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There's always a solution in steel.

Column Base Connections:

What Several Years of Testing has Taught Us

Presented by
Amit Kanvinde, Ph.D.
Associate Professor
University of California, Davis.

structural STEEL

Column base connections

Amit Kanvinde
Associate Professor of Structural Engineering
University of California, Davis

Acknowledgments

- AISC, Tom Schlafly
- Rick Drake, Fluor
- Ivan Gomez, AIR; Greg Deierlein, Stanford University, Santos Jordan, David Grilli, UC Davis
- Transbay Steel, Fairfield, CA
- PDM Steel
- Staff at NEES@Berkeley
- Charles Pankow Foundation

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Some background

- Review of design approaches in *Steel Design Guide One*

- AISC Literature Review on Column Base Connections (Jerry Hajjar)

- Ongoing (2006) work at UC Davis/Stanford on base plate welds

Major study funded by AISC

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Objectives

- Examine/verify current design standards

    - *Steel Design Guide One*

    - *Seismic Provisions, Specifications*

- Develop new data about seismic response of base connections (force/deformation/ductility/damage)

- Recommend improved design processes

- Develop models for analysis, examine other issues

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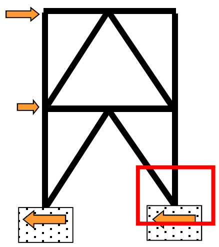
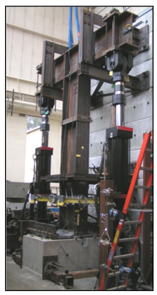
Research Overview

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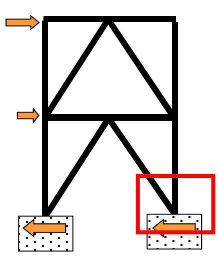
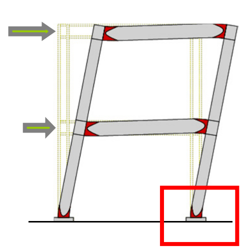
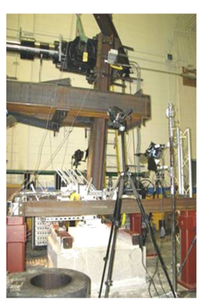
Research Overview



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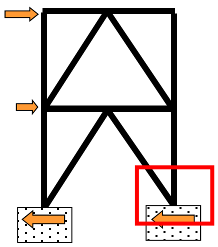
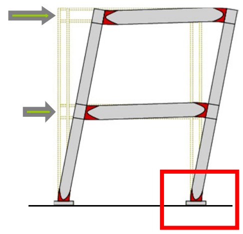
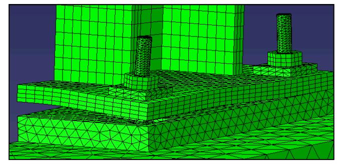
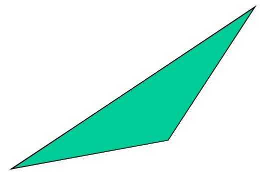
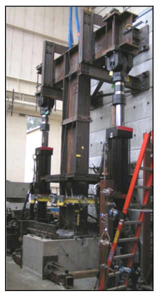
Research Overview


Better design approaches, models

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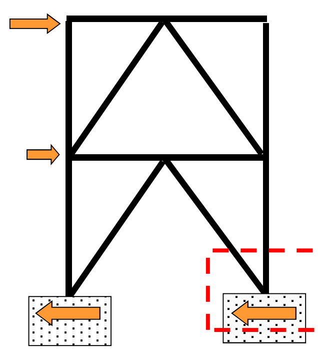
Base connections under shear and axial load





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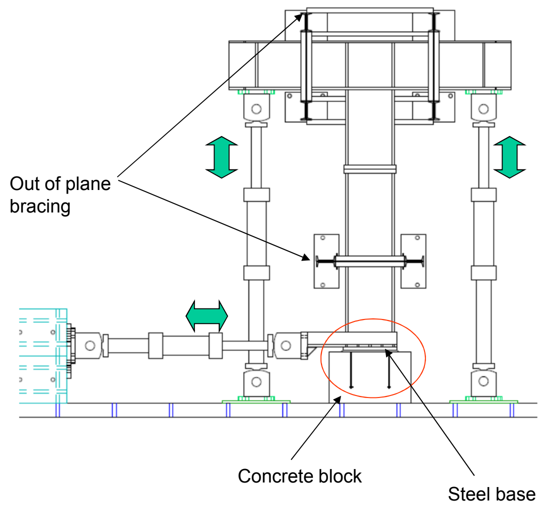
Test setup



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Shear transfer mechanisms in exposed column base-plates

Test #	Mechanism investigated	Test detail	Loading description
1	Surface friction	Shim stacks plus grout	Cyclic shear with various levels of constant axial compression
2			
3		Grout only	
4	Anchor rod bearing	3/4” diameter anchor rods with welded plate washers	Cyclic shear with constant axial tension
5		1-1/4” diameter anchor rods with welded plate washers	
6	Shear key bearing	6” bearing width with 5.5” embedment depth	Monotonic shear with small compressive axial load
7		6” bearing width with 3.0” embedment depth	

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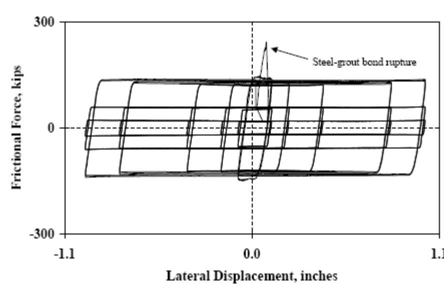
Key findings – Friction

- Suggest using a value of μ = 0.45
  - Current study had mill scale
  - Plates in prior studies were machined (increasing friction)
  - Prior studies did not feature shim stacks



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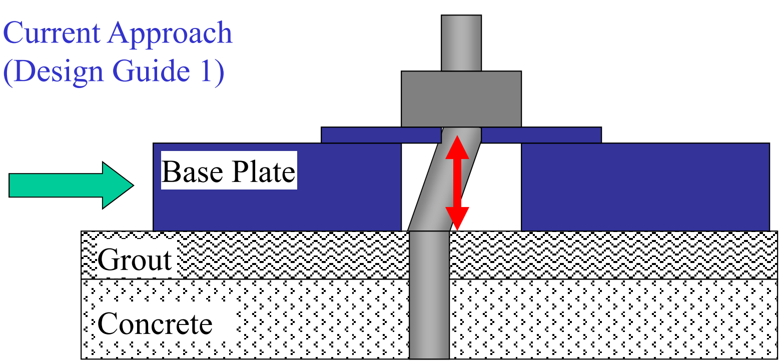
Key findings – Anchor rod bearing

Main issue – the appropriate consideration of effective bending length of anchor rod

Current Approach (Design Guide 1)



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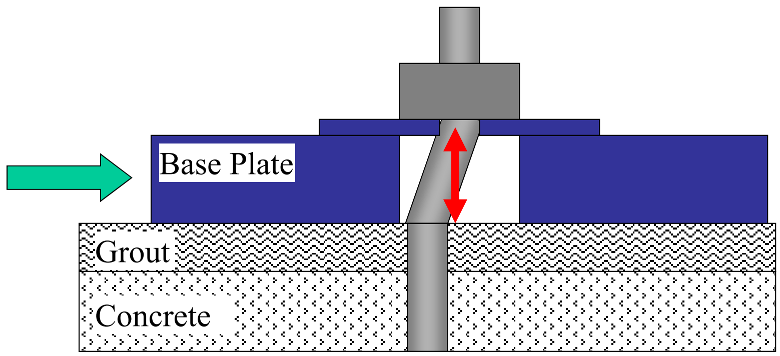
Test observations

Initial bending over base plate thickness



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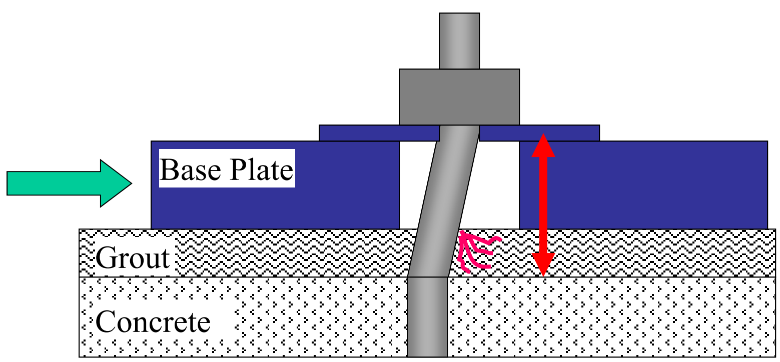
Test observations

Grout damage results in increase in bending length, strength degradation



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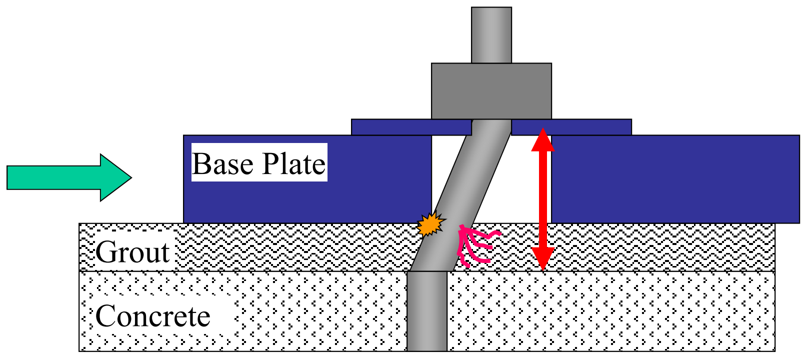
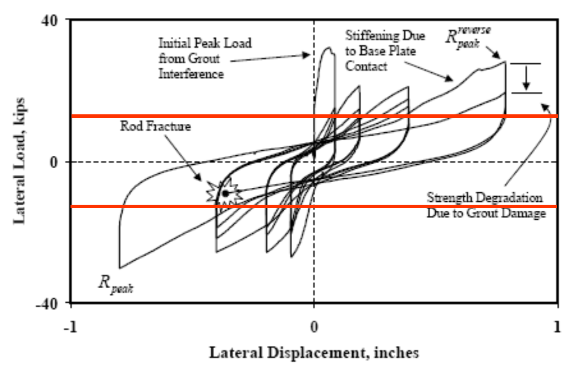
Test observations

Base plate contact increases strength





- Current method using the smaller effective length = (t_{base_plate} + 1/2t_{washer}) is reasonable

- Grout damage increases this length and degrades strength

- This is compensated for by other mechanisms, including base plate contact

Shear transfer mechanisms in exposed column base-plates

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Key findings – Shear Key Bearing

Current approach (Design Guide 1) -

$$V_n^{45} = \left(4\sqrt{f_c'}\right) A_{45}, \quad lb$$

Strength based on uniform stress projected on 45-degree cone projected from shear key onto free surface

Found to be unconservative, Test-Predicted ratios ≈ 0.5

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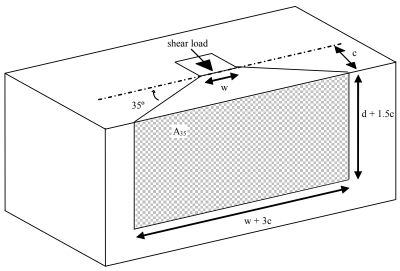
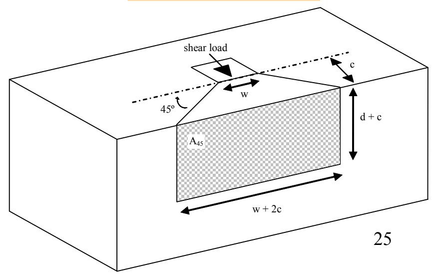
Incorporation of the “Size Effect” in concrete

- Strength governed by initiation of cracking
- Development of tensile stresses over entire cone might be unrealistic, especially when large blocks of concrete are involved

So -
$$\phi V_n = \min\left\{\phi_{CCD}\frac{1}{\sqrt{c}}\left(\frac{40}{9}\sqrt{f'_c}\right)A_{35}, \phi_{45}\left(4\sqrt{f'_c}\right)A_{45}\right\}$$





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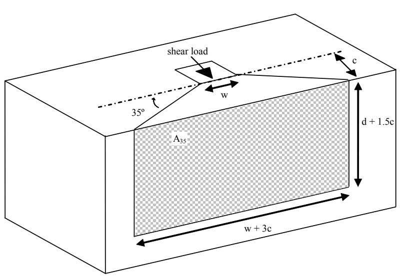

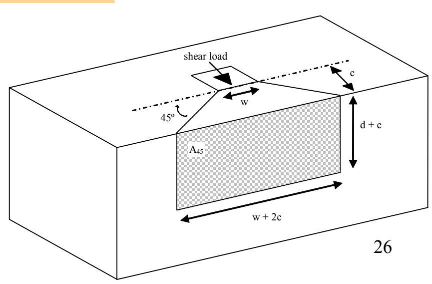

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Incorporation of the "Size Effect" in concrete

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27

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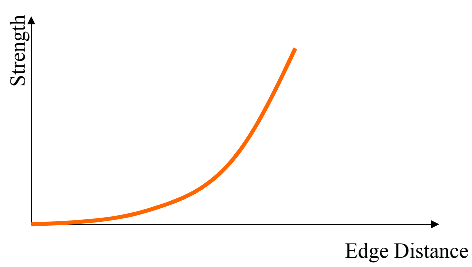

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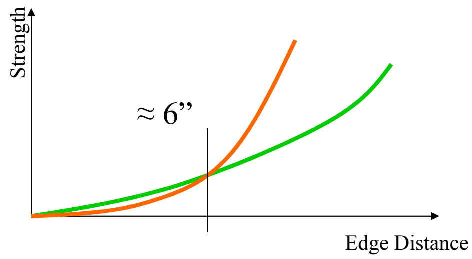
Incorporation of the "Size Effect" in concrete

$$\phi V_n = \min\left\{ \phi_{CCD} \frac{1}{\sqrt{c}} \left(\frac{40}{9} \sqrt{f_c'} \right) A_{35}, \phi_{45} \left(4\sqrt{f_c'} \right) A_{45} \right\}$$



With this approach, the Test-Predicted ratios are ≈ 1.1 with a COV of 0.2

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Summary of findings from shear tests

- Current guidelines adequate for friction/anchor rod bearing
- Shear lug bearing needs more consideration

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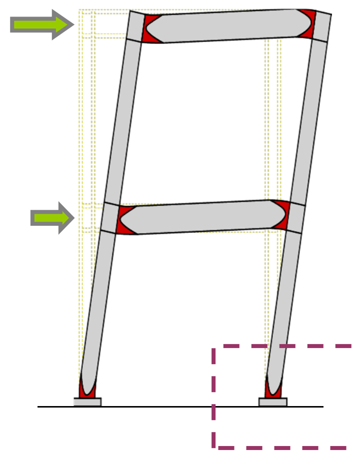
Base connections under axial load and flexure



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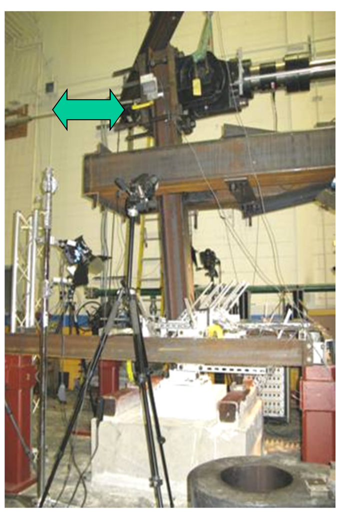
Exposed column base plates subjected to axial and flexural loading



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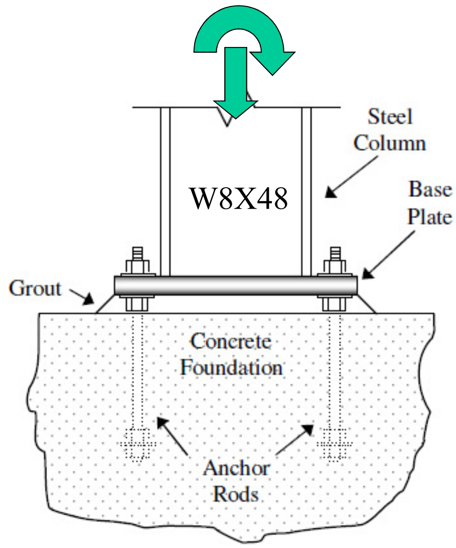
Basic connection configuration



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Test Matrix

Test #	Plate Thickness (inches)	Nominal Rod Yield Strength (ksi)	Number of Rods	Gravity Load (kips)	Lateral Loading
1	1	105	4	None	Monotonic
2	1	105	4	None	Cyclic
3	1	105	8	None	Cyclic
4	1.5	36	4	90	Cyclic
5	1	105	4	92.25	Cyclic
6	2	105	4	92.25	Cyclic
7	1	105	4	152.25	Cyclic

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Test Matrix

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1	1	105	4	None
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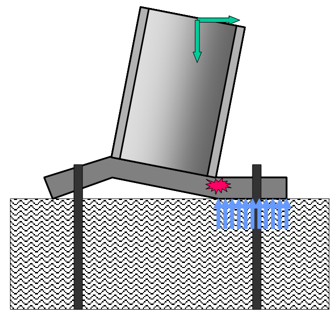

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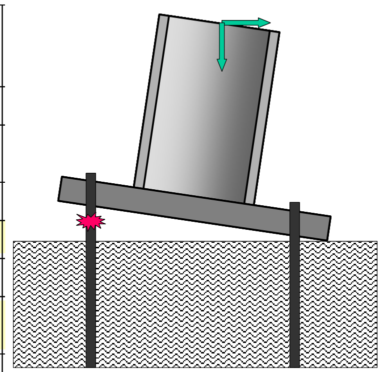

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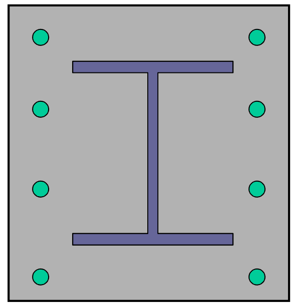
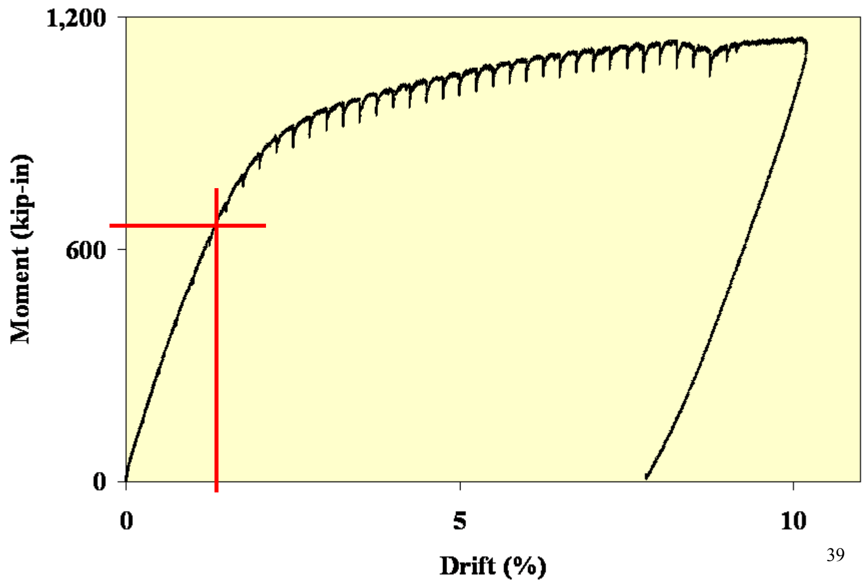


Test # 1 (1 inch plate, zero axial load, 105 ksi anchor rods, monotonic)

Test #1 (1 inch plate, 0 kips axial load, 105 ksi anchor rods)



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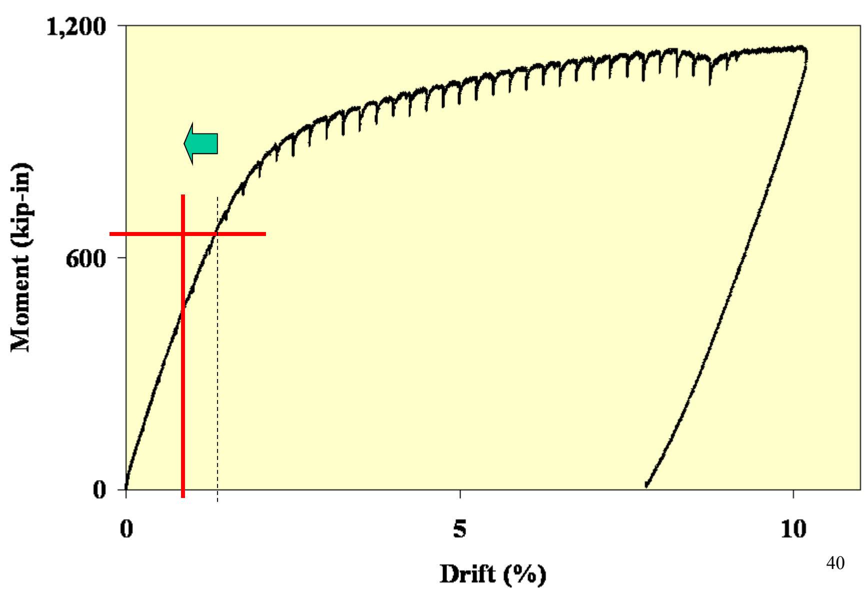
Test #1 (1 inch plate, 0 kips axial load, 105 ksi anchor rods)



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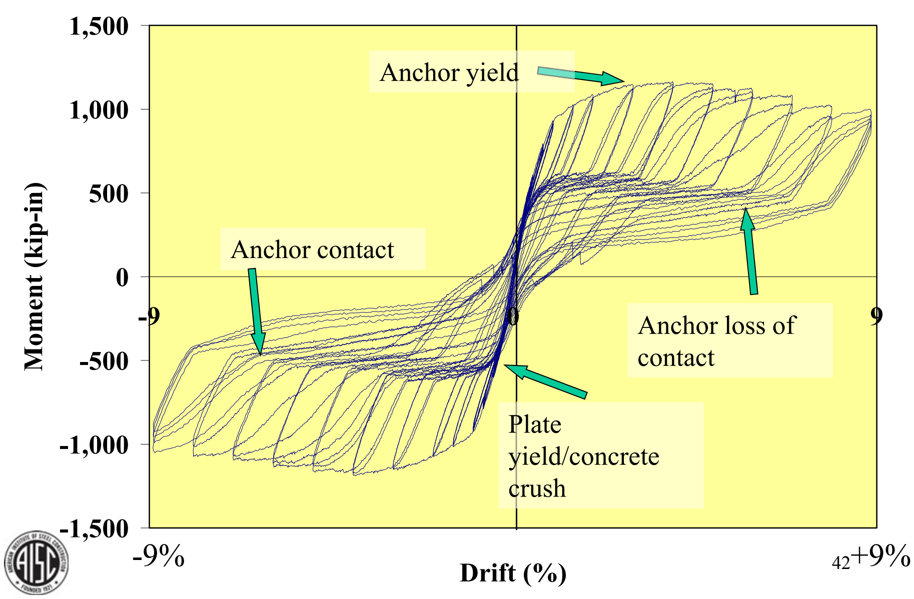
Test #4 (1.5 inch plate, 92 kips axial load, 36 ksi anchor rods)

Test #4 (1.5 inch plate, 92 kips axial load, 36 ksi anchor rods)



Test #5 (1 inch plate, 92 kips axial load, 105 ksi anchor rods)

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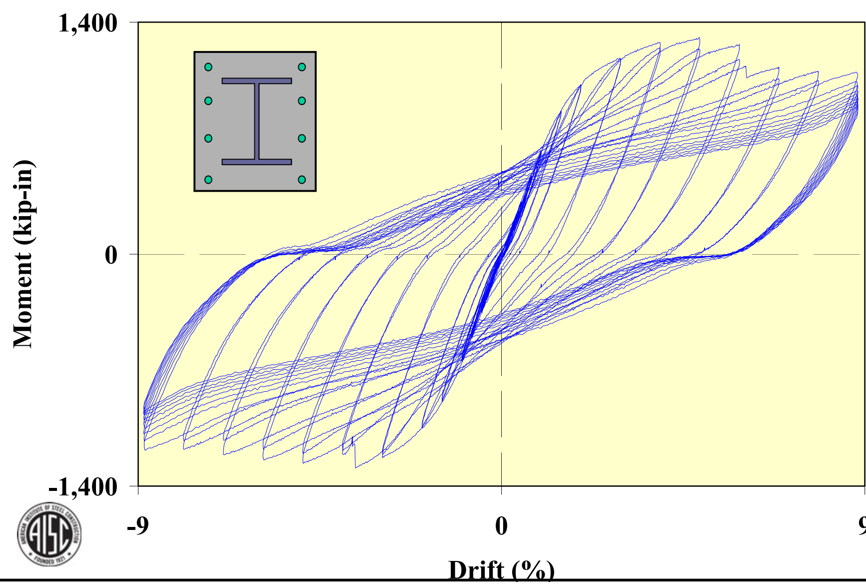
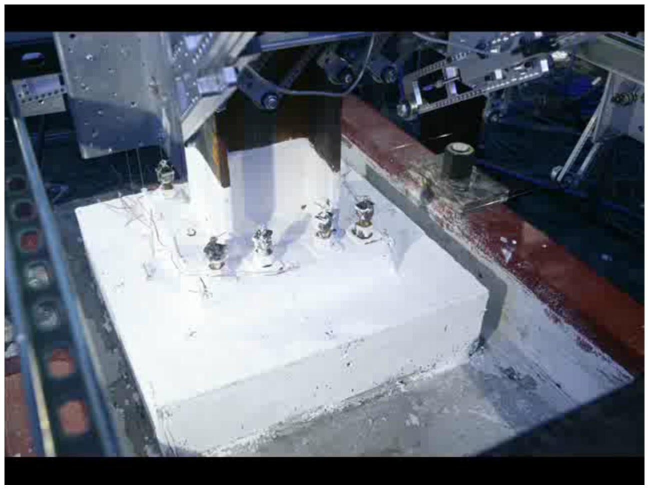
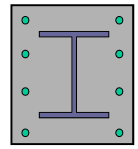
Test #3 (1 inch plate, 0 kips axial load, 105 ksi anchor rods, 8 rods in nonstandard pattern)



Test #3 (1 inch plate, 0 kips axial load, 105 ksi anchor rods, 8 rods in nonstandard pattern)





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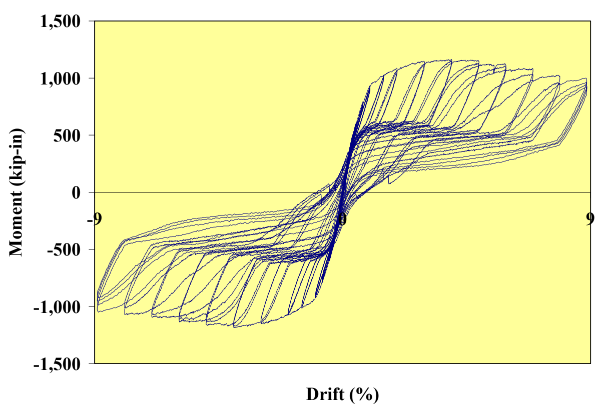
Data collected

1. Load deformation response



Evaluation of efficacy of current strength prediction approaches

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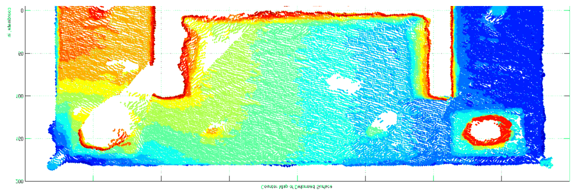
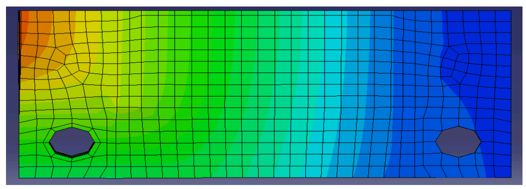
Data collected

2. Post-Experiment 3-d scan data





Qualitative comparisons with FEM simulations

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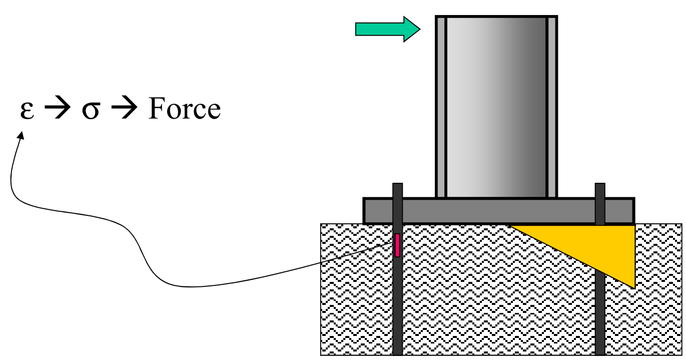
Data collected

3. Anchor rod strain data, converted to force data



Evaluation of Bearing Stress Block on compression side of base plate

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Summary of results

Test	t (inches)	Rod strength (ksi)	Rods	Pu (kips)	Failure Mode	Max Drift	M_{max} (kip-in)	$M_{compression}$ (kip-in)	$M_{tension}$ (kip-in)	M_{rod} (kip-in)
1	1	105	4	None	Grout Crushing (@ 3%) BP Tension Side Yielding	10%	1,140	813	1,298	1,162
2	1	105	4	None	Grout Crushing (@ 3%) BP Tension Side Yielding SW Rod Fracture (@ 7%)	7% (rod fracture)	1,100	813	1,298	1,162
3	1	105	8	None	Grout Crushing (@ 3%) BP Tension Side Yielding	9%	1,290	n/a	n/a	n/a
4	1.5	36	4	90	Grout Crushing (@ 3%) Rod Yielding	9%	1,160	n/a	2,825	1,126
5	1	105	4	92.25	Grout Crushing (@ 3%) BP Tension Side Yielding	9%	1,600	527	1,697	1,580
6	2	105	4	92.25	Grout Crushing (@ 3%) Rod Yielding SE Rod Fractured (@ 7%)	7% (rod fracture)	1,700	n/a	3,866	1,580
7	1	105	4	152.25	Grout Crushing (@ 3%) BP Tension Side Yielding	8%	1,800	749	1,889	1,785

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Summary of results

Test	t (inches)	Rod strength (ksi)	Rods	Pu (kips)	Failure Mode	Max Drift	M_{max} (kip-in)	$M_{compression}$ (kip-in)	$M_{tension}$ (kip-in)	M_{rod} (kip-in)
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7	1	105	4	152.25	Grout Crushing (@ 3%) BP Tension Side Yielding	**8%**	1,800	749	1,889	1,785

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Current approach for characterizing strength

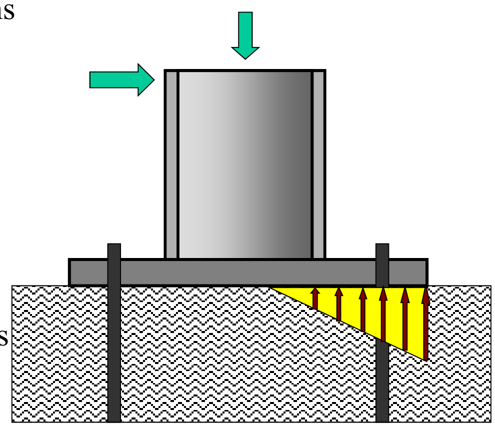
Step 1 – Size plan dimensions of the plate

Step 2 - Characterize stress block on compression side

Alternatives are Rectangular (RSB) or Triangular (TSB)

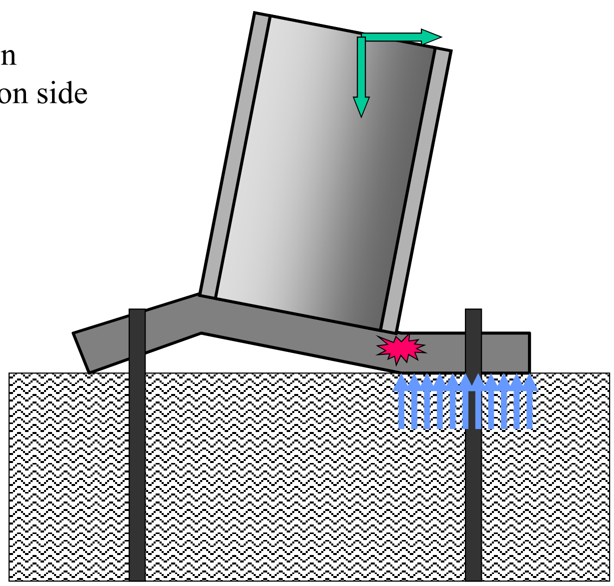
Step 3 - Based on this, calculate force in anchor rods

Step 4 – Determine strength associated with one of the following limit states



51

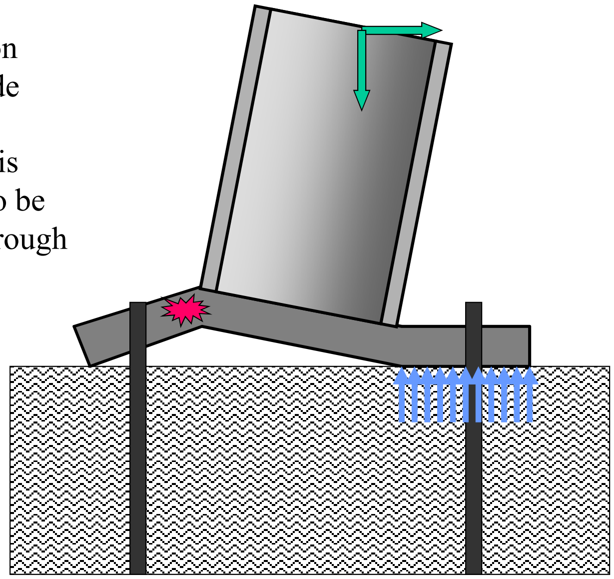
Yielding on compression side



52

Yielding on tension side

Yield line is assumed to be straight through



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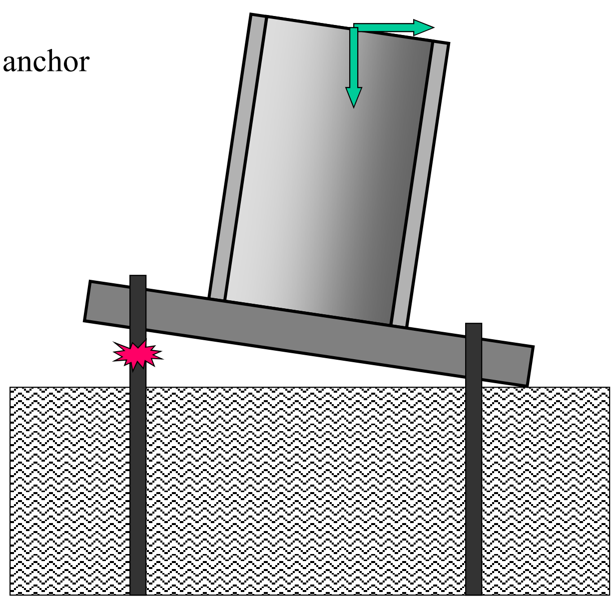
Yielding in anchor rods



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Summary of results

Test	t (inches)	Rod strength (ksi)	Rods	Pu (kips)	Failure Mode	Max Drift	M_{max} (kip-in)	$M_{compression}$ (kip-in)	$M_{tension}$ (kip-in)	M_{rod} (kip-in)
1	1	105	4	None	Grout Crushing (@ 3%) BP Tension Side Yielding	10%	1,140	**813**	1,298	1,162
2	1	105	4	None	Grout Crushing (@ 3%) BP Tension Side Yielding SW Rod Fracture (@ 7%)	7% (rod fracture)	1,100	**813**	1,298	1,162
3	1	105	8	None	Grout Crushing (@ 3%) BP Tension Side Yielding	9%	1,290	n/a	n/a	n/a
4	1.5	36	4	90	Grout Crushing (@ 3%) Rod Yielding	9%	1,160	n/a	2,825	1,126
5	1	105	4	92.25	Grout Crushing (@ 3%) BP Tension Side Yielding	9%	1,600	**527**	1,697	1,580
6	2	105	4	92.25	Grout Crushing (@ 3%) Rod Yielding SE Rod Fractured (@ 7%)	7% (rod fracture)	1,700	n/a	3,866	1,580
7	1	105	4	152.25	Grout Crushing (@ 3%) BP Tension Side Yielding	8%	1,800	**749**	1,889	1,785

55

Summary of results

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57

Summary of results

Test	t (inches)	Rod strength (ksi)	Rods	Pu (kips)	Failure Mode	Max Drift	M_{max} (kip-in)	$M_{compression}$ (kip-in)	$M_{tension}$ (kip-in)	M_{rod} (kip-in)
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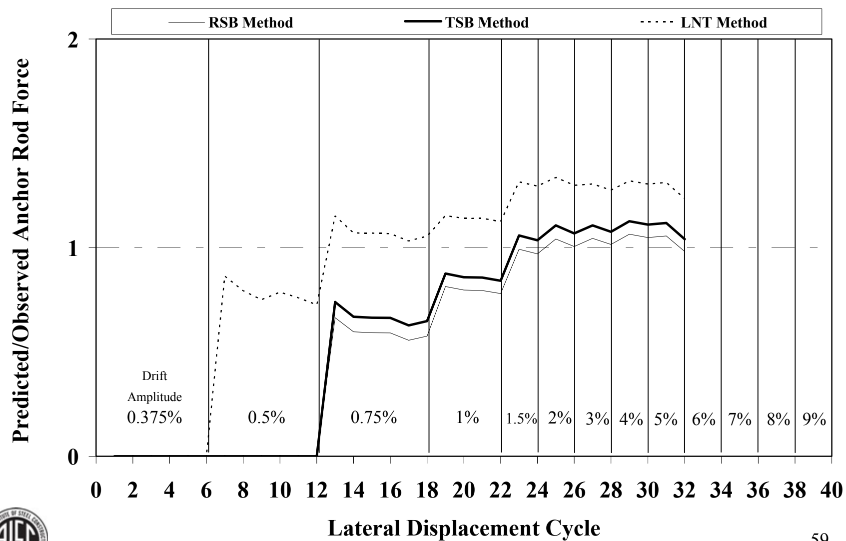
Evaluation of various stress-blocks based on anchor rod forces



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Inclined yield lines on the tension side

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Inclined yield lines on the tension side

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Inclined yield lines on the tension side

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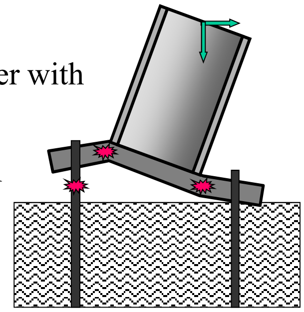
Observations

1. Large deformation capacities observed for all tests
2. Anchor rod forces estimated accurately, suggesting stress blocks are accurate, but….
3. If we just look at test-predicted ratios based on the "first-yield", results are conservative
4. However, observed capacities correlate better with anchor rod yield moment
5. Suggests that development of a mechanism (rather than a single hinge) will result in a peak load
6. Plate shows dishing and 3-d bending with nonlinear yield lines



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Proposed method, key features –

1. Use of inclined or straight yield lines on the tension side
2. Use of the Rectangular Stress Block Method to characterize bearing stresses
3. Most importantly, the use of a mechanism-based approach, rather than a "first-yield" approach

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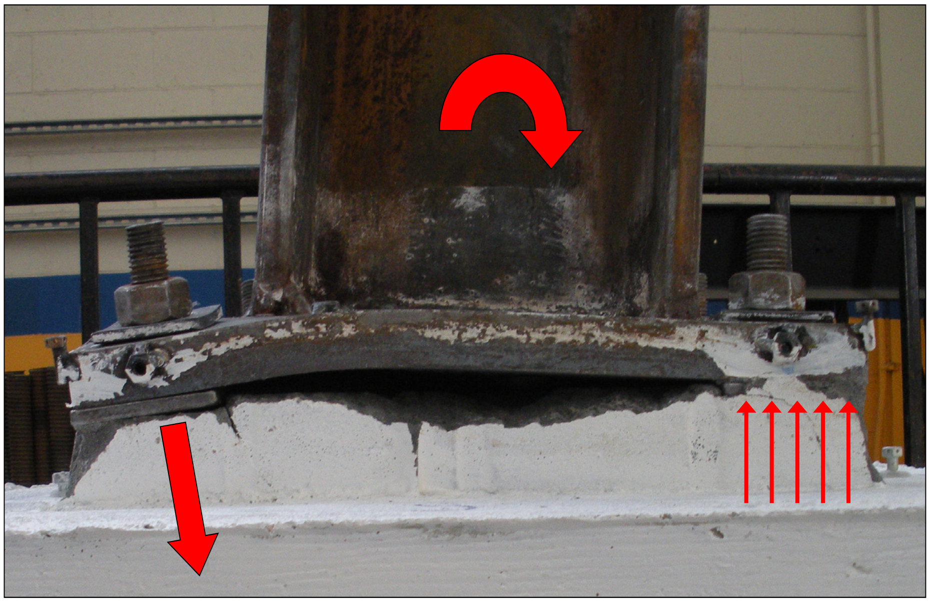

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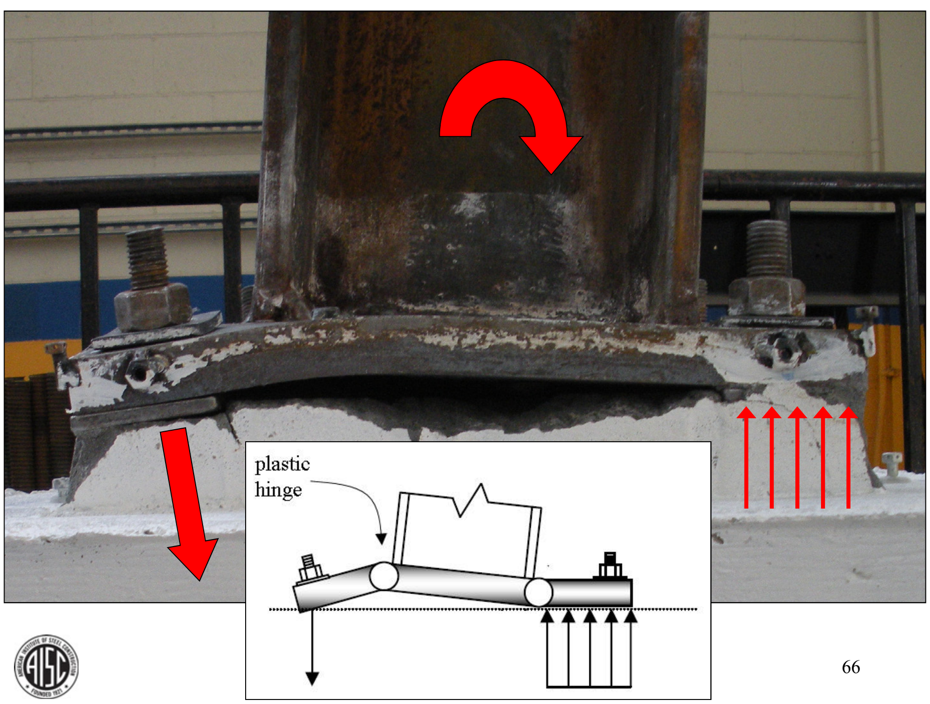

66

Rod yields

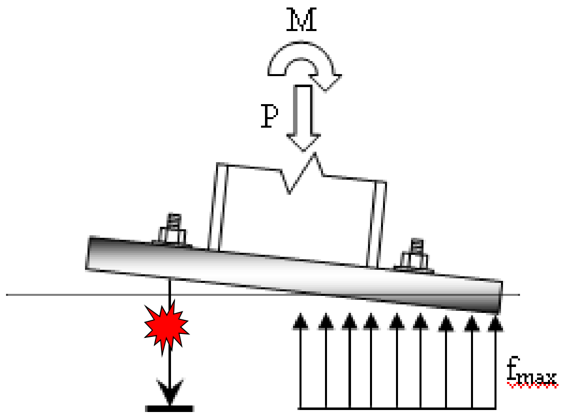

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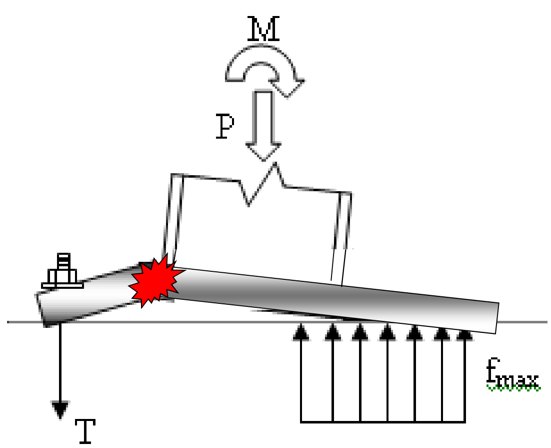
Plate yields on tension side



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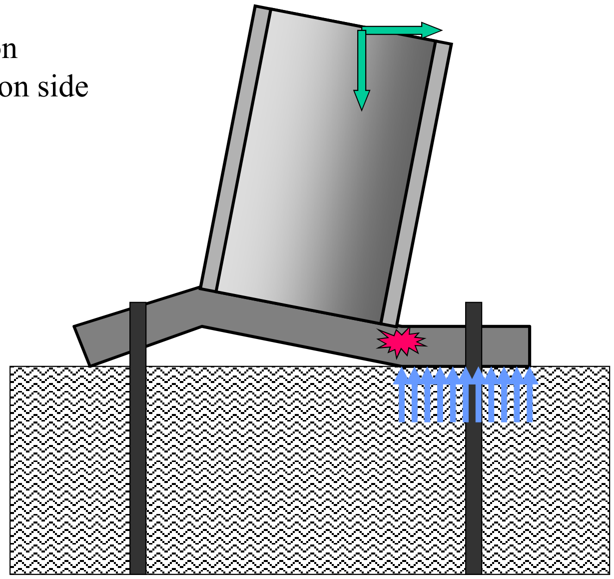
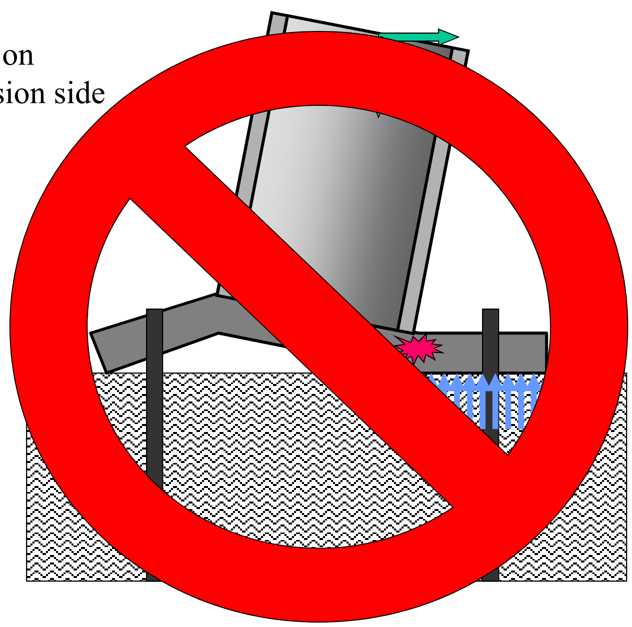
Yielding on
compression side



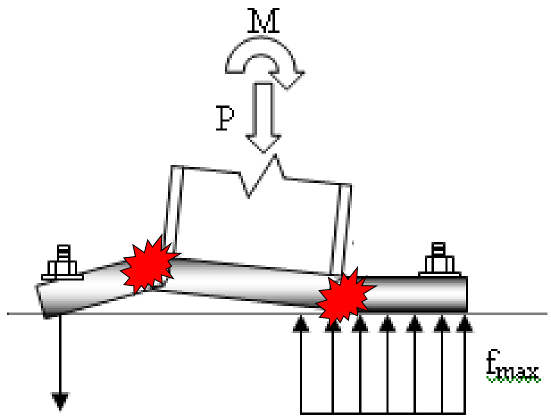
69

Yielding on
compression side



70

Plate yields on tension and compression side



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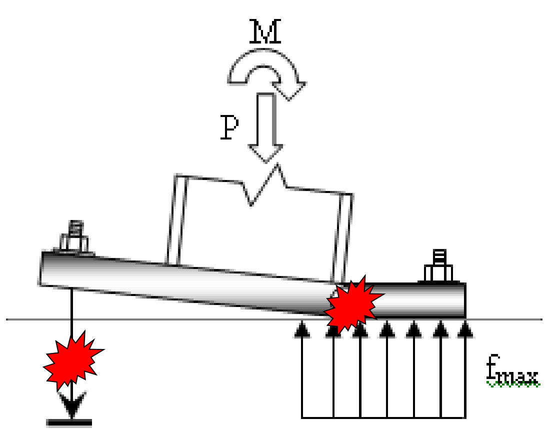
Rod yields + plate yields on compression side



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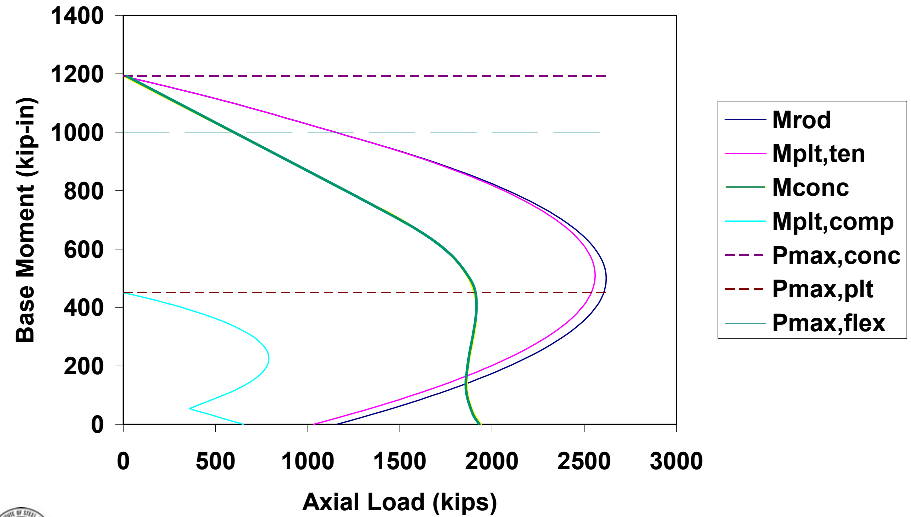
Base Plate Capacity - Moment-Axial Interaction



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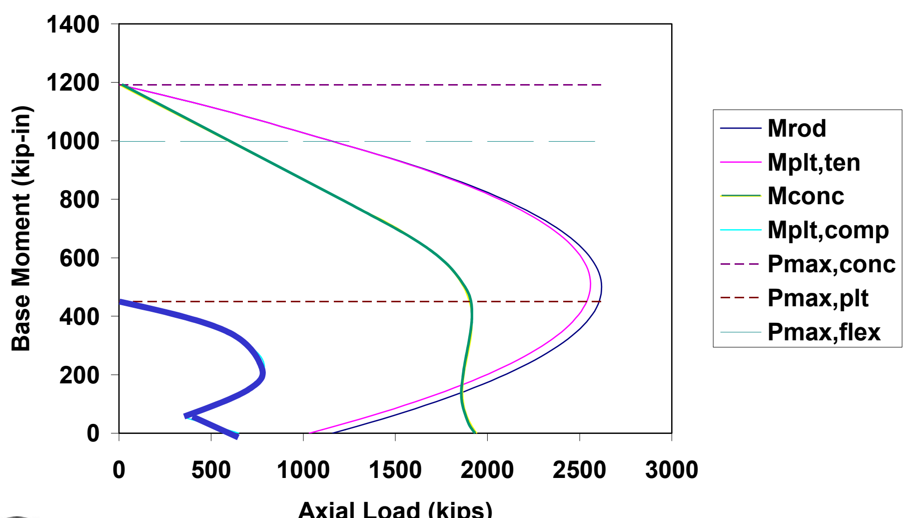
Base Plate Capacity - Moment-Axial Interaction



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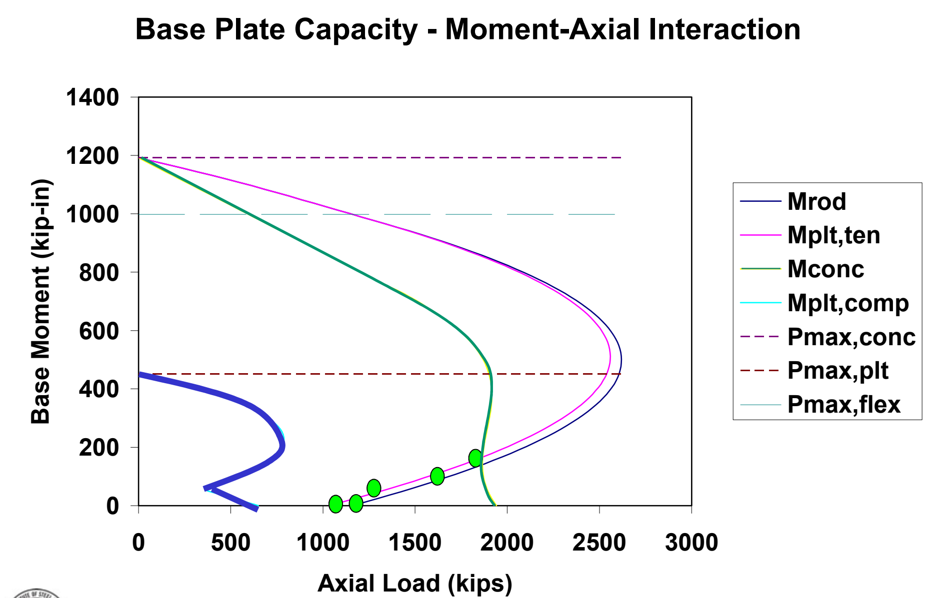
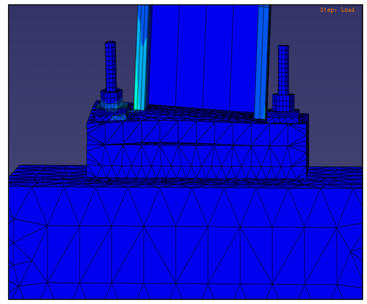


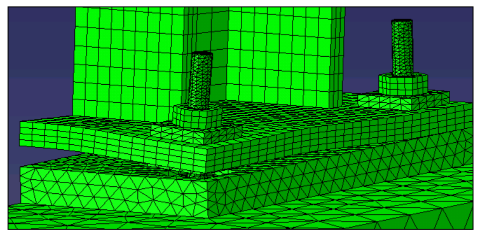
Results from Proposed Approach

Large scale test number	Average observed peak base moment (kip-in)	Predicted peak base moment (kip-in)	Predicted failure mechanism[1]	Test-to-predicted ratio
1	1,110	1,160	D	0.96
2	1,080	1,163	D	0.93
4	1,130	1,149	C	0.98
5	1,570	1,438	A	1.09
6	1,645	1,700	C	0.97
7	1,785	1,756	A	1.02
			Mean =	0.99
			COV =	0.057

Average Test-Predicted ratio from current approach = 1.86 76

FEM Simulations





Key findings from simulations

- Enormously challenging to model base connections

- Stress distributions are accurate, strength governed by mechanism

- The findings of the study are fairly general, and can be extended to larger column sizes

- Biaxial loading of the connection may be an important issue

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Summary –

1. Existing approach may be highly conservative, since it does not rely on the development of mechanisms
2. However, assumptions within the approach (e.g. RSB) are fairly accurate
3. Consideration of inclined yield lines is important

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Summary (continued)

3. Extraordinary deformation capacity in the connections we tested

   - Raises issues regarding design philosophy, including design moments

4. Finite element simulations corroborate the proposed approach for tested and larger specimens

   - Concerns about biaxial bending

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Implementation –

Incorporation into AISC Design Guide 1

Already in commentary of 2010 Seismic Provisions www.aisc.org/2010SP

2010 AISC Steel Specifications

Future/Ongoing Research –

Building performance, design forces, philosophy

Stiffness models

Embedded columns

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Ongoing Research

Seismic Performance of Embedded Column Connections

and

Tensile Capacity of Anchor Bolt Groups

CHARLES PANKOW FOUNDATION

Building Innovation through Research

STRUCTURAL ENGINEERS ASSOCIATION CALIFORNIA

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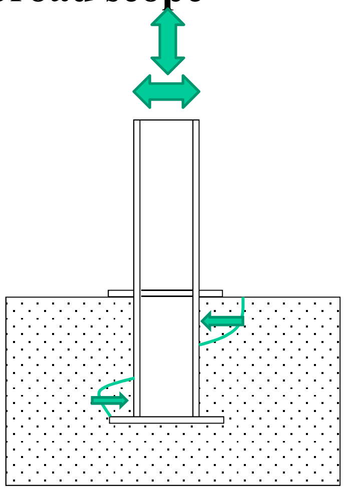
Part 1 – Embedded bases; motivation and broad scope



5-6 tests on embedded columns to resist moment

- Difficult to transfer moment through anchor rods
- Fixed bases use commonly for mid to high rises
- Fixing bases reduces drift, tonnage of steel
- Very limited (if any) large scale test data

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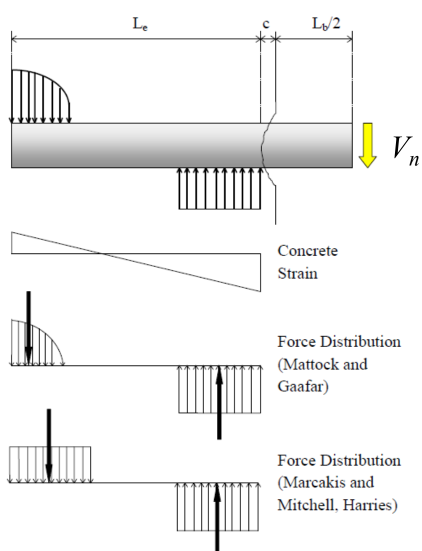
American Institute of Steel Construction (AISC)

- AISC Seismic Provisions for steel brackets connecting concrete shear walls
- Based on small scale models
- Minimum Reinforcement
- Concrete confinement based on thickness of shear wall
- Based on Mattock and Gaafar (1981), Marcakis and Mitchell (1980), Harries et al (1997)



$$V_n = 0.85 f'_c \beta_1 b \ell_e \left(\frac{0.58 - 0.22\beta_1}{0.88 + a/\ell_e} \right)$$

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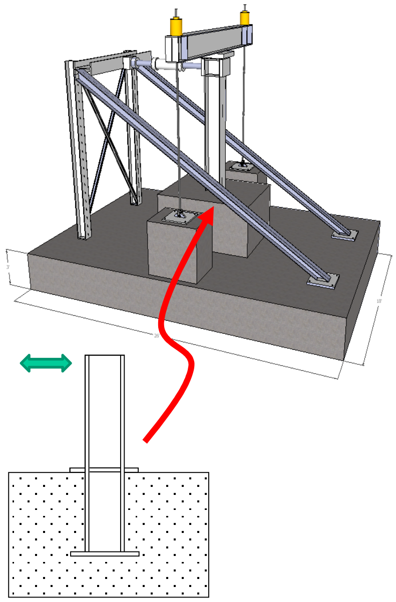
Overview/Objectives (Embedded base)



1. Develop fundamental understanding of the force transfer mechanisms

2. To demonstrate the strength, stiffness and ductility and damage states

3. To develop equations for strength, design methods

4. To develop design aids, examples, software and other tools

5. To inform building codes, standards and specifications

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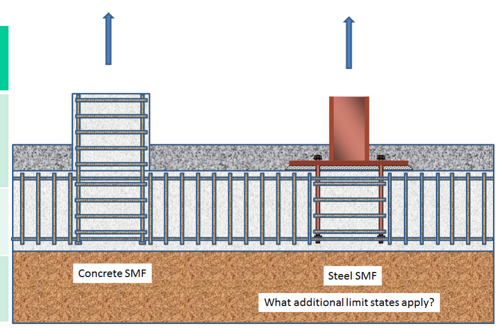
Part 2 – Anchorages to concrete; motivation and broad scope

ACI-318 Provisions	Concrete Tensile Capacity	
	$L_{anchorage}$ = 12”	$L_{anchorage}$ = 24”
Anchor Breakout	184k	328k
Punching Shear	389k	1069k



1. Dichotomy between Appendix D (anchor breakout) and rebars
2. Use of alternate details to circumvent Appendix D
3. Appropriate strength calculation method

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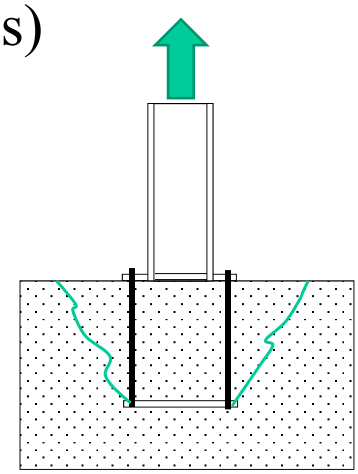
Ref R. Sabelli

Objectives (Anchorages)

1. Develop understanding of force transfer mechanisms in anchor group details subjected to tension uplift
2. Develop design provisions for these details that are otherwise specifically excluded from ACI 318-08 Appendix D.
3. Develop qualified details



2-3 Tests on anchorages under tension

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American Concrete Institute (ACI-318)

- ACI-318 provisions used for tensile strength estimates

$$\phi N_{cbg} = \phi\psi_3 16\sqrt{f'_c}\, h_{ef}^{\,5/3}\frac{A_N}{A_{No}} \quad \text{for } h_{ef} \ge 11 \text{ in.}$$

where

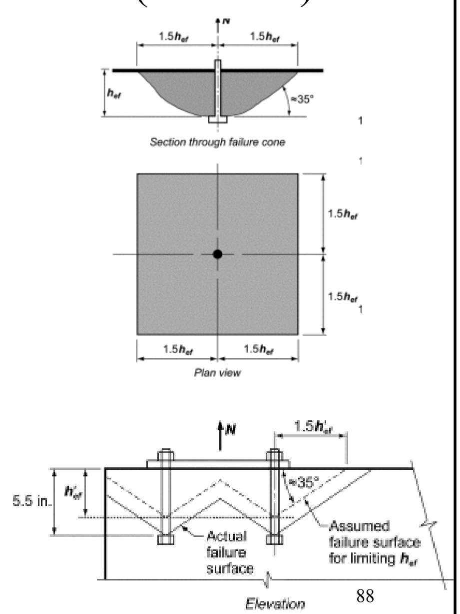
ϕ = 0.70

ψ_3 = 1.25 considering the concrete to be uncracked at service loads, otherwise =1.0

h_{ef} = depth of embedment, in.

A_N = concrete breakout cone area for group

A_{No} = concrete breakout cone area for single anchor



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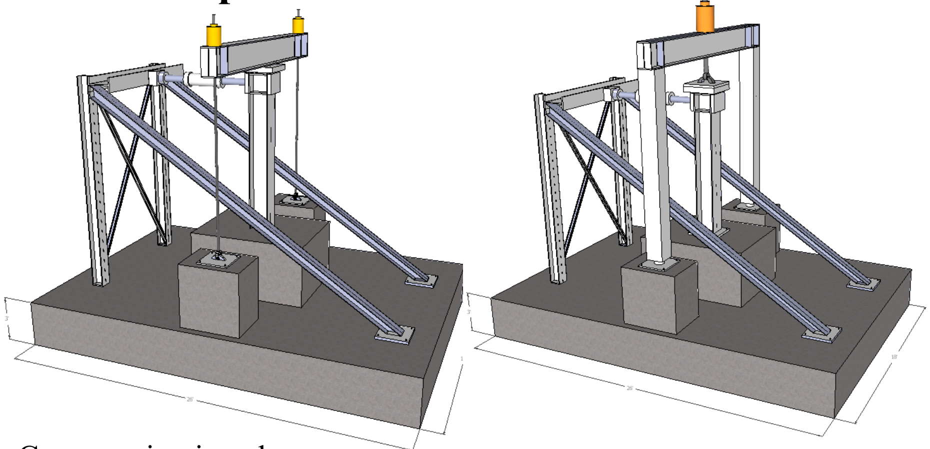
Test Setup



Compression in column

Tension in column

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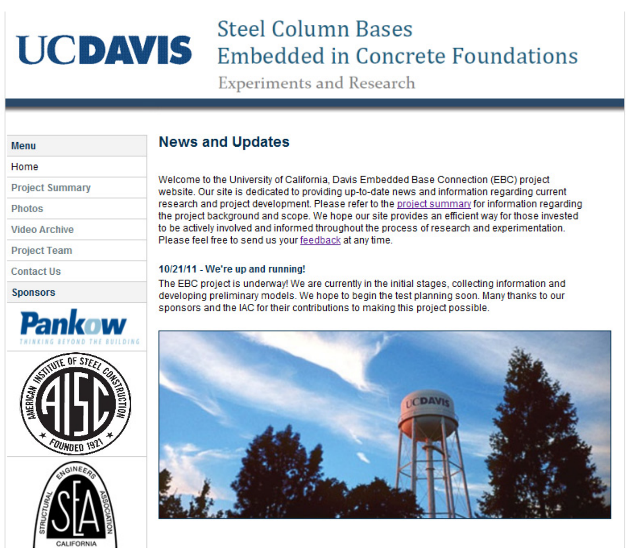
Website
http://columnbases.engr.ucdavis.edu



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There's always a solution in steel.

Thank you!

structural STEEL

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- OR…

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