rolled <sup>2</sup>	
Bonded	Cut Threads	Fully threaded			2" φ F1554 Grade 55 in example could be any of these			
		Smooth shank, threaded ends						
	Rolled Threads	Fully threaded	Probably meets Grade 55 requirements					Not available in large diameter
Smooth shank, threaded ends								
	Upset threads	Smooth shank, threaded ends						NA
Debonded	Cut Threads	Fully threaded						
		Smooth shank, threaded ends						
	Rolled Threads	Fully threaded					UCSD testing	Not available in large diameter
		Smooth shank, threaded ends						
	Upset threads	Smooth shank, threaded ends				Based on ASTM (but very expensive)		NA

~~3x3x3x2x2=108~~

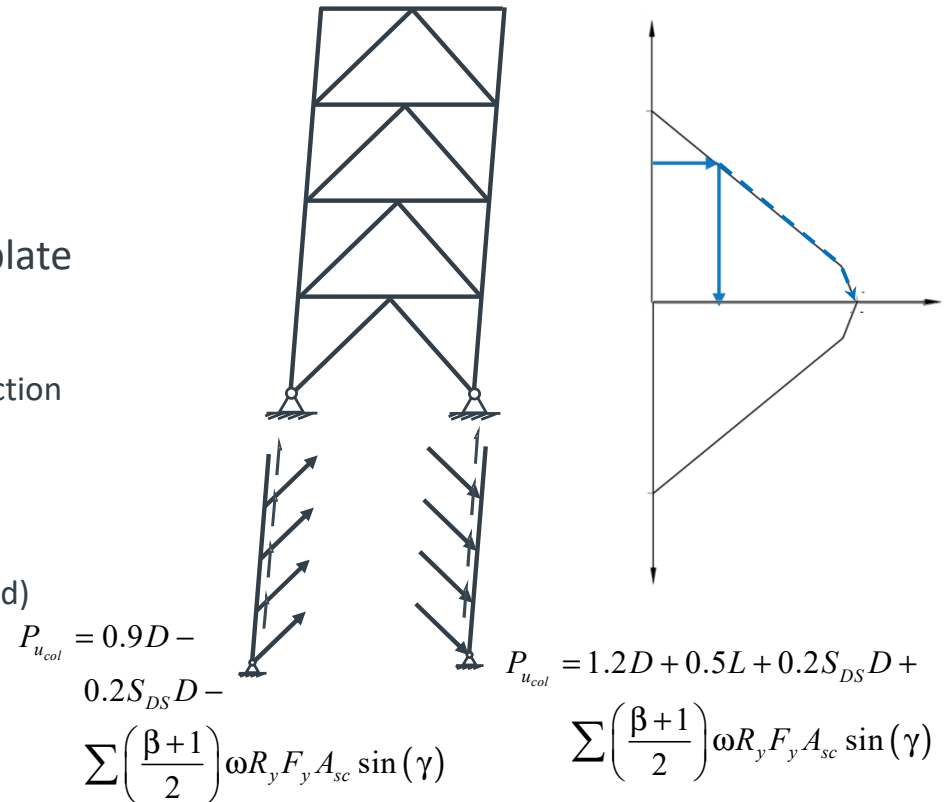
38 Combinations

No annealing, forging, etc. for grade 105

## Recommendations for practice (under current provisions)

- Analysis

- Model CBF base-plate connections as pinned
  - Size BRBs for analysis forces
- Determine maximum compression force on base plate
  - Sum of BRB strain-hardened capacities, plus gravity, etc.
  - Determine corresponding moment from column P-M interaction
- Determine maximum uplift force on base plate
  - Sum of BRB strain-hardened capacities, minus gravity, etc.
  - Corresponding moment from column P-M interaction (if used)
- Determine maximum moment
  - Limited by column?
  - Limited by ductile foundation flexure?
  - Limited by ductile connection mechanism?

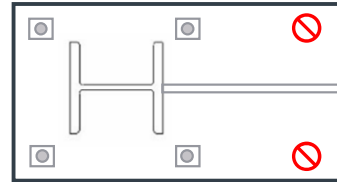


# Recommendations for practice (under current provisions)

- Design

- Configuration

- Forgo additional eccentric anchors



- Tension

- Design anchors for required (capacity-design) uplift
    - Check base plate bending for anchor-rod yield strength

- Compression (+Moment)

- Refer to AISC Design Guide 1

- Moment

- Check nonductile elements for maximum moment
    - $M_{ucol}$

- Refer to AISC Design Guide 1

- Gusset

- Maximum brace force
    - Maximum moment
    - Maximum brace force and moment

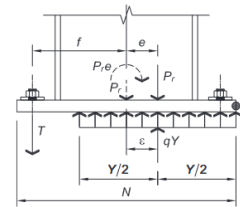
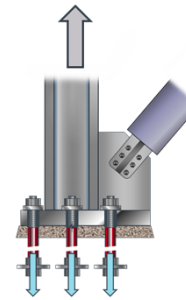


Fig. 4-7. Base plate with low moment.

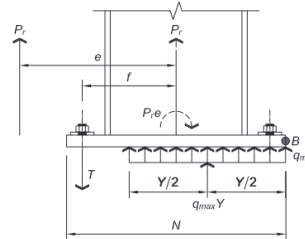
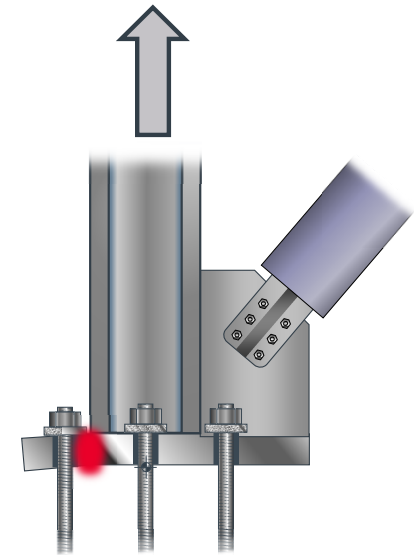


Fig. 4-9. Tension force falling outside of anchor rod group extents.

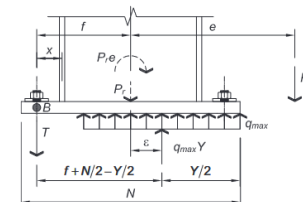
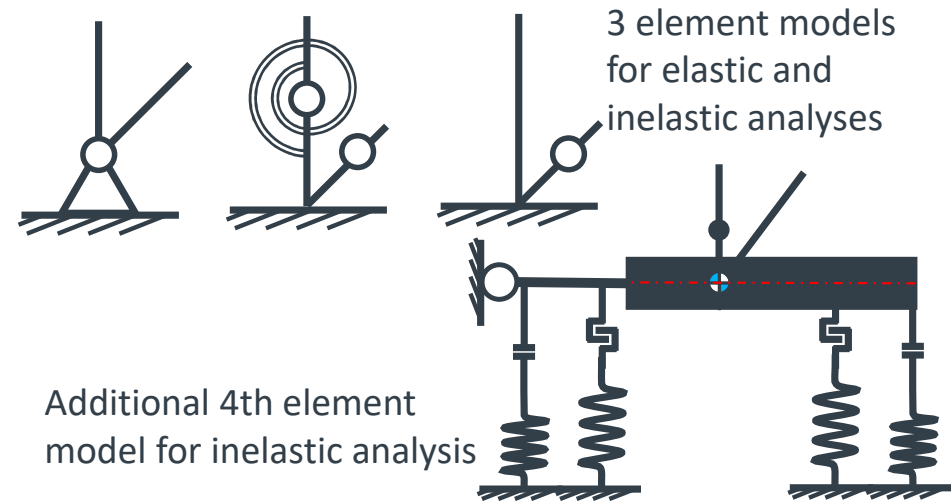


Fig. 4-8. Base plate with large moment.

## Recommendations for research

- Frame response
  - For elastic design, does selection of pin/spring/fixed base affect required strength of elements (such as BRBs)
    - Frame design consequence for frame is minimal
    - Foundations not studied
  - For NLRHA, does connection selection of pin/spring/**nonlinear**/fixed base affect:
    - Ductility demands?
    - Performance evaluation?
    - Rotation?
  - How well do code required strengths compare to analyzed demands?
    - Especially uplift



- Connection behavior
  - Calibrate hook-and-gap model to more detailed FEM
    - Establish approximate bearing locations appropriate for any loading
  - Establish elongation capacity of anchor rods of various types

# Design idealizations

Ensure required rotation can be reached

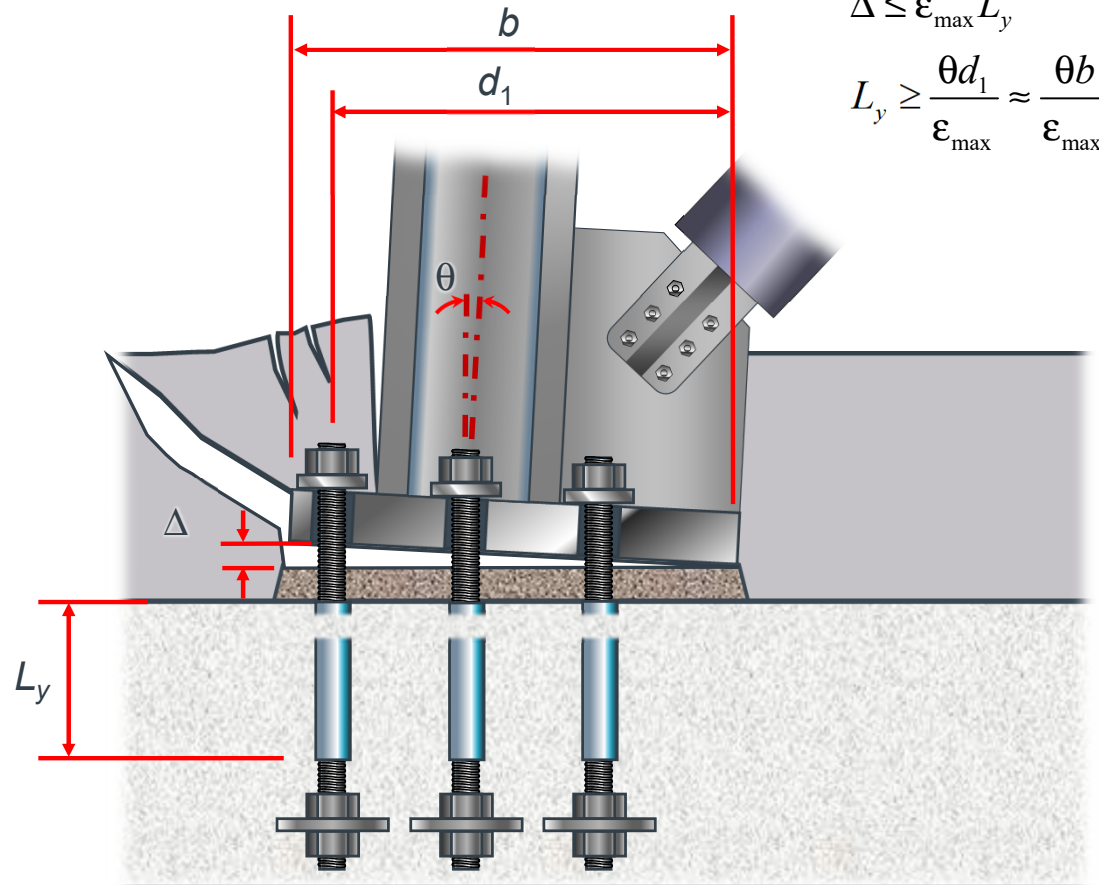
Assume 2.5% rotation  
Use base-plate length  $b$  as  $d_1$

Grade 55: 10% strain

$$L_y \geq b/4, \text{ use } b/2 \text{ where possible}$$

Grade 105: 5% strain

$$L_y \geq b/2, \text{ use } b \text{ where possible}$$



$$\Delta \leq \epsilon_{\max} L_y$$
$$L_y \geq \frac{\theta d_1}{\epsilon_{\max}} \approx \frac{\theta b}{\epsilon_{\max}}$$

---

## Recommendations for codes

- Consider requiring ductile rods
  - Current “capacity design” for axial does not preclude yielding
  - Moment capacity would need to be considered to preclude yielding
- Consider requiring minimum rotation capacity
  - Potentially 2.5% for consistency
    - Preferable to obtain from frame analyses
  - Allow full T+M as an alternative (very conservative)
- Consider allowing ductile uplift for some force less than sum of full, strain-hardened capacities
  - As adequate performance validated by future research

---

# Q & A