Column Base Connections: Research, Design, and a Look to the Future

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2022 T.R. HIGGINS LECTURESHIP AWARD

Acknowledgments

Sponsors

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- California Department of Conservation

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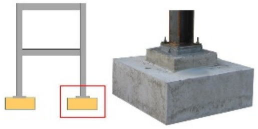
Tom Sabol – Englekirk Structural Engineers

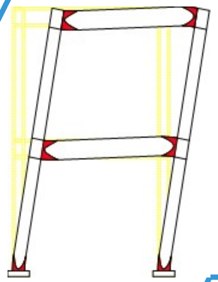
Matthew Eatherton – Virginia Tech

Matt Smith – L&M Industrial Fabrication

Column base connections

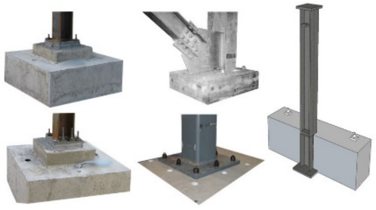


Used in all buildings



Wide range of details

Used in many contexts



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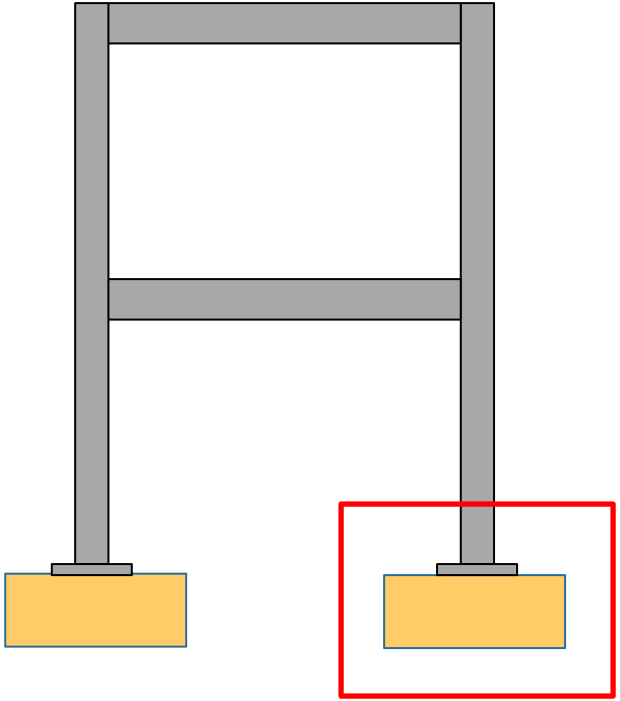

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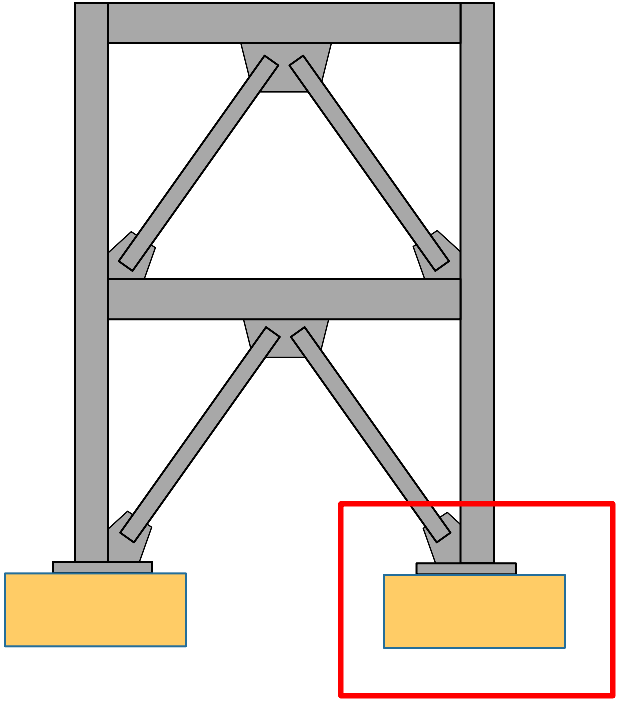


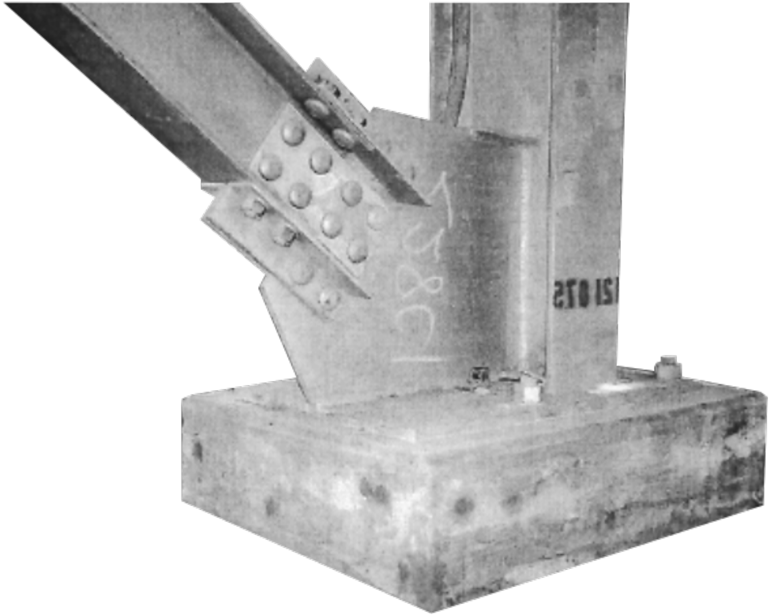
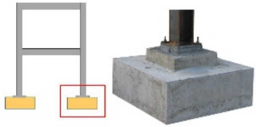


Photo credit: Rick Drake (2003)

Column base connections



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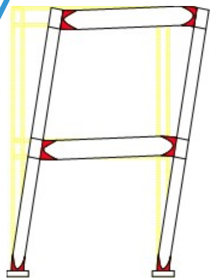

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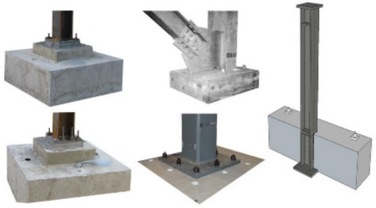
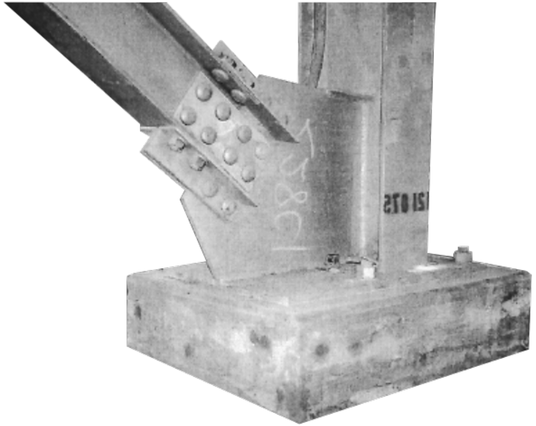
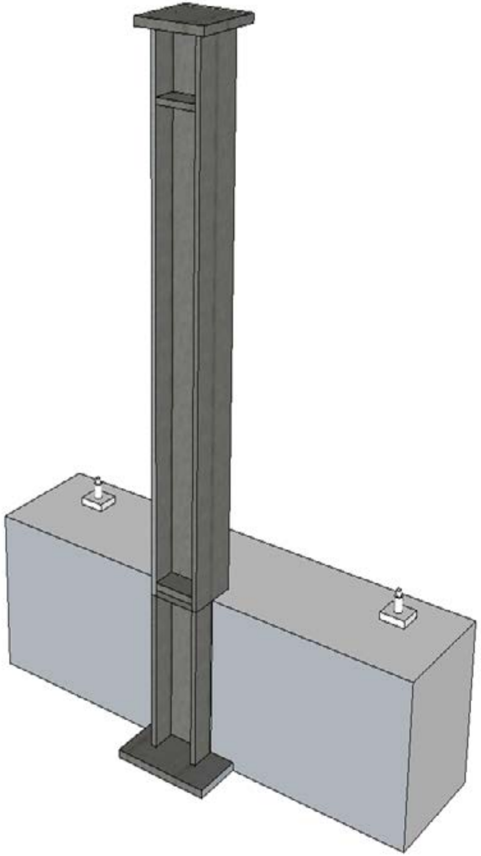
Used in many contexts

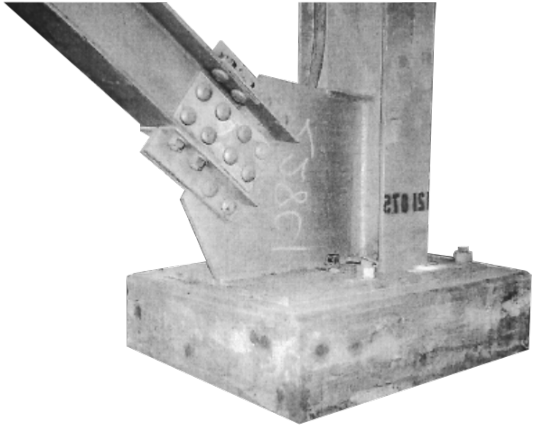


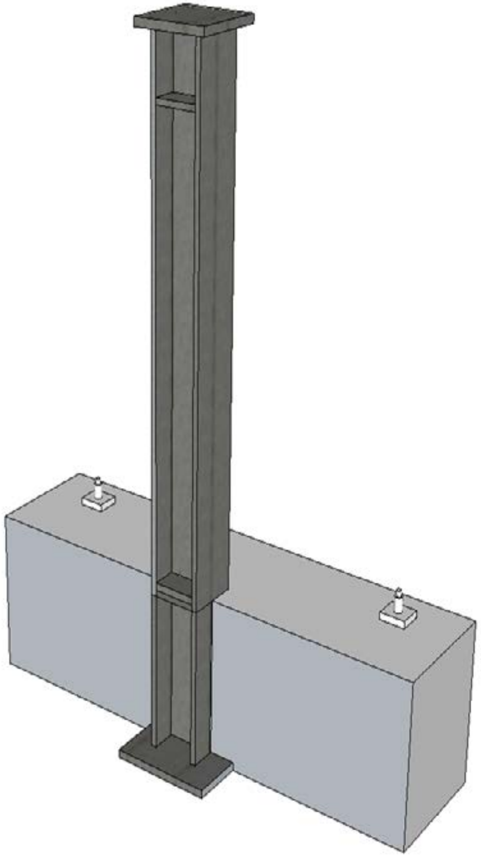
Diversity in details



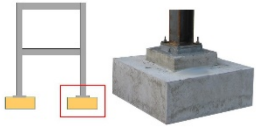


Always at steel/concrete interface



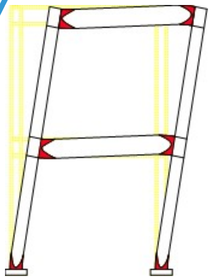


Column base connections

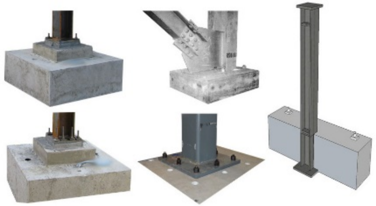


Used in all buildings

Wide range of details

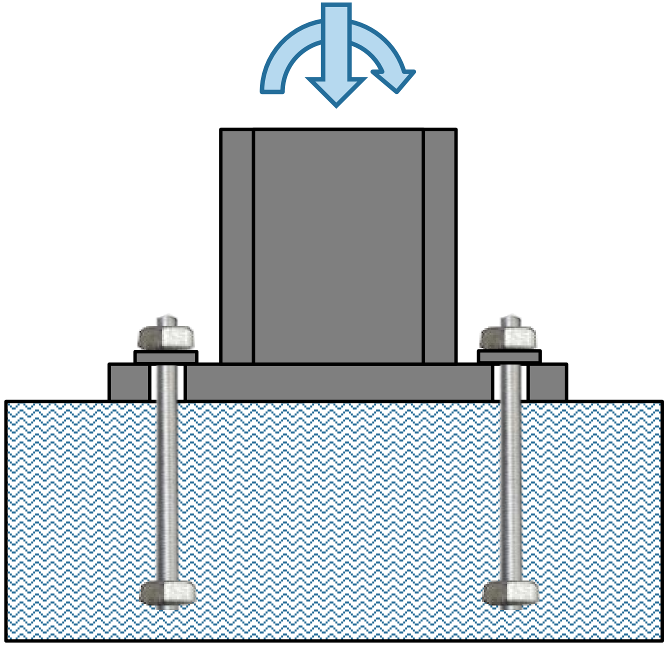


Used in many contexts



Interesting in many contexts

- Static loads
- Seismic loads
- Interactions with frame



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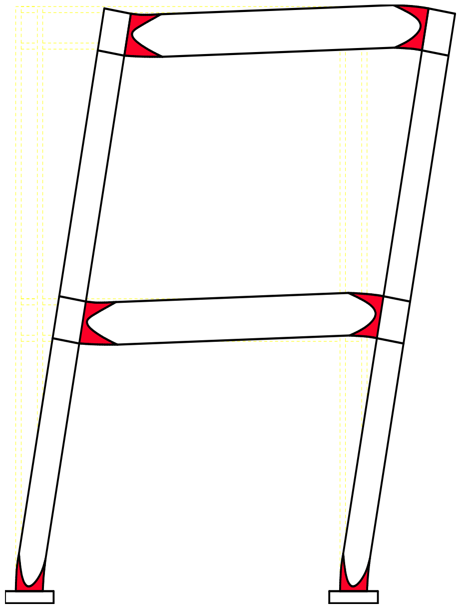

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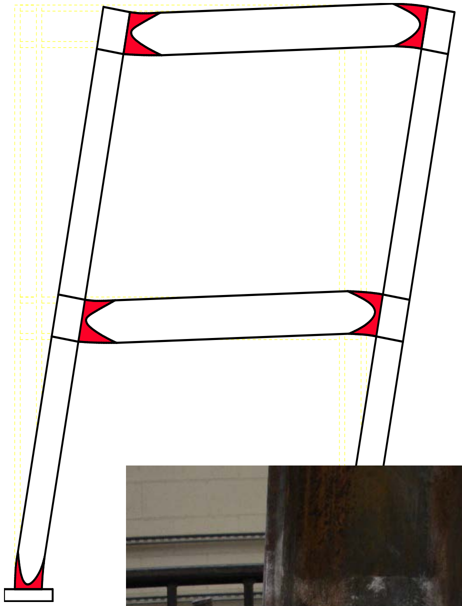

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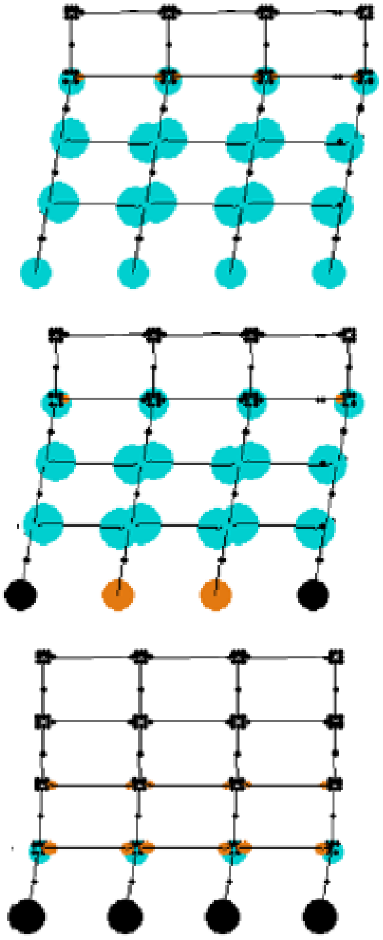

Interesting in many contexts

- Static loads
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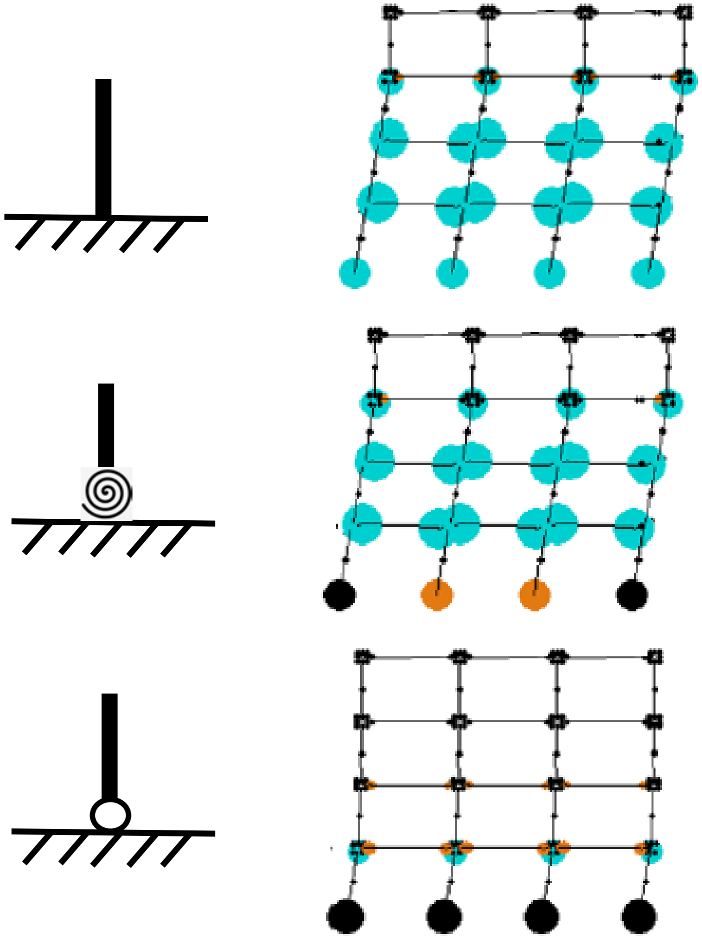
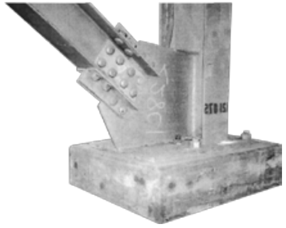
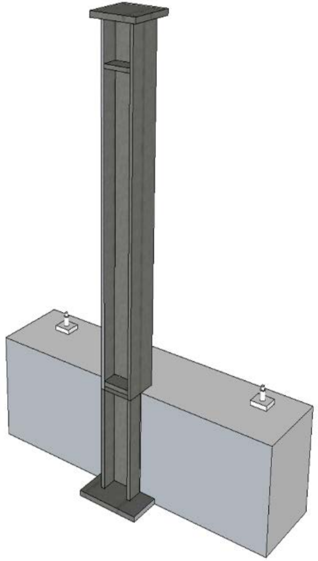


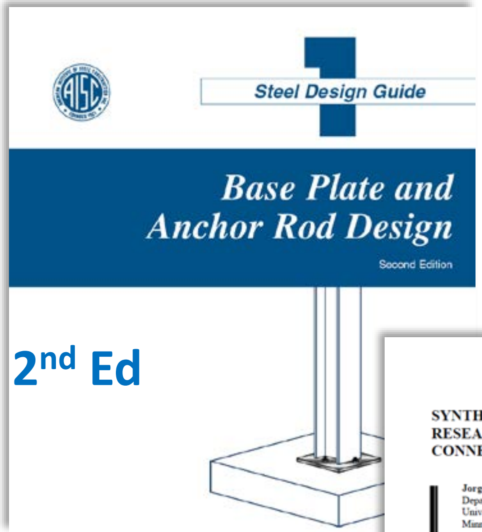
Challenging to navigate

- Static loads
- Seismic loads
- Interactions with frame

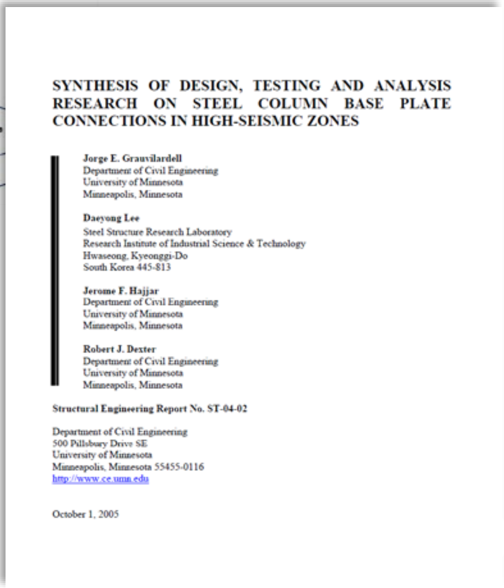



Timeline and scope



2nd Ed

2005-2006



SYNTHESIS OF DESIGN, TESTING AND ANALYSIS RESEARCH ON STEEL COLUMN BASE PLATE CONNECTIONS IN HIGH-SEISMIC ZONES

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Structural Engineering Report No. ST-04-02

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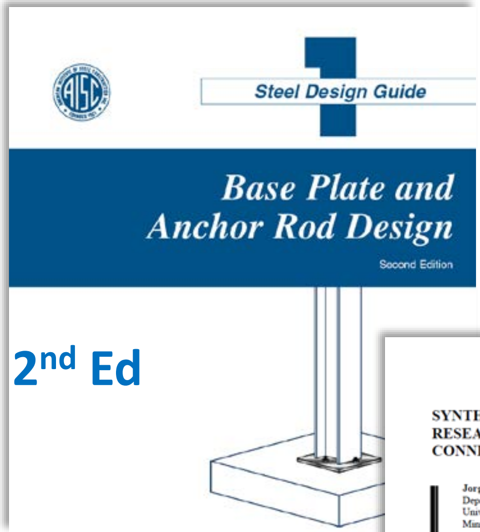
http://www.ce.umn.edu

October 1, 2005

Timeline and scope



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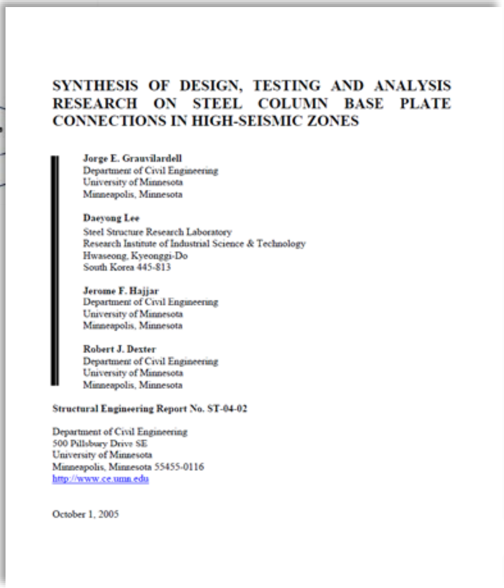

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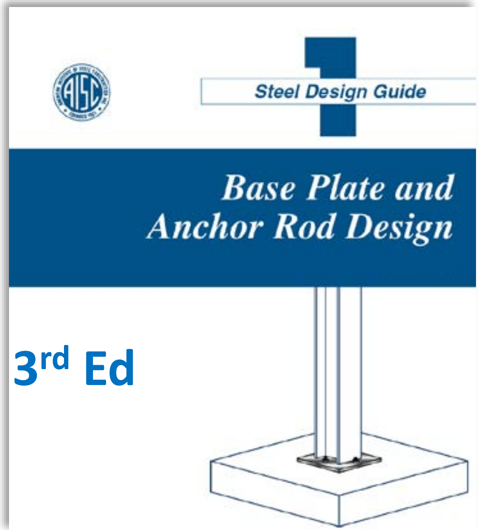
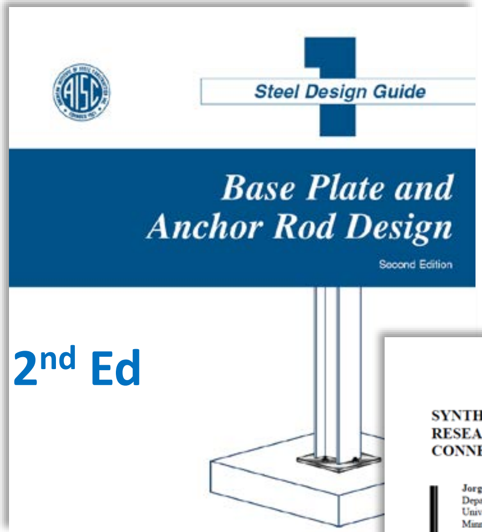


3rd Ed

2024-ish

Timeline and scope



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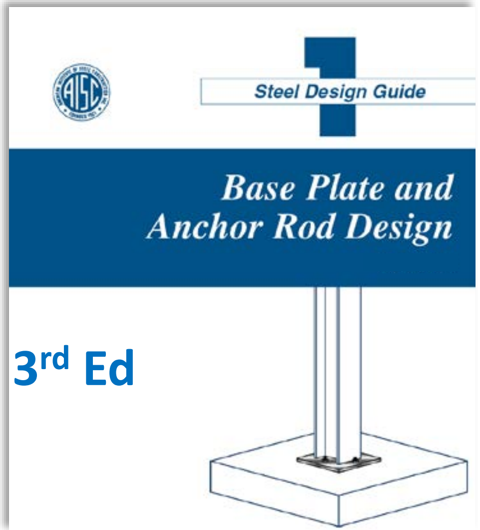
New developments



3rd Ed

2024-ish

Organization

Part 1

Exposed Base Plates

- Prevailing understanding and design methods
- New Developments

~35 mins

Part 2

Embedded Bases

- Prevailing understanding and design methods
- New Developments

~15 mins

Part 3

A look to the future

- "Resolved" issues
- Ongoing work
  Unresolved issues

~15 mins

Organization

Part 1

Exposed Base Plates

- Prevailing understanding and design methods
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Embedded Bases

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Part 3

A look to the future

- “Resolved” issues
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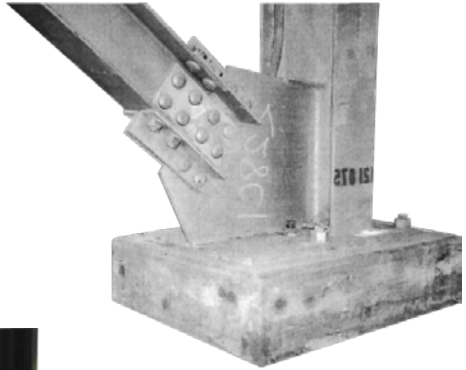
Part 1 – Exposed Base Plate Connections

Exposed Base Plates

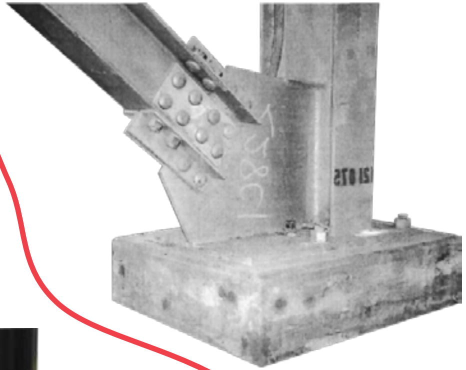
- Prevailing understanding and design methods
- New Developments



Part 1 – Exposed Base Plate Connections

Exposed Base Plates

- Prevailing understanding and design methods
- New Developments



Part 1 – Exposed Base Plate Connections

Exposed Base Plates

- Prevailing understanding and design methods
- New Developments

Design Guide One Approach

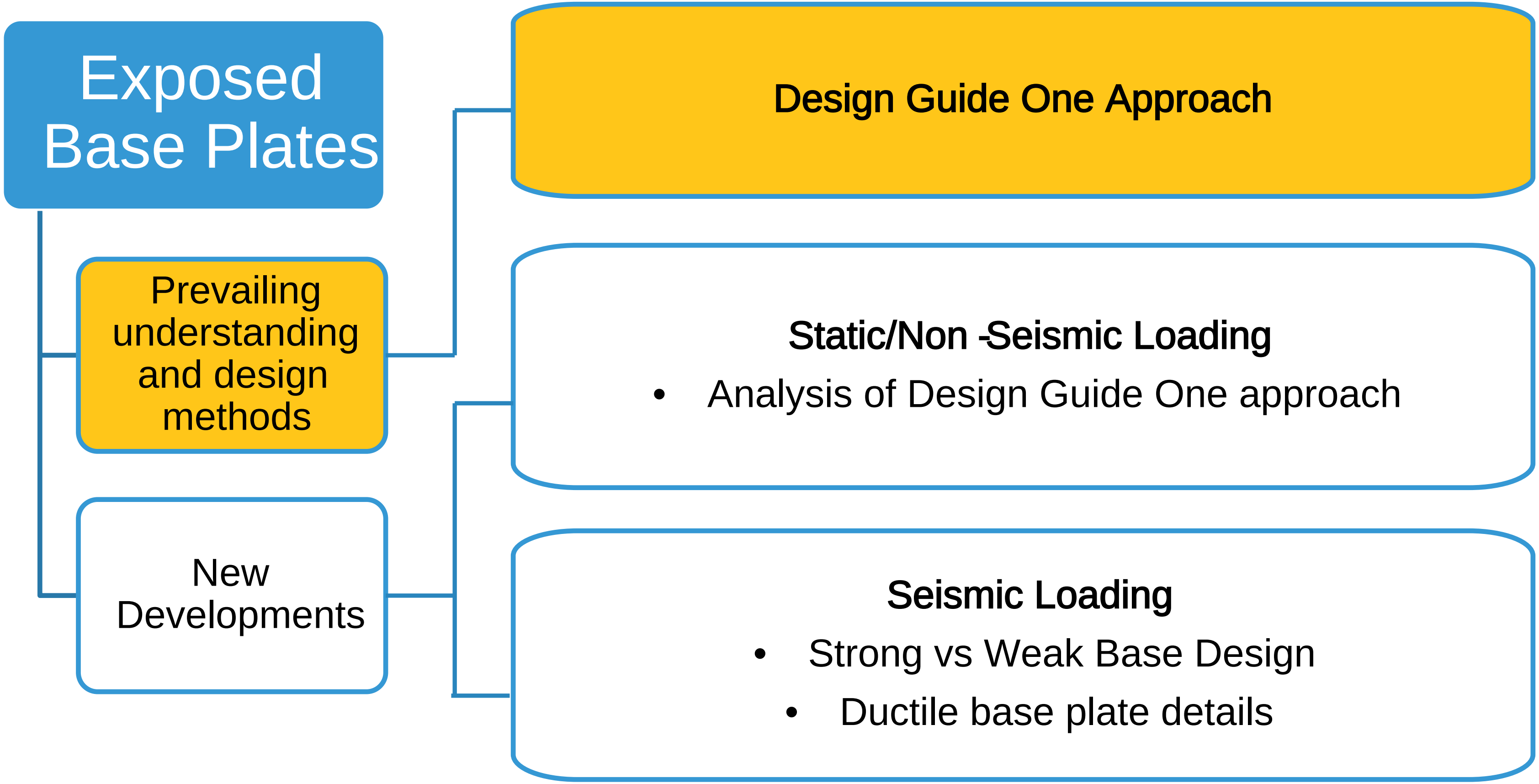
Static/Non -Seismic Loading

- Analysis of Design Guide One approach

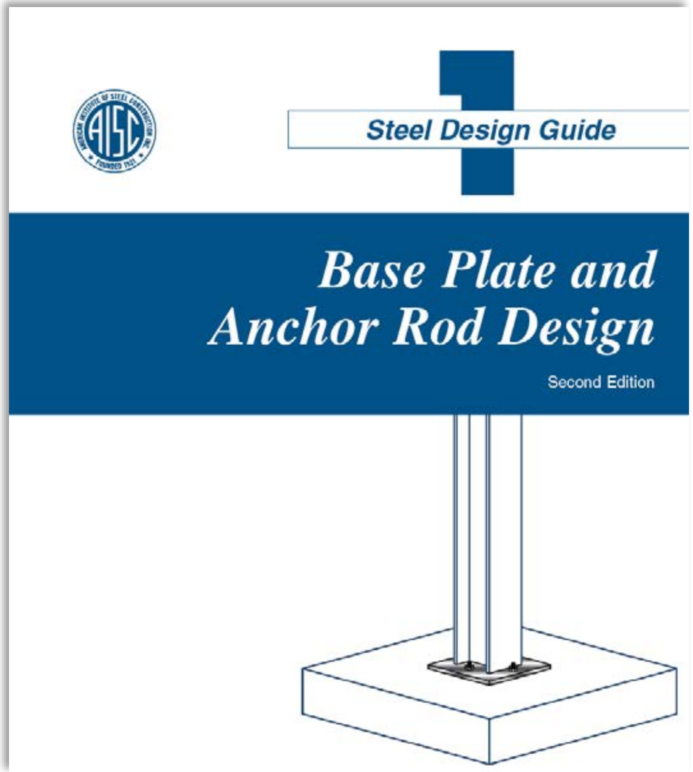
Seismic Loading

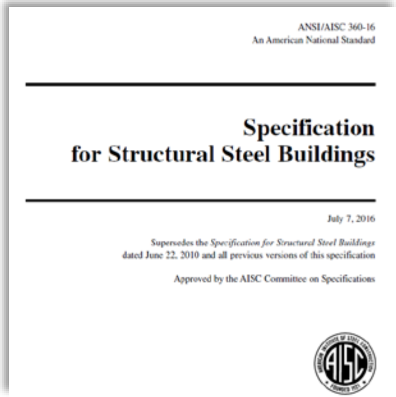
- Strong vs Weak Base Design
- Ductile base plate details

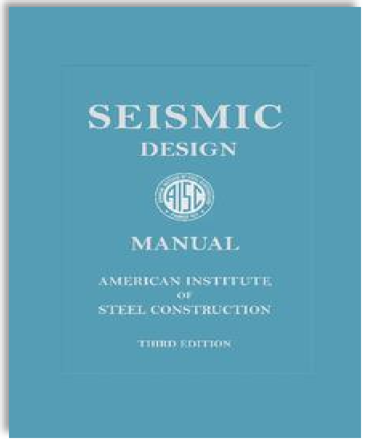
Part 1 – Exposed Base Plate Connections

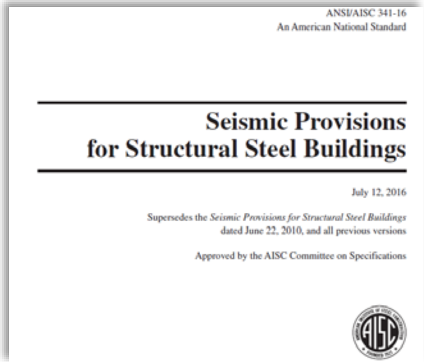


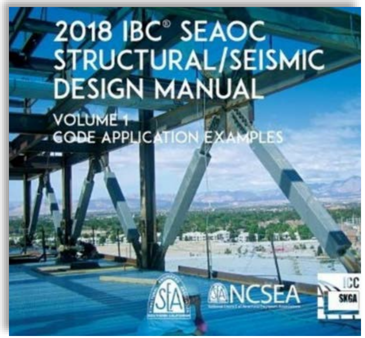
State of the art– Exposed base plate connections







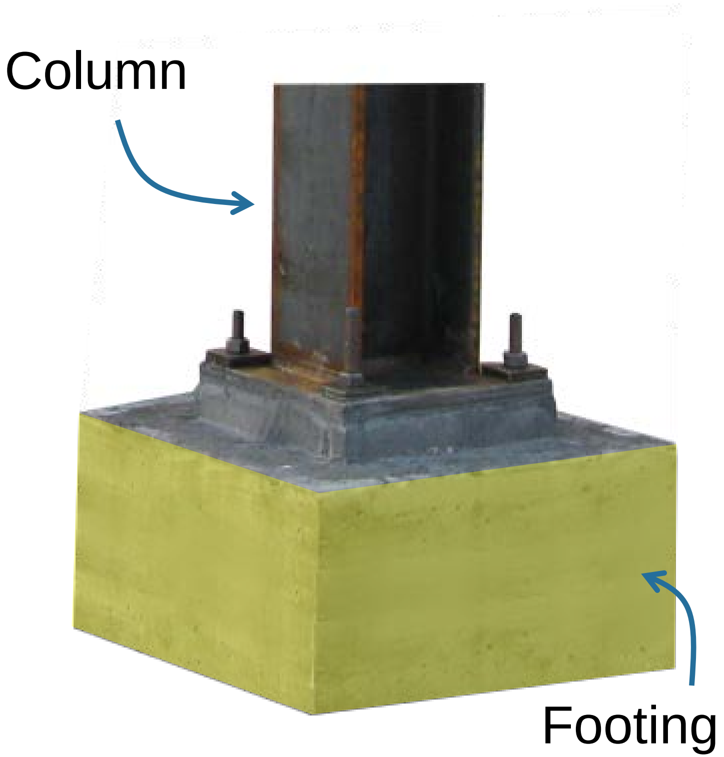




Design Guide One

Focusing on one configuration

Design Guide One



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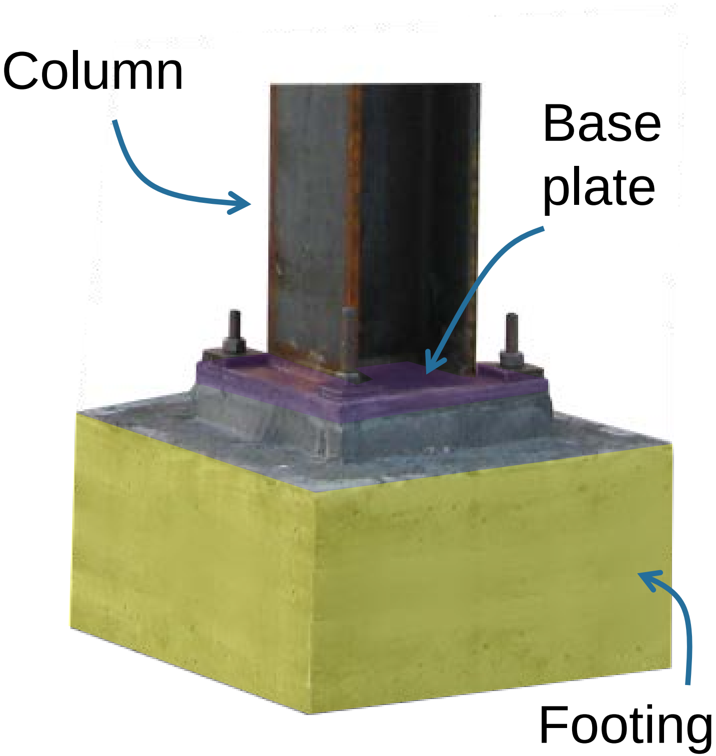

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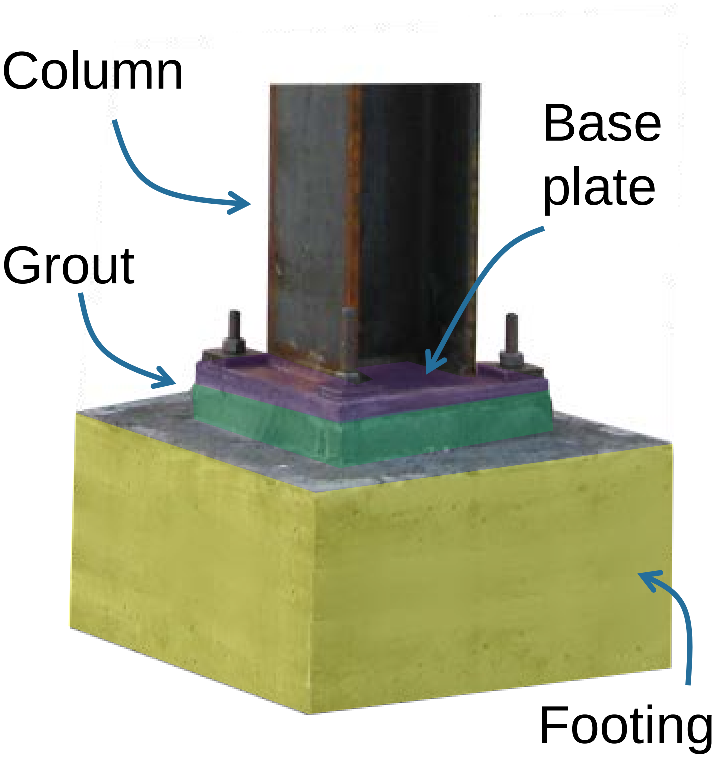

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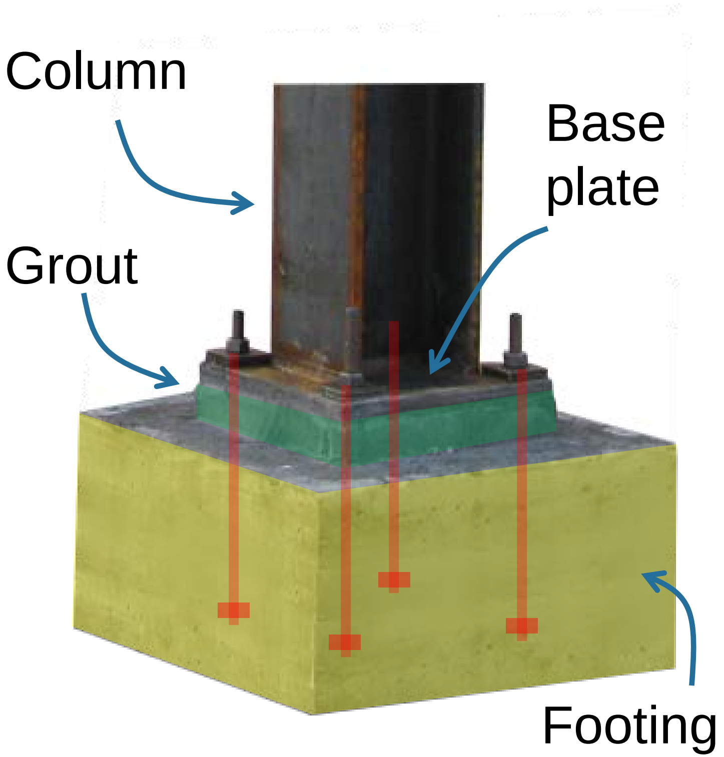

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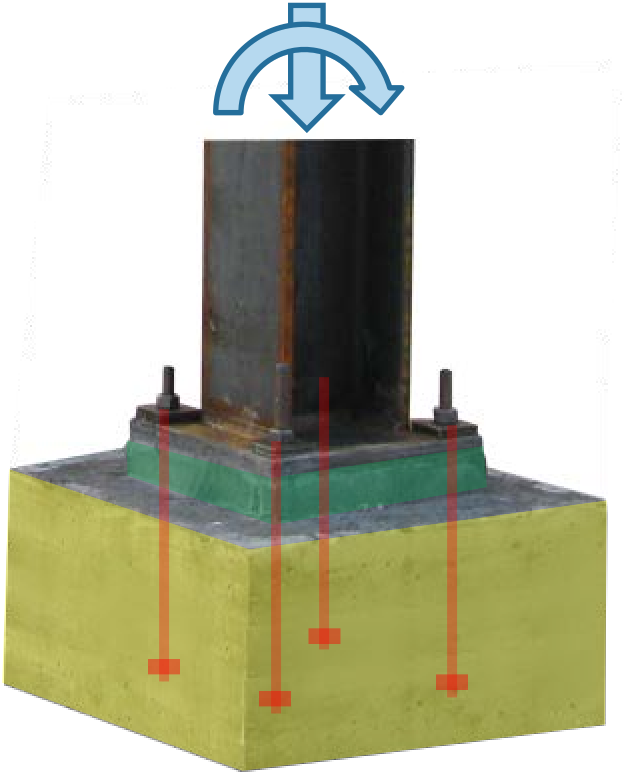
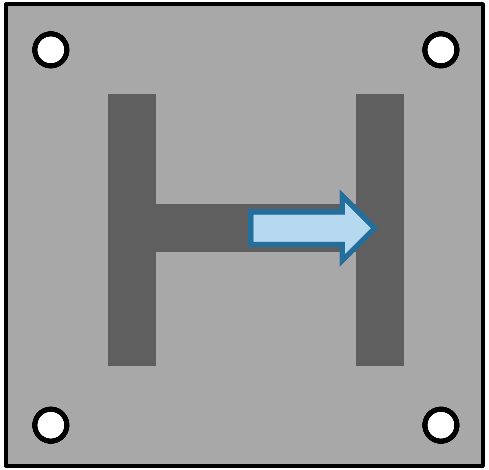
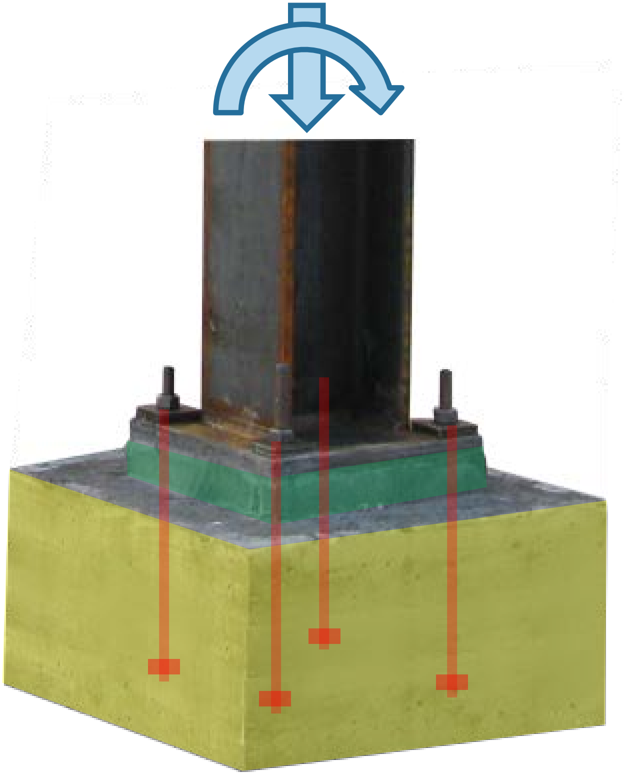


Uniaxial bending with axial compression



Two rows of anchors resisting bending

Design Guide One



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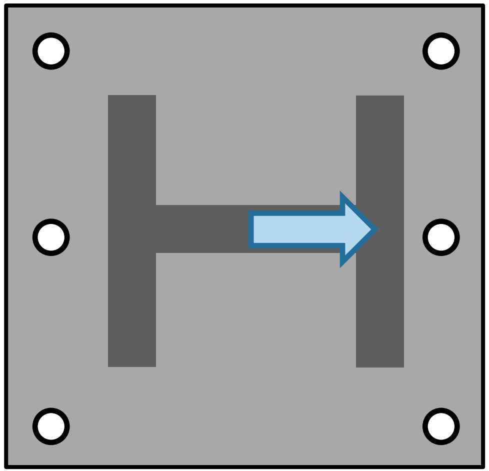
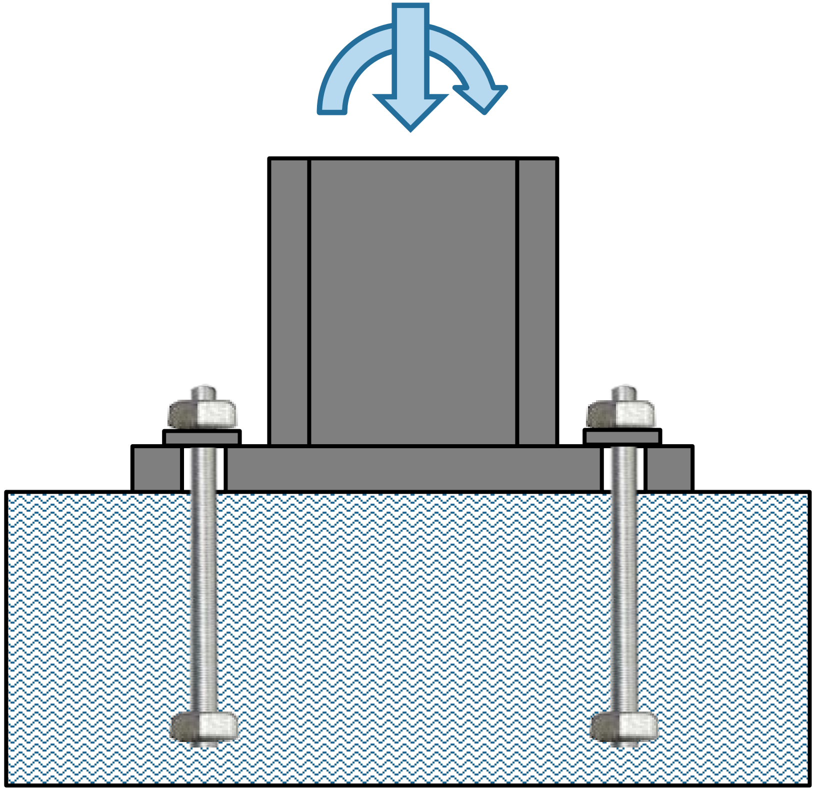


Two rows of anchors resisting bending

The mechanics

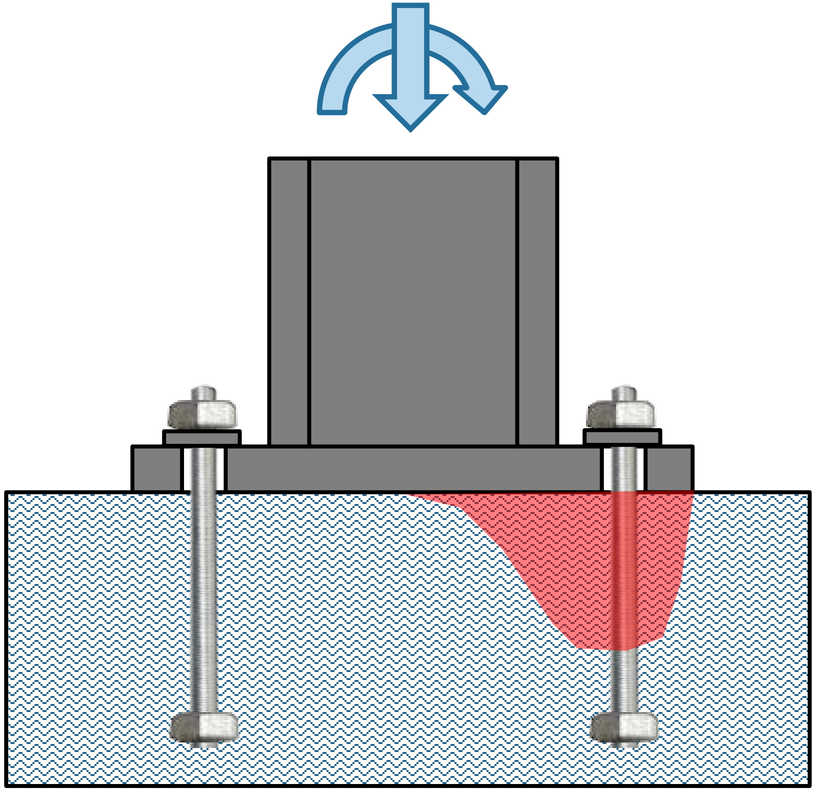
Simple in principle



The mechanics

Simple in principle

- Bearing in footing



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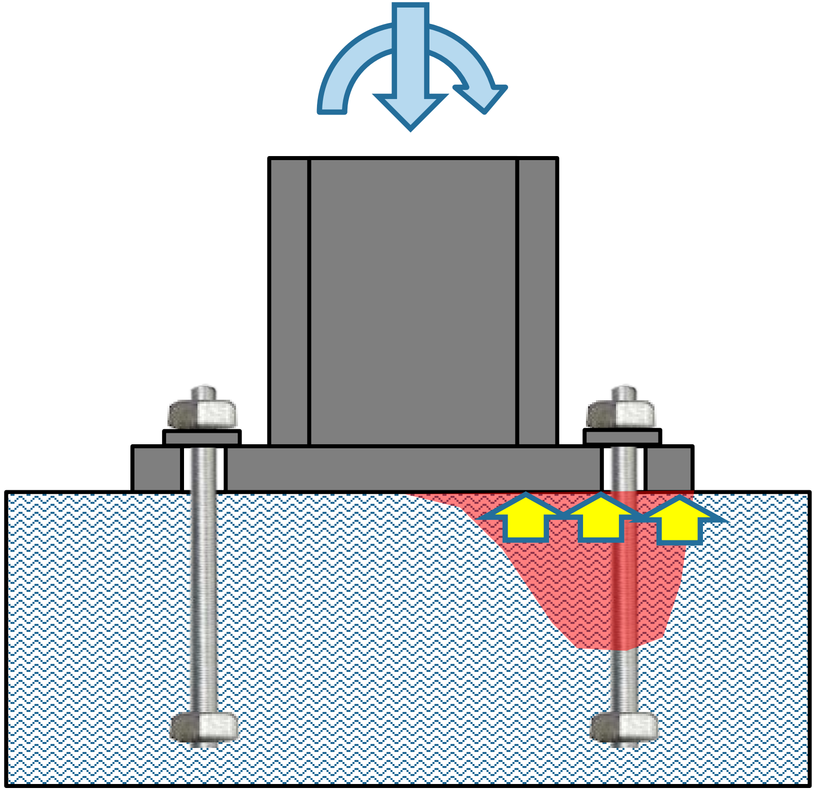
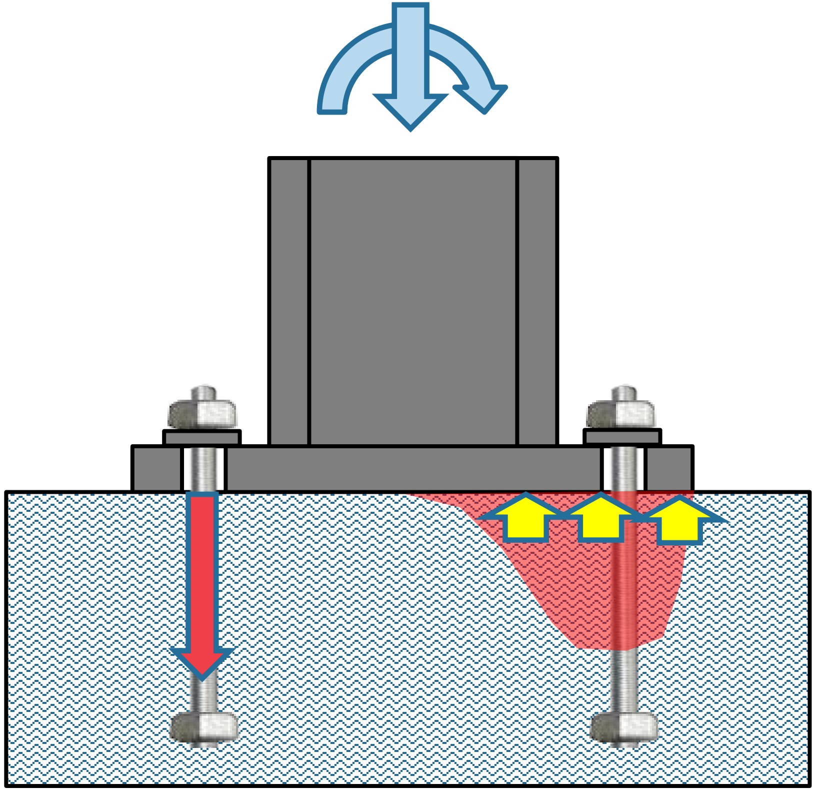


The mechanics

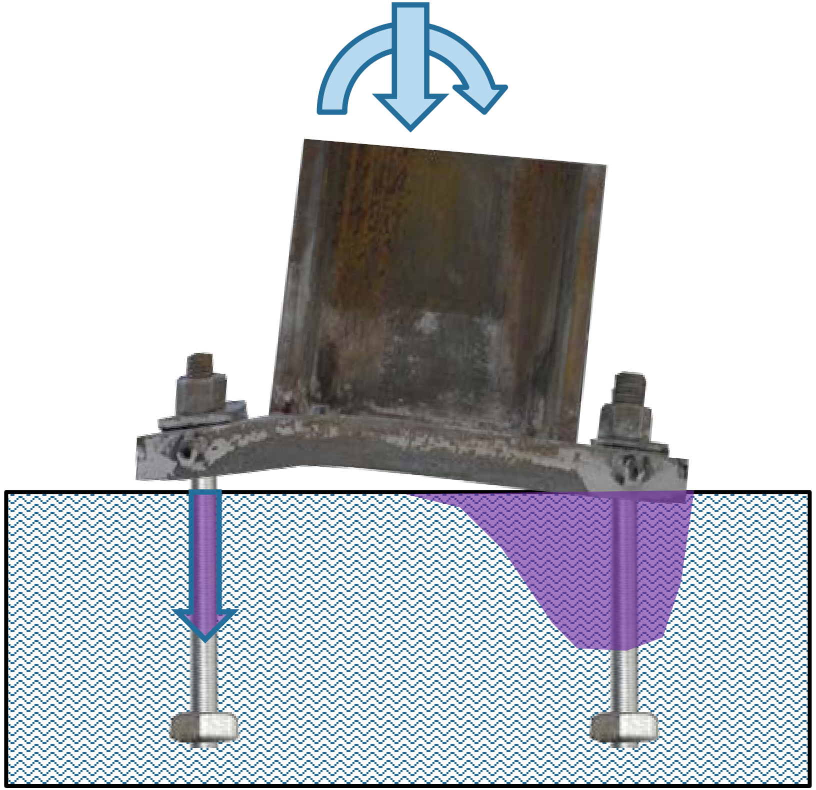
Simple in principle

- Bearing in footing
- Tension in rods



The mechanics

- Multiple distributions satisfy equilibrium
- True distributions depend on interplay of plate, rod, and flexibility and nonlinearity
- Determining these is non-trivial



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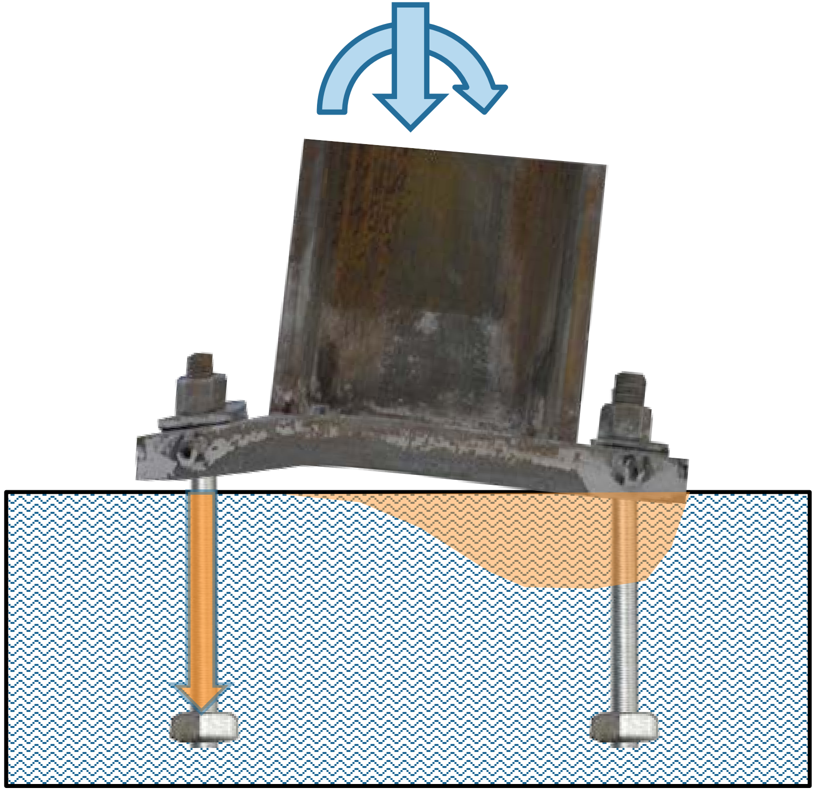

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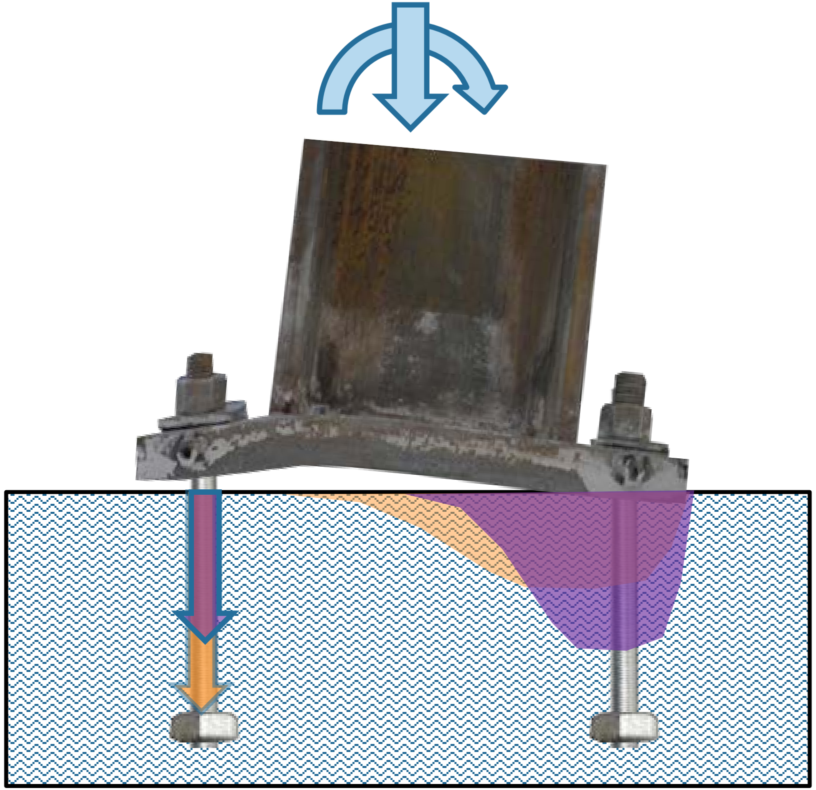
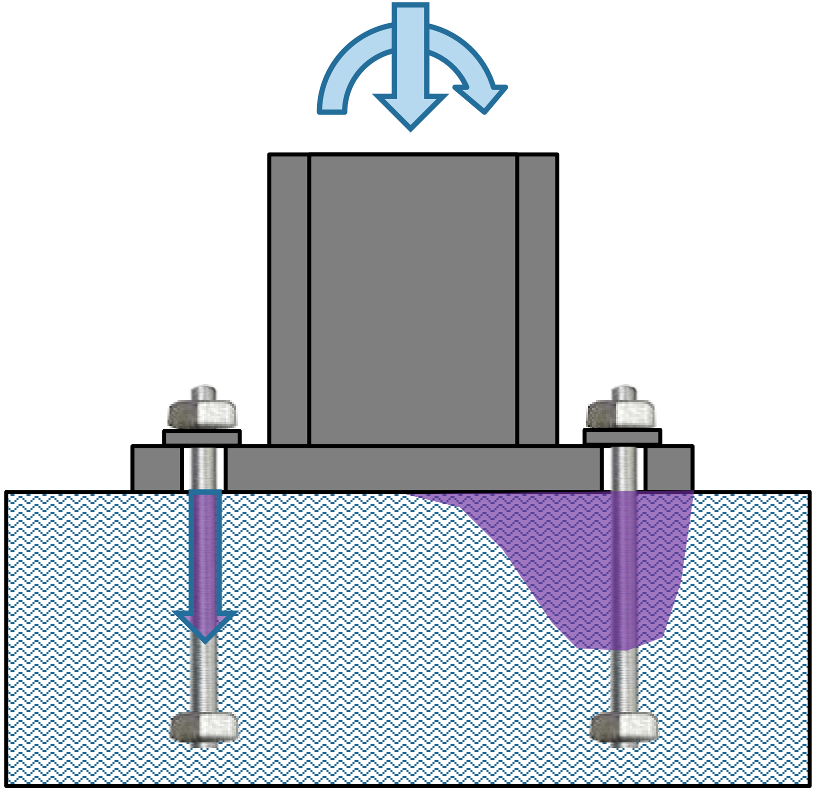


Design Guide One approach

Culmination and integration of work by researchers

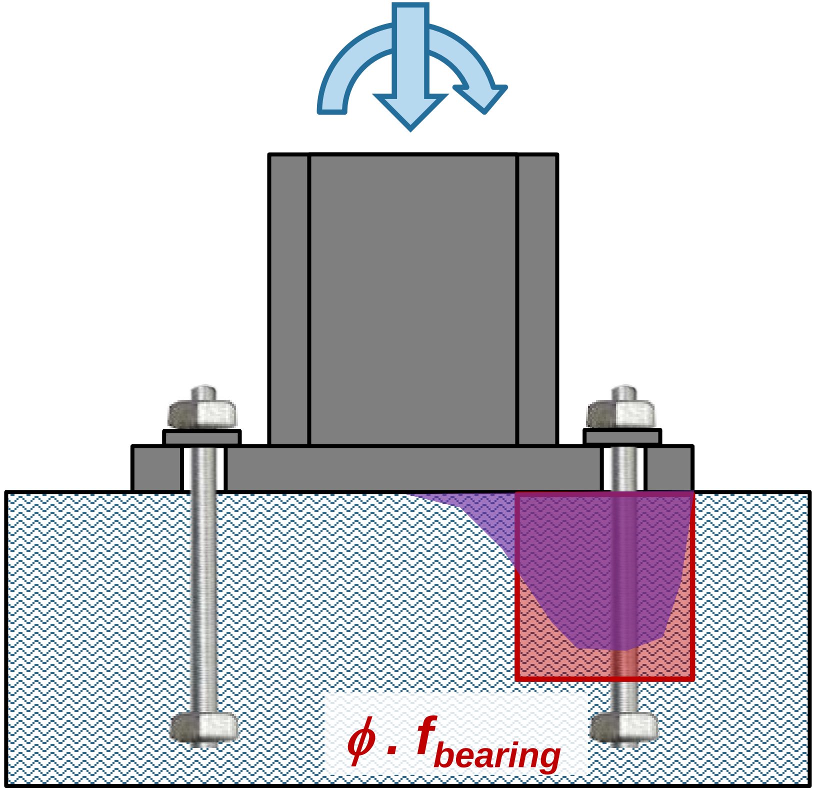
- DeWolf and Sarisley (1978,80,82)
- Thambiratnamand Paramasivam(1986)
- Drake and Elkin (1999)



Design Guide One approach

STEP 1

- Idealize distribution based on bearing strength of footing



*High eccentricity condition

Design Guide One approach

STEP 1

- Idealize distribution based on bearing strength of footing

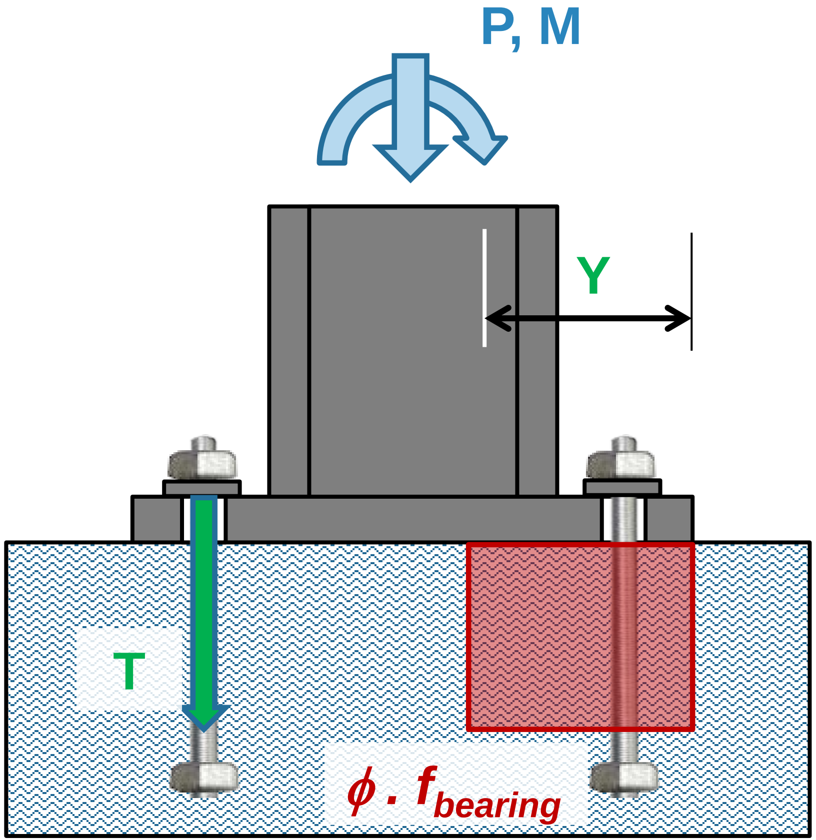
  $\phi \,.\, f_{bearing} \quad (\phi = 0.65)$

- Two equilibrium equations

  P and M

- Two unknowns

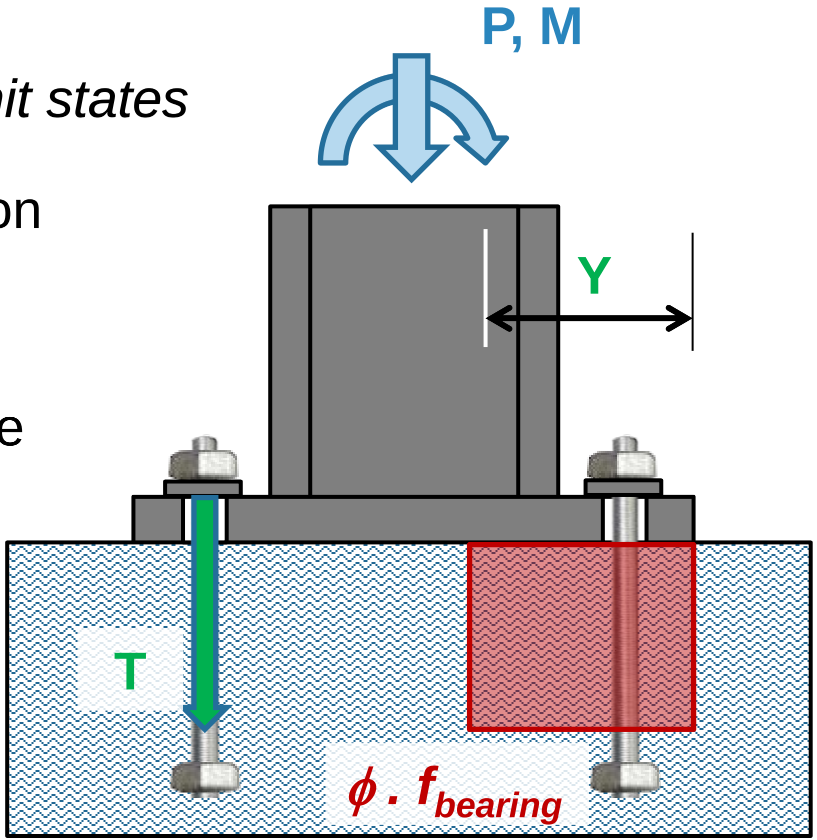
  Y and T



Design Guide One approach

STEP 2 – Given Y and T, evaluate limit states

- Base plate yielding on compression side
- Base plate yielding on tension side
- Anchor rod yielding
- Bearing failure of footing (implicit)

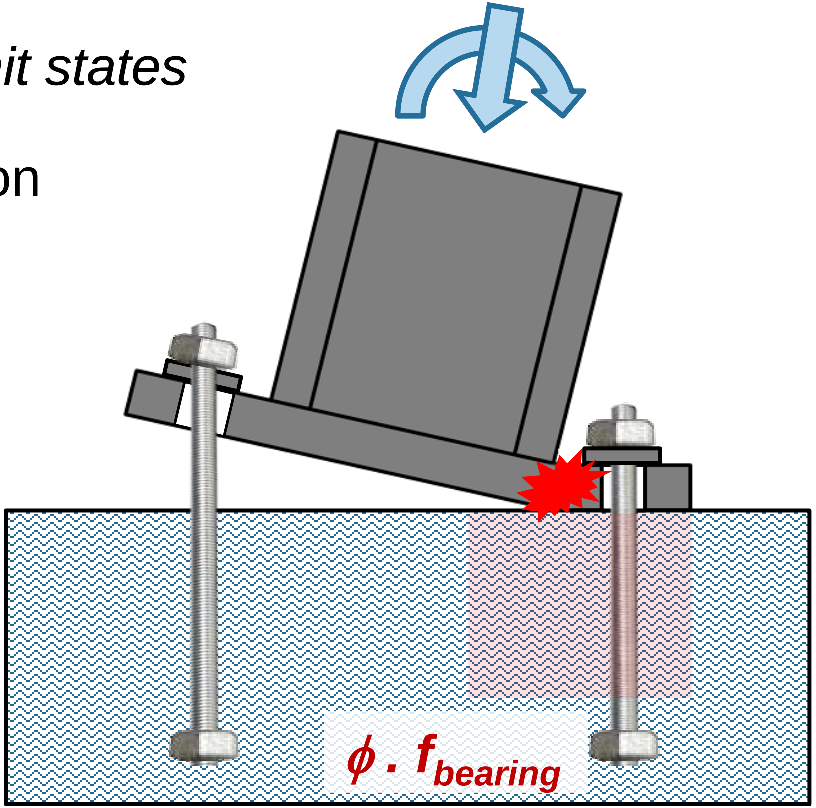


Design Guide One approach

STEP 2 – Given Y and T, evaluate limit states

- Base plate yielding on compression side

$$M_{comp} < \phi .\ M_{plate}$$

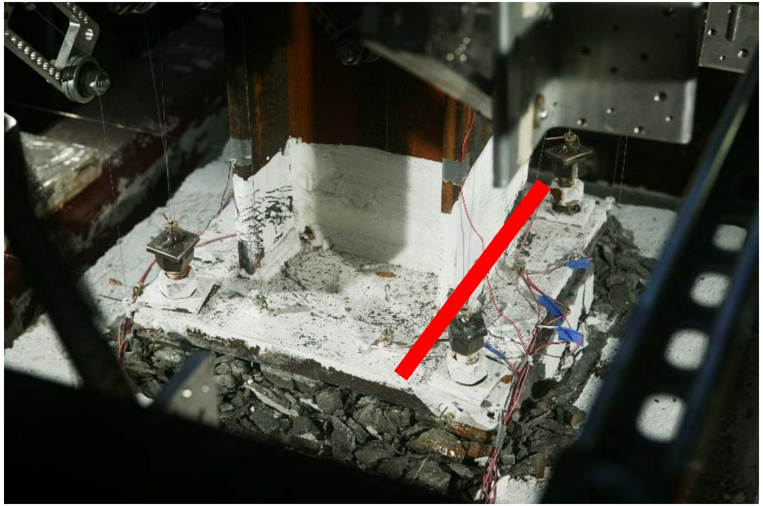


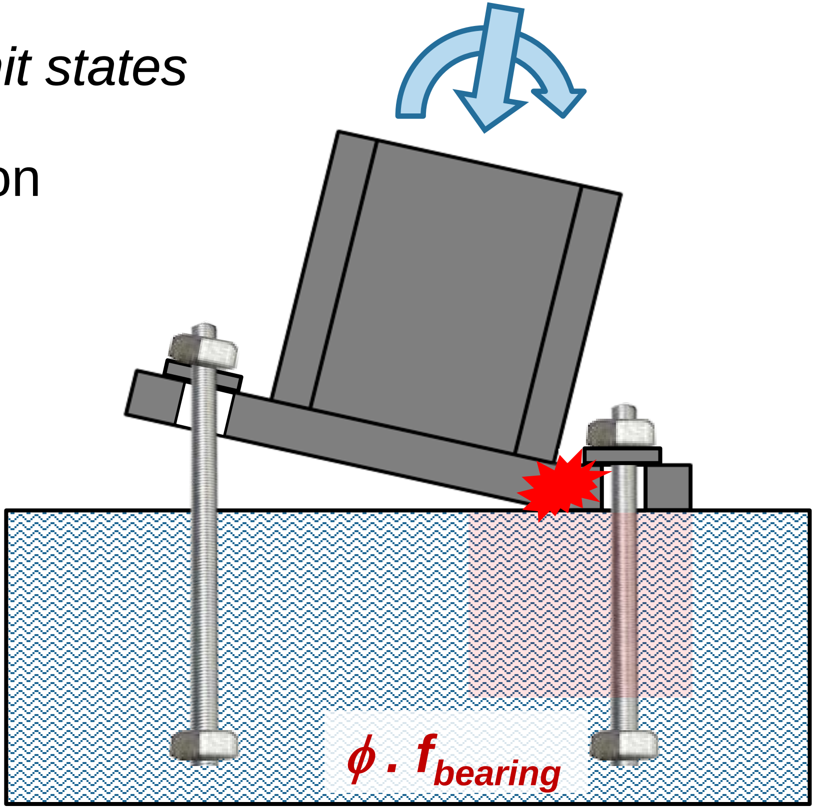
Design Guide One approach

STEP 2 – Given Y and T, evaluate limit states

- Base plate yielding on compression side

$$M_{comp} < \phi . M_{plate} \ (\phi = 0.9)$$



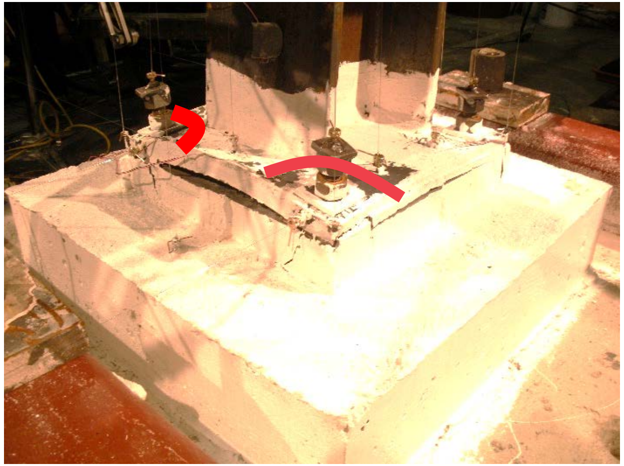


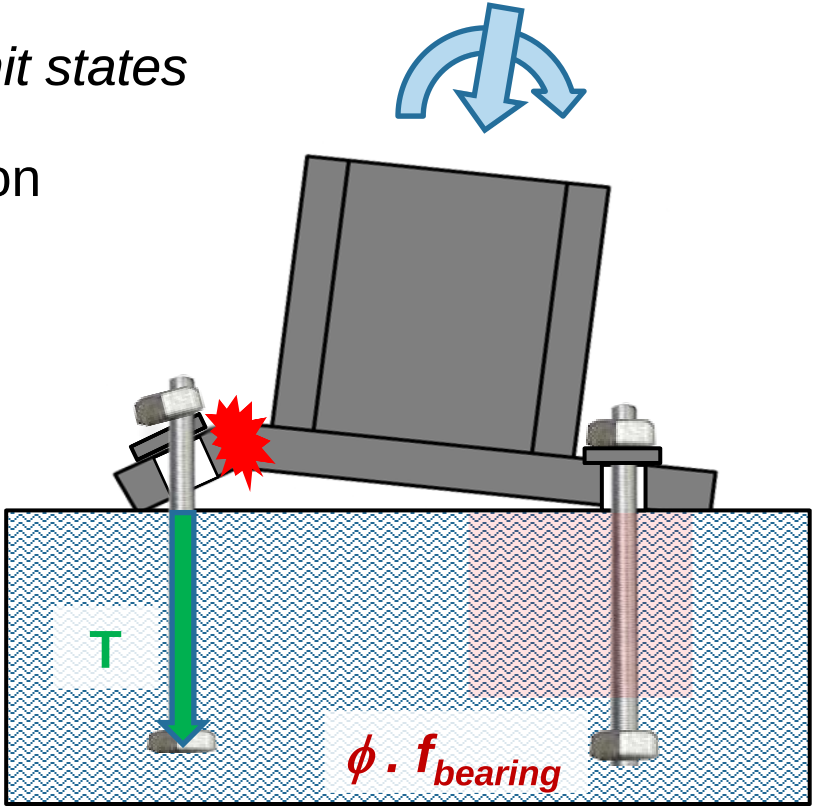
Design Guide One approach

STEP 2 – Given Y and T, evaluate limit states

- Base plate yielding on compression side

$$M_{tens} < \phi . M_{plate} \; (\phi = 0.9)$$





Design Guide One approach

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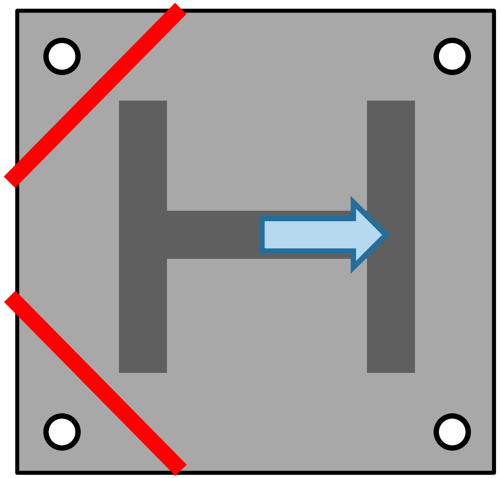
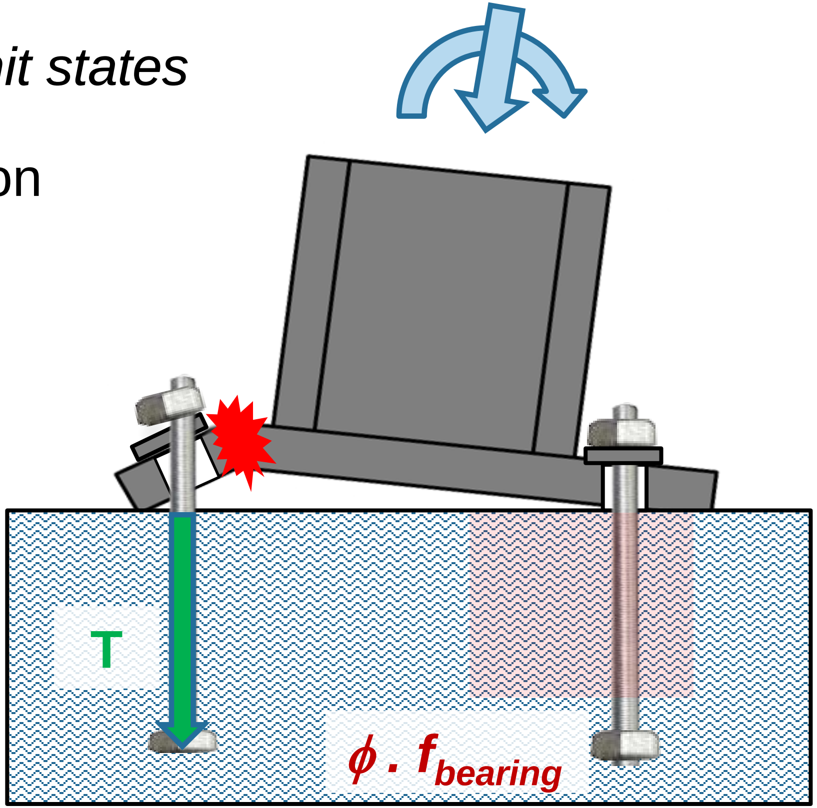


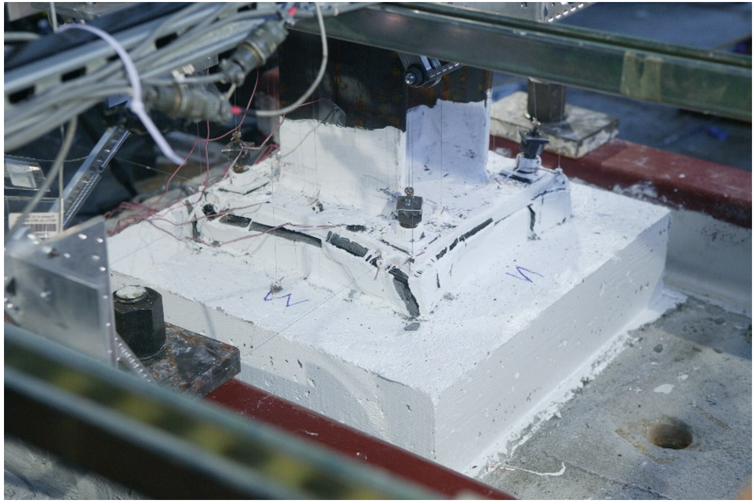


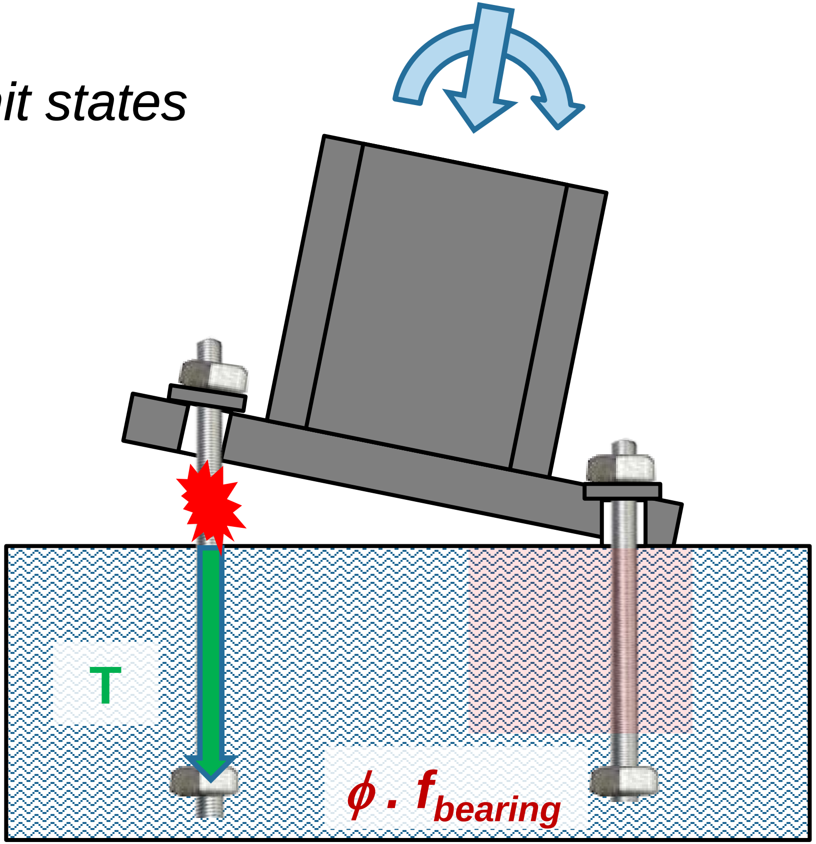
Design Guide One approach

STEP 2 – Given Y and T, evaluate limit states

- Yielding or failure of the anchors

$$T < \phi . T_{rod} \; (\phi = 0.9)$$





Design Guide One approach

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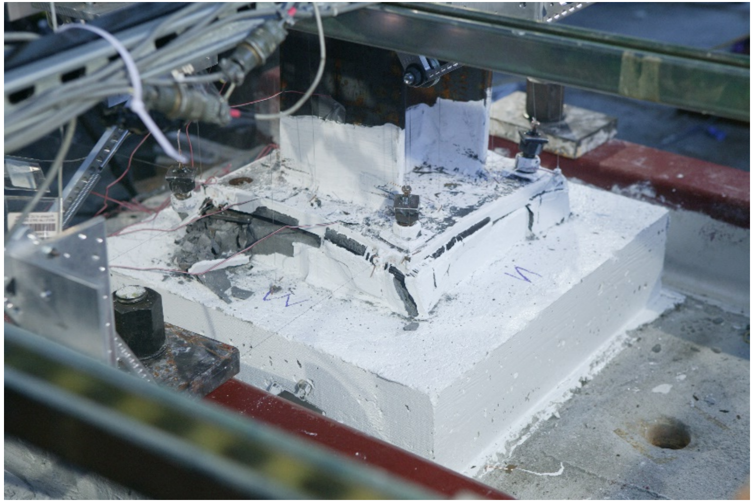

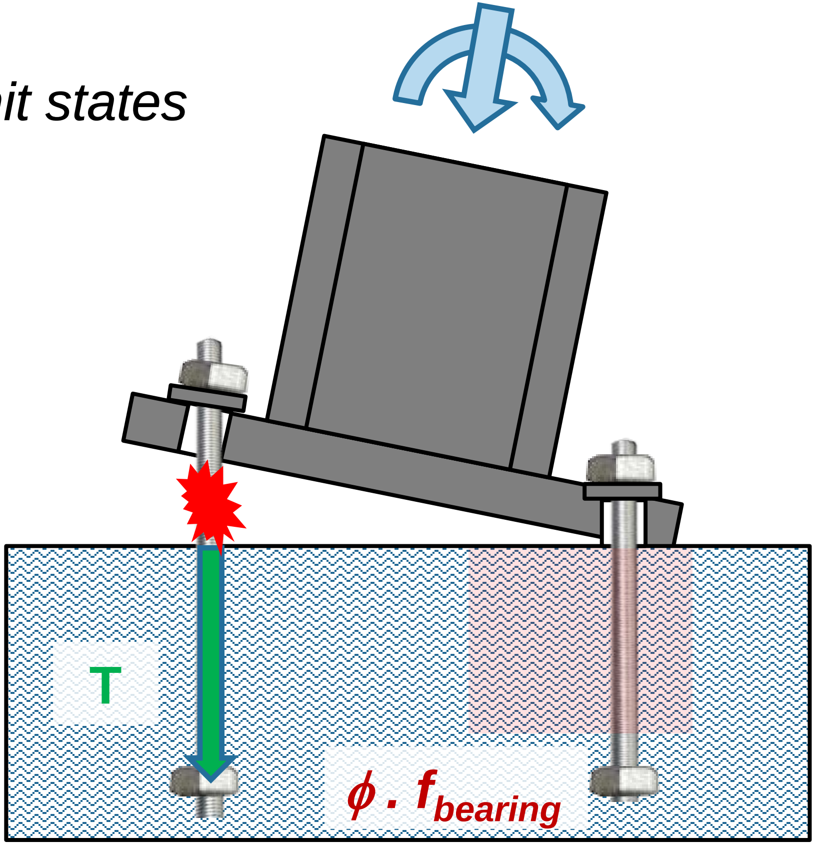

Design Guide One approach

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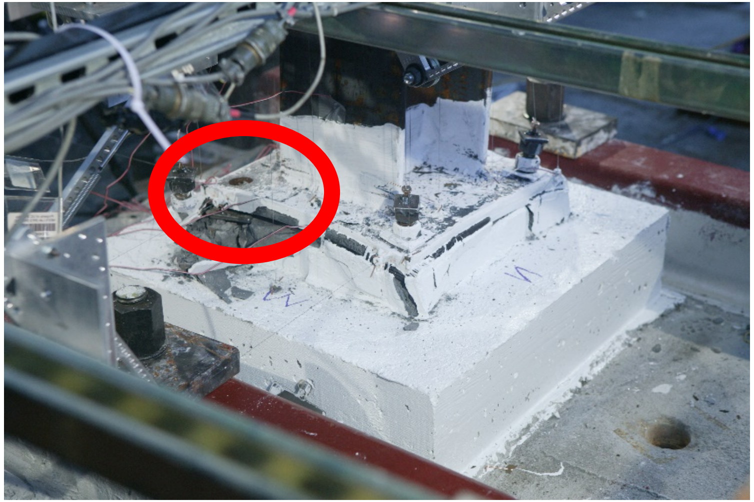
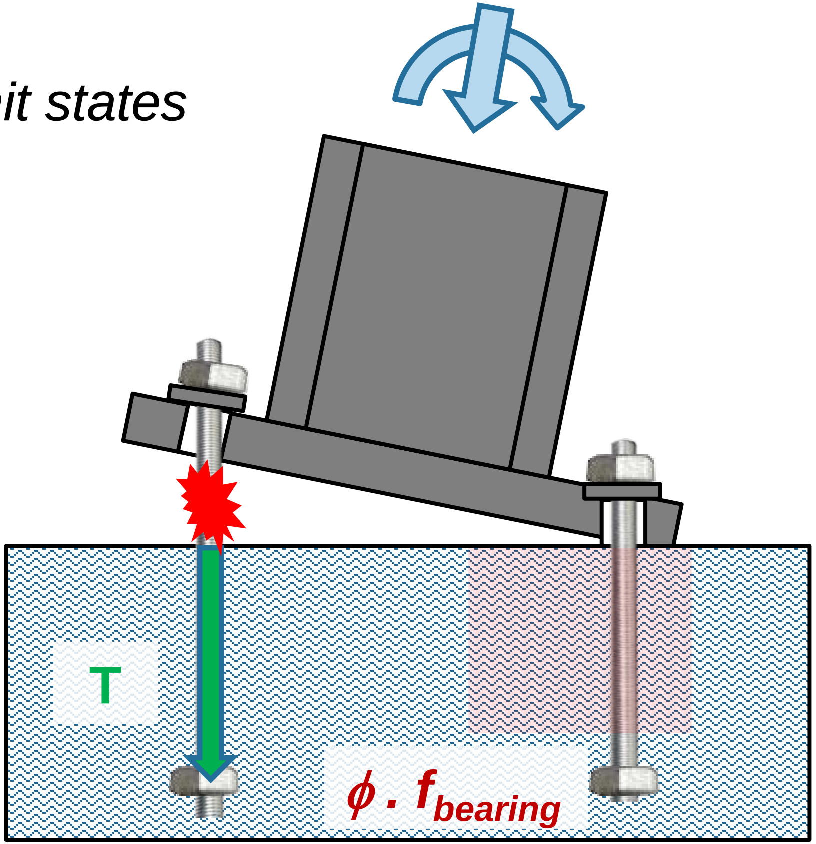
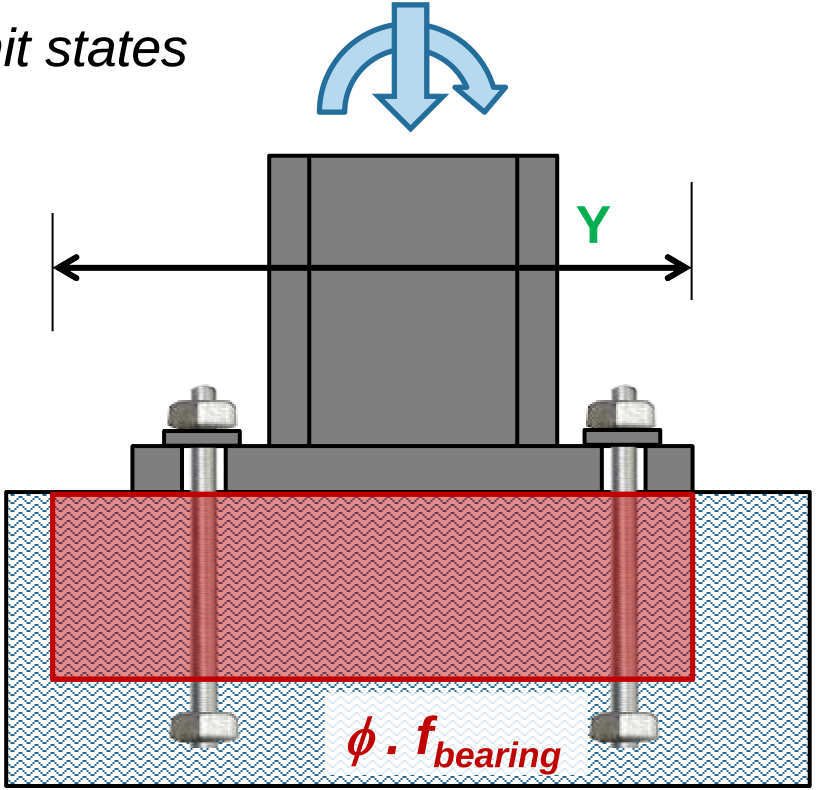




Design Guide One approach

STEP 2 – Given Y and T, evaluate limit states

- Bearing failure of footing (implicit check)
- Bearing stress over plate footprint cannot accommodate compression
- Resize the plate plan dimensions



Design checks

STEP 2 – Given Y and T, evaluate limit states

- Base plate yielding on compression side
- Base plate yielding on tension side
- Anchor rod yielding
- Bearing failure of footing (implicit)

Part 1 – Exposed Base Plate Connections

Exposed Base Plates

Prevailing understanding and design methods

New Developments

Design Guide One Approach

Static/Non -Seismic Loading

- Analysis of Design Guide One approach

Seismic Loading

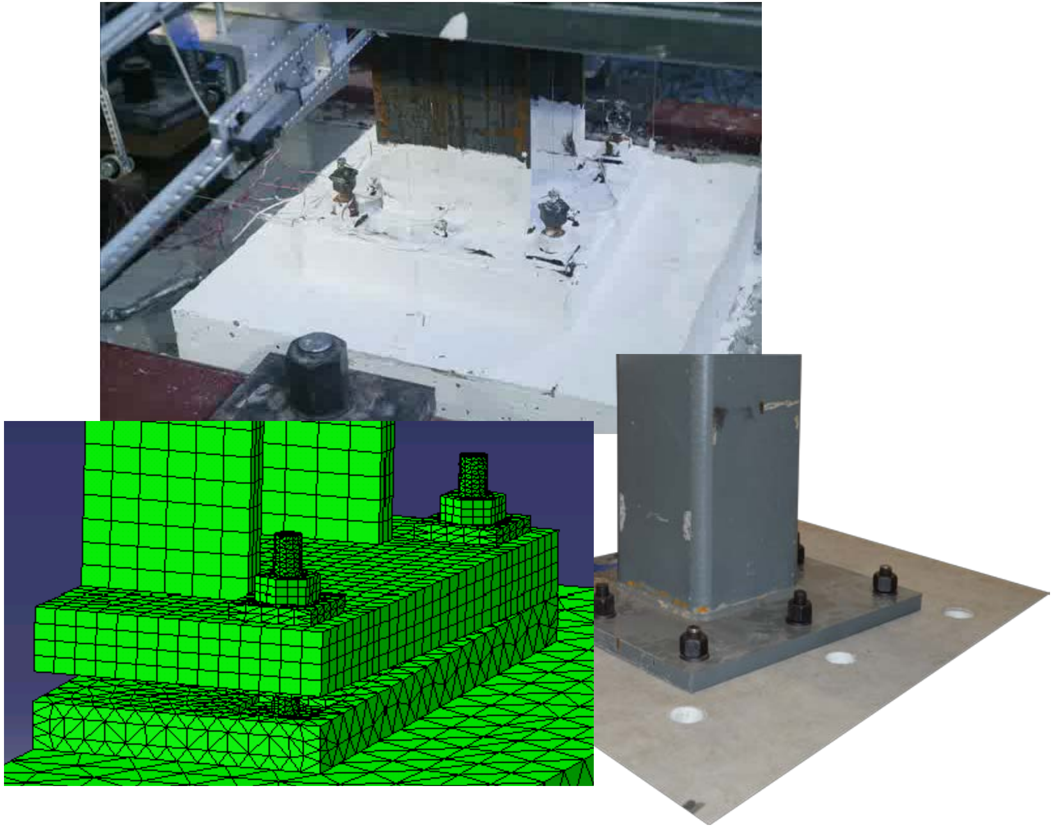
- Strong vs Weak Base Design
- Ductile base plate details

Research in the last 15 years

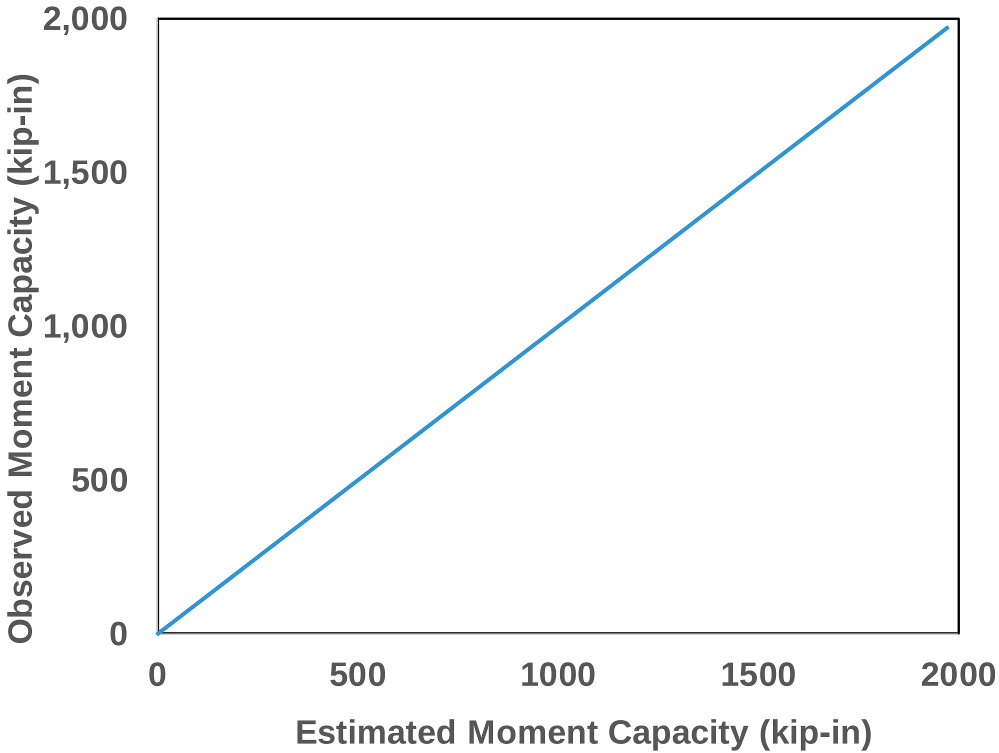
- Many Experiments (34 large scale tests at UCD)

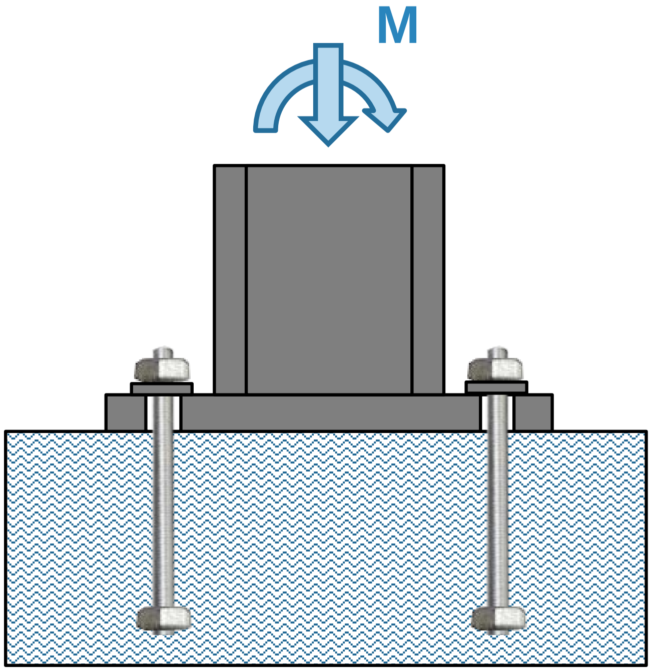
- Finite element and line based simulations

- Monte-Carlo based Reliability analysis



Strength estimation based on Design Guide One





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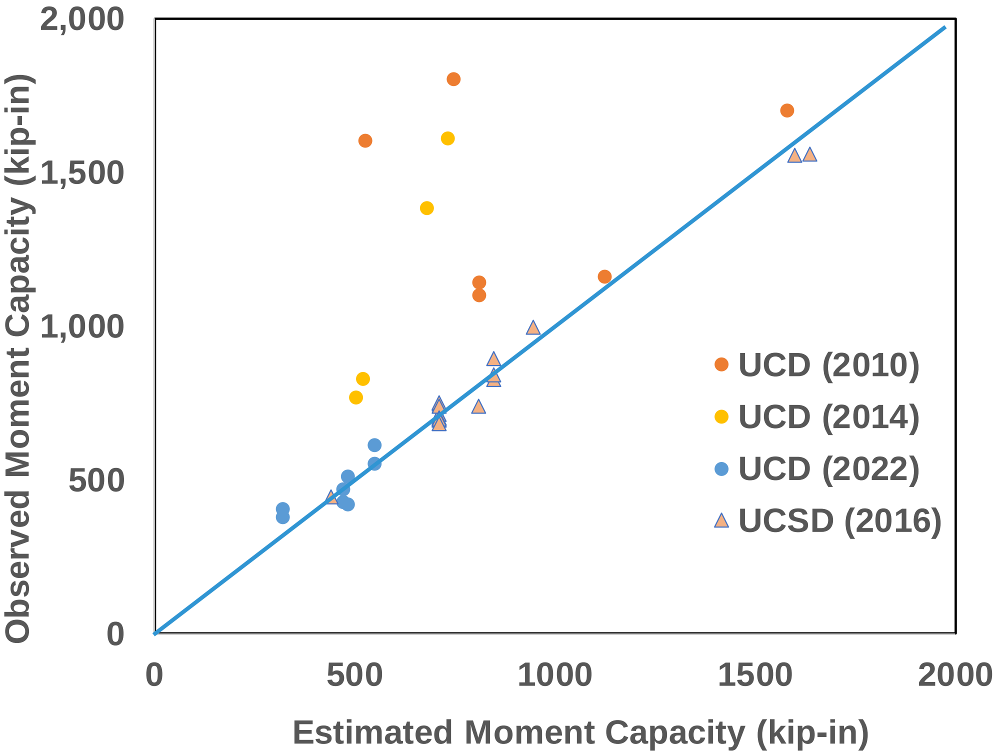

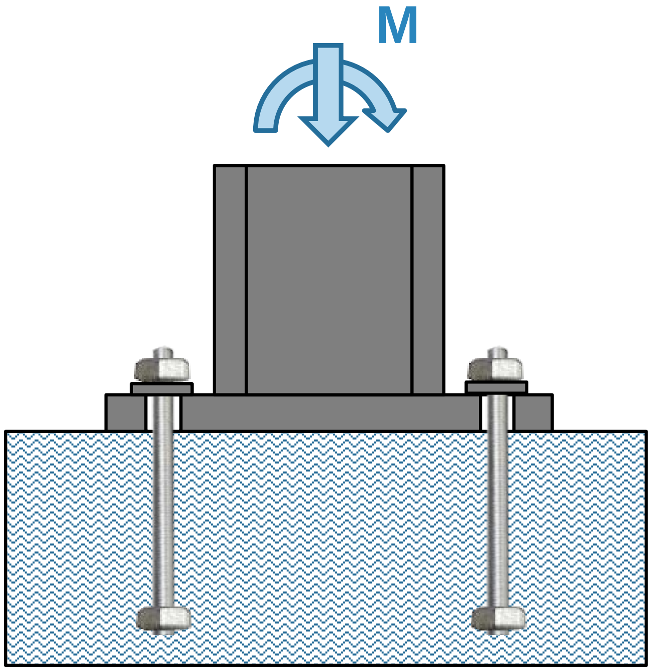

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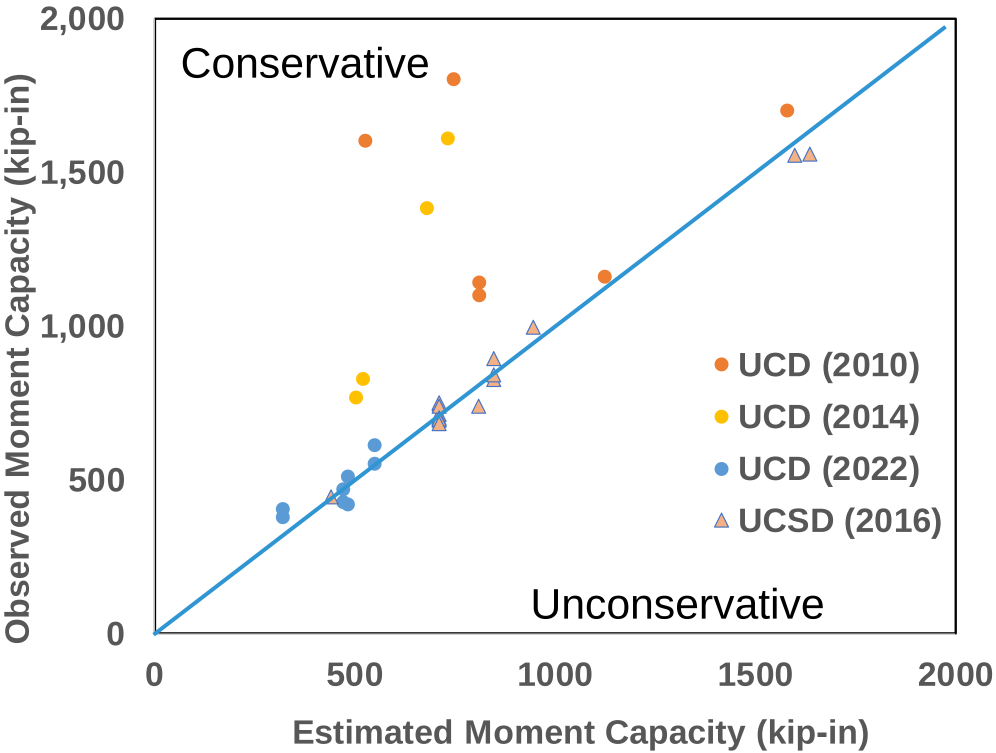

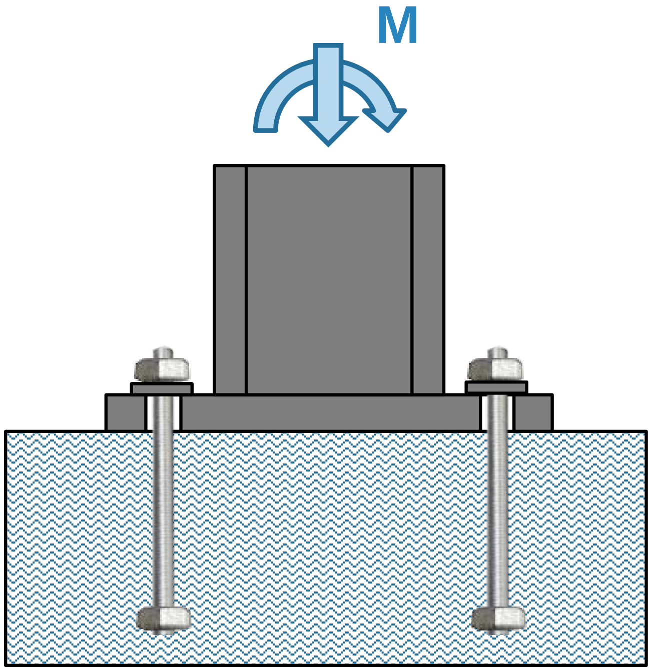

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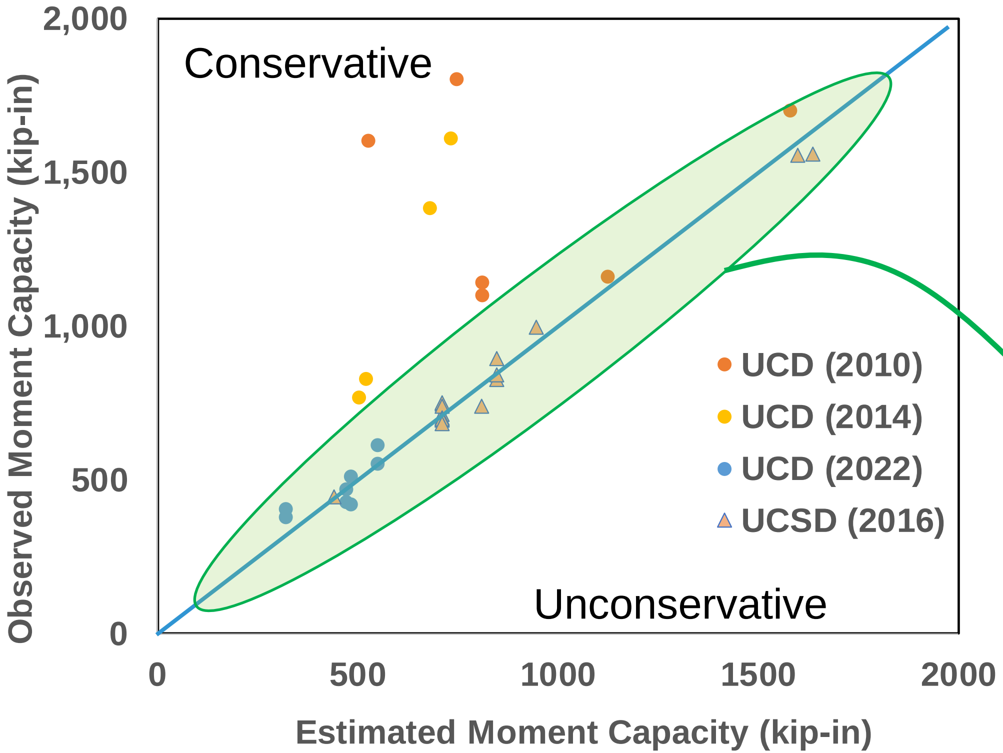

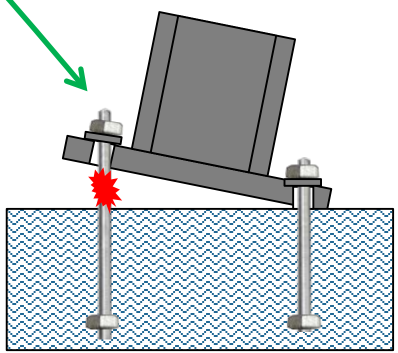

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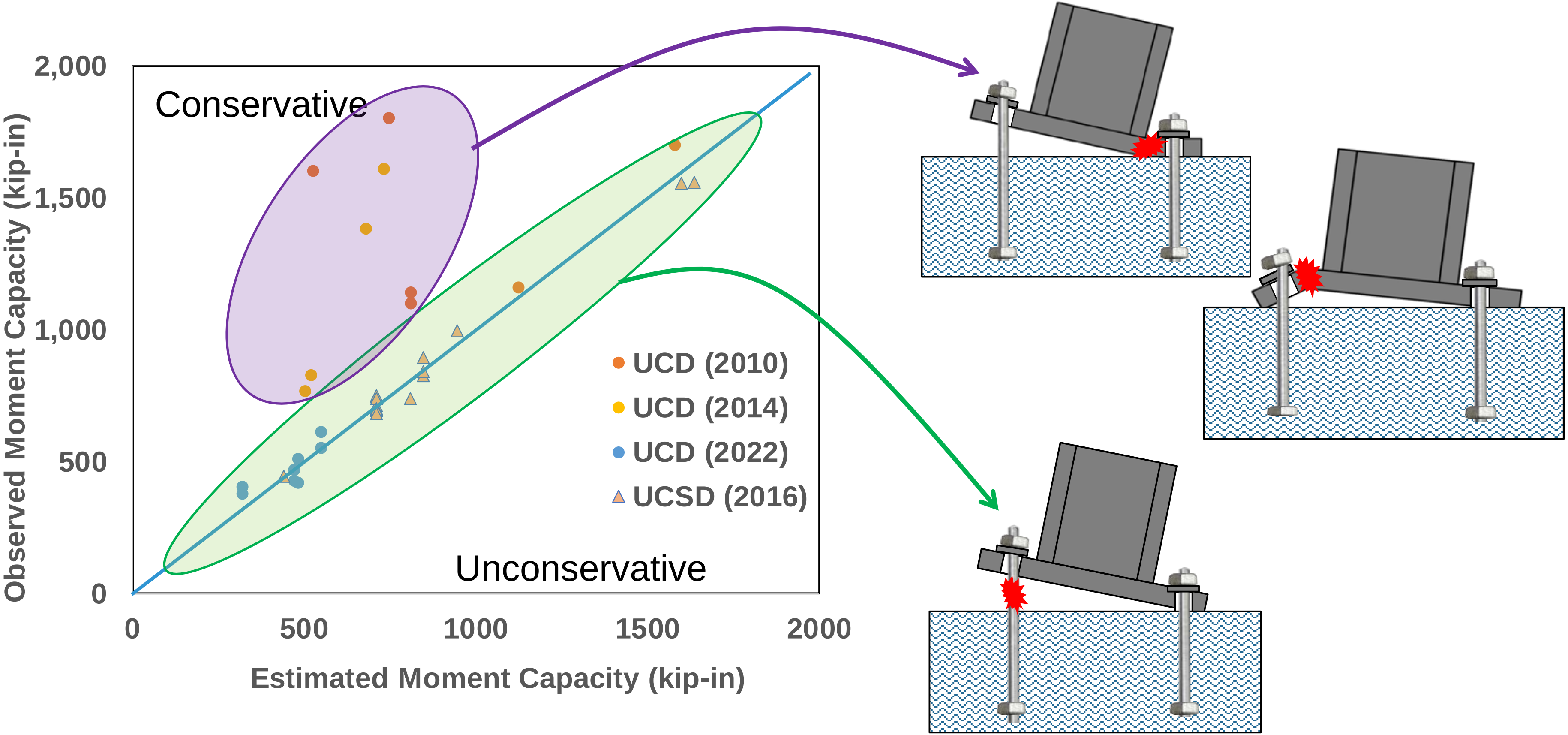

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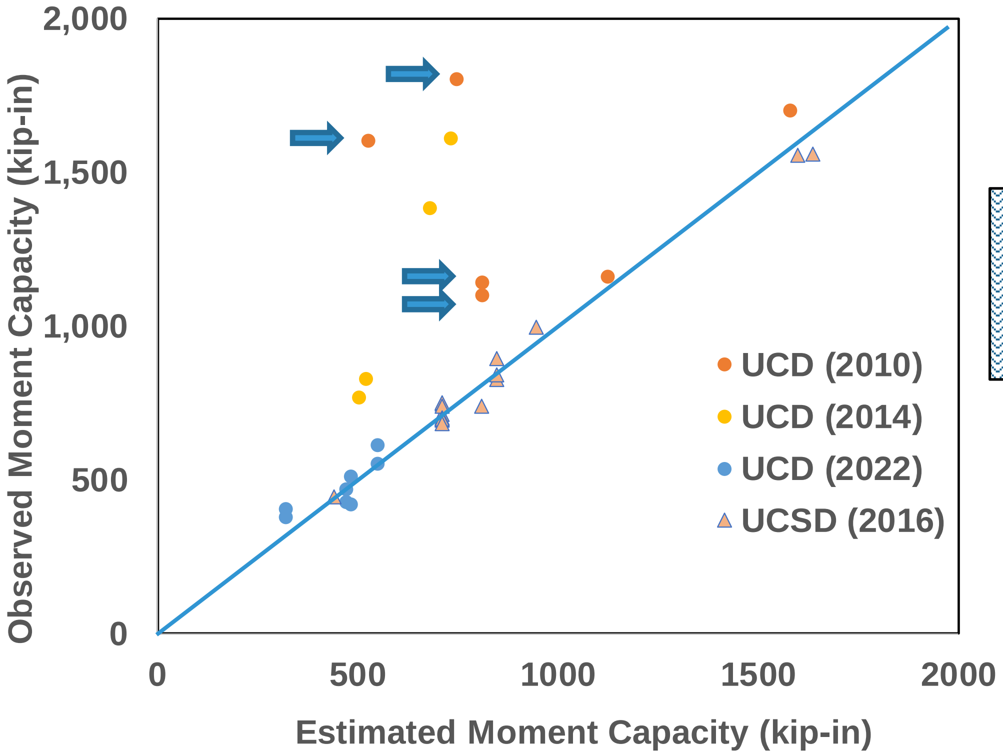


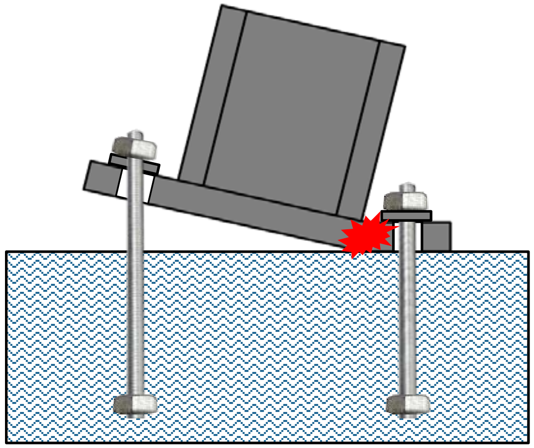
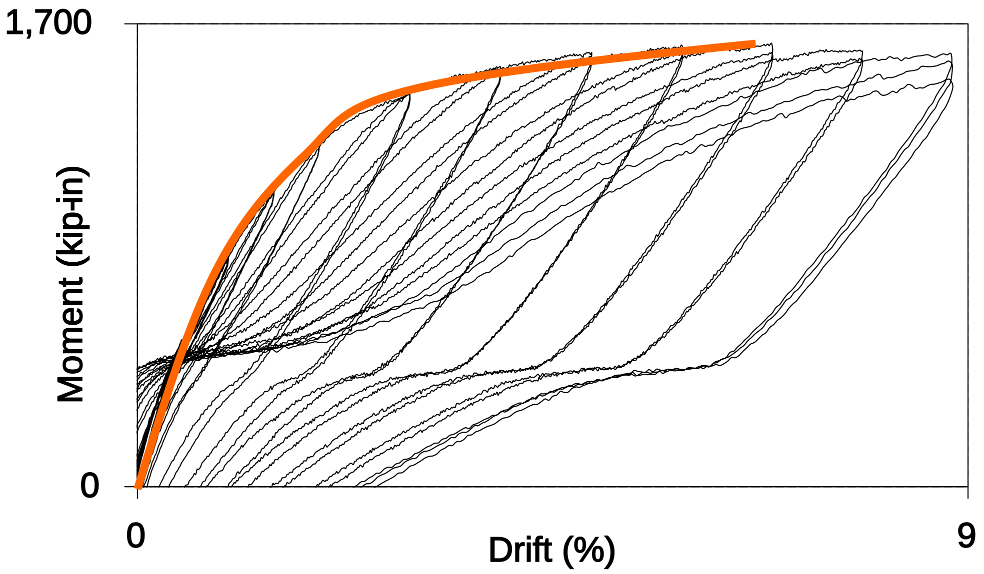
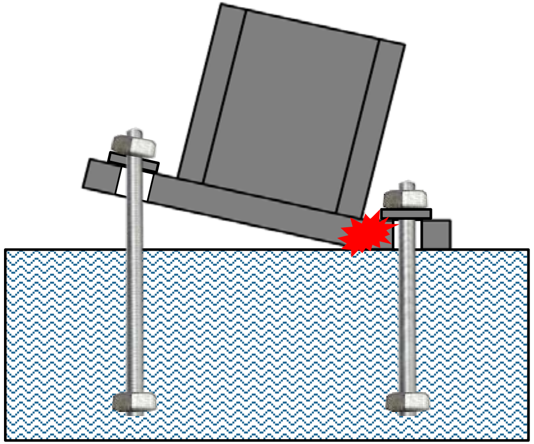
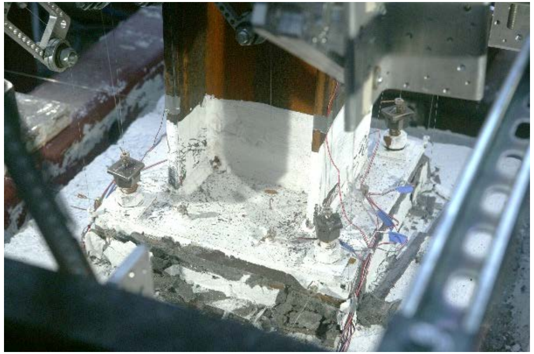


Plate bending on compression side not consequential







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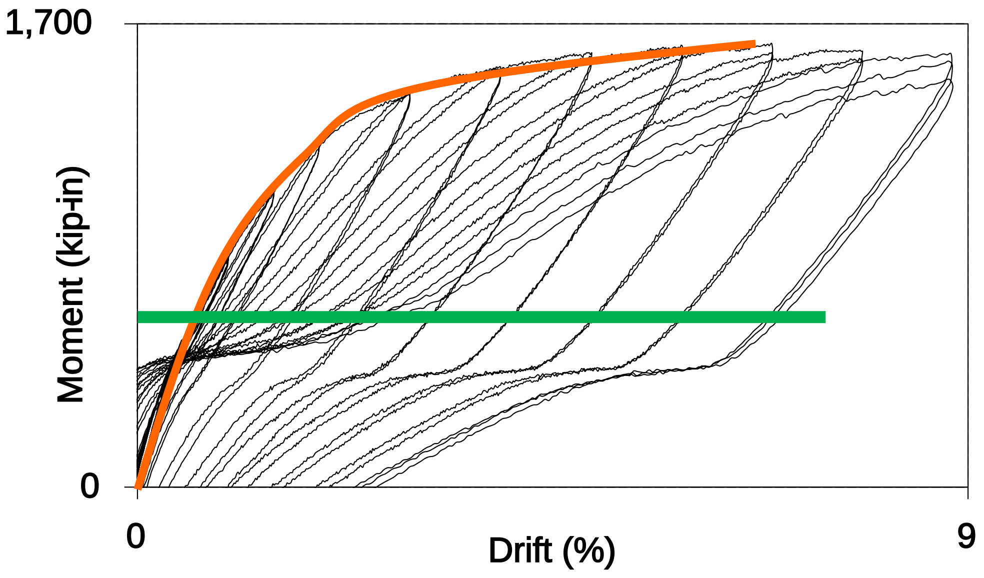

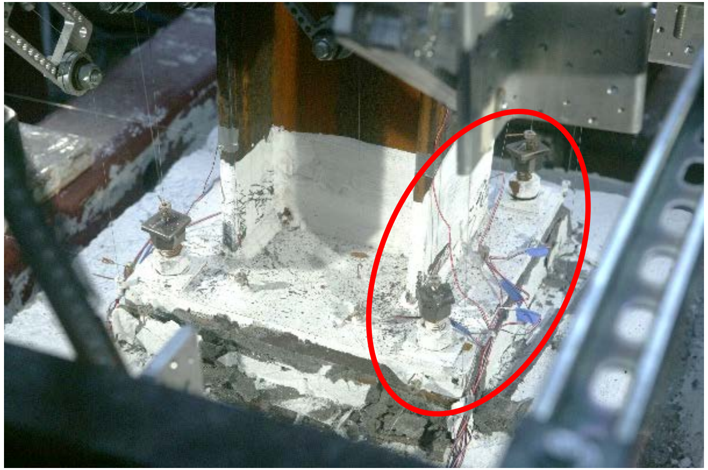

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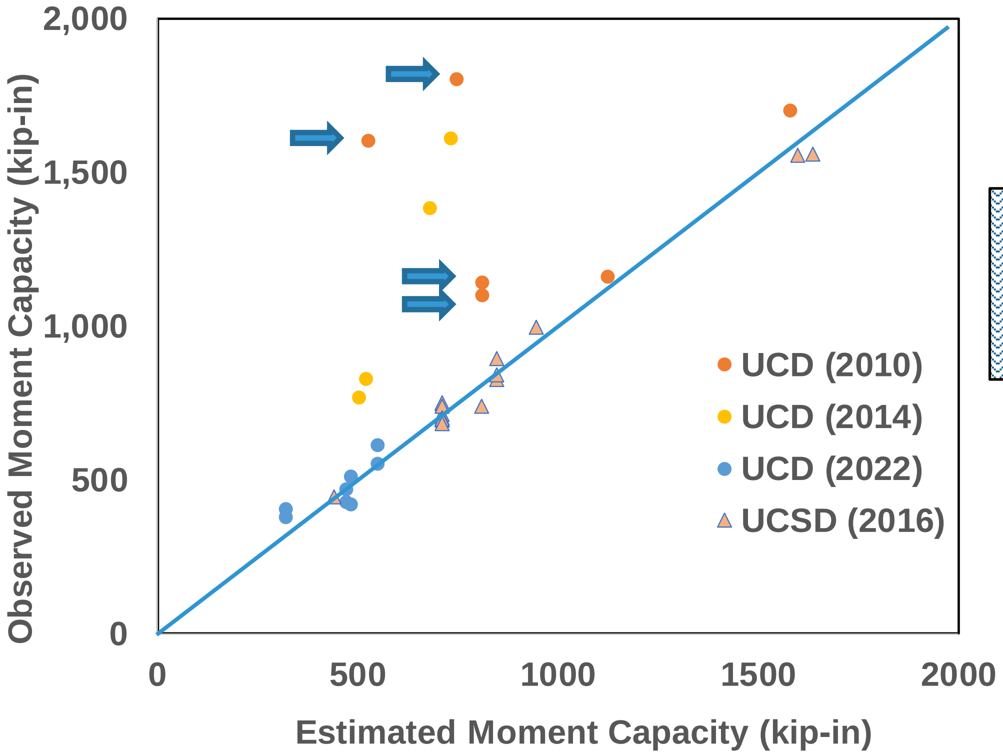
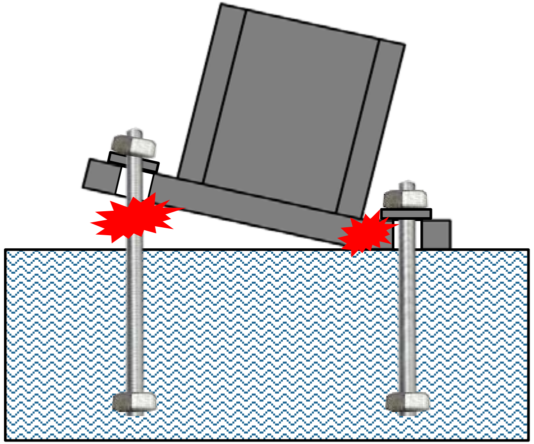
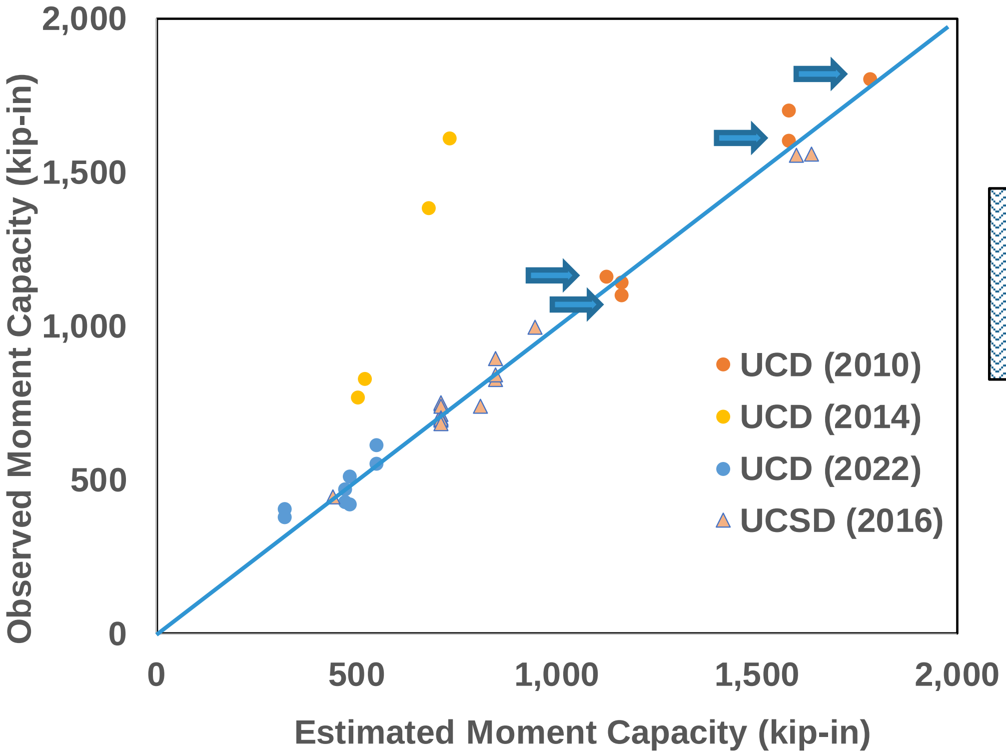
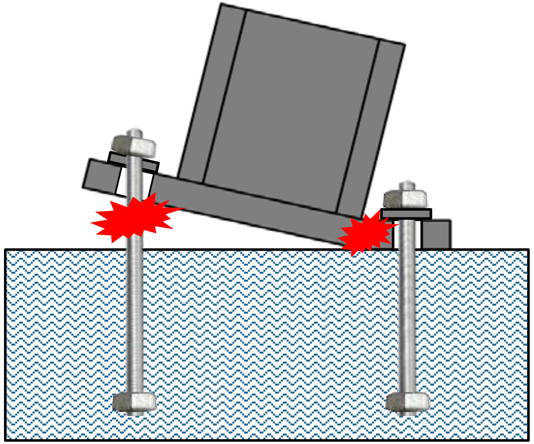




- Compression side yielding did not result in reaching capacity
- Tension side limit state needed

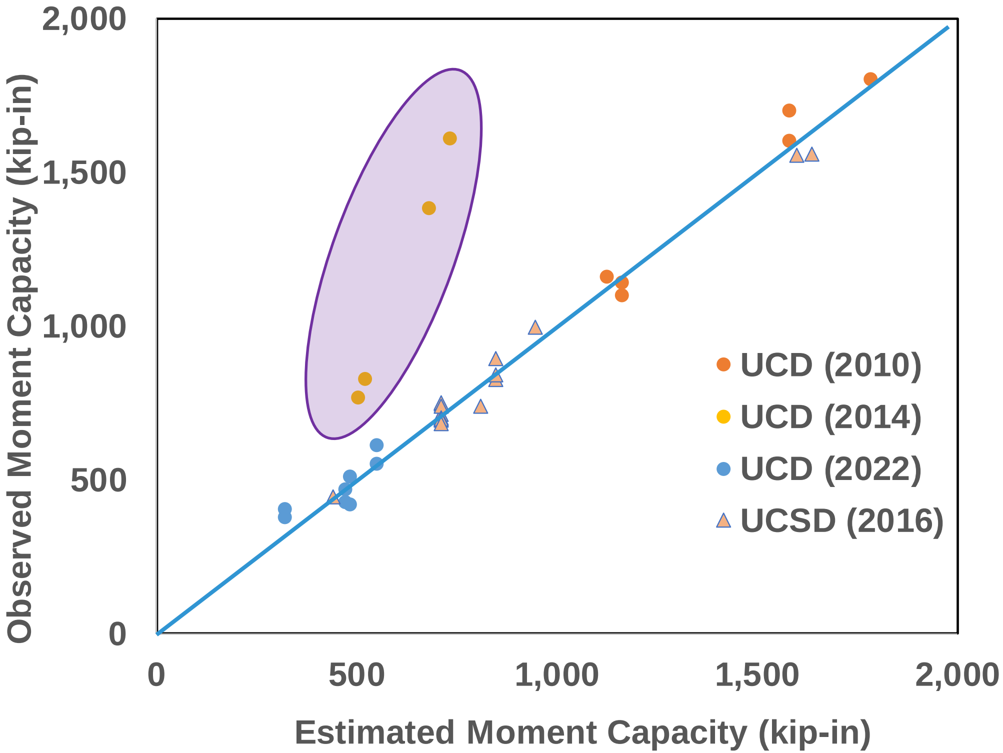
Plate bending on compression side not consequential

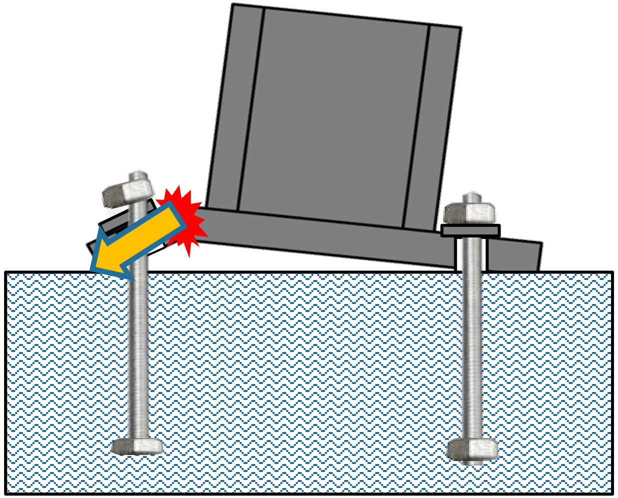




- Determination of a mechanism load addresses this

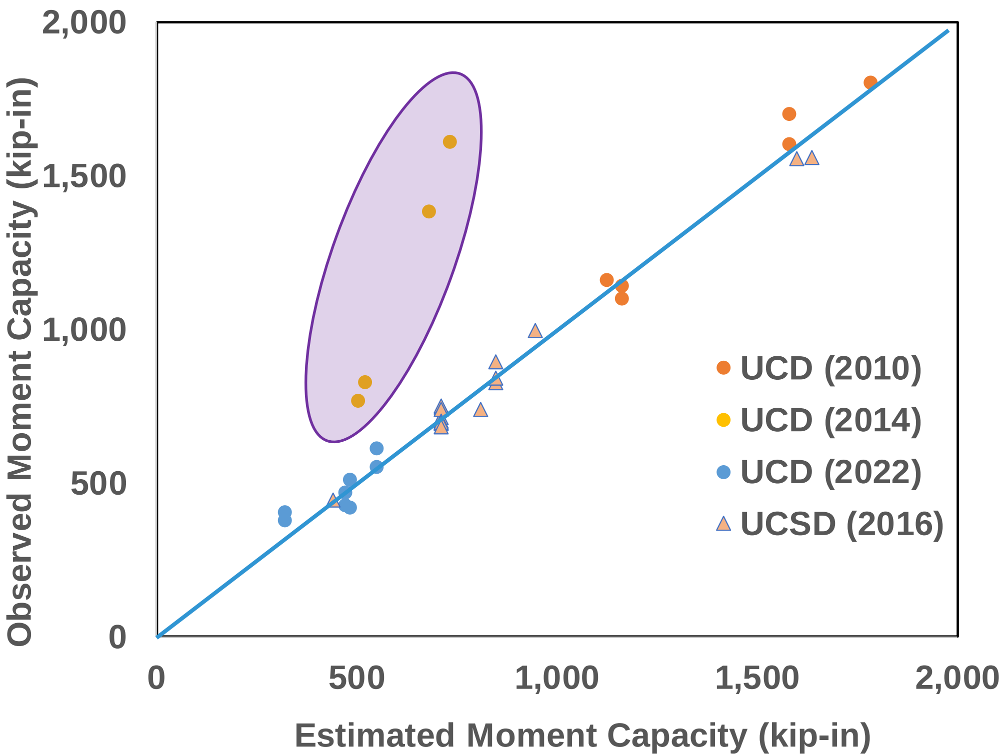
Plate bending on tension side

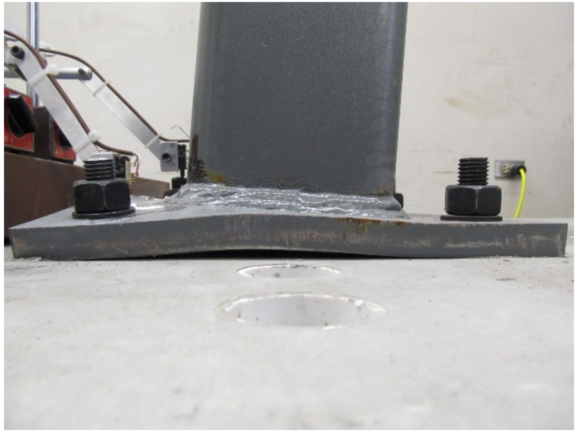




- No eventual yielding of rods
- Strength increase due to membrane action

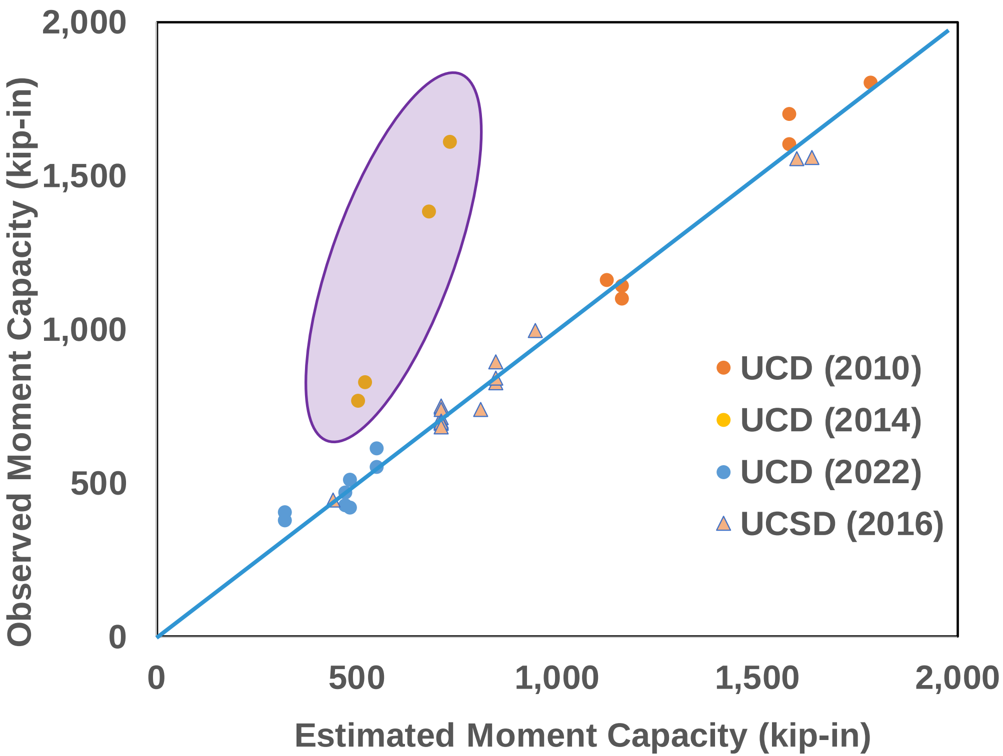
Plate bending on tension side

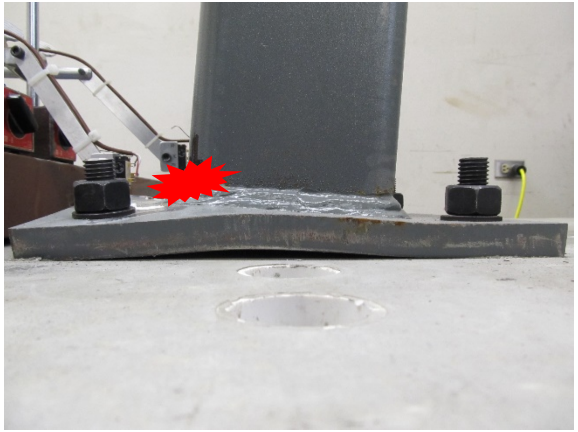




- No eventual yielding of rods
- Strength increase due to membrane action
- Fracture

Plate bending on tension side



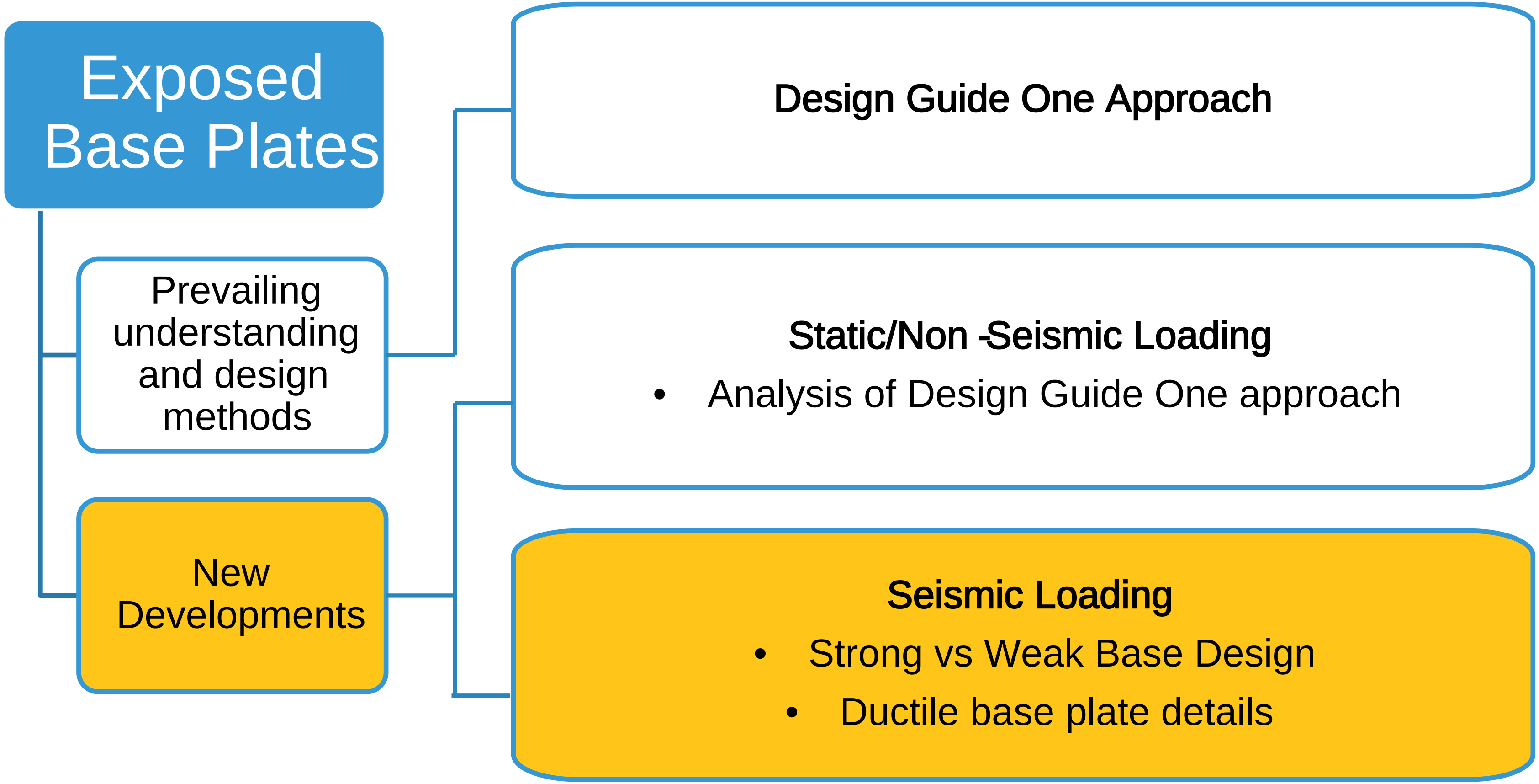


- No eventual yielding of rods
- Strength increase due to membrane action
- Fracture

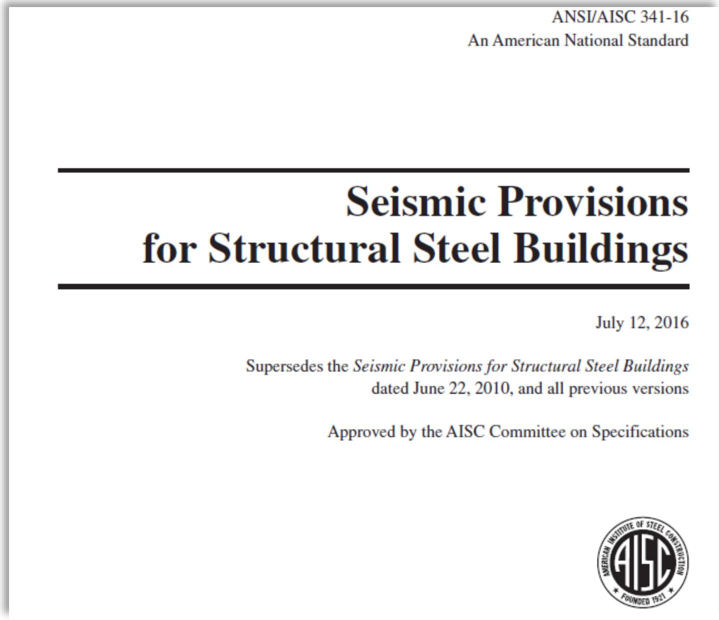
Summary– Design Guide One

- Fairly accurate for strength characterization
- Conservative when plate-bending controls
- Scope does not include
  - Seismic connections
  - Embedded connections
  - Modeling

Part 1 – Exposed Base Plate Connections



Seismic considerations– exposed base plates

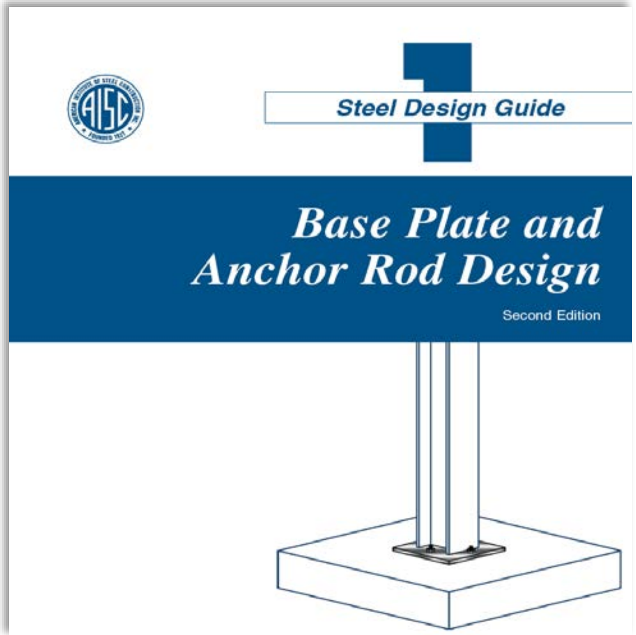

ANSI/AISC 341-16
An American National Standard

Seismic Provisions
for Structural Steel Buildings

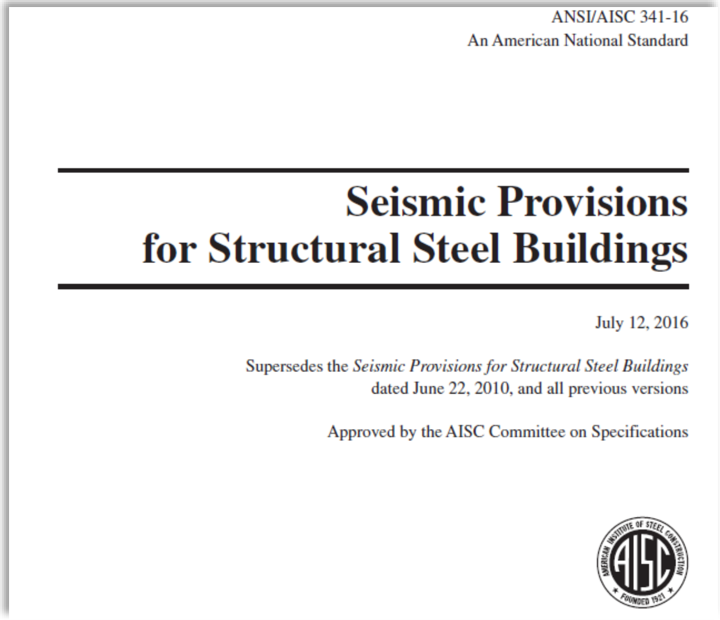
July 12, 2016

Supersedes the *Seismic Provisions for Structural Steel Buildings* dated June 22, 2010, and all previous versions

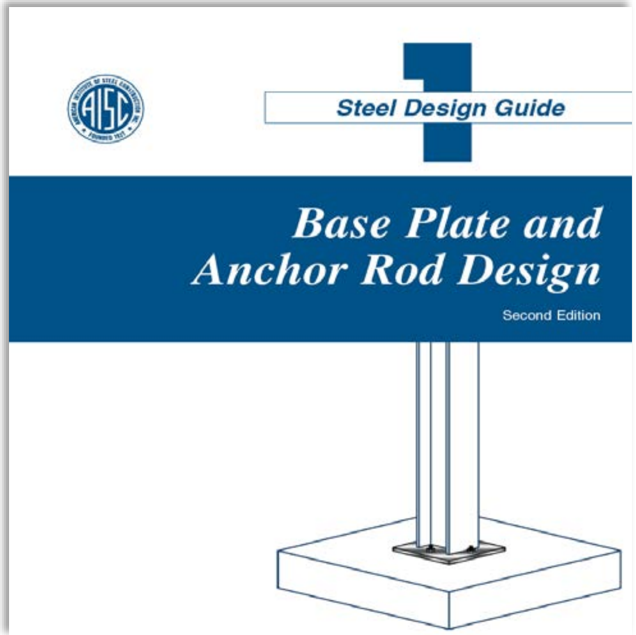
Approved by the AISC Committee on Specifications



Seismic considerations – exposed base plates



Broad principles and philosophy



Design and detailing

Seismic considerations – exposed base plates

ANSI/AISC 341-16
An American National Standard

Seism
for Structural St

Supersedes the *Seismic Prov*
dated June

Approved by the

6c. Required Flexural Strength

Where column bases are designed as moment connections to the foundation, the required flexural strength of column bases that are designated as part of the SFRS, including their attachment to the foundation, shall be the summation of the required connection strengths of the steel elements that are connected to the column base as follows:

(a) For diagonal braces, the required flexural strength shall be at least equal to the required flexural strength of diagonal brace connections.

(b) For columns, the required flexural strength shall be at least equal to the lesser of the following:

(1) $1.1R_yF_yZ/\alpha_s$ of the column; or

(2) The moment calculated using the overstrength seismic load, provided that a ductile limit state in either the column base or the foundation controls the design.

Broad principles and philosophy

Two ways to design seismic base connections

Strong base design

6c. Required Flexural Strength

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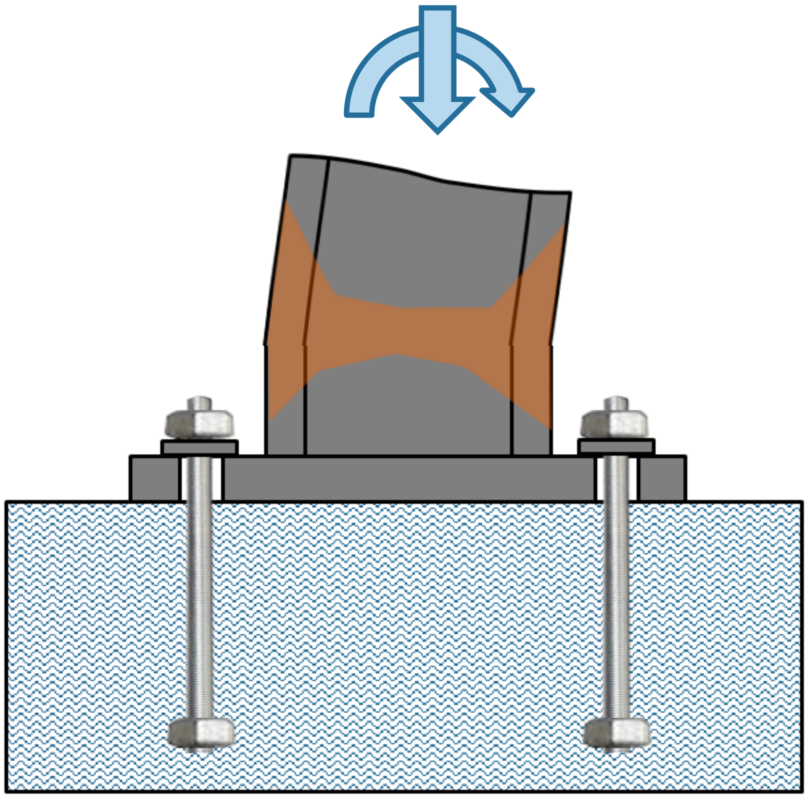
Strong base design

- Direct application of Design Guide One

- Large rods, thick plate



Two ways to design seismic base connections

Weak base design using Ω_0 loads

6c. Required Flexural Strength

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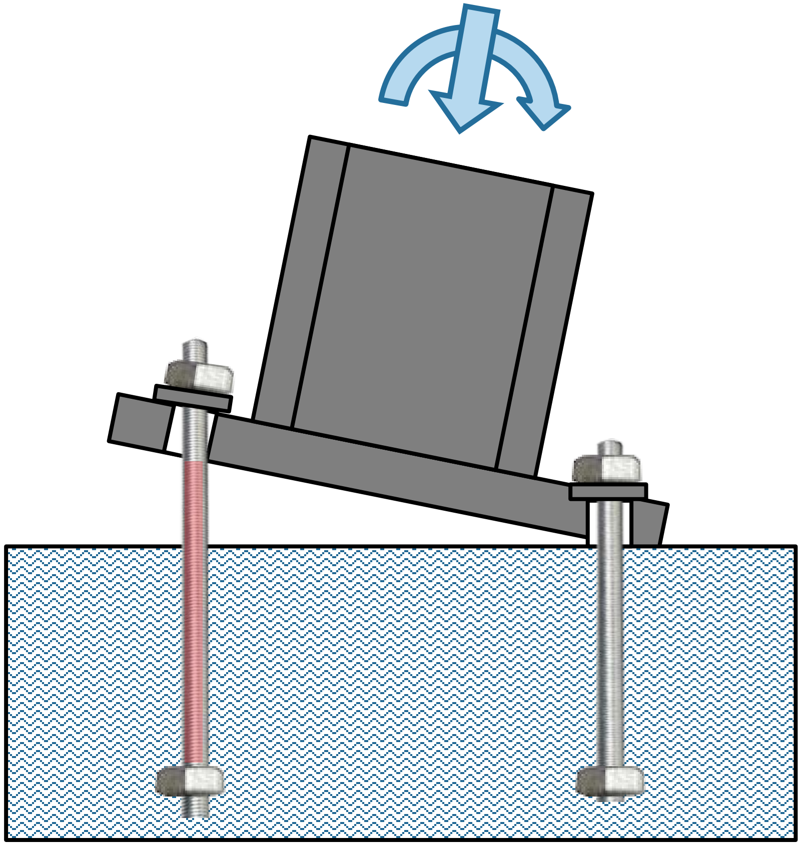
(2) The moment calculated using the overstrength seismic load, provided that a ductile limit state in either the column base or the foundation controls the design.

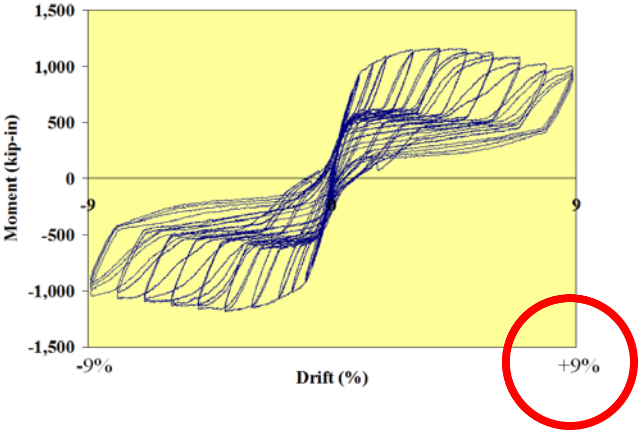
Weak base design

- Weak base design
- Cheaper connection
- Requires ductility
  - Limited specific guidance on how to achieve this



Inherent ductility of exposed base connections

Great inherent ductility (rotation >5%)



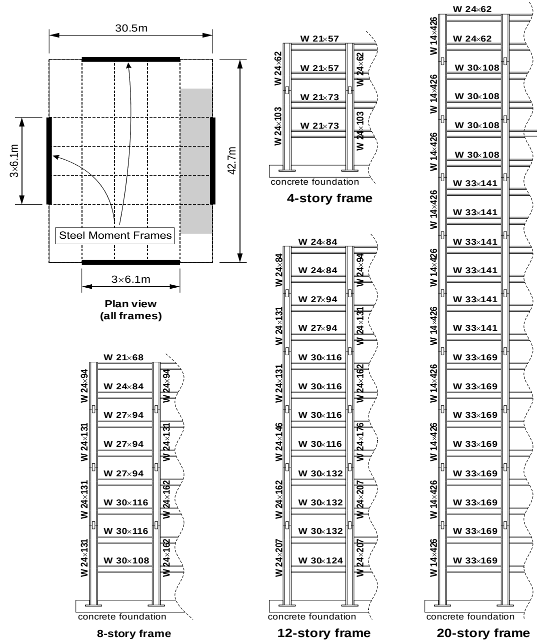
Gomez et al. (2010), Kanvinde et al. (2015), Trautner et al. (2017),
Astaneh et al. (1992), Fahmy et al. (1999), Burda & Itani (1999), Lee et al. (2008) and Wald et al. (2020)

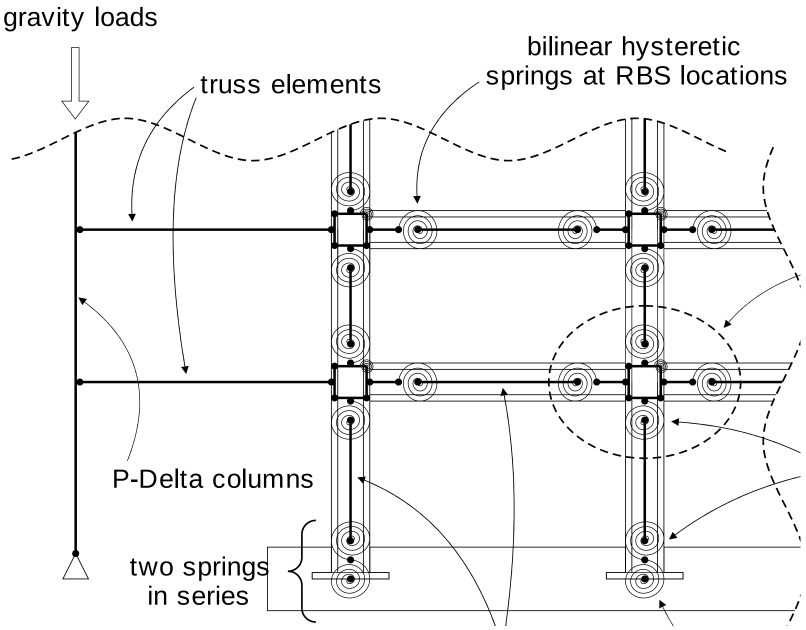
How to achieve weak base design?

- Develop understanding of base rotation demands
- Engineer details that can meet these demands, with confidence
- Demonstrate effectiveness of these details

How to achieve weak base design?

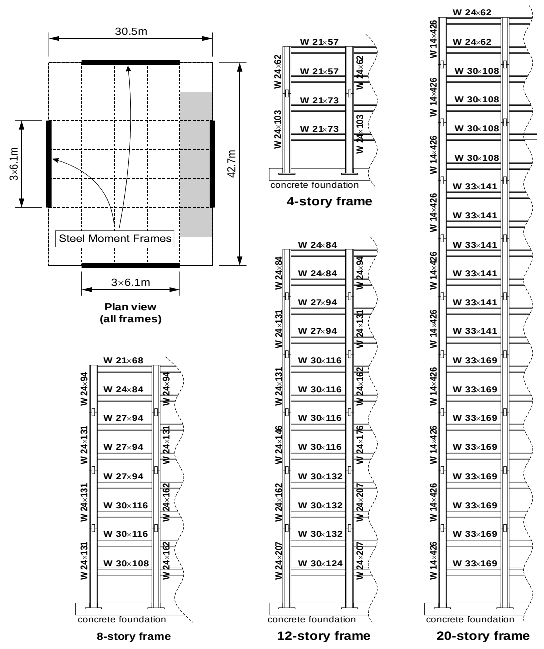
Develop understanding of base rotation demands through NLTHA

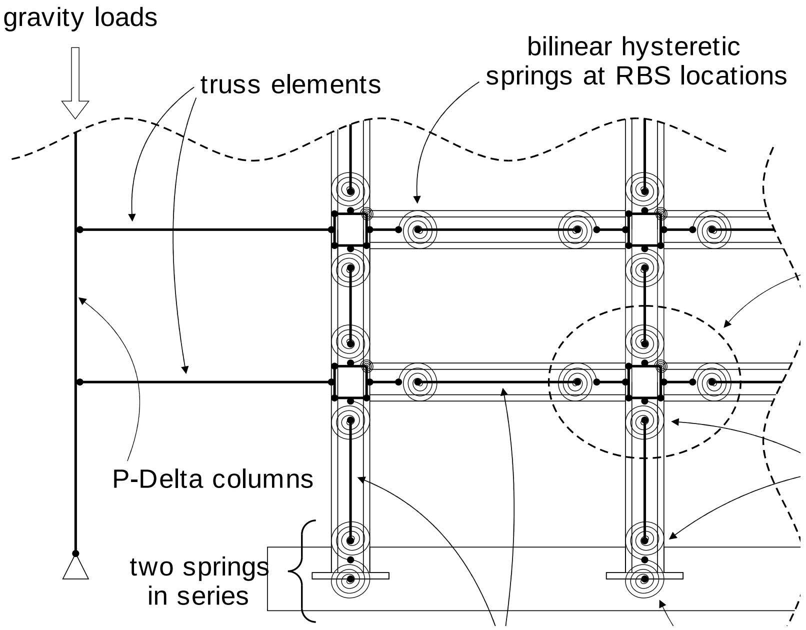




How to achieve weak base design?

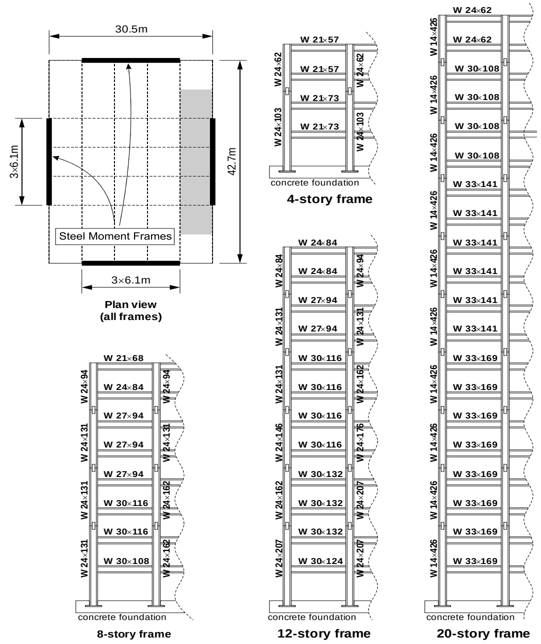
Rotation in the range of 4-5% provides great performance

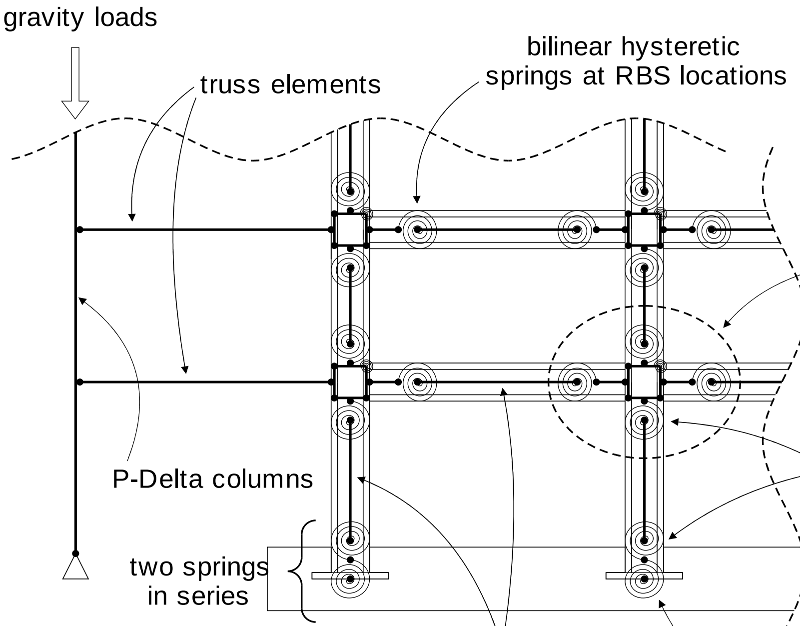




How to achieve weak base design?

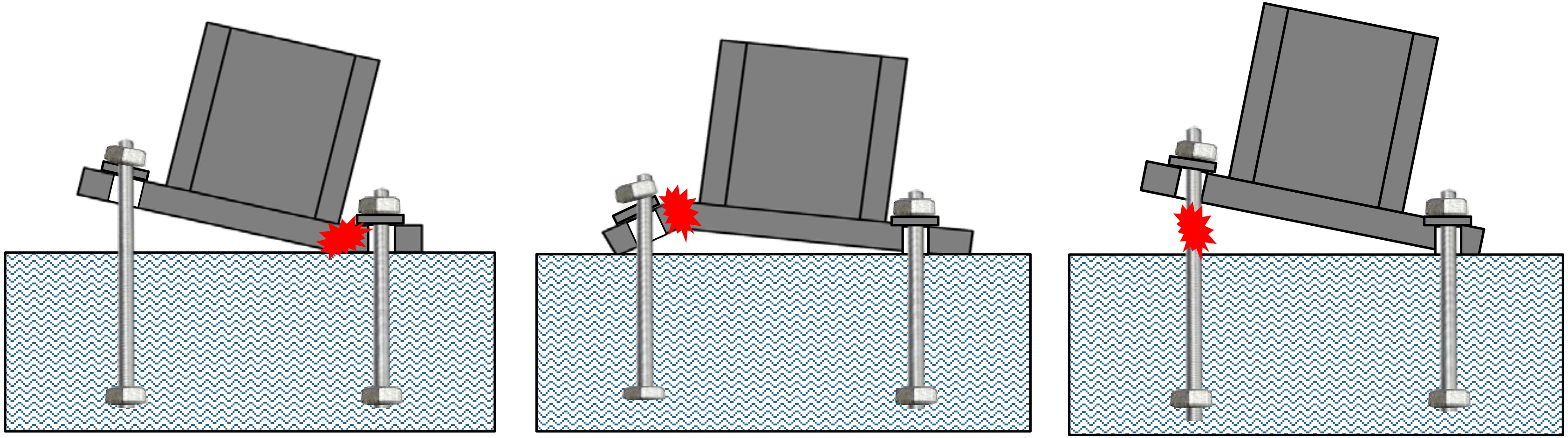
Weak-base design is well within reach



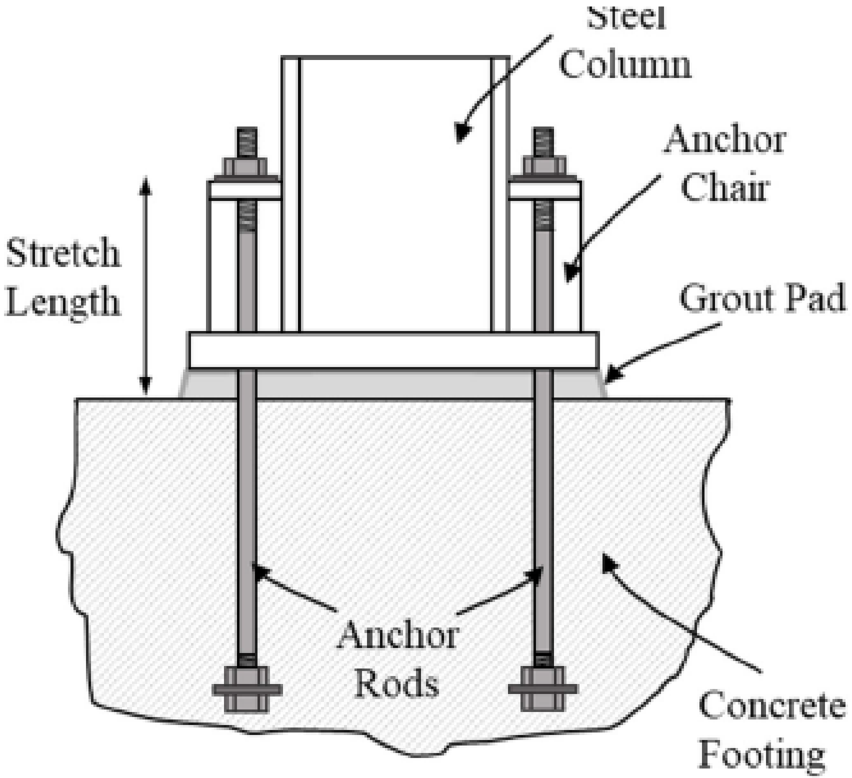


Engineering such a connection

Which ductile mode to use?



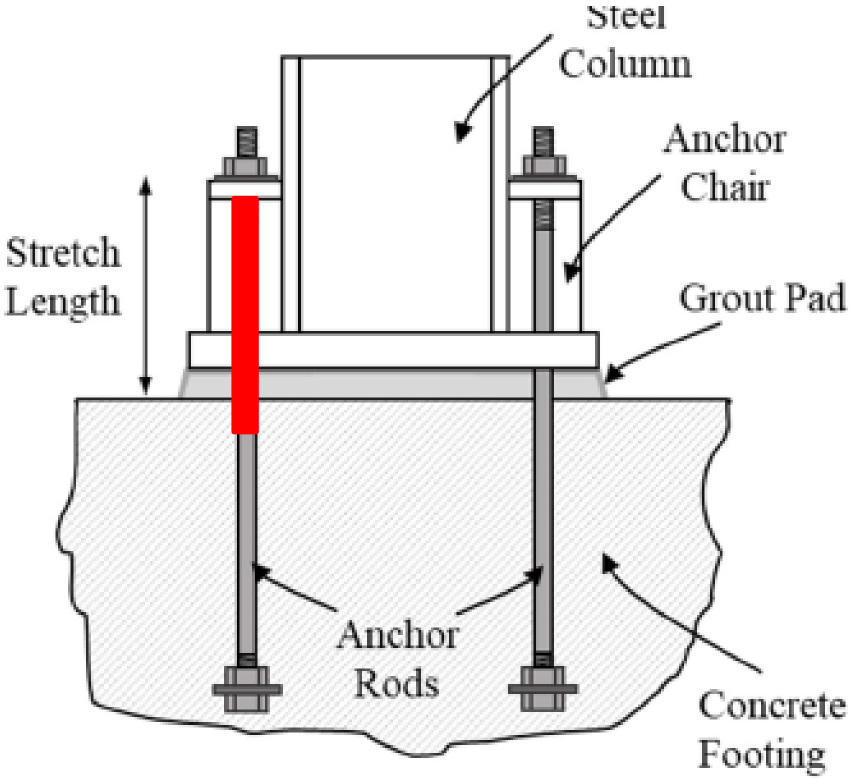
Ductile base connections through rod elongation



Soules et al (2016)

- Good performance observed under high shaking
- Attributed to stretch length

Ductile base connections through rod elongation



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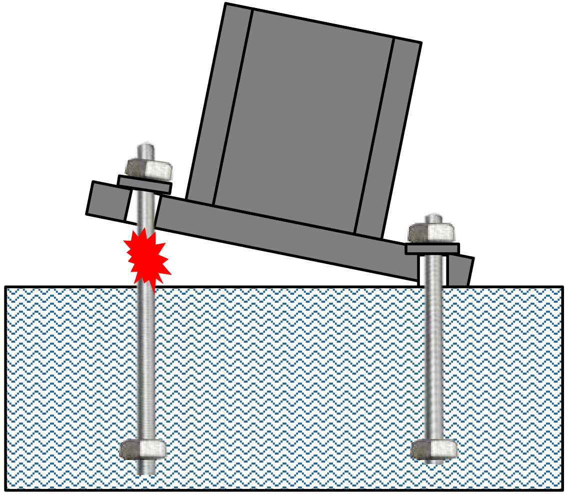
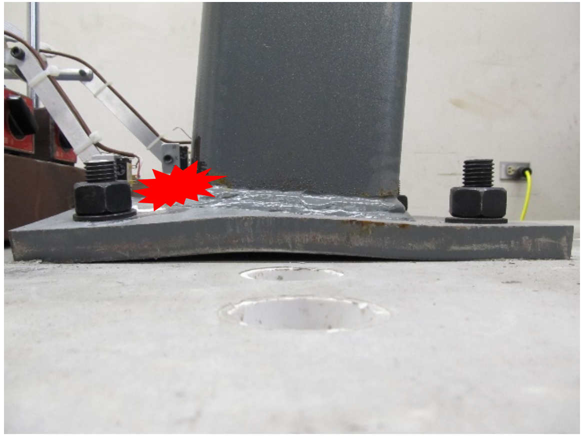
Achieving ductility in base connections

Consensus around rod elongation vs base plate yielding





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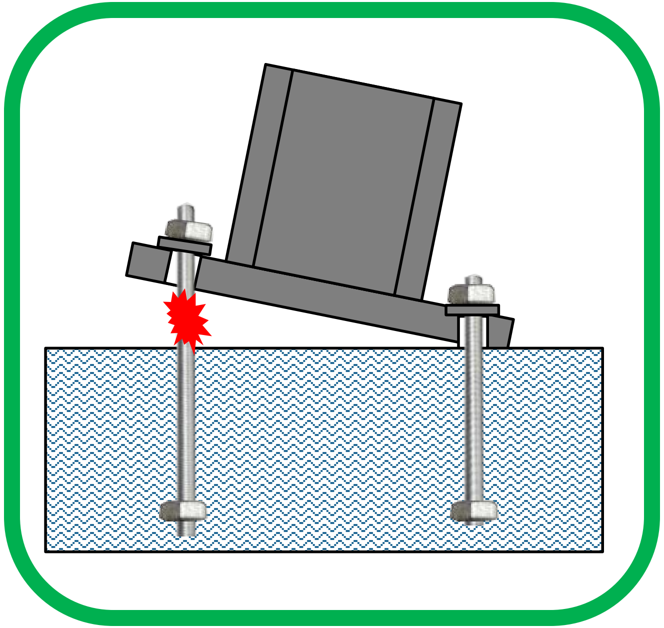
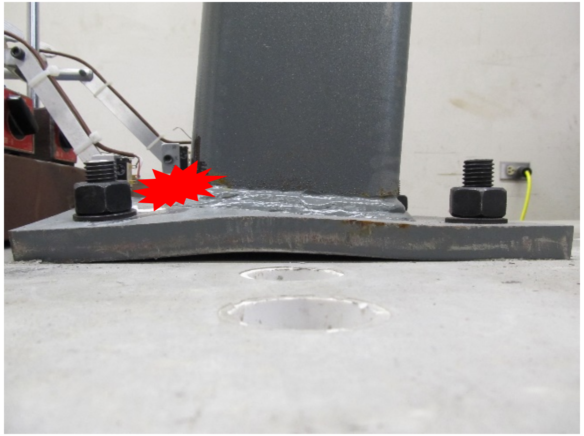
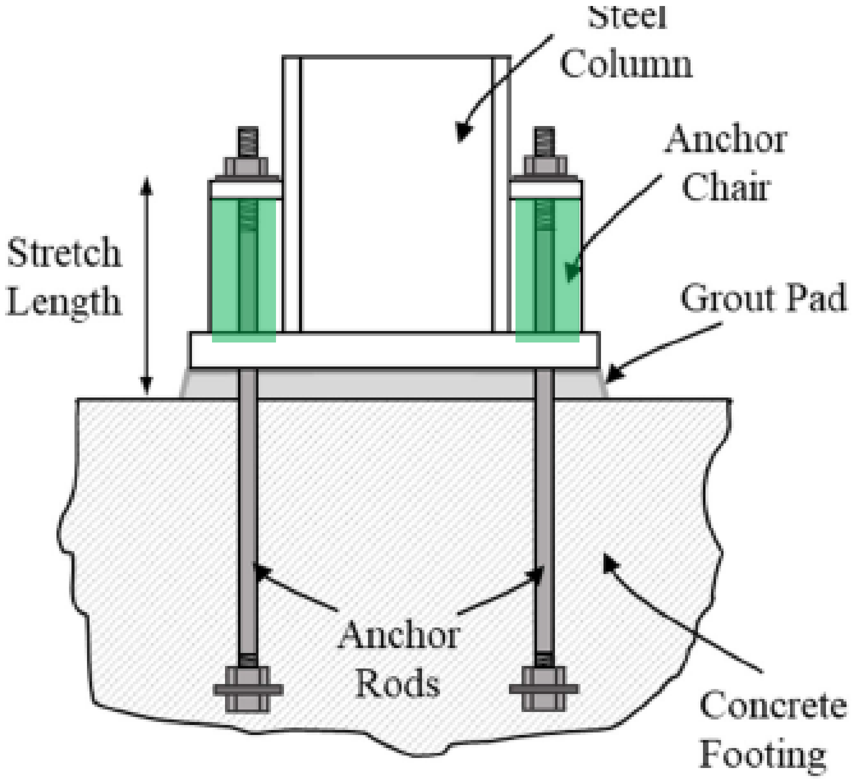
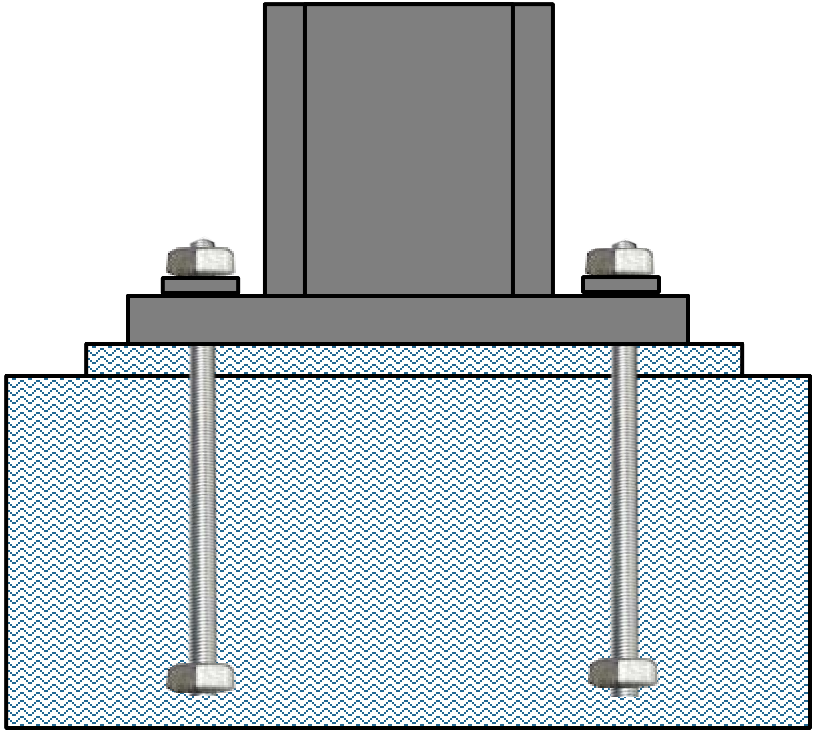




Stretchlength requires additional fabrication

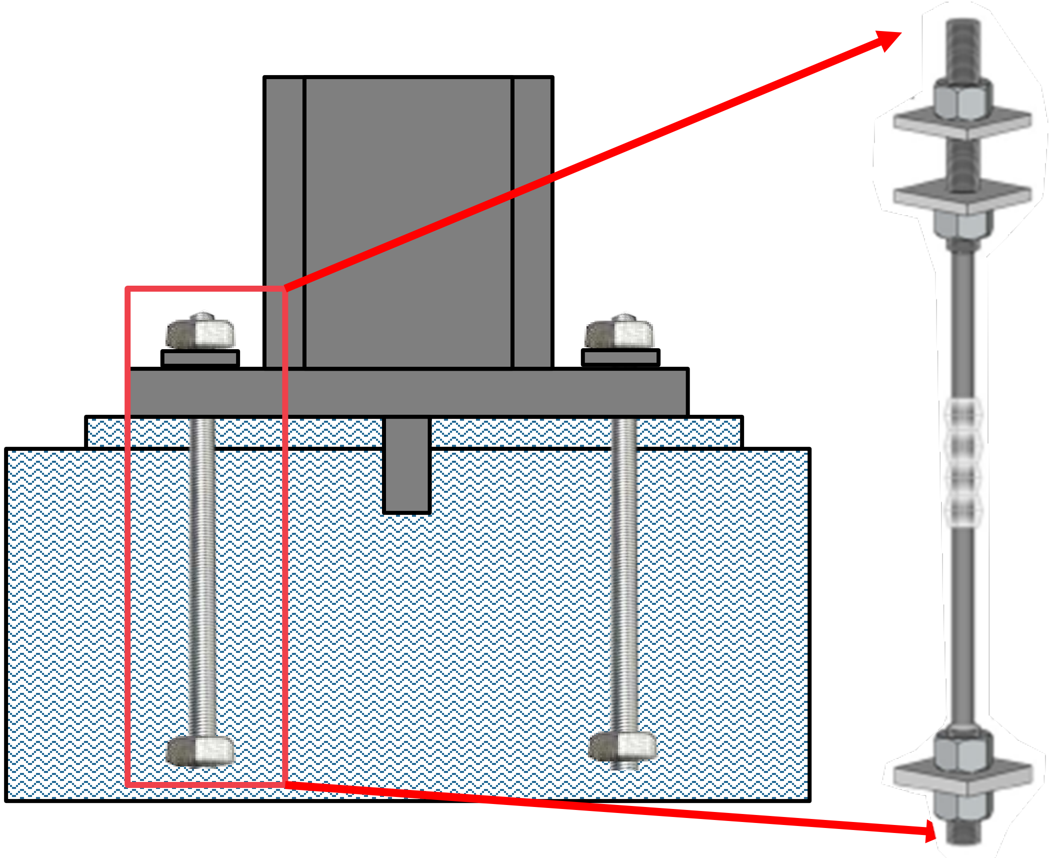


A new “reliably ductile” detail – AISC/Pankow Project



- Consultation with design engineers, fabricators
- Focus on convenience of fabrication
- Minimal changes to existing practice
- High confidence in ductile response

The Upset Thread Detail



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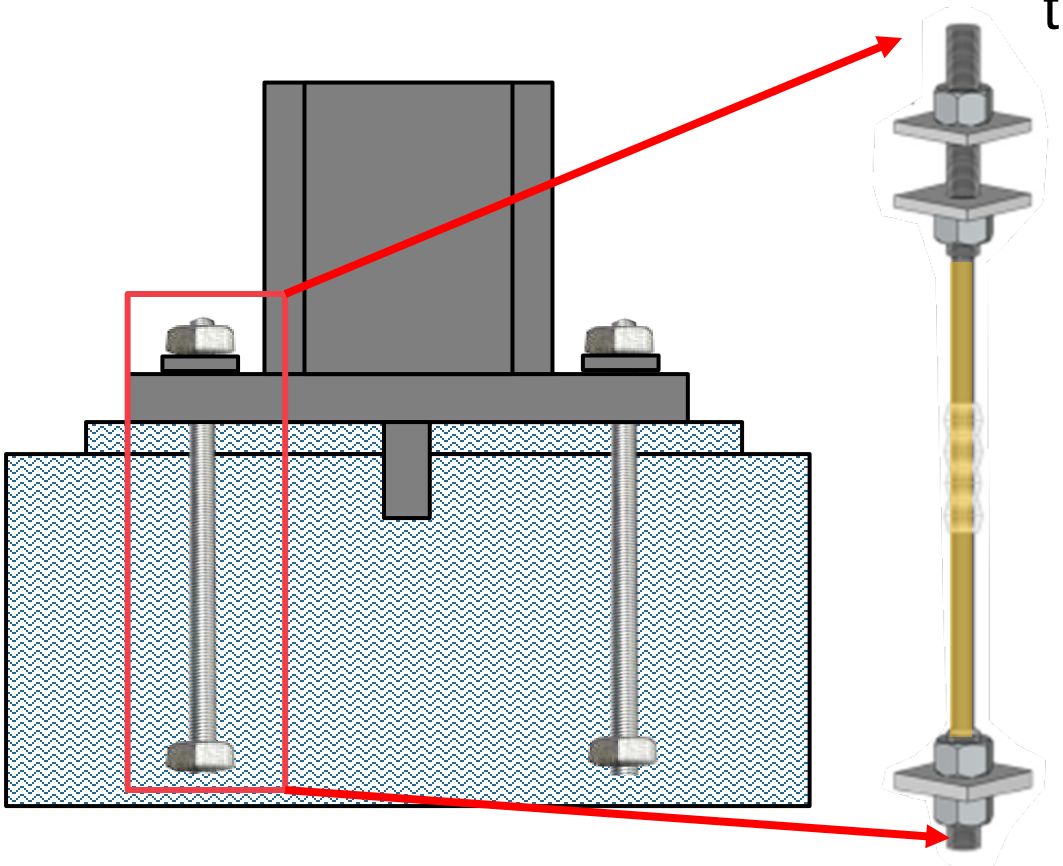
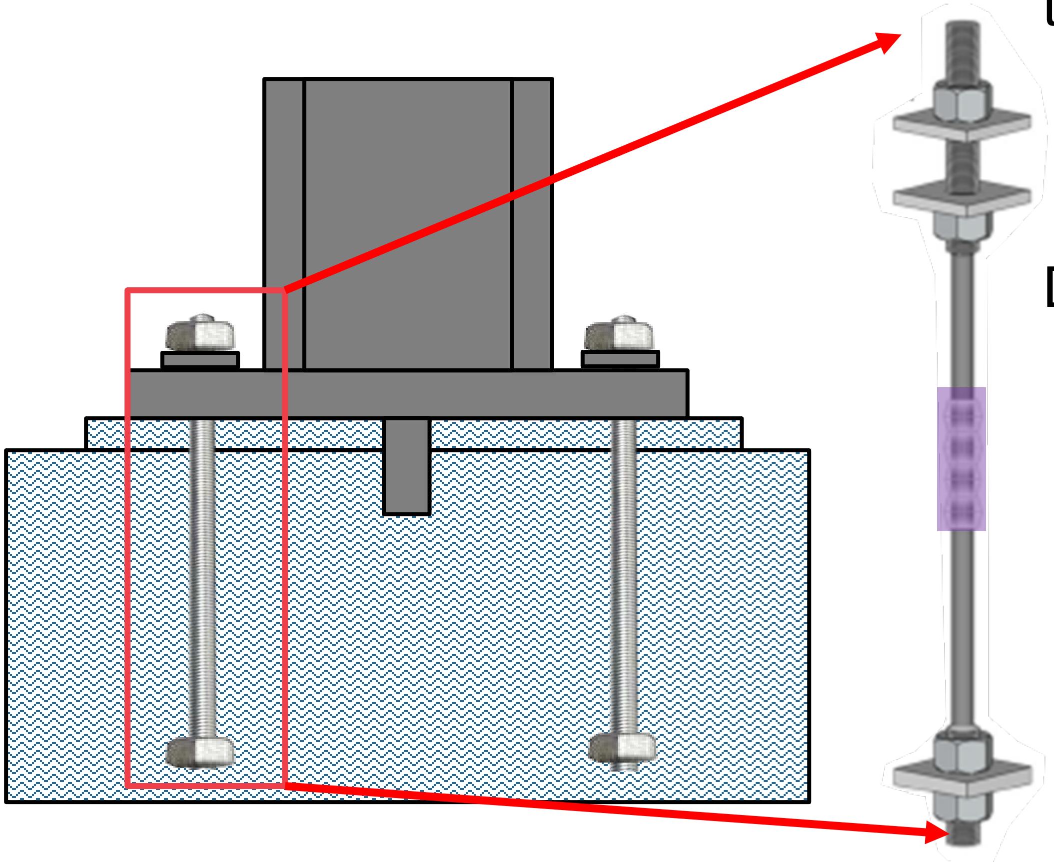


Milled down "upset" threads

- Enhance ductility
- Define yielding zone

The Upset Thread Detail



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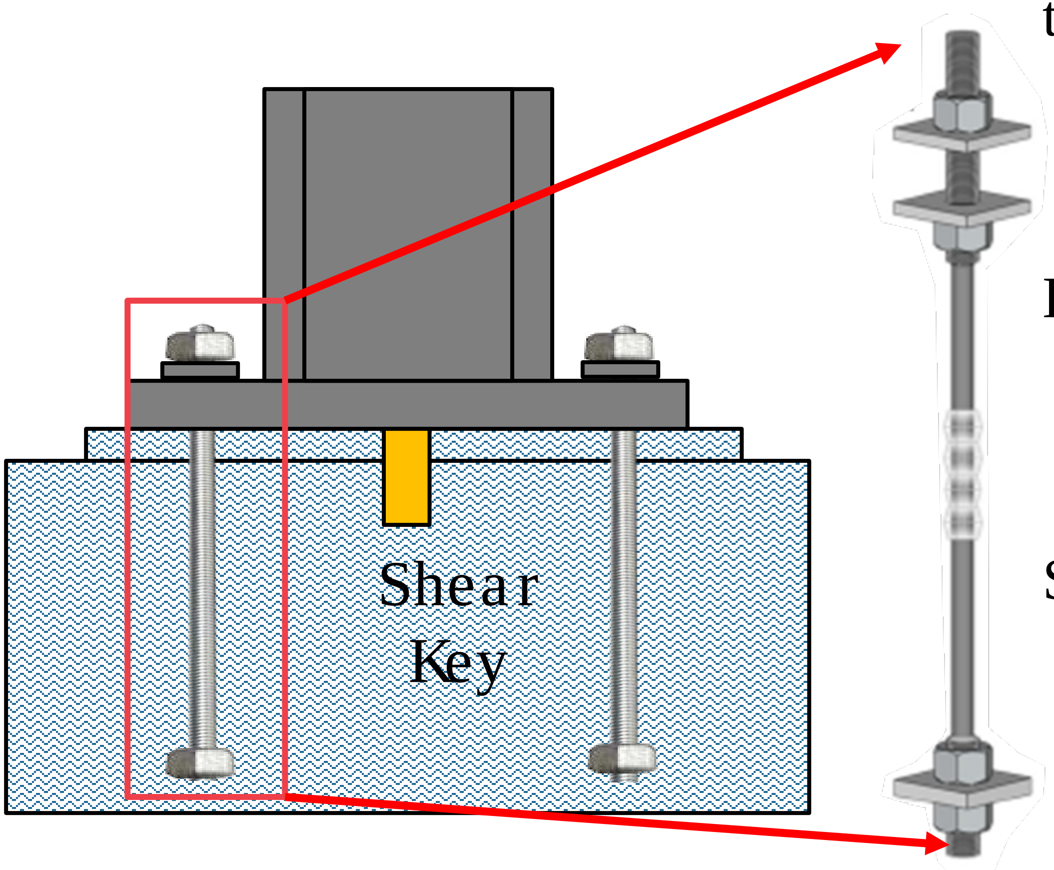
Debonding tape

- Prevents rod catching
- Similar to BRB

The Upset Thread Detail



Milled down "upset" threads

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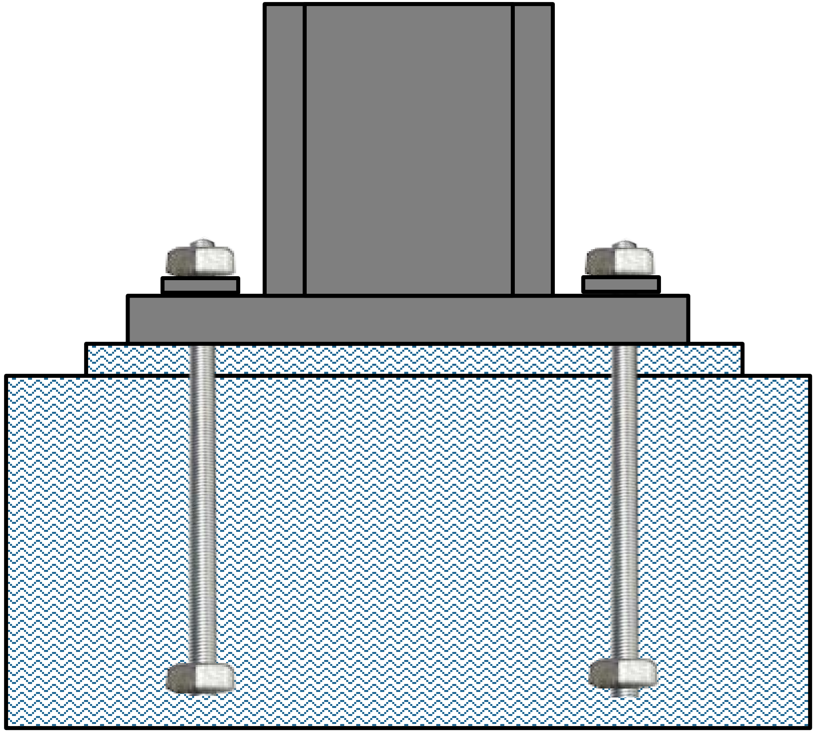
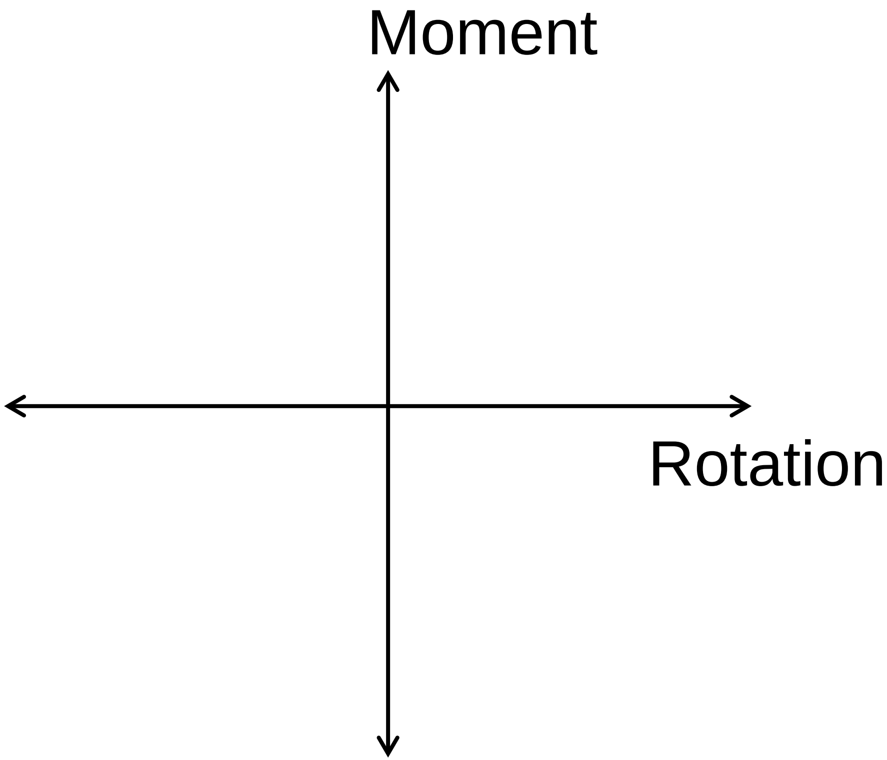
Shear Key

- Protects rods from shear

Intended behavior





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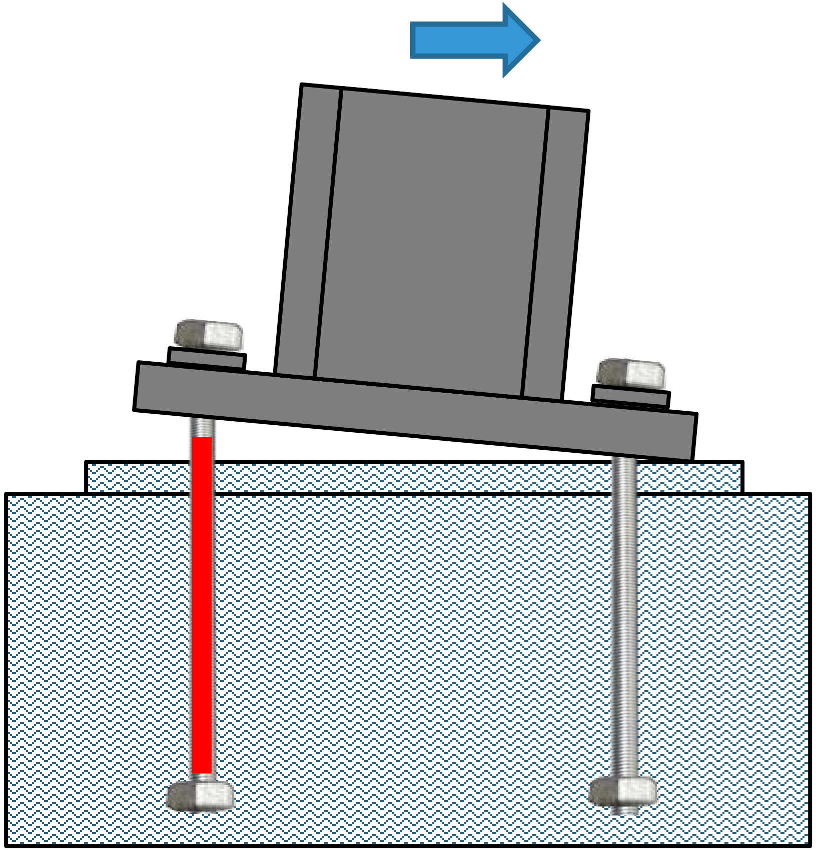

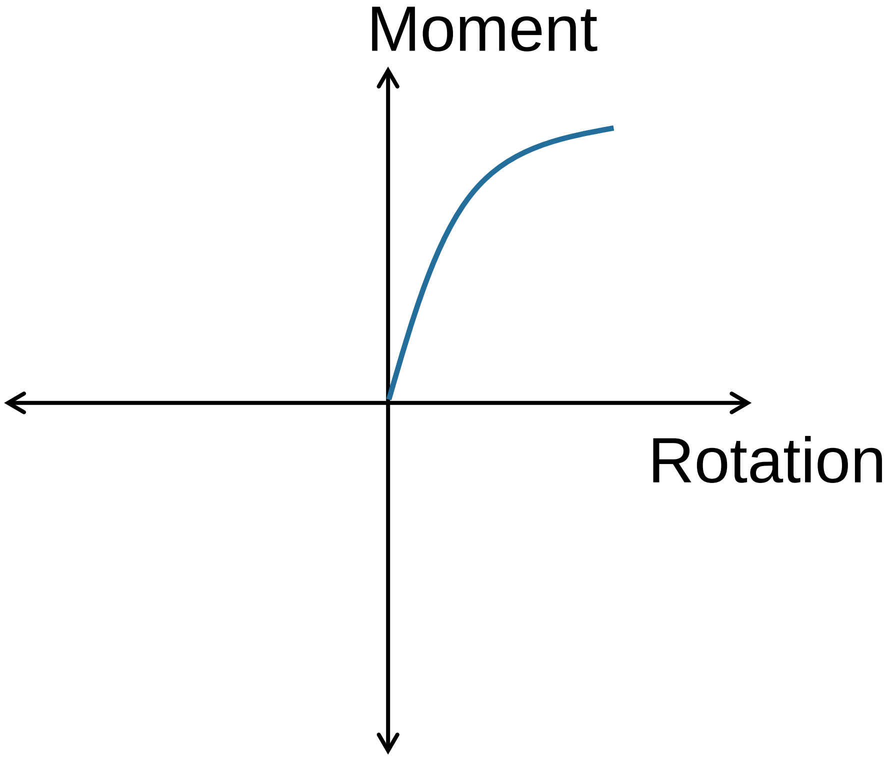

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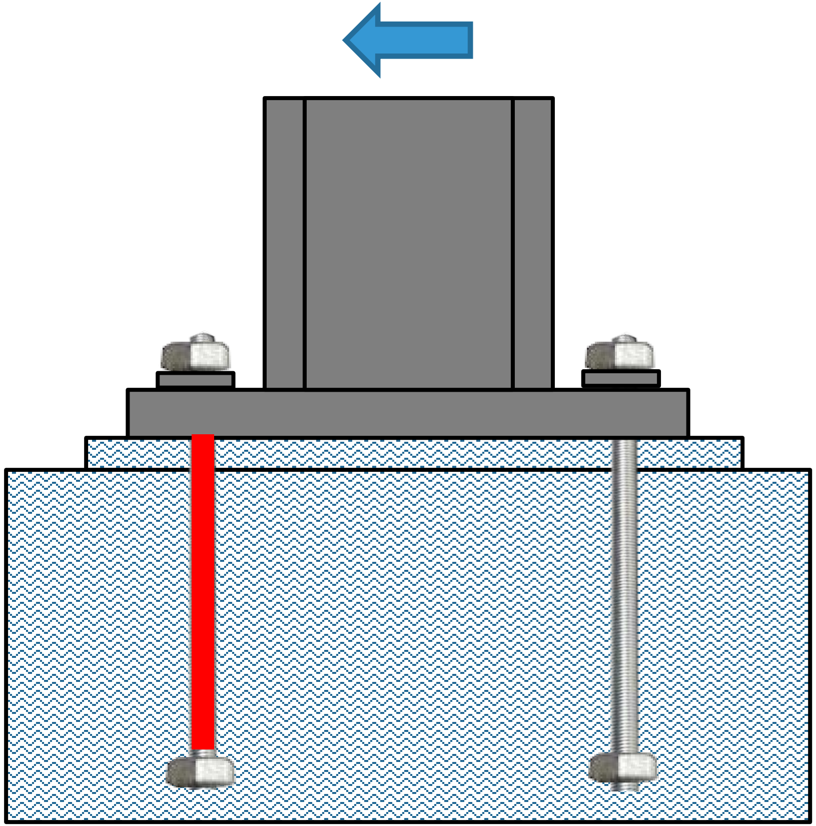

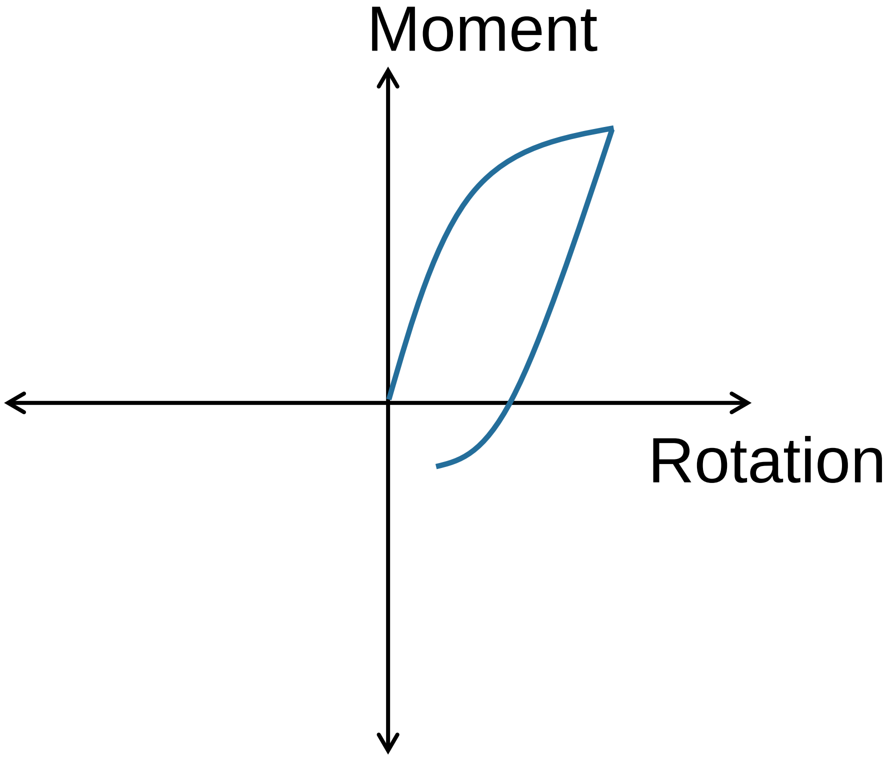

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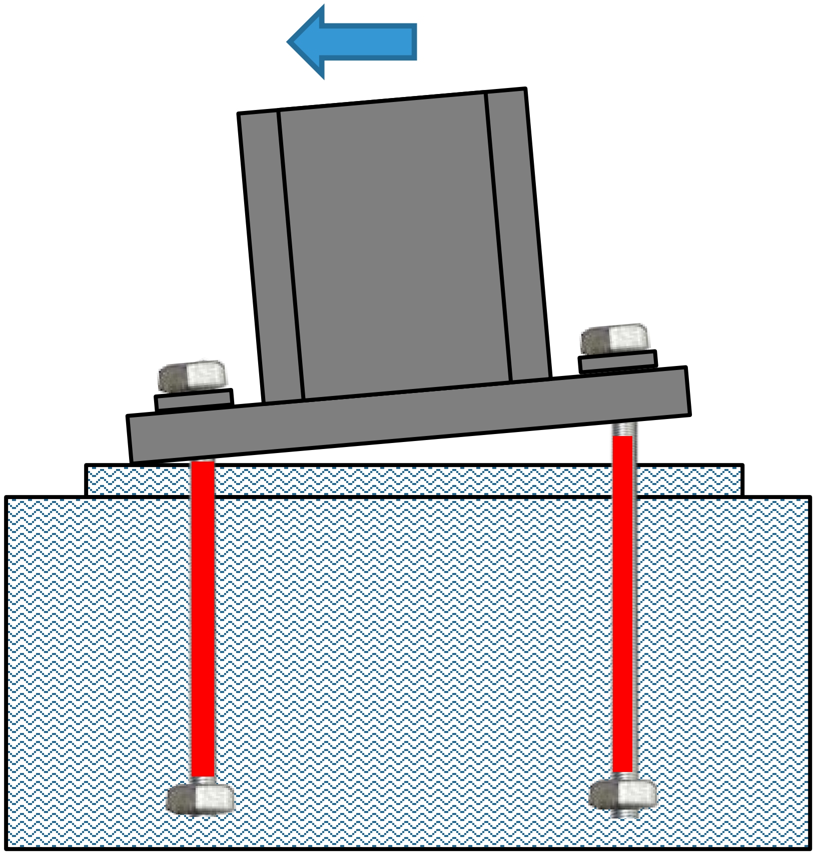
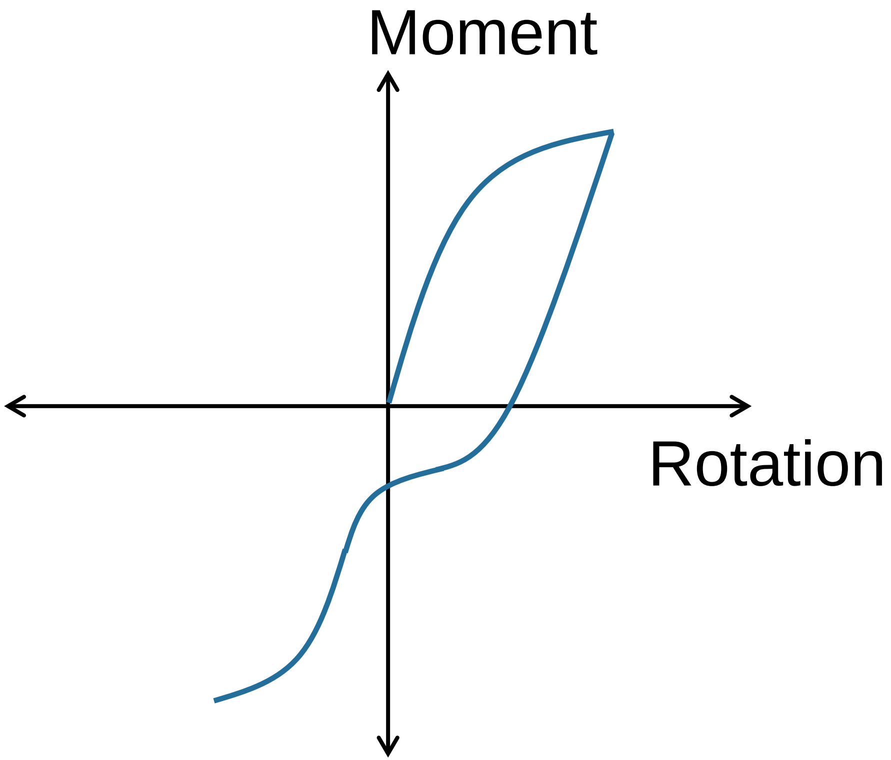
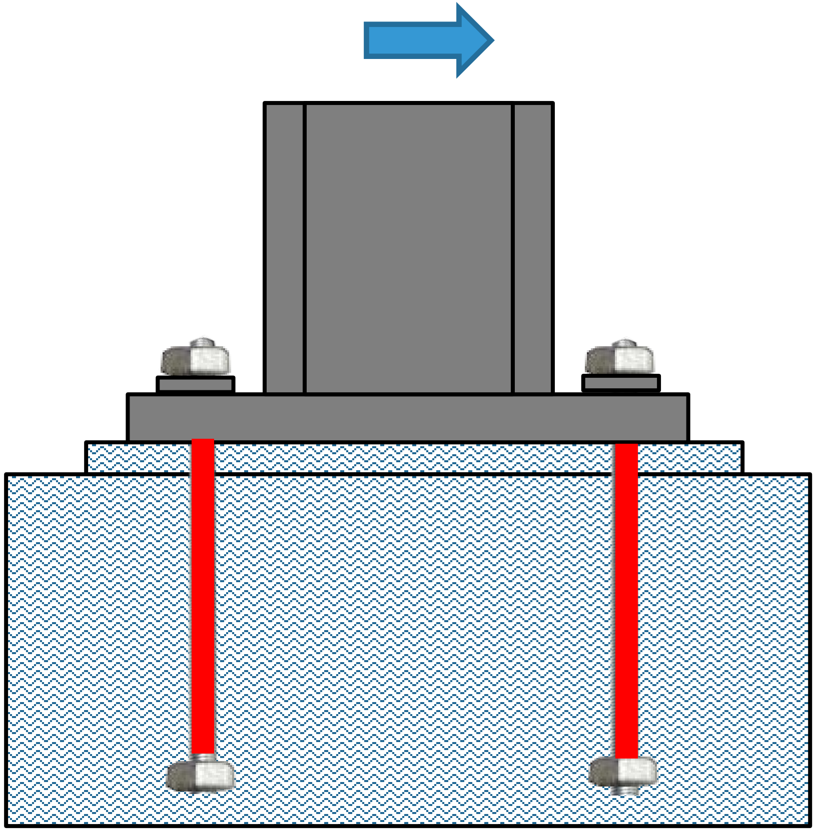
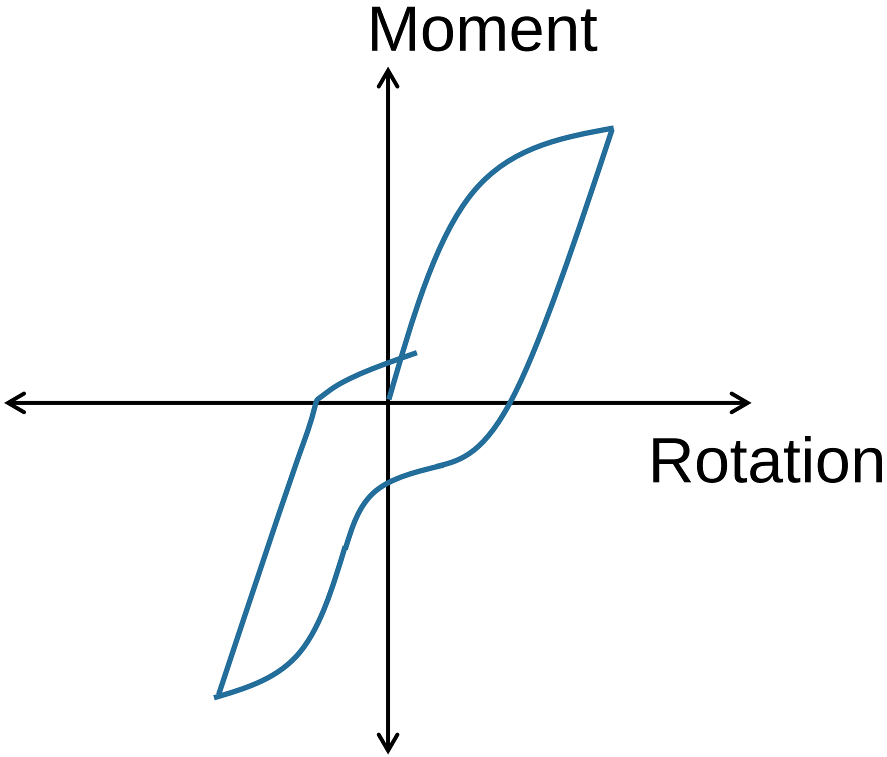




Intended behavior





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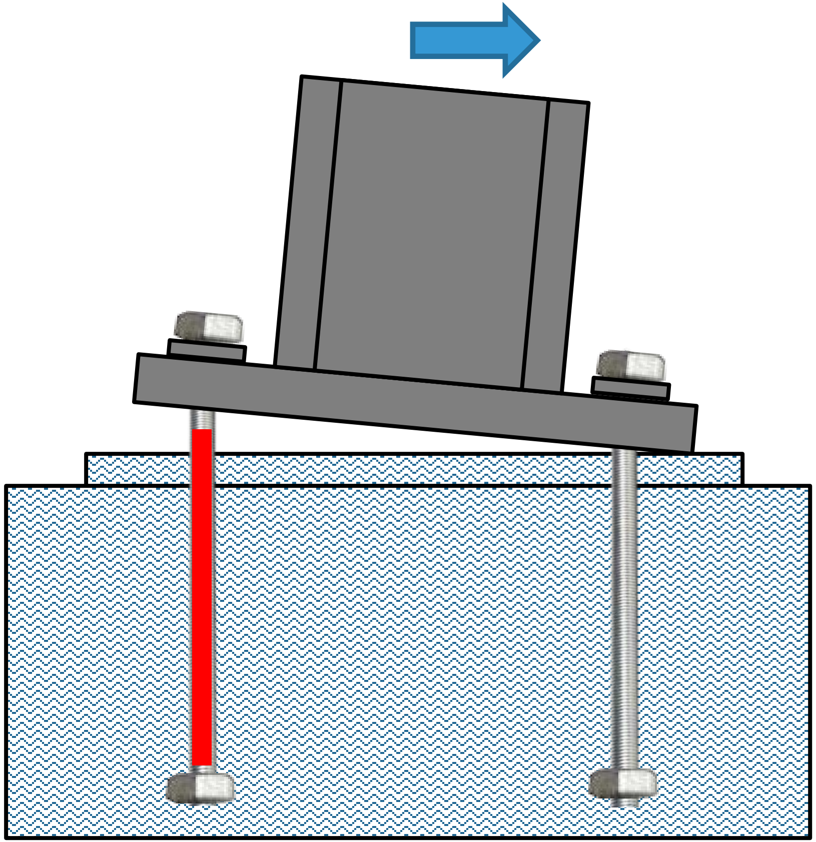

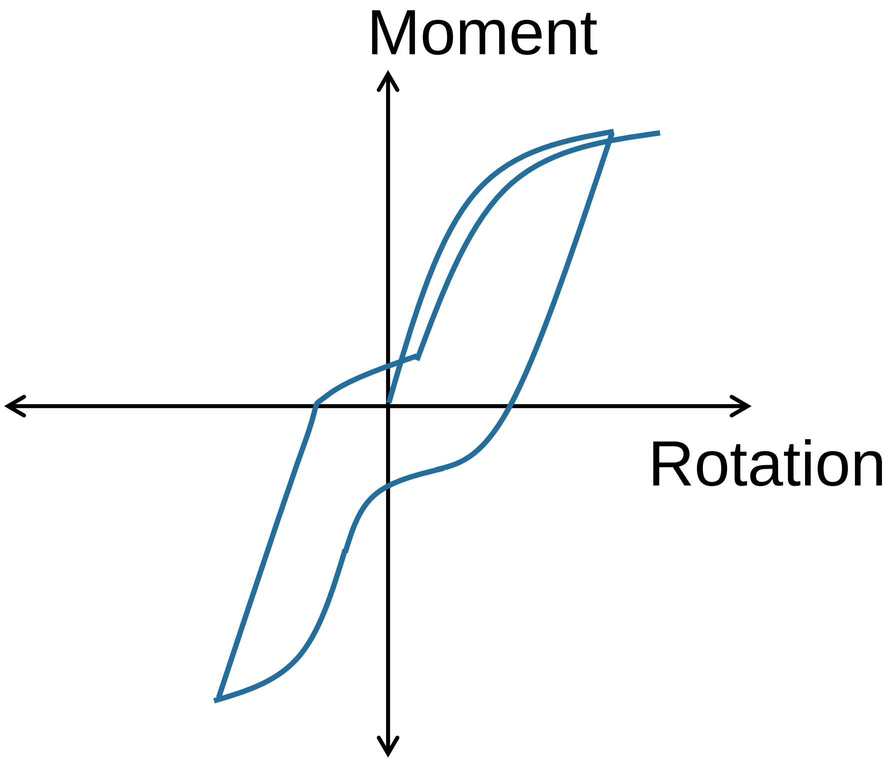

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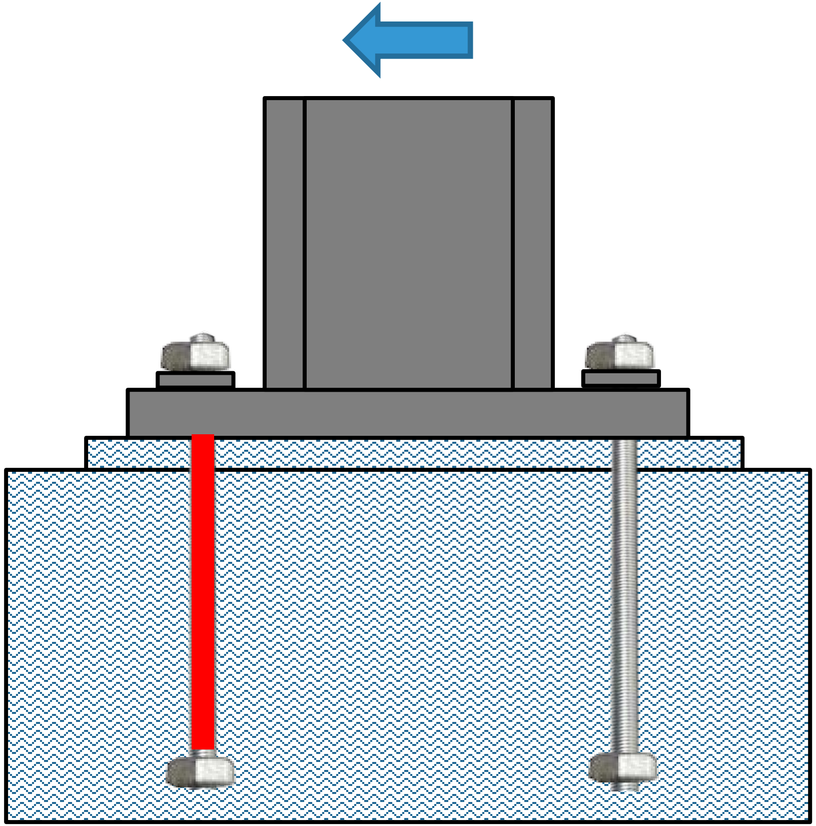
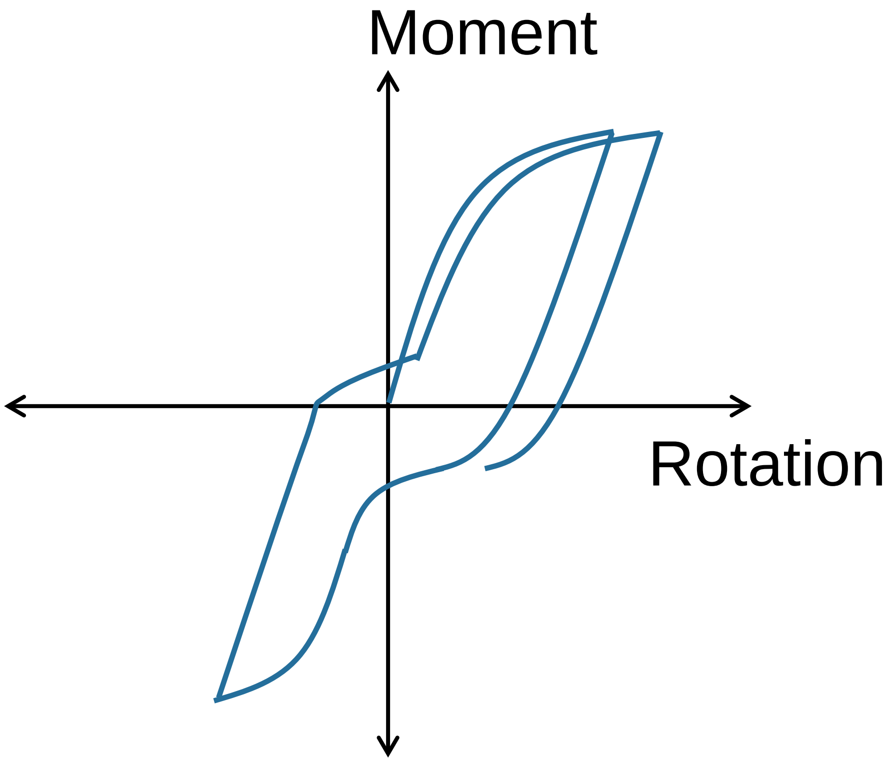
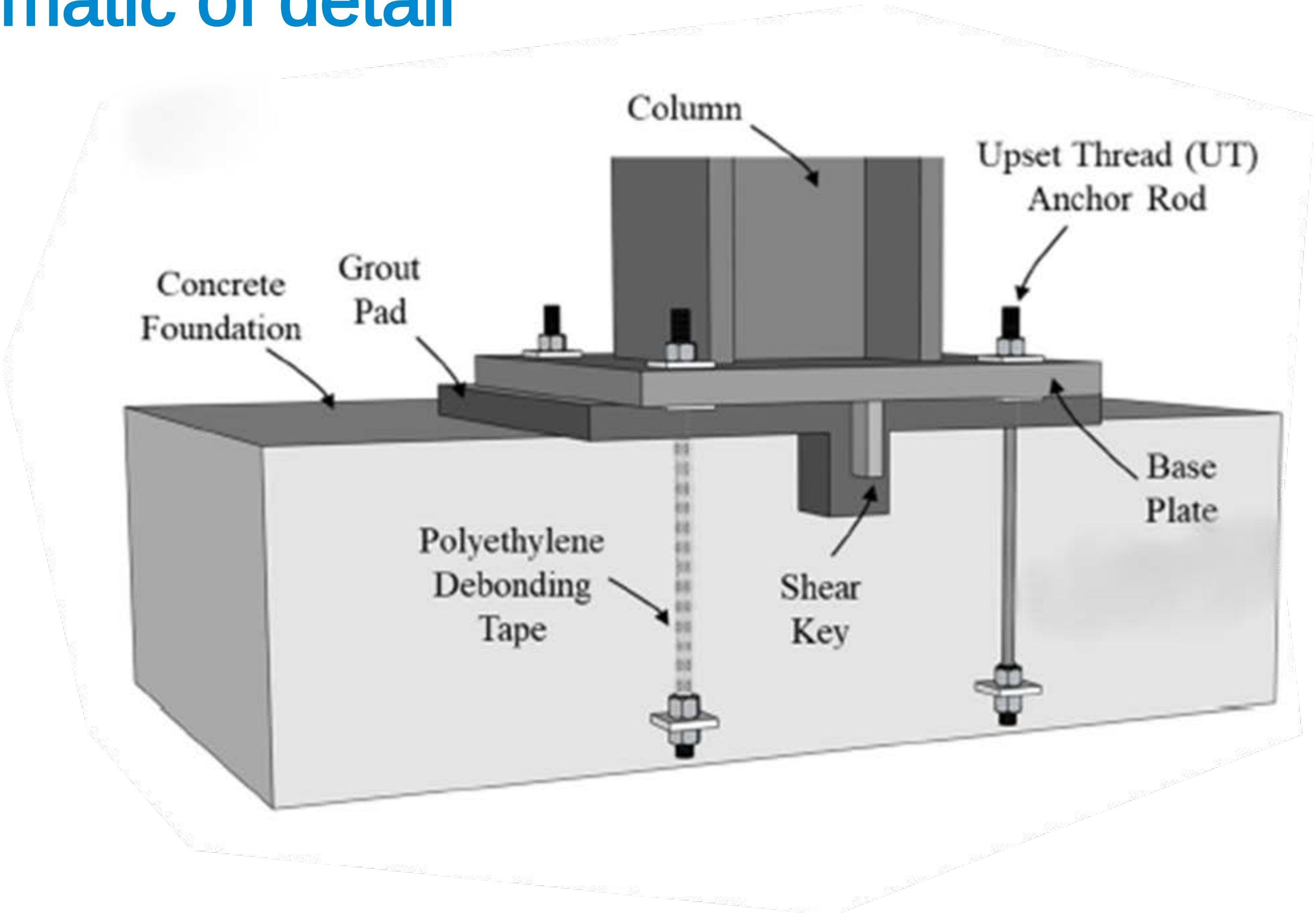


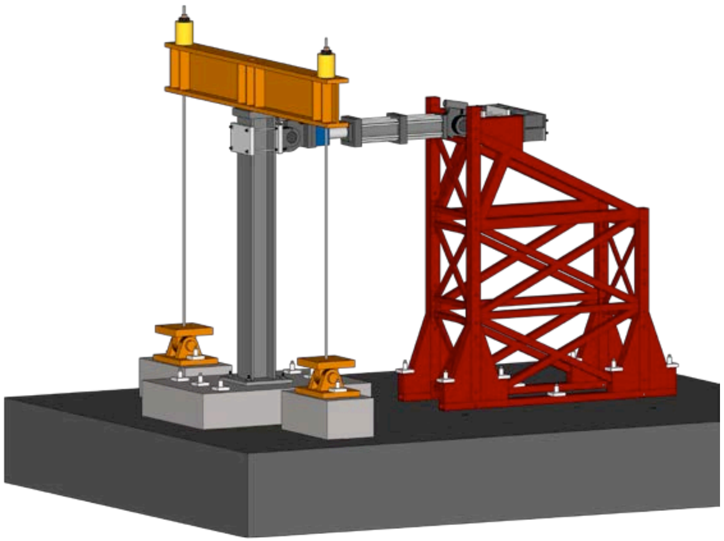


Schematic of detail



Large scale tests and performance

Test #	Base Plate size [in]	Anchor Grade	Anchor Dia [in]	Axial Load [kip]
1	30 x 30 x 2	55	0.75	120 (C)
2			1.00	120 (C)
3		105		120 (C)
4				0



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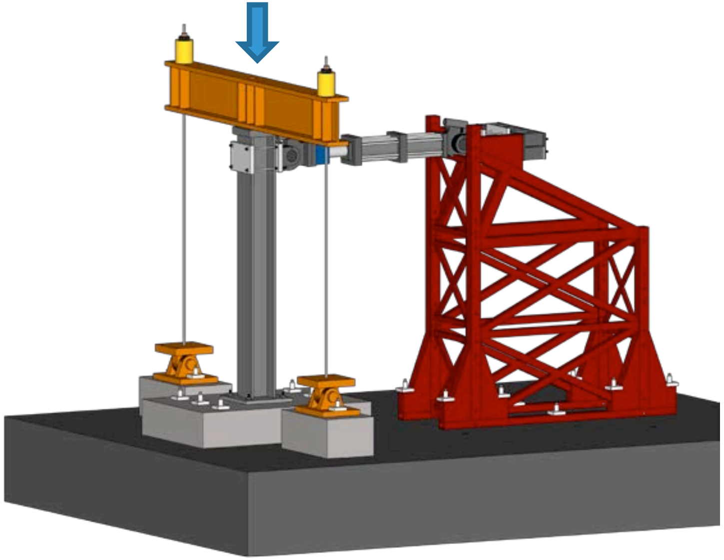

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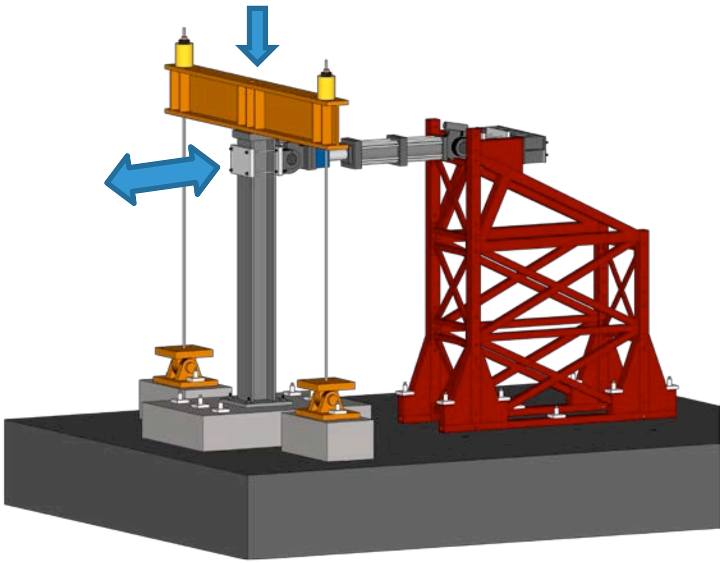
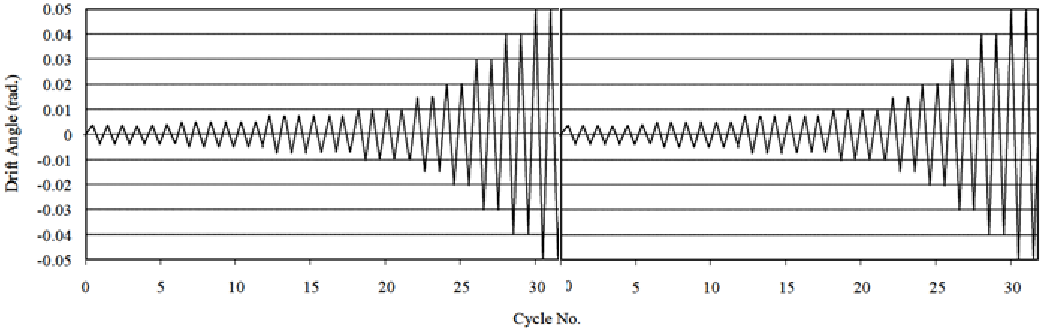


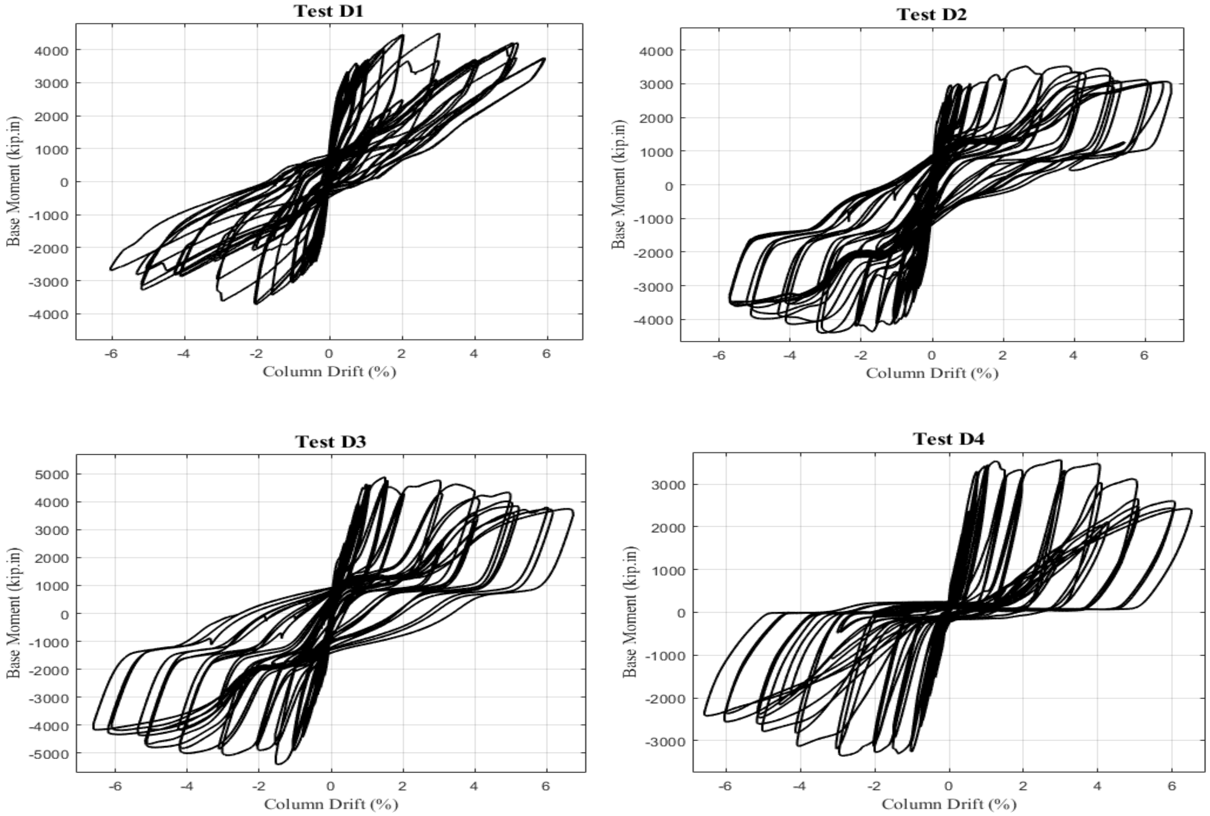


ATC-SAC Protocol applied twice followed by 6.5% cycles

Results

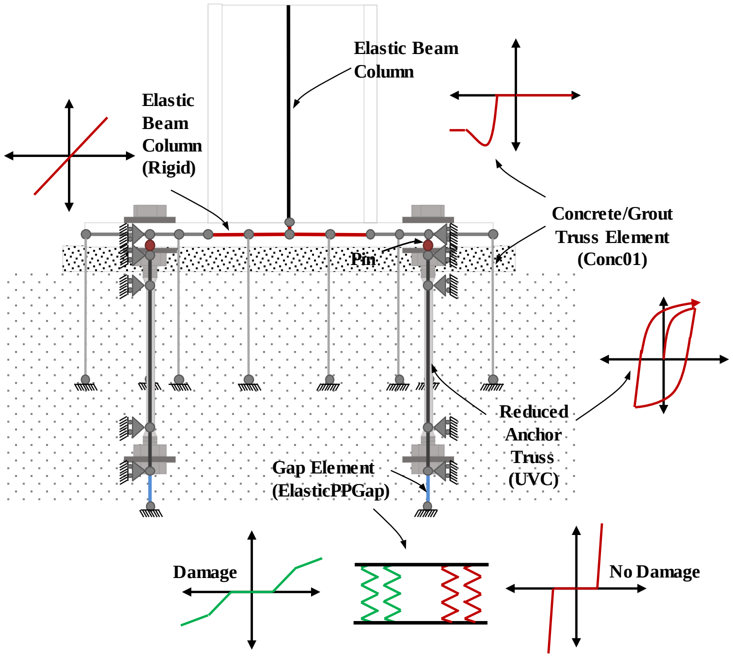
All specimens survived back to back applications of SAC protocol (to 5%) and additional cycles to 6.5% with no rod fracture

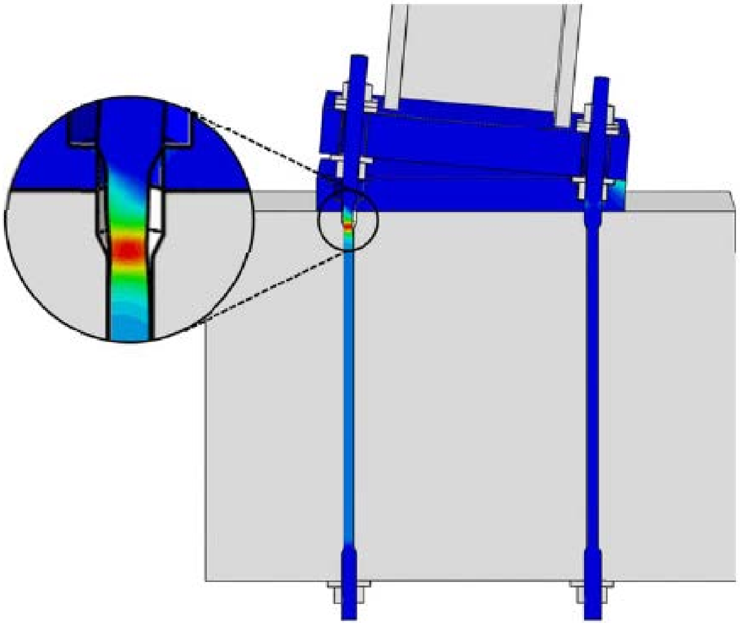
Results



Predominant damage – grout crushing

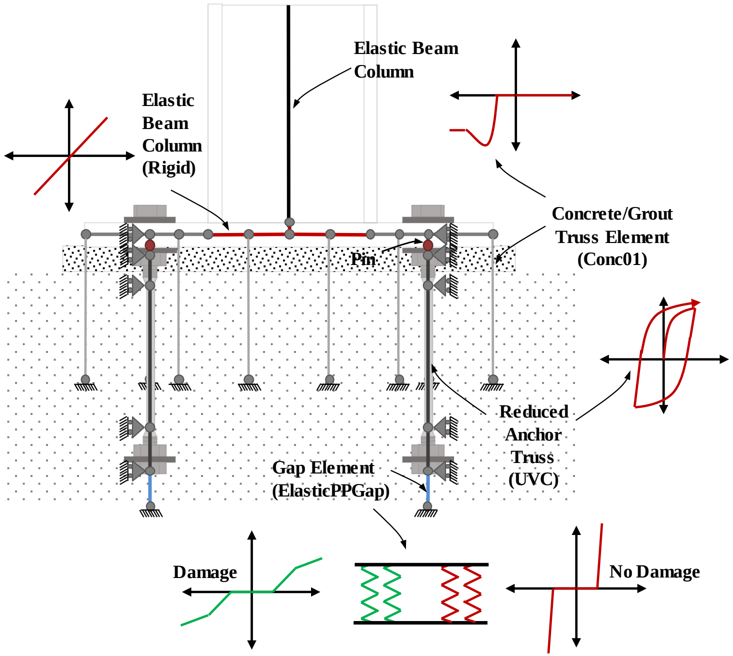
Generalization using material testing, FEM, and line based simulations

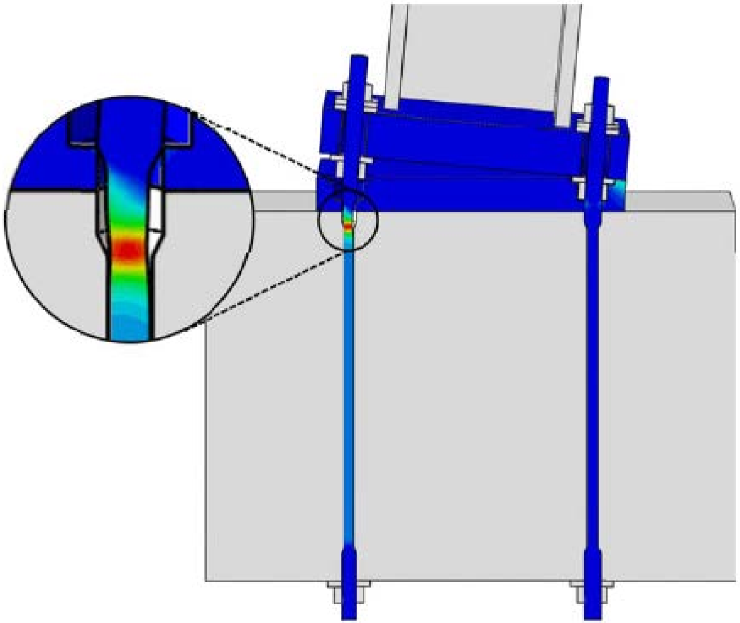




Simulation of Necking, Ultra Low Cycle Fatigue, Bending

Generalization using material testing, FEM, and line based simulations

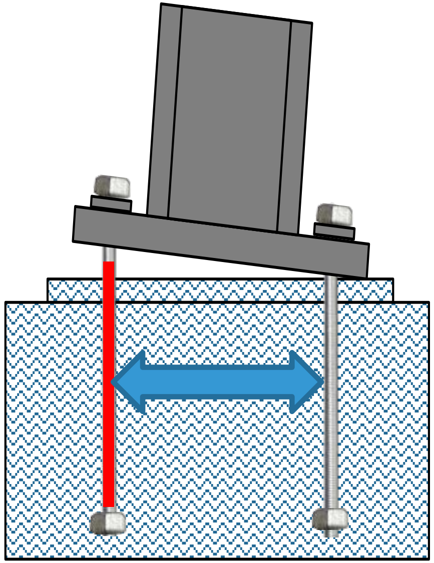




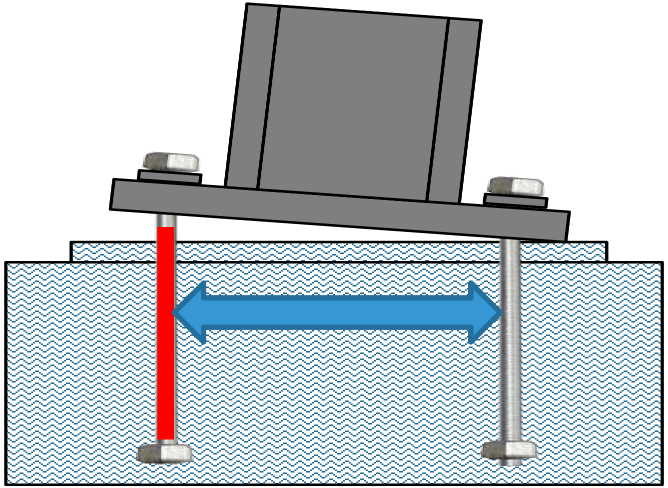
~60 parametric simulations with variations in plate and rod dimensions, rod materials, loading histories etc.

Parametric Simulation – findings

- Behavior appears to hold across a large number of configurations
- Ratio of stretch length to plate length is key



$L_{stretch} > 0.5 \text{ X } L_{plate}$



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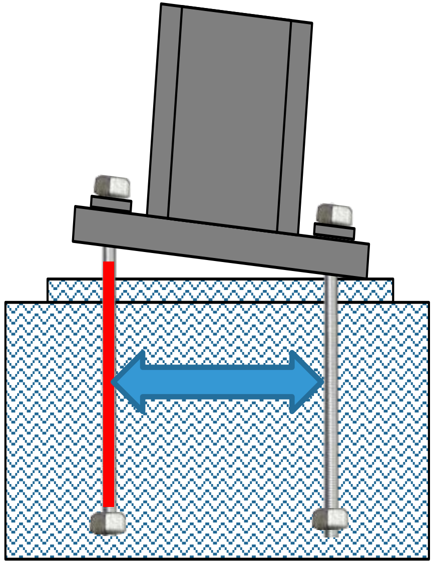

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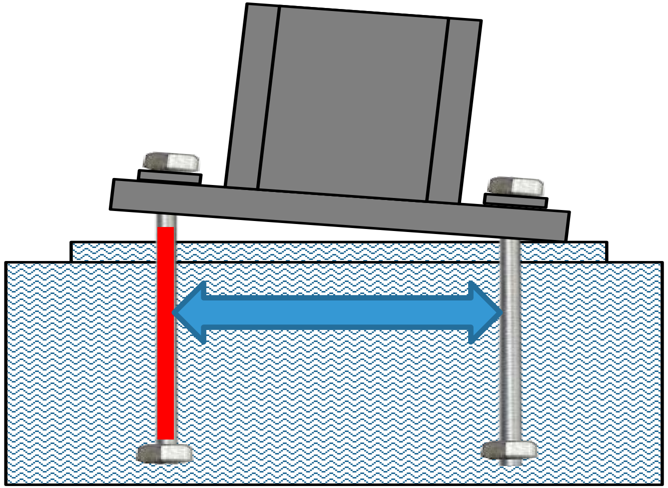
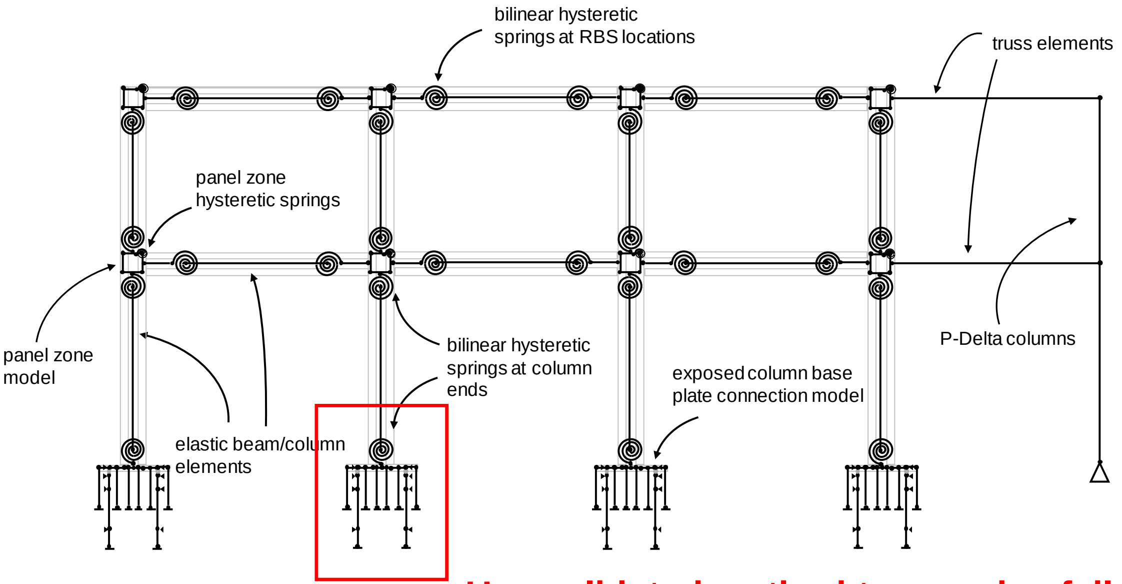


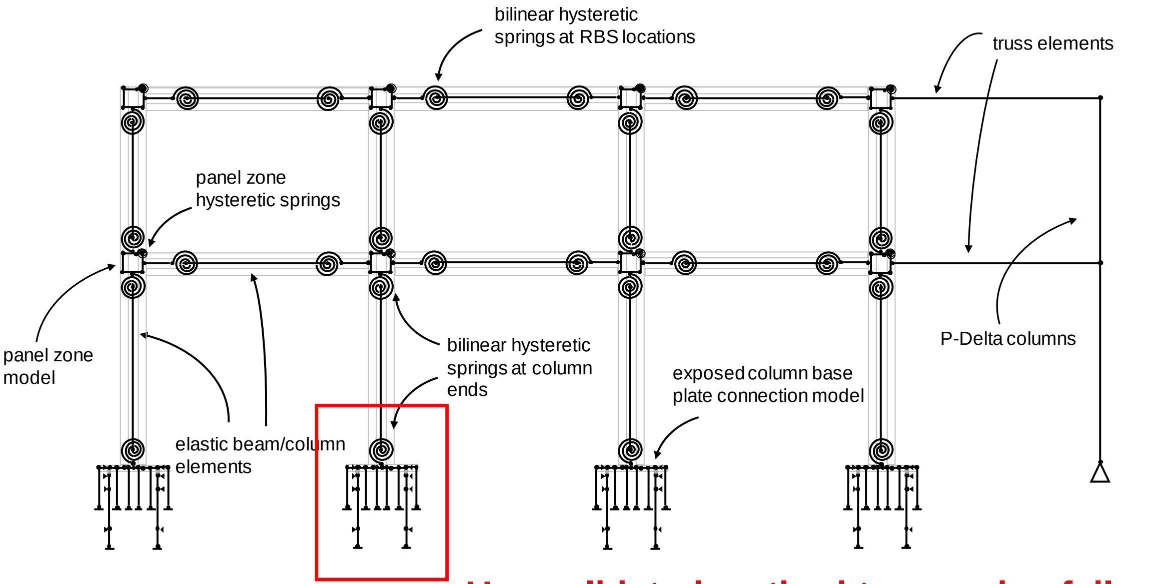
$L_{stretch} < 0.5 \times L_{plate}$

NLTHA Results and summary



Use validated method to examine failure

NLTHA Results and summary



Use validated method to examine failure

- Upset Thread detail with $L_{stretch} > 0.5 \times L_{plate}$
- Design for Ω_0 or even lower forces

→ Excellent performance

Organization

Part 1

Exposed Base Plates

- Prevailing understanding and design methods
- New Developments

Part 2

Embedded Bases

- Prevailing understanding and design methods
- New Developments

Part 3

A look to the future

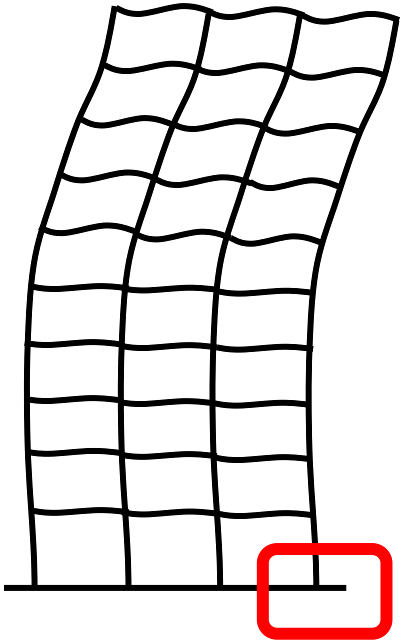
- "Resolved" issues
- Ongoing work

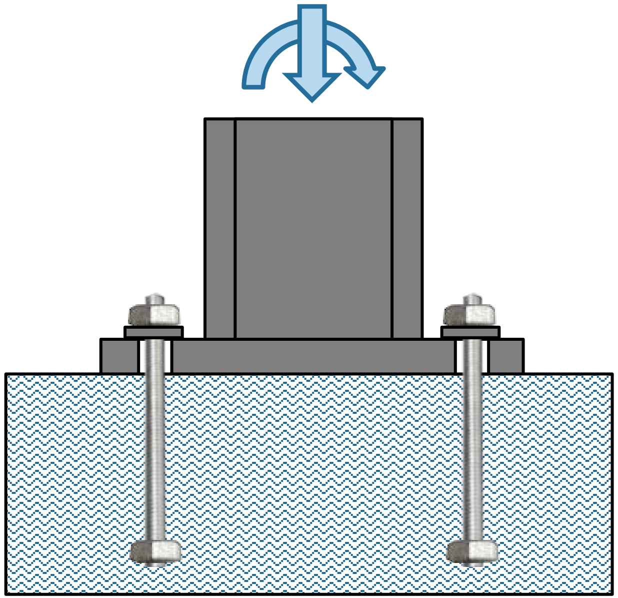
  Unresolved issues

Part 2 – Embedded Base Connections

Embedded Bases

- Prevailing understanding and design methods
- New Developments





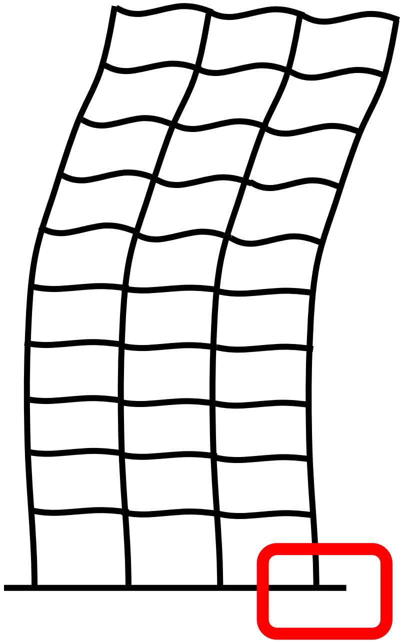
High rise buildings

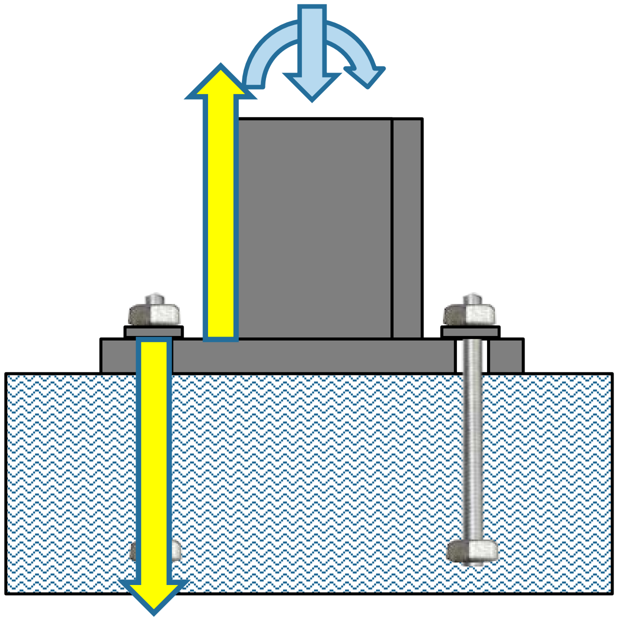
Large column moments

Part 2 – Embedded Base Connections

Embedded Bases

- Prevailing understanding and design methods
- New Developments





Developing column capacity is challenging

Part 2 – Embedded Base Connections

Embedded Bases

- Prevailing understanding and design methods
- New Developments

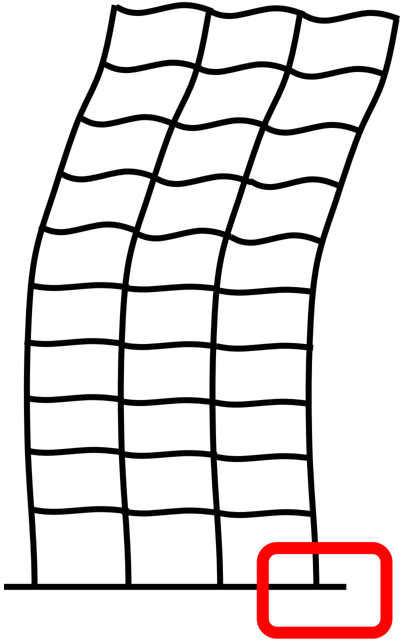


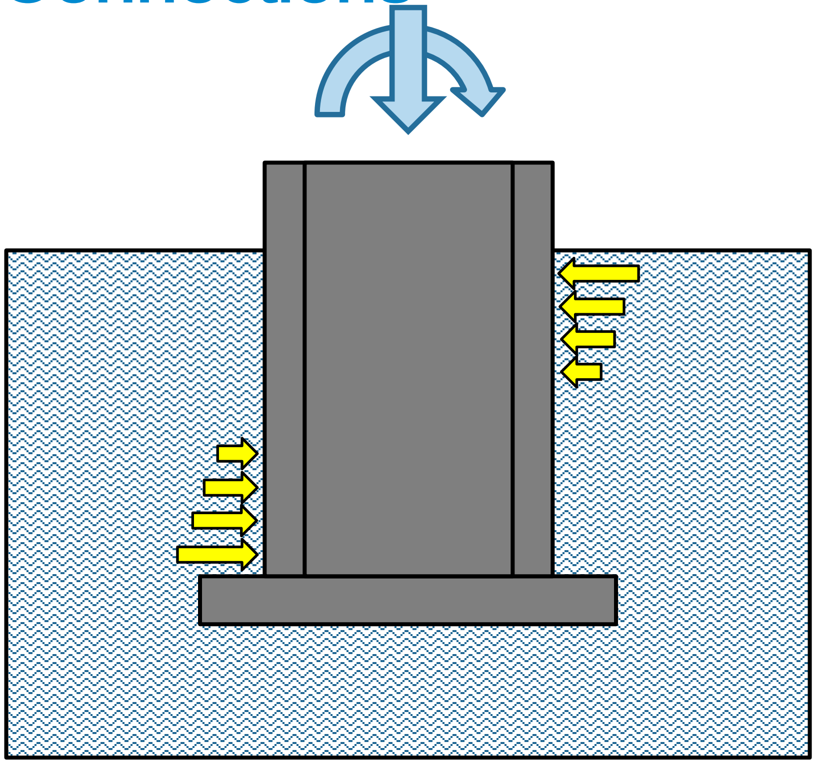
Photo credit: Josh Buckholt and Mahmoud Maamouri, CSD Engineers

Developing column capacity is challenging

Part 2 – Embedded Base Connections

Embedded Bases

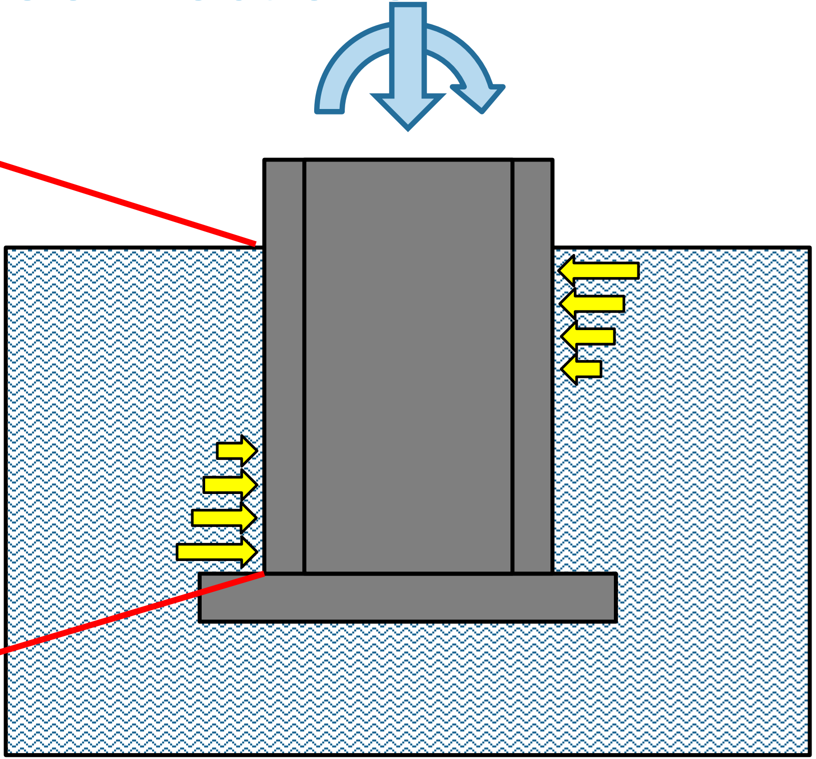
- Prevailing understanding and design methods
- New Developments



Resistance through concrete bearing

Part 2 – Embedded Base Connections

Photo credit: Nabih Youssef, Simpson Gumpertz and Heger

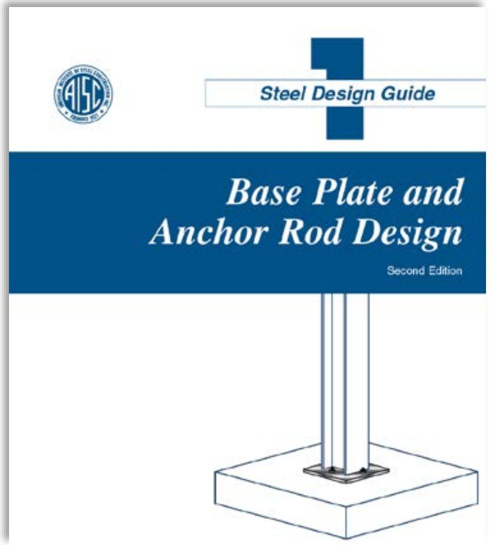


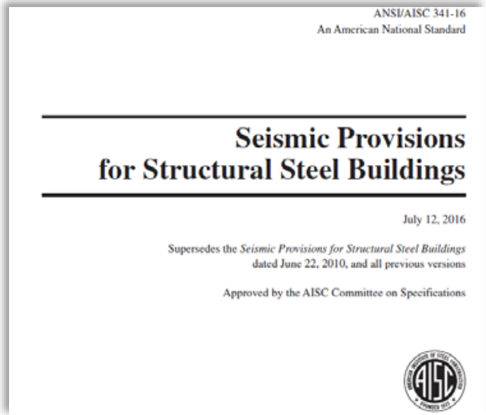
Resistance through concrete bearing

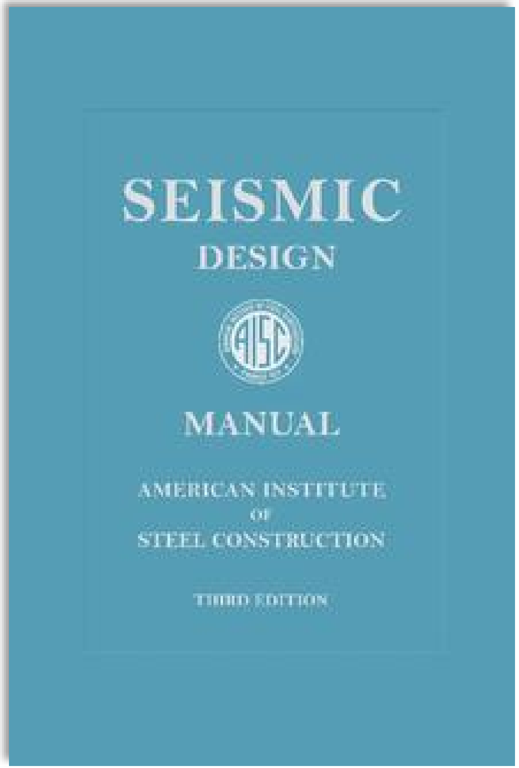
Overview

Embedded Bases

- Prevailing understanding and design methods
- New Developments







Takeaways from Design Documents

- AISC 341 and Design Guide One identify embedded details
- AISC 341 – Commentary points to similar details
- SSDM uses coupling beam analogy

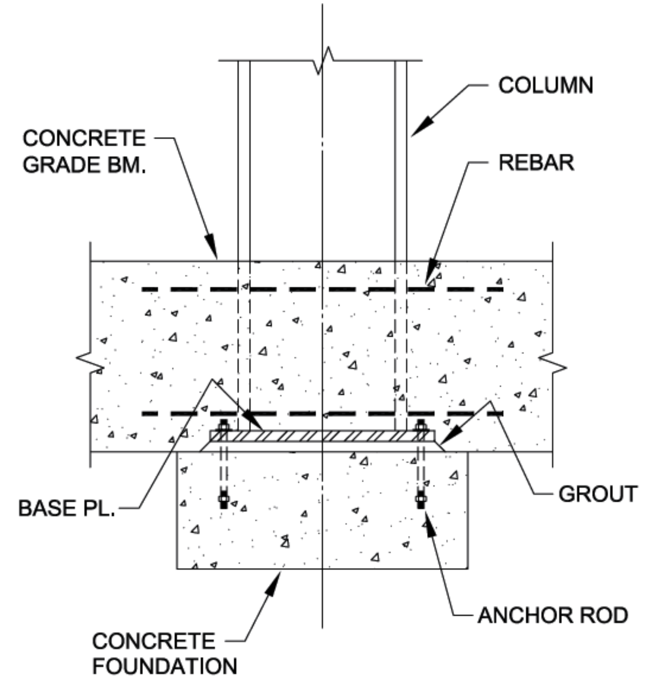


Figure 2.7. Embedded moment base detail.

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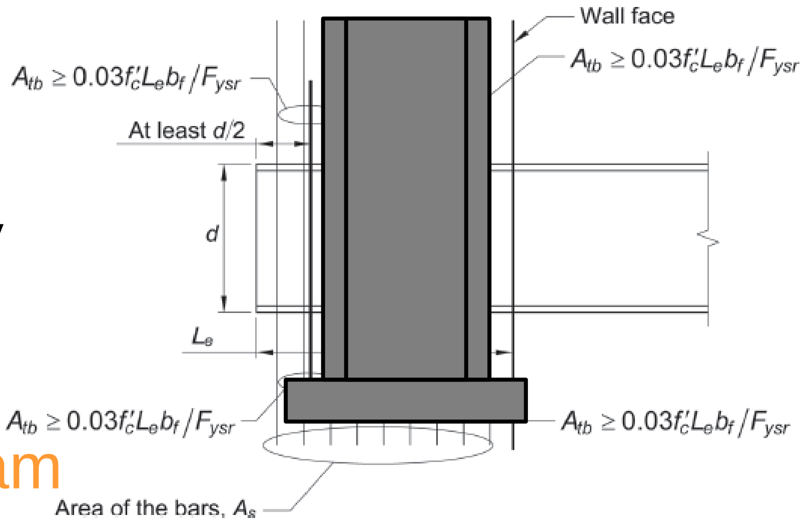

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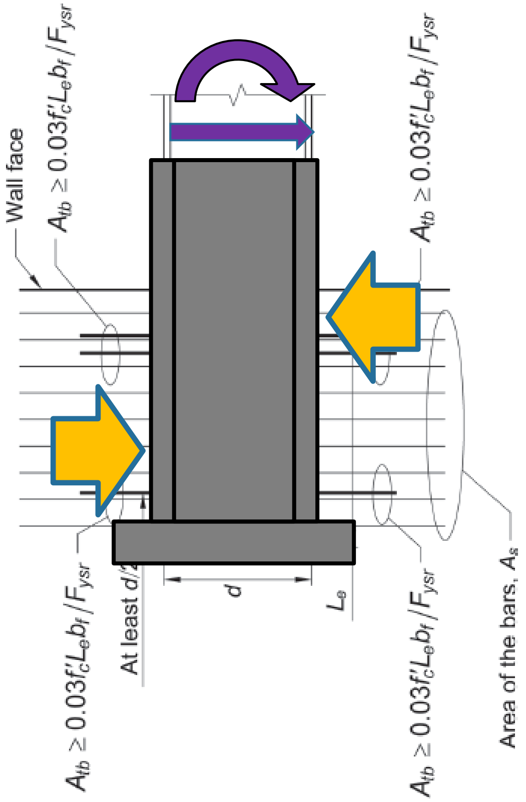
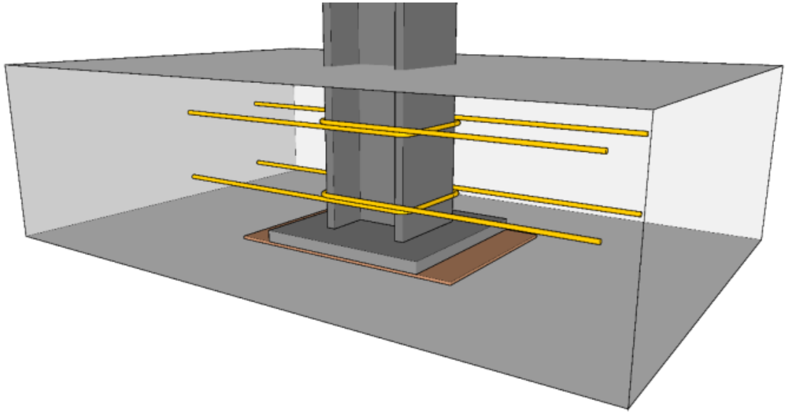


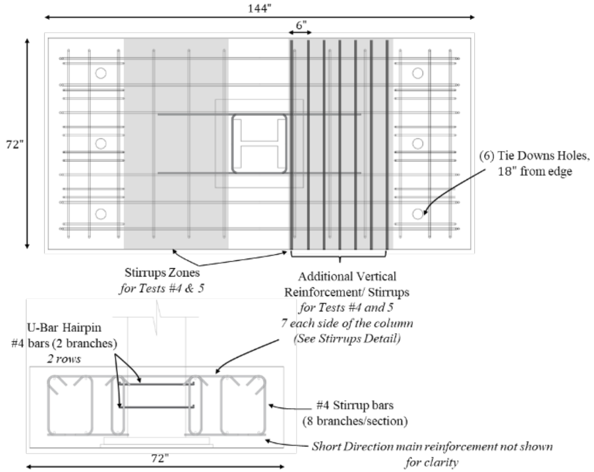
Research in the last 15 years

- 10 Experiments
- Finite element simulations
- Strength and stiffness models

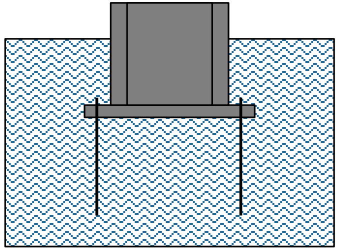
Various variables investigated

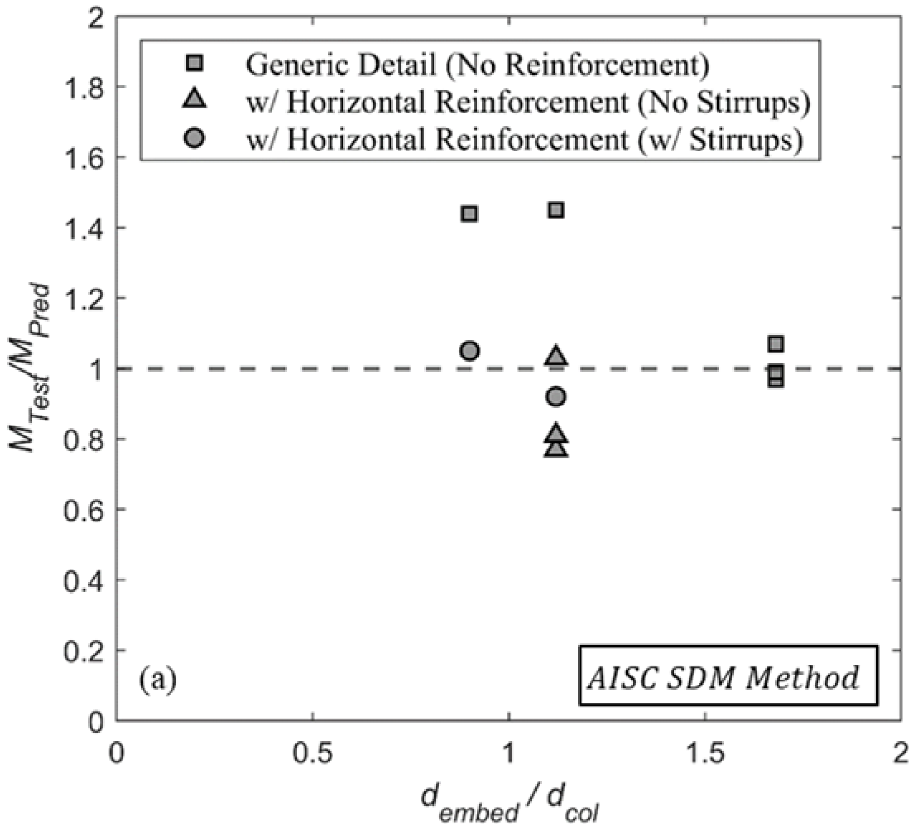
- Embedment depth
- Axial compression
- Column size
- Reinforcement (horizontal and vertical)

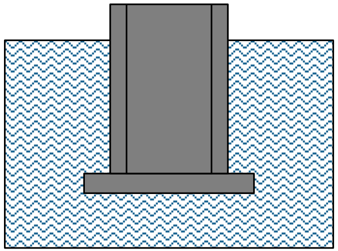




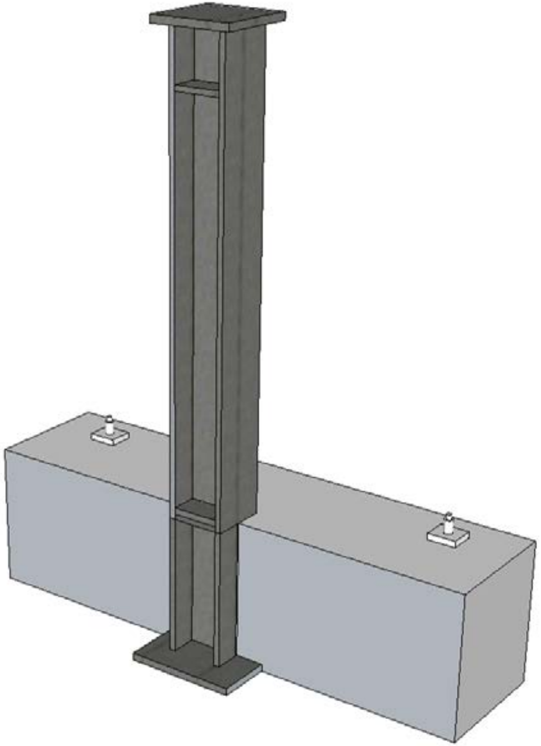
Coupling beam approach applied to test data







Embedded base connections are NOT coupling beams



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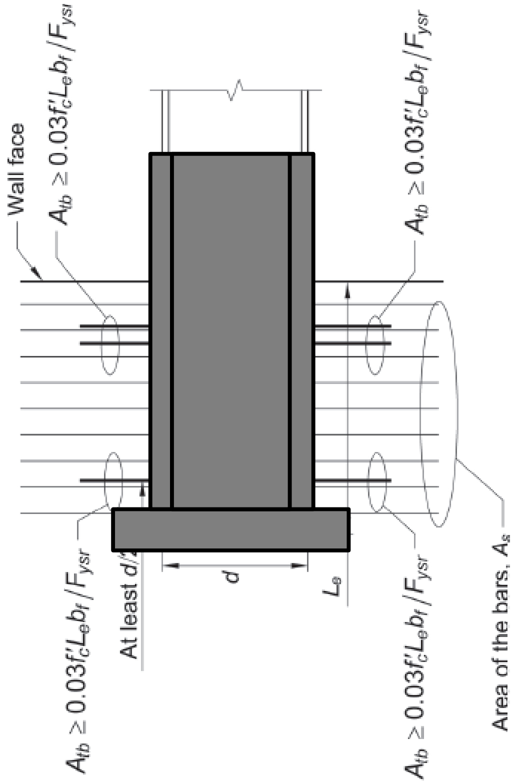

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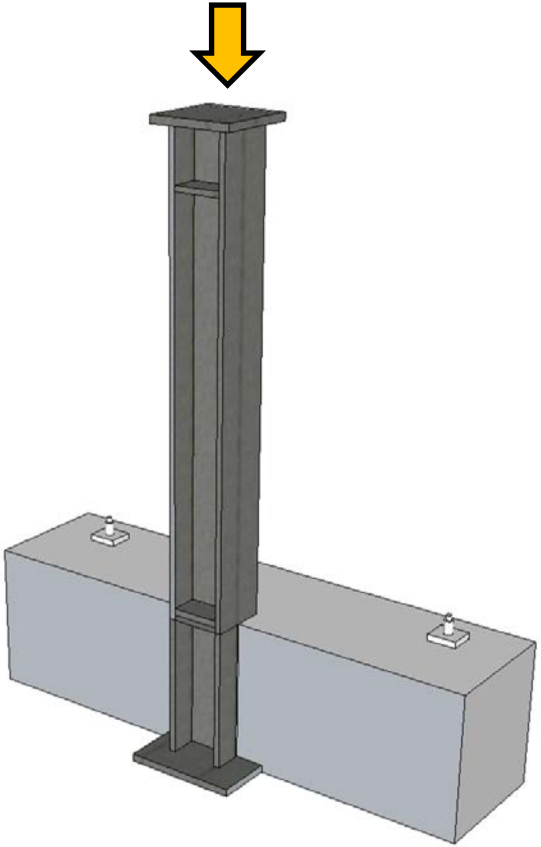

- Effect of axial force
- Additional confinement around column flanges
- Fixity and strength due to vertical bearing

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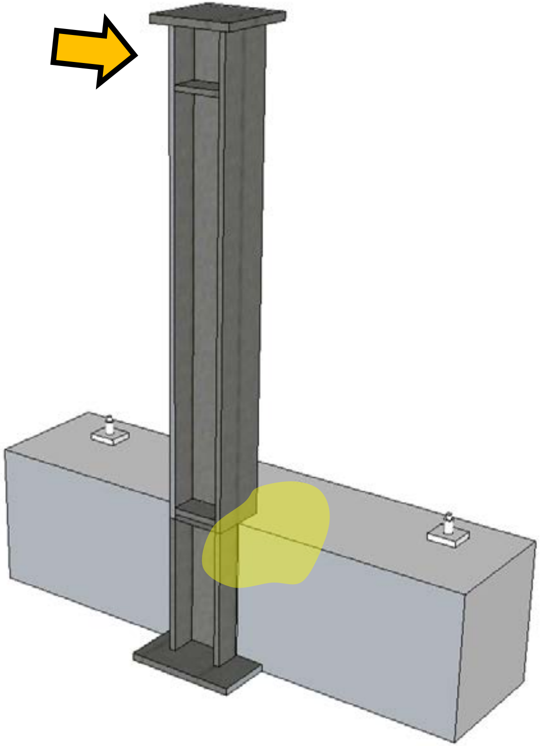

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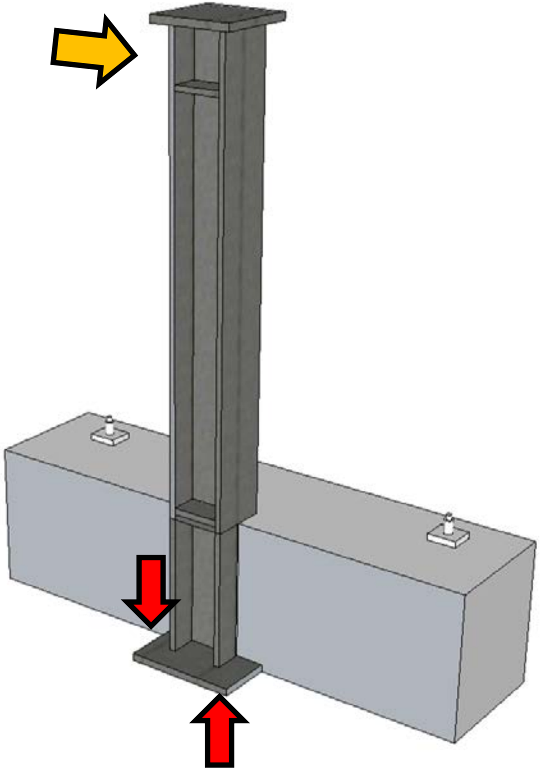

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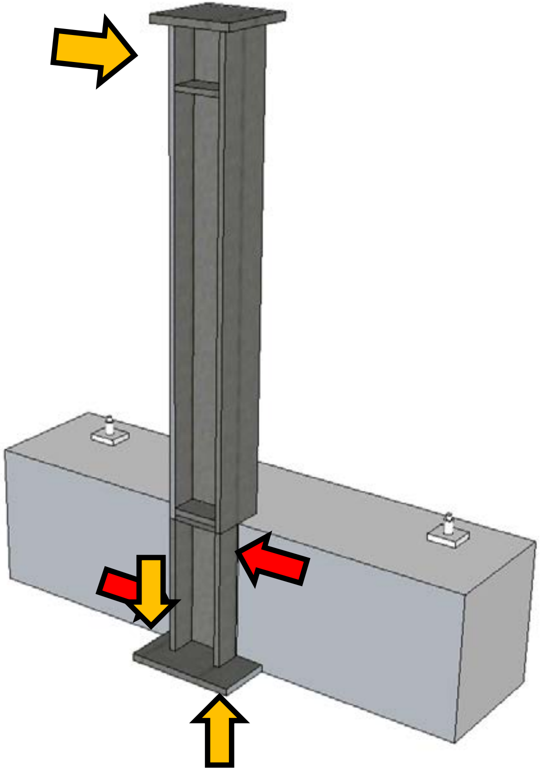
- Fixity and strength due to vertical bearing

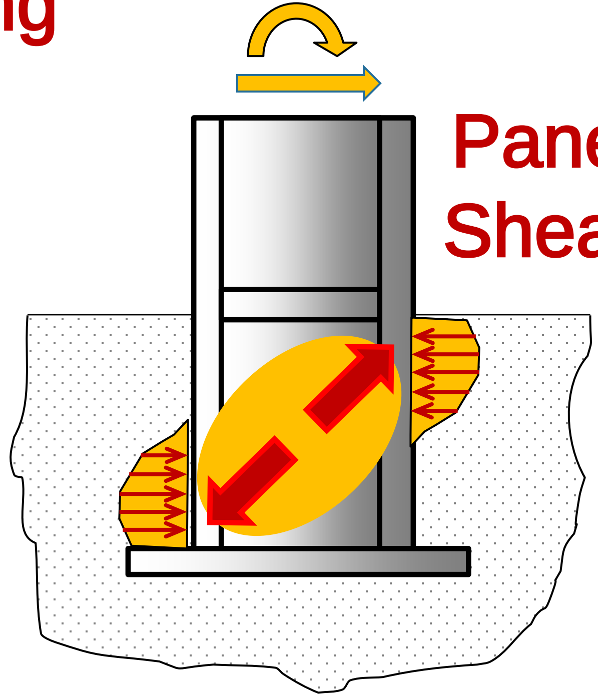
New model for embedded base connections



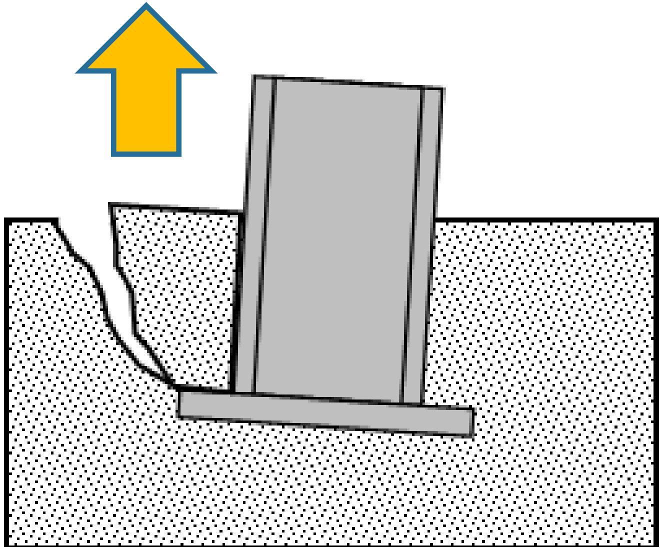
- Horizontal bearing against column flanges
- Vertical bearing against embedded plate
- Consideration of interactions and failure modes

Horizontal Bearing and panel shear– similar to coupling beams

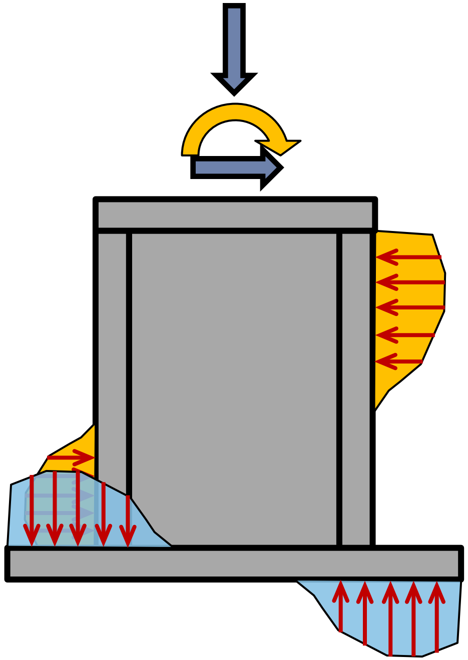
Bearing



Vertical bearing



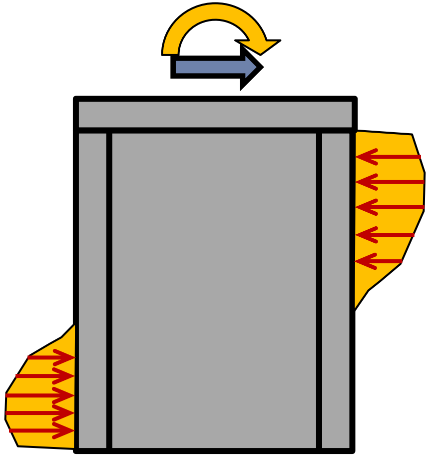
Strength Model– considering both mechanisms

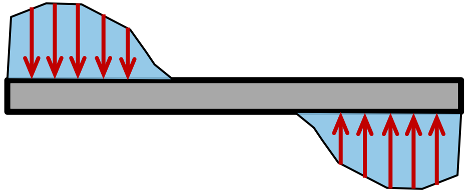


- Idealization of stress blocks
- Consideration of failure modes in each direction
- Consideration of reinforcement patterns

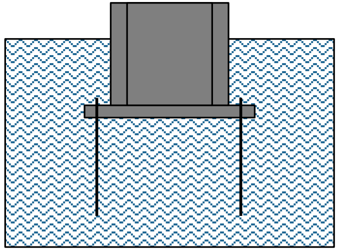
Strength Model

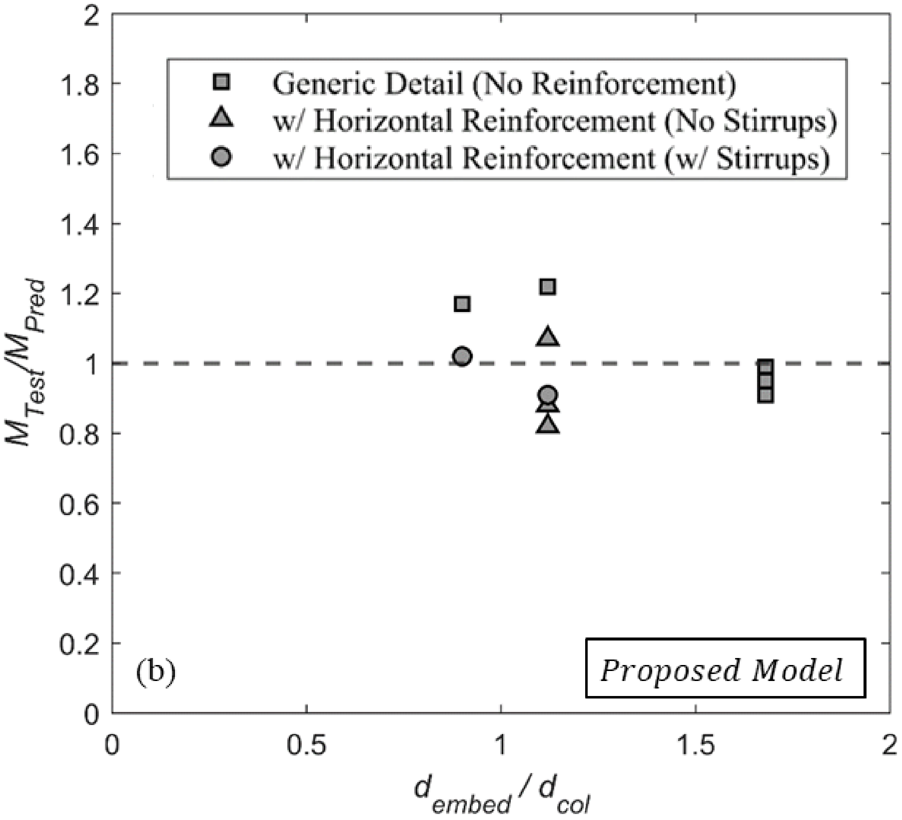
Consideration of failure modes in each direction

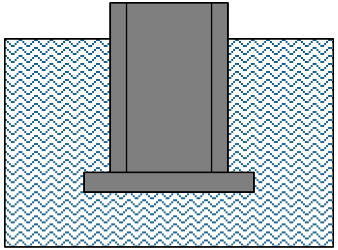




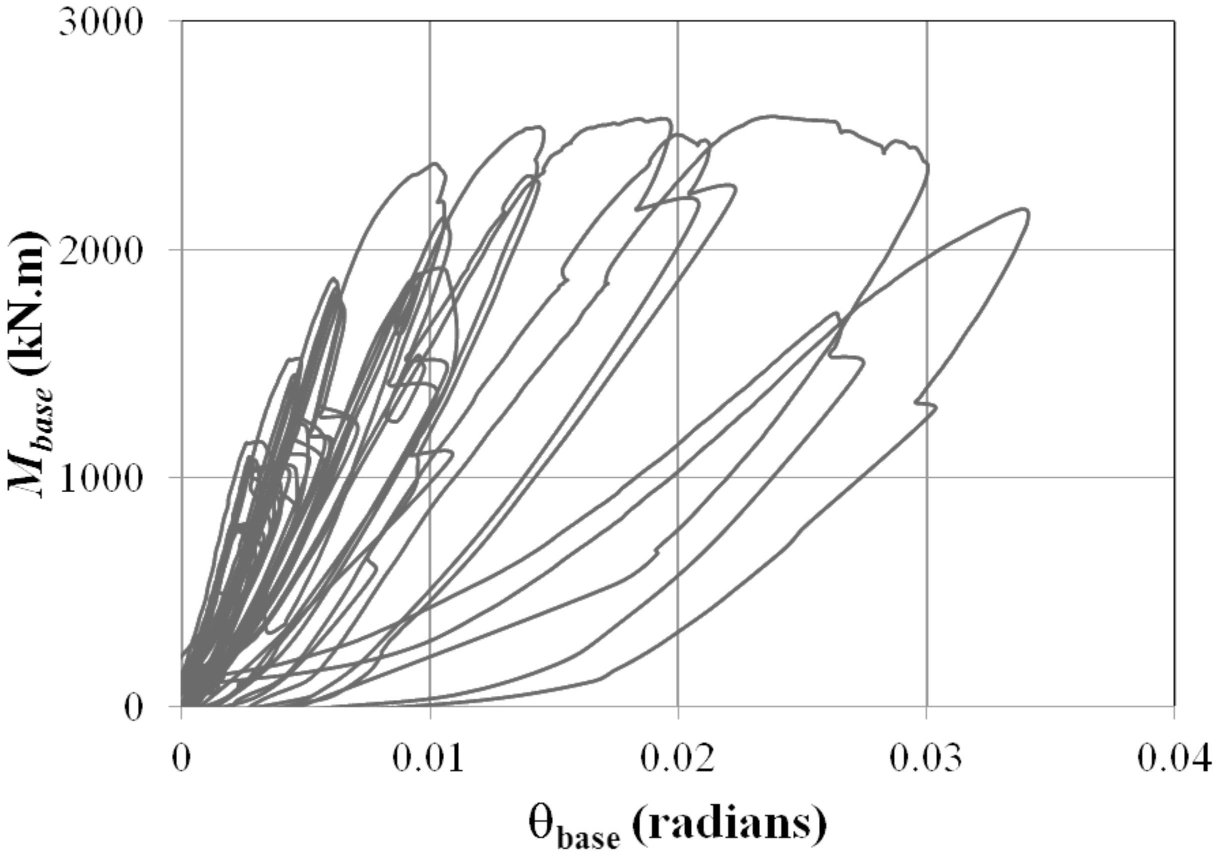
Improved models for embedded bases



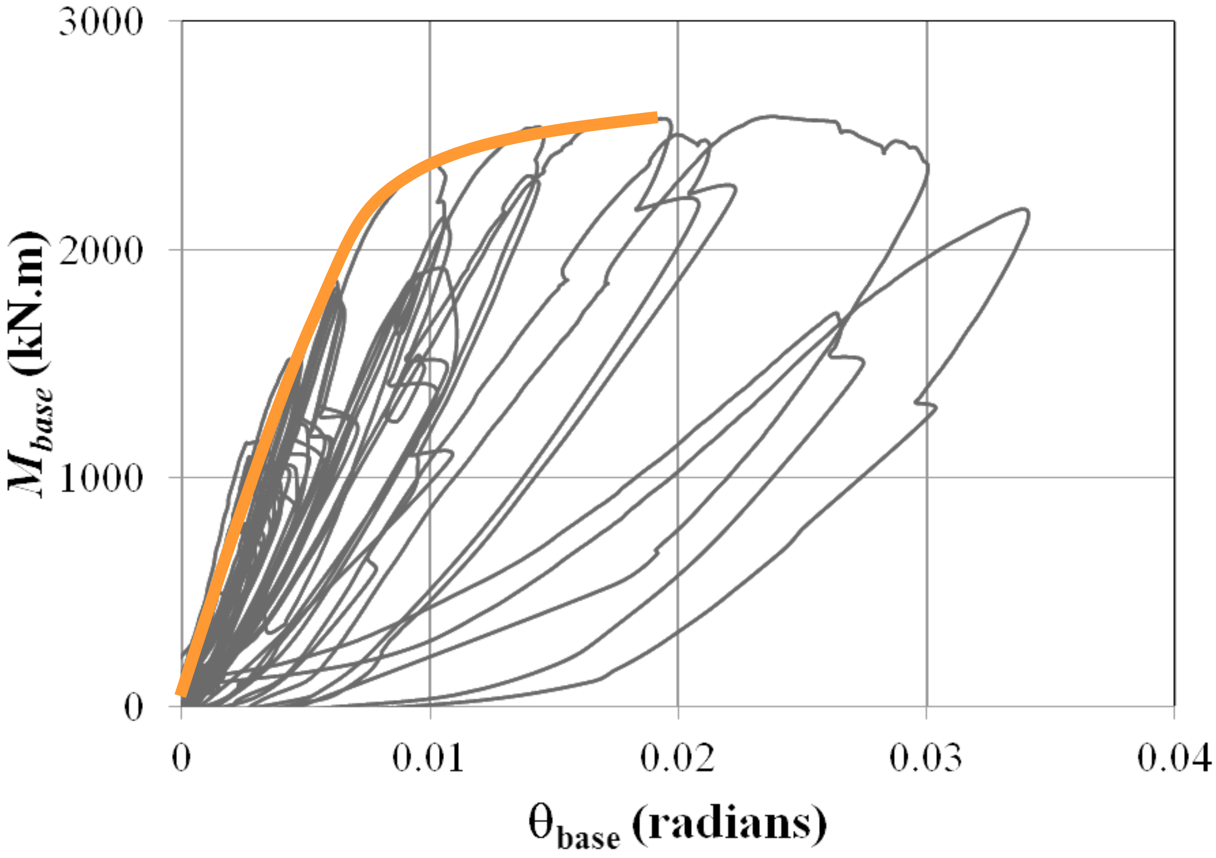




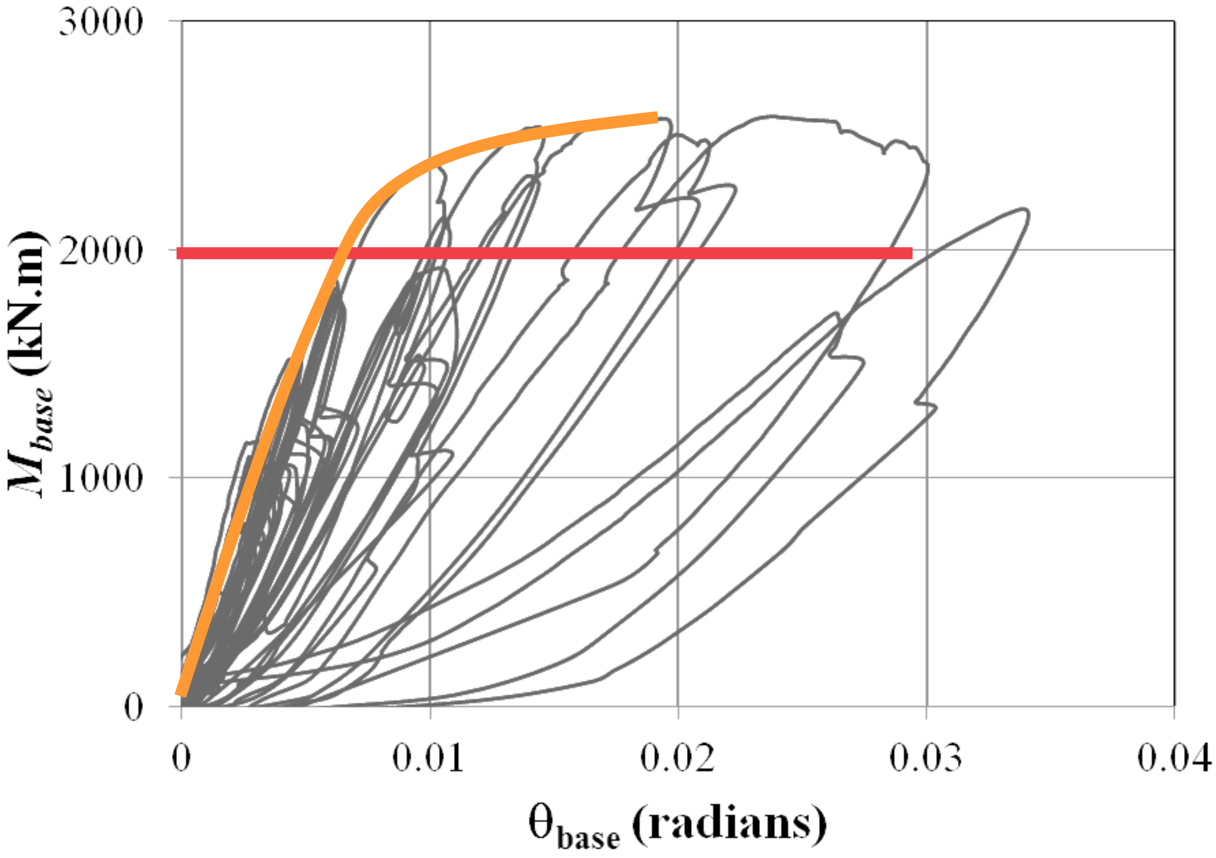
Rotational stiffness of embedded bases



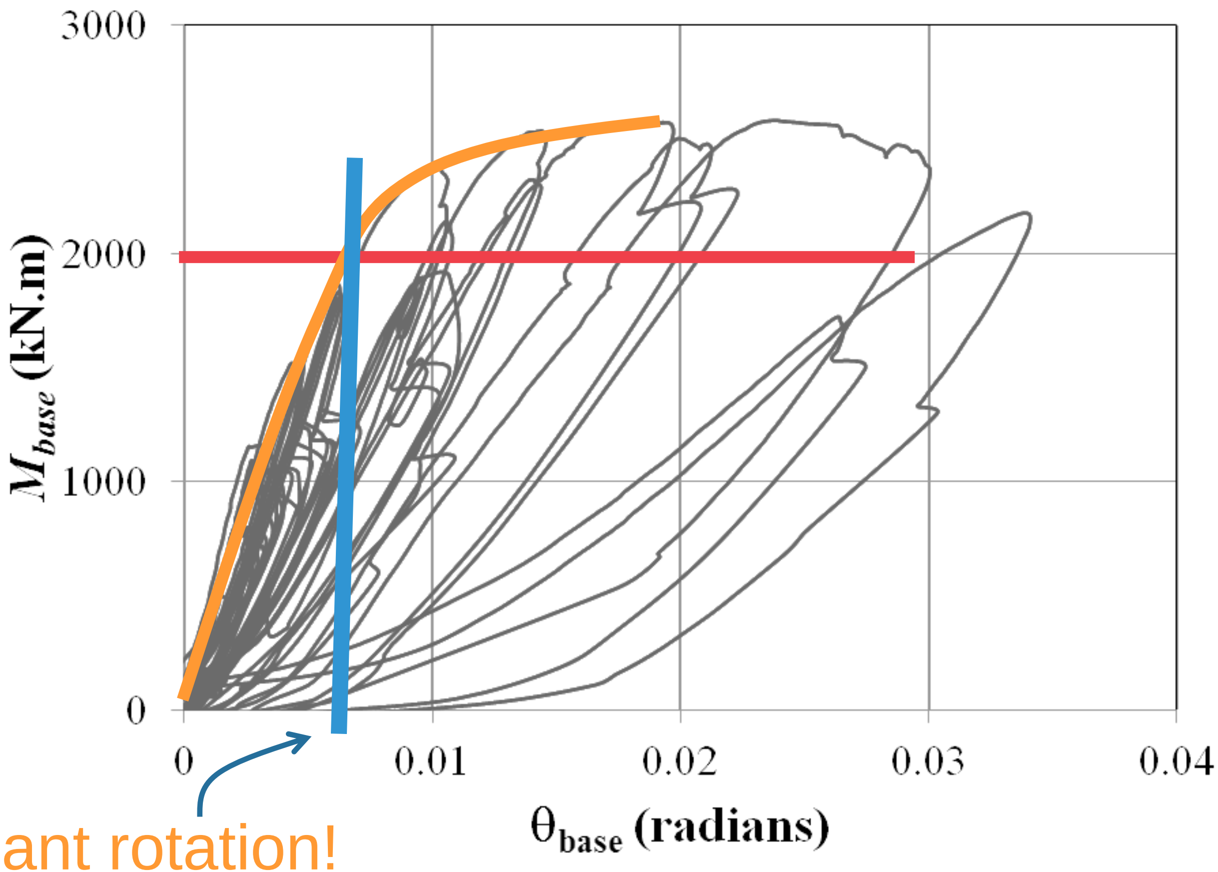
Rotational stiffness of embedded bases



Rotational stiffness of embedded bases



Rotational stiffness of embedded bases

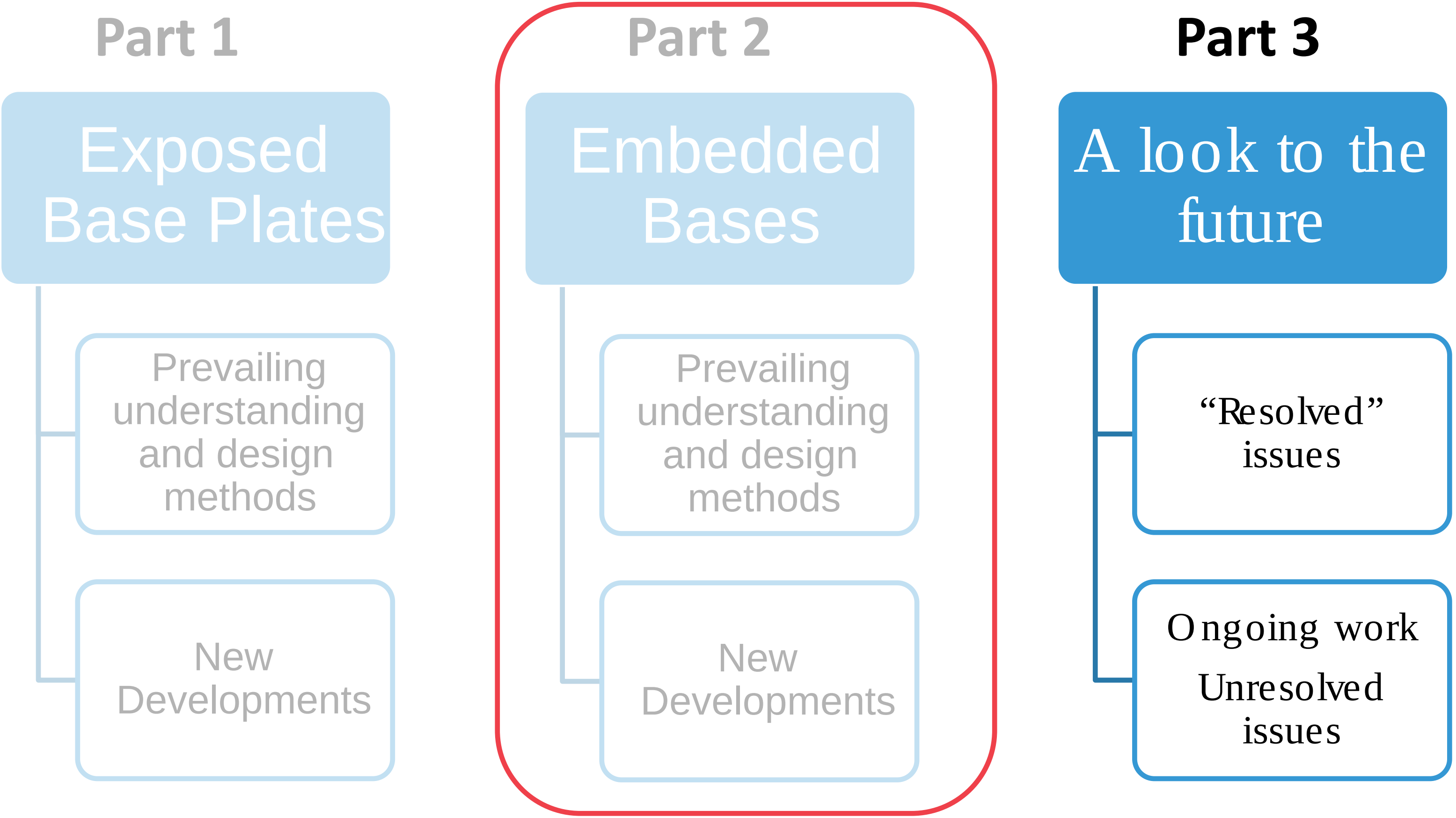


Significant rotation!

Summary– embedded base connections

- Knowledge almost entirely new
- Existing methods do not fully capture complexity and mechanisms
- New test data has led to improved methods
- Rotational flexibility is an issue

Organization



A look to the future

Part 3

A look to the future

- “Resolved” issues
- Ongoing work

  Unresolved issues

A look to the future

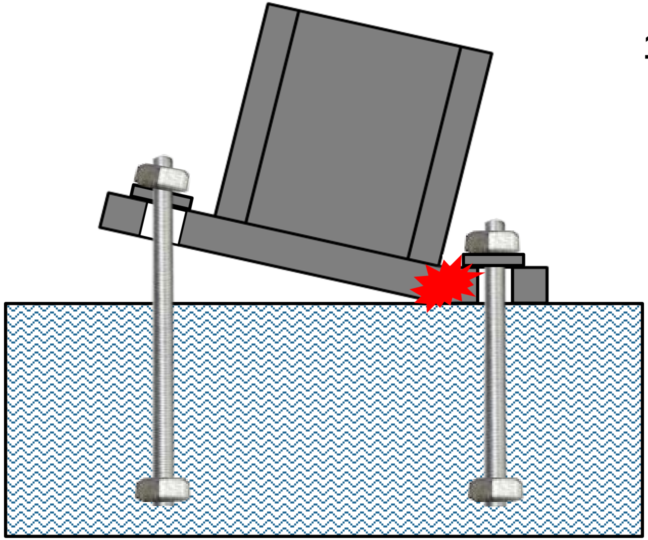
Part 3

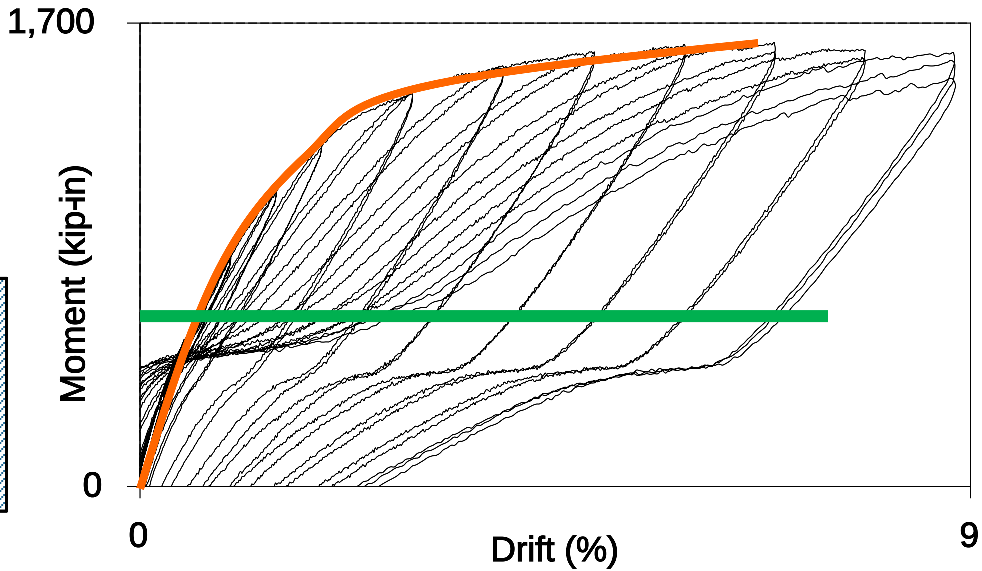
A look to the future

- "Resolved" issues
- Ongoing work
  Unresolved issues

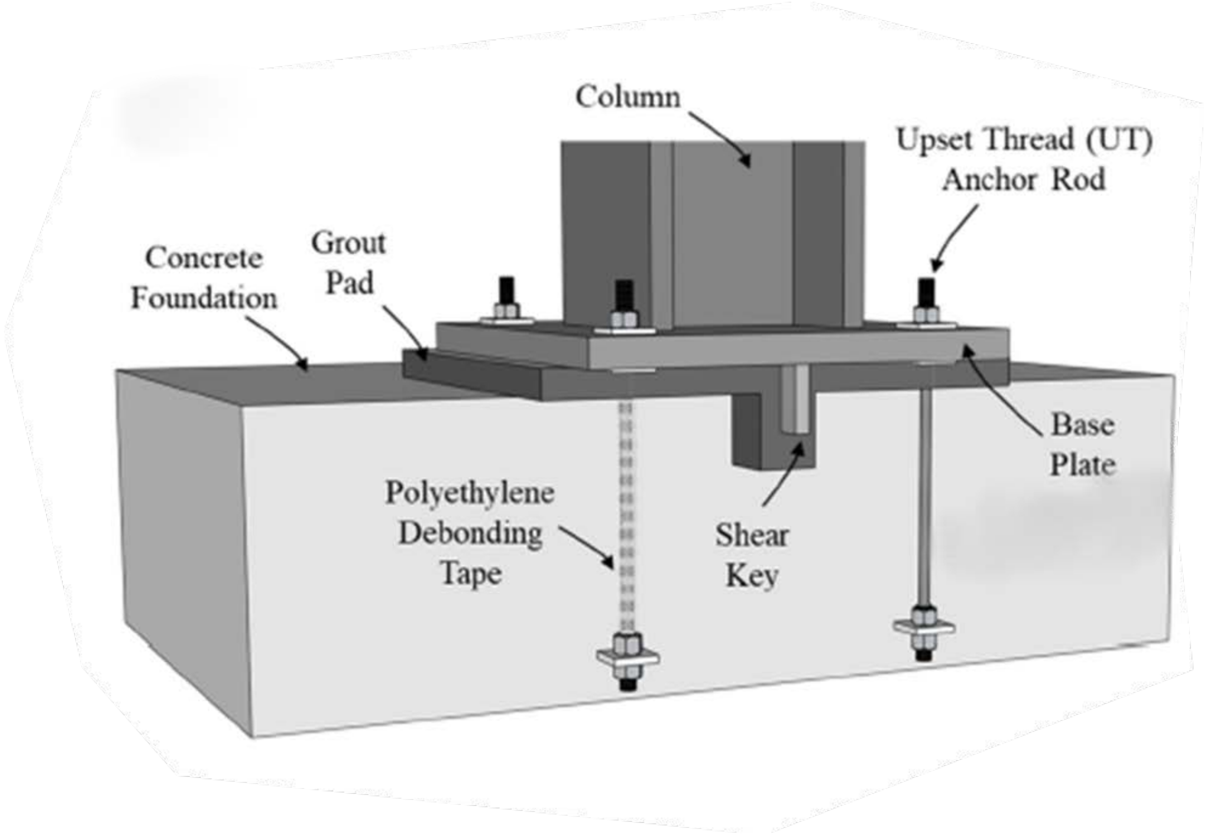
- Minor modifications to strength model
- Ductile details for weak base design
- Reliability analysis
- Biaxial bending
- Anchorages
- Shear transfer
- Alternate anchor rod patterns
- Modeling tools
- Strength models for embedded details
- Effect of slab overtopping

Modifications to strength models to reduce conservatism

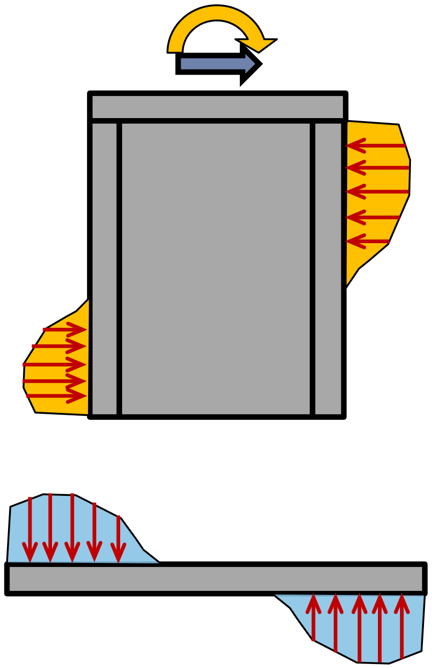




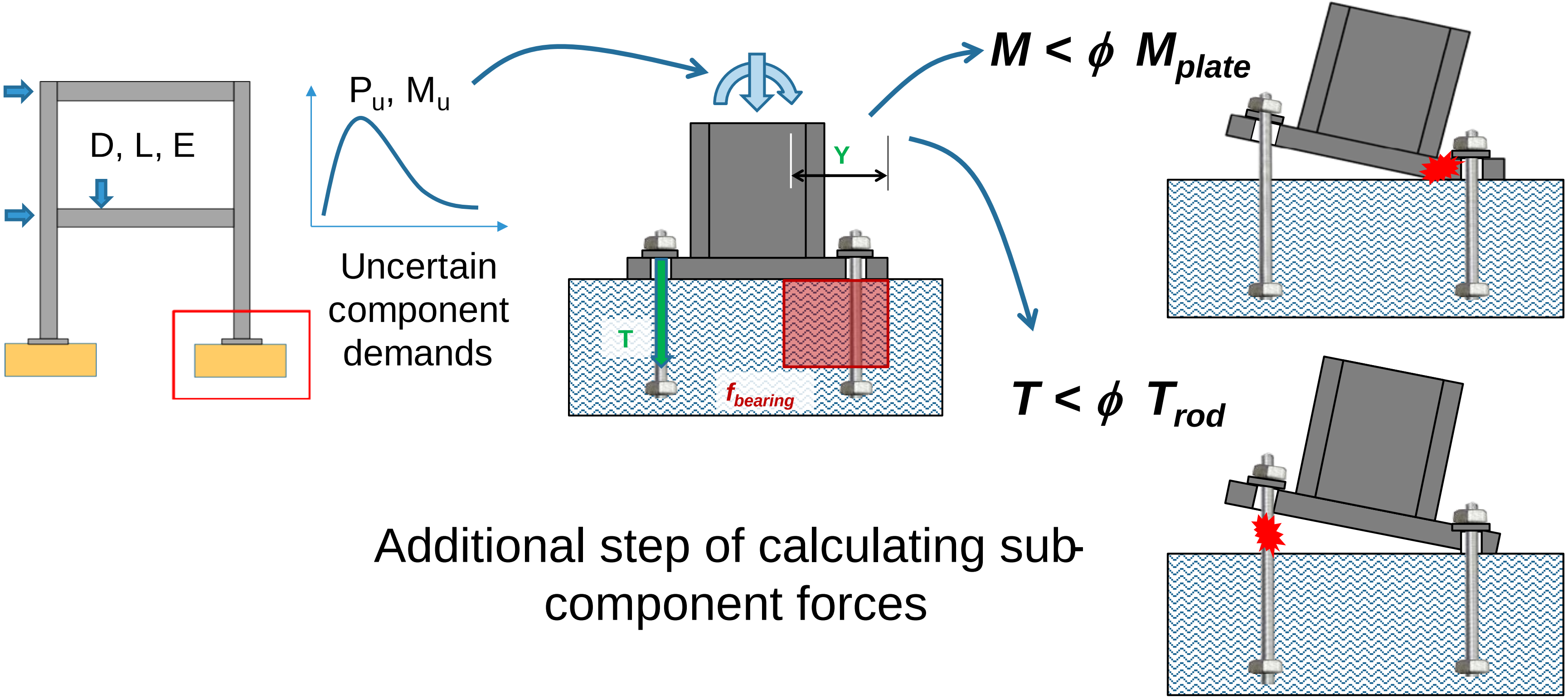
Ductile details for weak base design



Embedded bases– new strength models

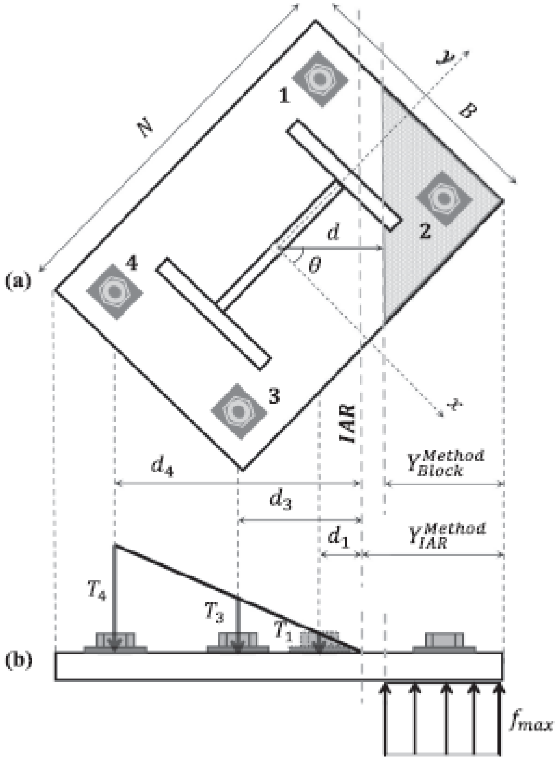


Reliability analysis

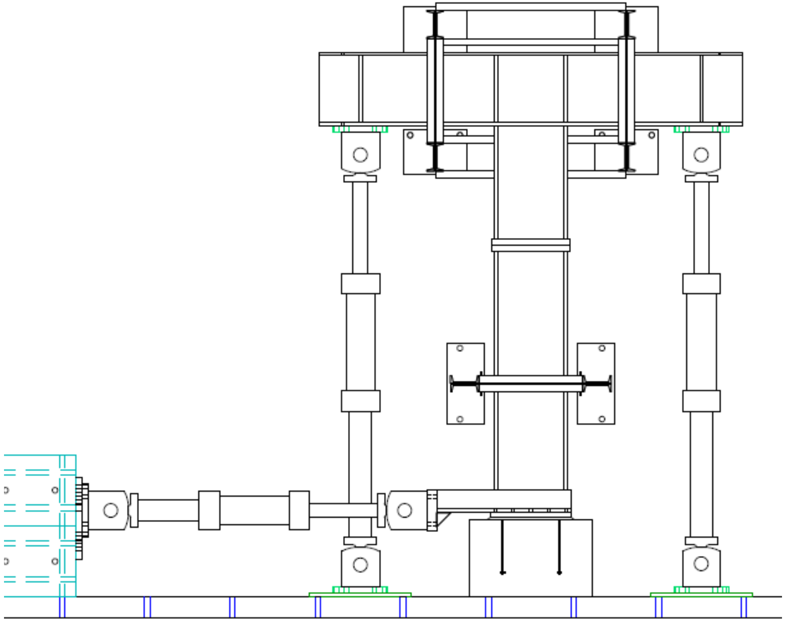


Additional step of calculating sub-component forces

Biaxial bending and alternate rod patterns

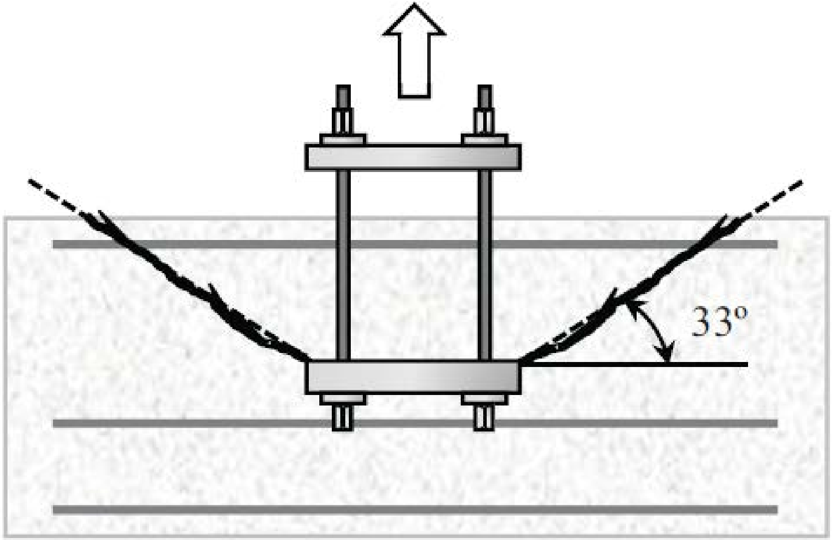


Shear transfer

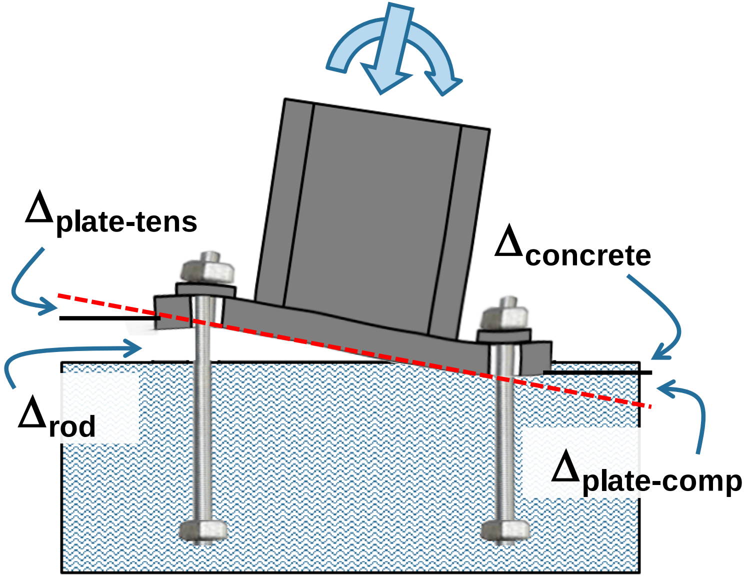


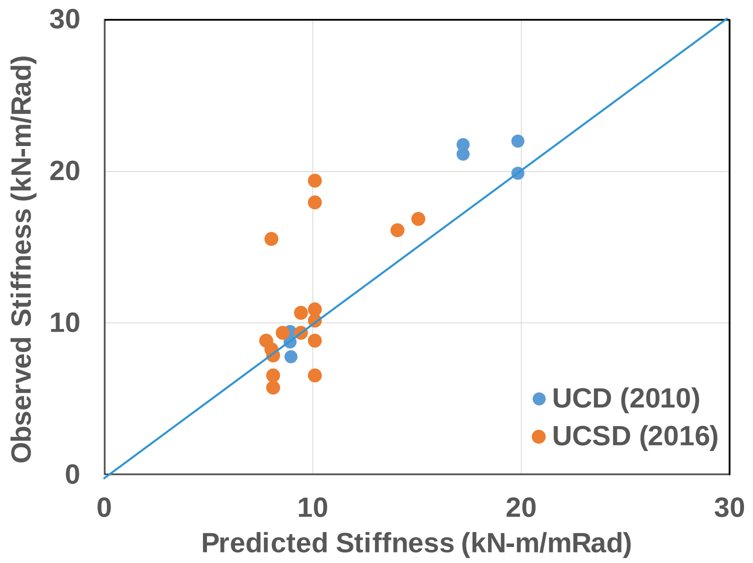
Strength of anchorages

Differences between concrete and steel column bases



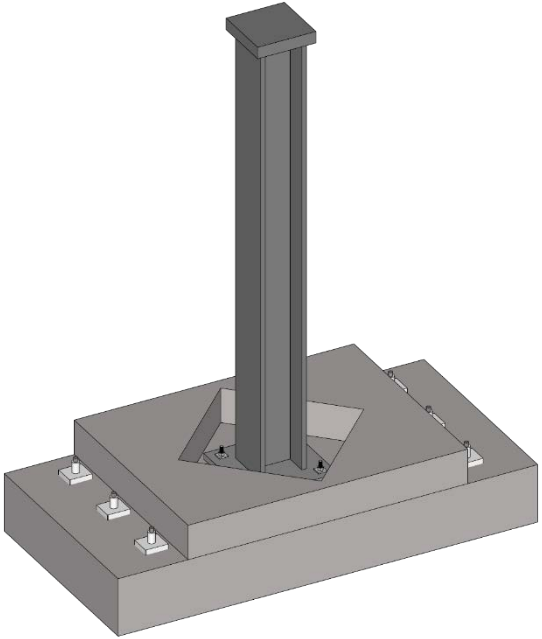
Models for base flexibility – exposed and embedded



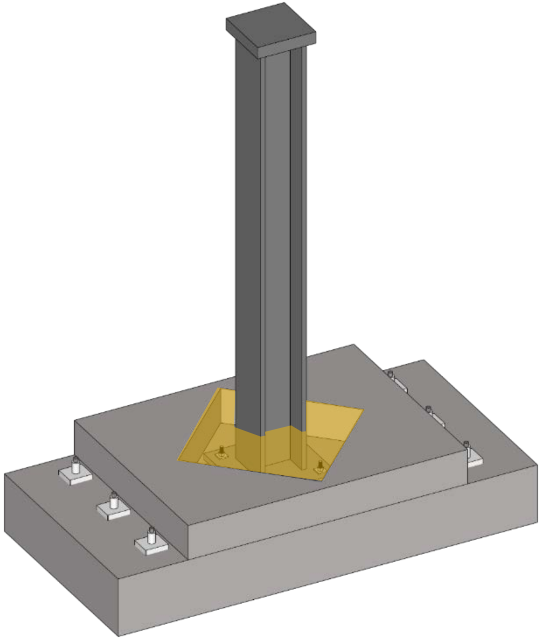


Kanvinde, A.M., Grilli, D.A., and Zareian, F. (2012). “Rotational Stiffness of Exposed Column Base Connections – Experiments and Analytical Models,” Journal of Structural Engineering, ASCE, 138(5), 549-560.

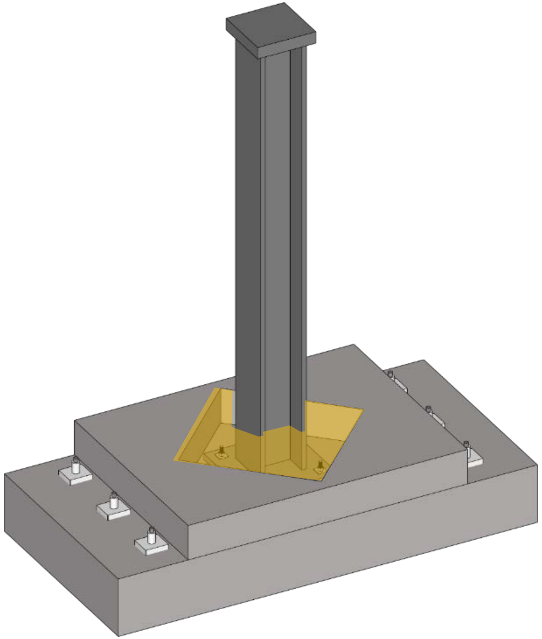
Blockoutconnections and overtopping slab

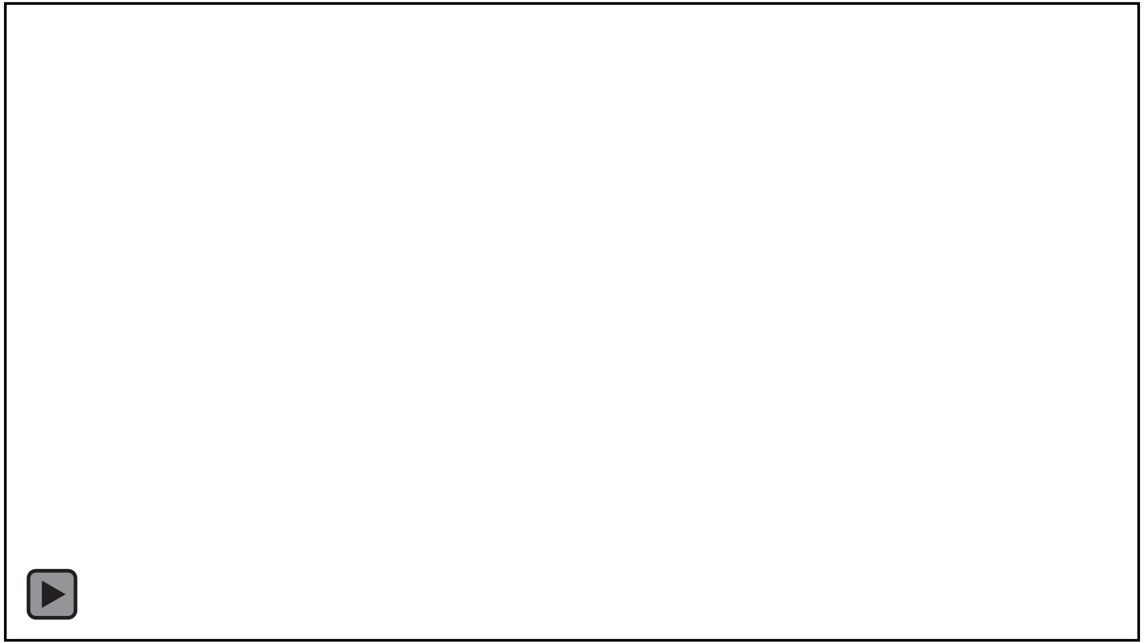


Blockoutconnections and overtopping slab



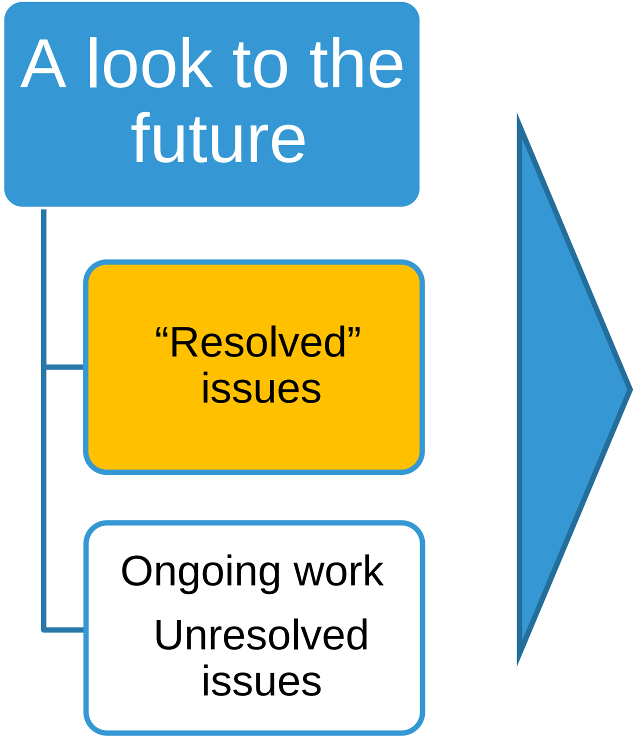
Blockoutconnections and overtopping slab





Work done at BYU (Paul Richards) and UC Davis

Potential proposals



- New (3rd) Edition of Design Guide One (~2024) – in progress
- AISC 341 – Next code cycle
- Seismic Design Manual

AISC Design Guide One 3rd Ed

Amit Kanvinde, Mahmoud Maamouri, Josh Buckholt

- New chapter on embedded connections
- Detailed consideration of seismic issues (including weak base design)
- Configurations not addressed currently (rod patterns, biaxial bending)
- Stiffness models
- Guidelines for computer analysis
- Alternate methods of design to remove conservatisms
- Web tools for strength and stiffness models!

A look to the future

A look to the future

"Resolved" issues

Ongoing work

Unresolved issues

- Braced frame base plates
- Overall foundation response and soil structure interaction
- Base frame interactions
- Resilience, design for repair

Braced frame base plates

A look to the future

- "Resolved" issues
- Ongoing work
  Unresolved issues

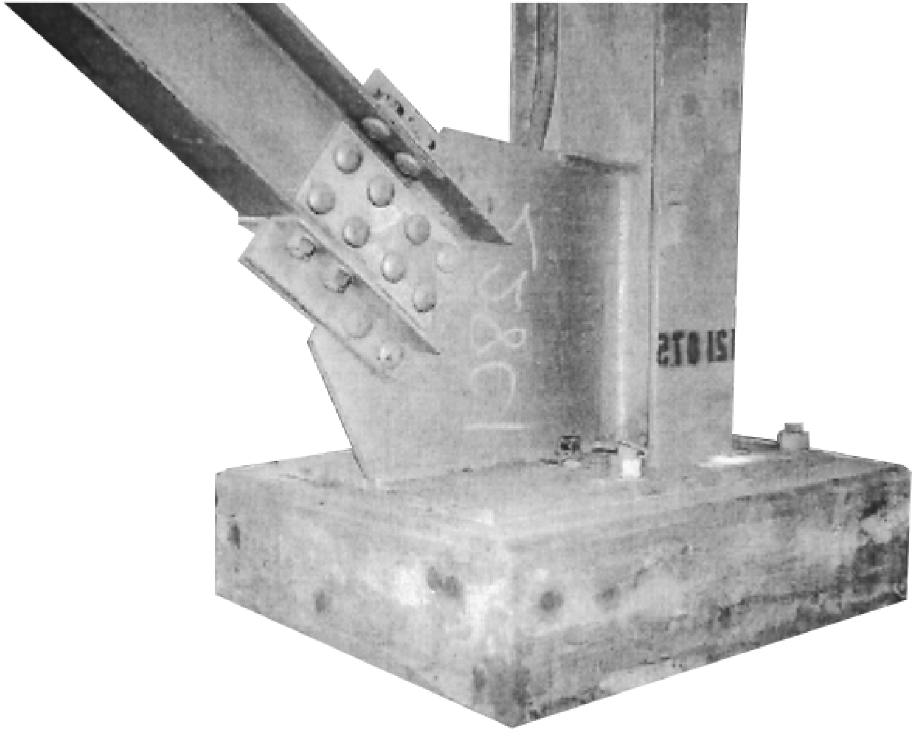


Photo credit: Rick Drake (2003)

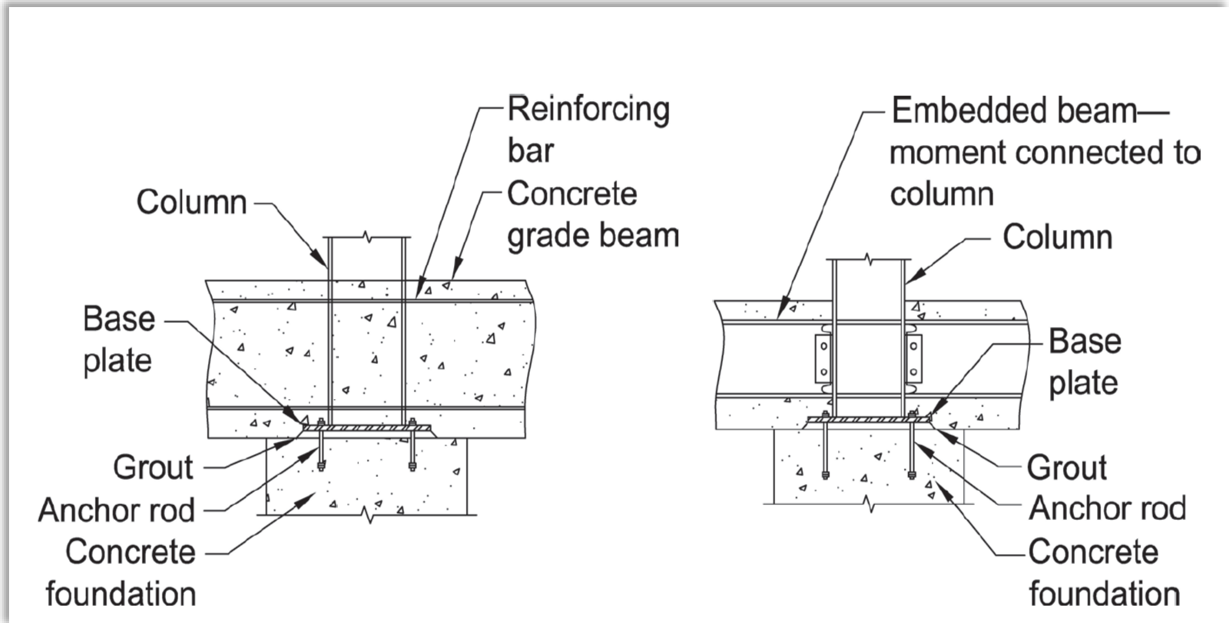
Overall foundation response

A look to the future

"Resolved" issues

Ongoing work

Unresolved issues

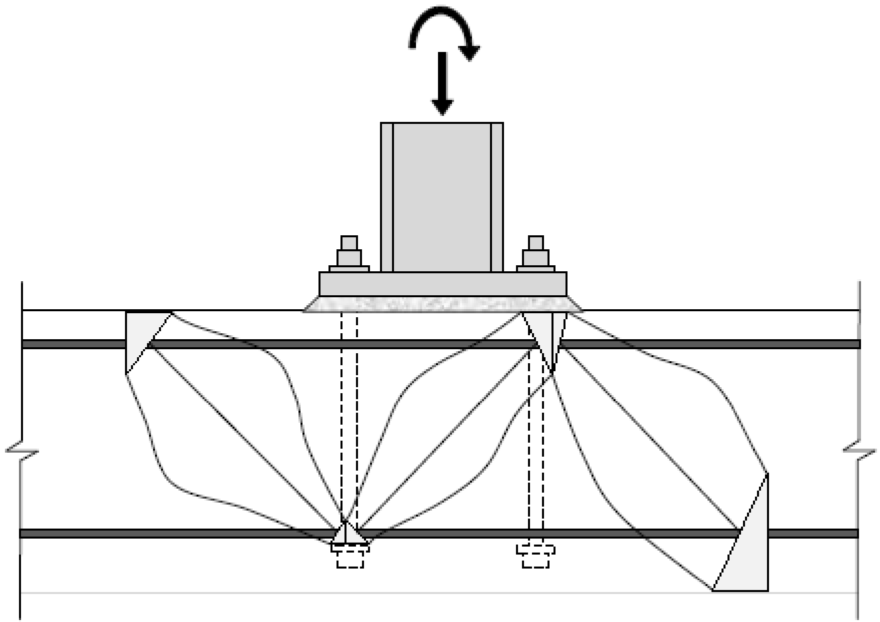


Grade beams

Overall foundation response

A look to the future

- "Resolved" issues
- Ongoing work
  Unresolved issues

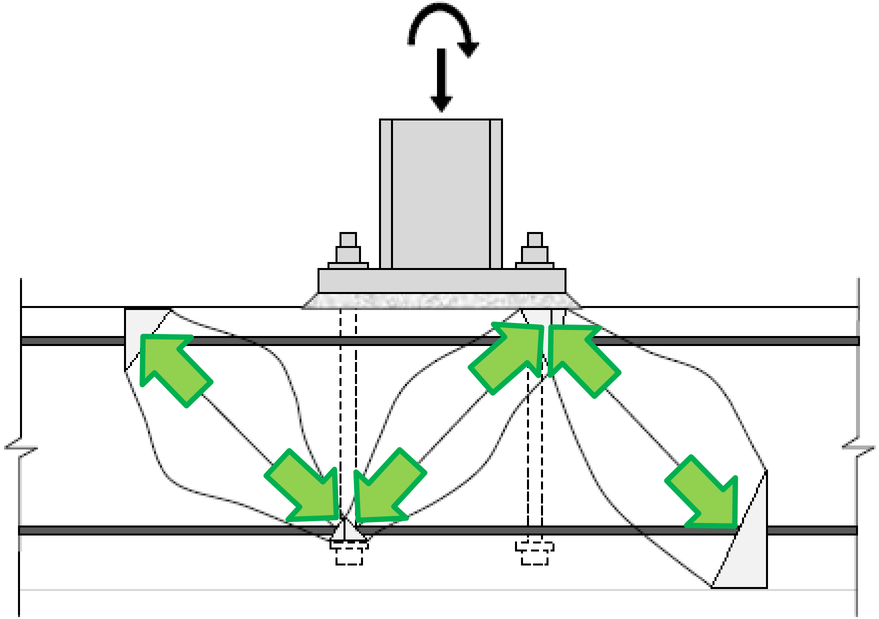


Grade beams and overall foundation response

Overall foundation response

A look to the future

- “Resolved” issues
- Ongoing work
  Unresolved issues



…all the way to soil structure interaction

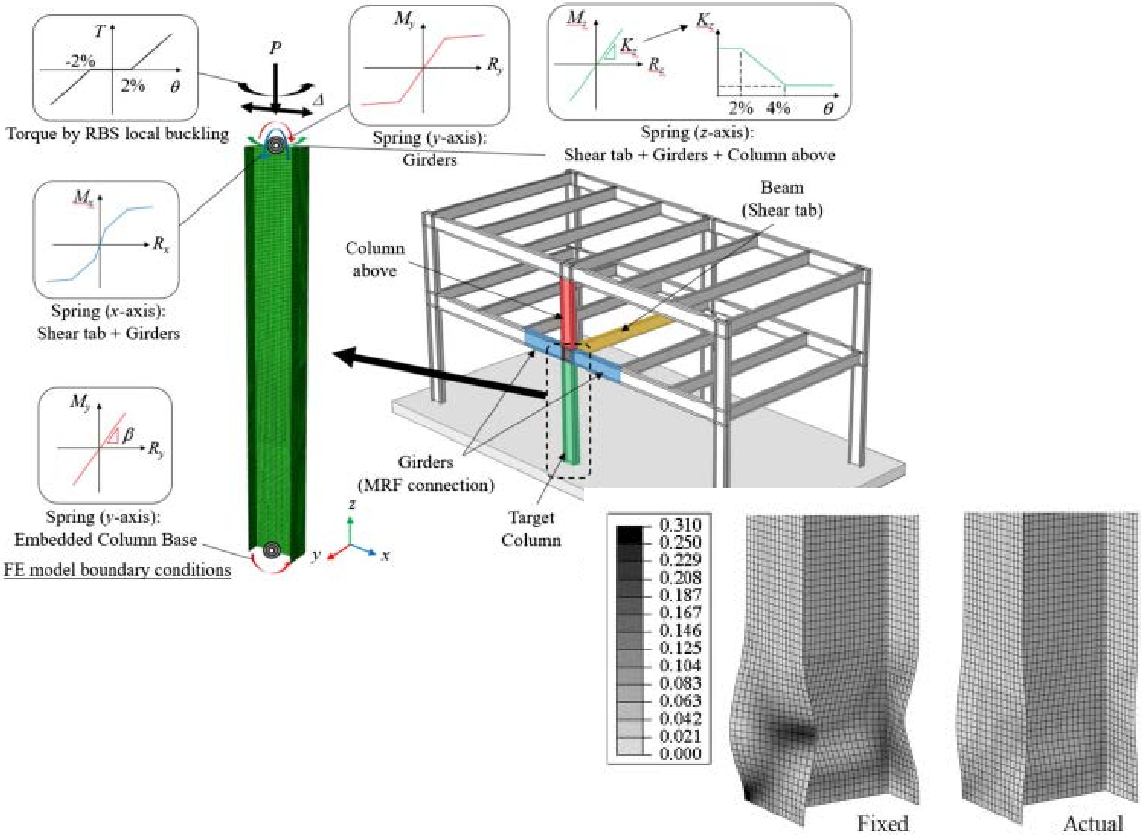
Base frame interactions

A look to the future

"Resolved" issues

Ongoing work

Unresolved issues



Inamasu, I., Kanvinde, A.M., and Lignos, D., (2019). "Seismic Stability of Wide-Flange Steel Columns Interacting with Embedded Column Base Connections," Journal of Structural Engineering, American Society of Civil Engineers, 145 (12), 04019151.

Still an exciting area with many opportunities

A look to the future

- “Resolved” issues
- Ongoing work

  Unresolved issues

* Resilience and remaining life
* Design to minimize damage
* Design for repair

UC DAVIS

CIVIL AND ENVIRONMENTAL ENGINEERING

Thank you!

https://faculty.engineering.ucdavis.edu/kanvinde/