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

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Acknowledgments

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Column base connections

- Used in all buildings
- Used in many contexts
- Wide range of details
Used in all buildings
Used in all buildings

Photo credit: Rick Drake (2003)
Column base connections

- Used in all buildings
- Used in many contexts
- Wide range of details
Diversity in details
Always at steel/concrete interface
Column base connections

- Used in all buildings
- Used in many contexts
- Wide range of details
Interesting in many contexts

- Static loads
- Seismic loads
- Interactions with frame
Interesting in many contexts

- Static loads
- Seismic loads
- Interactions with frame
Interesting in many contexts

- Static loads

- Seismic loads

- Interactions with frame
Interesting in many contexts

- Static loads
- Seismic loads
- Interactions with frame
Interesting in many contexts

• Static loads

• Seismic loads

• Interactions with frame
Challenging to navigate

- Static loads
- Seismic loads
- Interactions with frame
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

October 1, 2005
Timeline and scope

2005 - 2006

2nd Ed

3rd Ed

2024 - ish
Timeline and scope

2nd Ed

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

2005 - 2006

New developments

3rd Ed

2024 - ish
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 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

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
State of the art– Exposed base plate connections
Design Guide One

Focusing on one configuration
Design Guide One

Column

Footing
Design Guide One

Column

Base plate

Footing
Design Guide One

- Column
- Grout
- Base plate
- Footing
Design Guide One

Column

Grout

Base plate

Footing
Design Guide One

Uniaxial bending with axial compression

Two rows of anchors resisting bending
Design Guide One

Uniaxial bending with axial compression

Two rows of anchors resisting bending
The mechanics

Simple in principle
The mechanics

Simple in principle

• Bearing in footing
The mechanics

Simple in principle

- Bearing in footing
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
The mechanics

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

• Multiple distributions satisfy equilibrium

• True distributions depend on interplay of plate, rod, and flexibility and nonlinearity

• Determining these is non-trivial
Culmination and integration of work by researchers

- DeWolf and Sarisley (1978, 80, 82)
- Thambiratnam and 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
  \[ \phi \cdot f_{bearing} \quad (\phi = 0.65) \]

- 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)
STEP 2 – Given Y and T, evaluate limit states

• Base plate yielding on compression side

\[ M_{\text{comp}} < \phi \cdot M_{\text{plate}} \]
STEP 2 – Given Y and T, evaluate limit states

- Base plate yielding on compression side

\[ M_{\text{comp}} < \phi \cdot M_{\text{plate}} (\phi = 0.9) \]
Design Guide One approach

STEP 2 – Given $Y$ and $T$, evaluate limit states

- Base plate yielding on compression side

$$M_{tens} < \phi \cdot M_{plate} (\phi = 0.9)$$
Design Guide One approach

STEP 2 – Given Y and T, evaluate limit states

• Base plate yielding on compression side

\[ M_{tens} < \phi \cdot M_{plate} (\phi = 0.9) \]

\[ \phi \cdot f_{bearing} \]
Design Guide One approach

STEP 2 – Given Y and T, evaluate limit states

- Yielding or failure of the anchors
  \[ T < \phi \cdot T_{rods} (\phi = 0.9) \]
STEP 2 – Given $Y$ and $T$, evaluate limit states

- Yielding or failure of the anchors

$$T < \phi \cdot T_{rod} (\phi = 0.9)$$
STEP 2 – Given Y and T, evaluate limit states

- Yielding or failure of the anchors
  \[ T < \phi \cdot T_{rod} (\phi = 0.9) \]
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

![Graph showing the relationship between observed and estimated moment capacities, with a linear trend line.](image-url)
Strength estimation based on Design Guide One

- Observed Moment Capacity (kip-in)
- Estimated Moment Capacity (kip-in)

Points on the graph:
- Orange circles: UCD (2010)
- Yellow circles: UCD (2014)
- Blue circles: UCD (2022)
- Gray triangles: UCSD (2016)
Strength estimation based on Design Guide One

![Graph showing observed versus estimated moment capacity](image)
Strength estimation based on Design Guide One

Conservative

Unconservative

- UCD (2010)
- UCD (2014)
- UCD (2022)
- UCSD (2016)
Strength estimation based on Design Guide One

Conservative

Unconservative

Observed Moment Capacity (kip-in)

Estimated Moment Capacity (kip-in)

UCD (2010)
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Strength estimation based on Design Guide One

Conservative

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Observed Moment Capacity (kip-in)

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UCD (2010)
UCD (2014)
UCD (2022)
UCSD (2016)
Strength estimation based on Design Guide One

Observed Moment Capacity (kip-in) vs. Estimated Moment Capacity (kip-in)

- UCD (2010)
- UCD (2014)
- UCD (2022)
- UCSD (2016)
Plate bending on compression side not consequential
Plate bending on compression side not consequential
Plate bending on compression side not consequential

- 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

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
Seismic considerations – exposed base plates
Seismic considerations - exposed base plates

Broad principles and philosophy

Design and detailing
Seismic considerations—exposed base plates

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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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.
Strong base design

- Direct application of Design Guide One
- Large rods, thick plate
Two ways to design seismic base connections

Weak base design using $\Omega_0$ loads

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:

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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%)
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 45% provides great performance
How to achieve weak base design?

Weak-base design is well within reach

Plan view

8-story frame

4-story frame

12-story frame

20-story frame

gravity loads

truss elements

bilinear hysteretic springs at RBS locations

P-Delta columns
two springs in series
Engineering such a connection

Which ductile mode to use?
Ductile base connections through rod elongation

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

Soules et al (2016)
Ductile base connections through rod elongation

Soules et al (2016)

- Good performance observed under high shaking
- Attributed to stretch length
Achieving ductility in base connections

Consensus around rod elongation vs base plate yielding
Achieving ductility in base connections

Consensus around rod elongation vs base plate yielding
Stretch length 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
The Upset Thread Detail

Milled down “upset” threads

- Enhance ductility
- Define yielding zone
The Upset Thread Detail

Milled down “upset” threads
- Enhance ductility
- Define yielding zone

Debonding tape
- Prevents rod catching
- Similar to BRB
The Upset Thread Detail

Milled down “upset” threads
- Enhance ductility
- Define yielding zone

Debonding tape
- Prevents rod catching
- Similar to BRB

Shear Key
- Protects rods from shear
Intended behavior
Intended behavior
Intended behavior
Intended behavior
Intended behavior
Intended behavior
Intended behavior
Schematic of detail
# Large scale tests and performance

<table>
<thead>
<tr>
<th>Test #</th>
<th>Base Plate size [in]</th>
<th>Anchor Grade</th>
<th>Anchor Dia [in]</th>
<th>Axial Load [kip]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30 x 30 x 2</td>
<td>55</td>
<td>0.75</td>
<td>120 (C)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
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<td>120 (C)</td>
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<tr>
<td>3</td>
<td></td>
<td>105</td>
<td>1.00</td>
<td>120 (C)</td>
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<tr>
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## Large scale tests and performance

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[Image of a large scale test setup]
### Large scale tests and performance

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ATCSAC 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

\[ L_{\text{stretch}} > 0.5 \times L_{\text{plate}} \]

\[ L_{\text{stretch}} < 0.5 \times L_{\text{plate}} \]
Parametric Simulation - findings

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

\[ L_{\text{stretch}} > 0.5 \times L_{\text{plate}} \]

\[ L_{\text{stretch}} < 0.5 \times L_{\text{plate}} \]
NLTHA Results and summary

Use validated method to examine failure
Use validated method to examine failure

- Upset Thread detail with $L_{stretch} > 0.5 \times L_{plate}$
- Design for $\Omega_0$ or even lower forces

Excellent performance
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

- Prevaling understanding and design methods

New Developments

Developing column capacity is challenging

Photo credit: Josh Buckholt and Mahmoud Maamouri, CSD Engineers
Part 2 – Embedded Base Connections

Embedded Bases

- Prevaling understanding and design methods
- New Developments

Resistance through concrete bearing
Part 2 – Embedded Base Connections

Resistance through concrete bearing

Photo credit: Nabih Youssef, Simpson Gumpertz and Heger
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.
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
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
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

![Diagram showing coupling beam approach applied to test data](image-url)

- **Generic Detail (No Reinforcement)**
- **w/ Horizontal Reinforcement (No Stirrups)**
- **w/ Horizontal Reinforcement (w/ Stirrups)**

The graph illustrates the comparison between test data ($M_{\text{Test}}$) and predicted data ($M_{\text{Pred}}$) normalized by $d_{\text{embed}}/d_{\text{col}}$. The AISC SDM Method is highlighted in the plot.
Embedded base connections are NOT coupling beams
Embedded base connections are NOT coupling beams

- Effect of axial force
- Additional confinement around column flanges
- Fixity and strength due to vertical bearing
Embedded base connections are NOT coupling beams

- Effect of axial force
- Additional confinement around column flanges
- Fixity and strength due to vertical bearing
Embedded base connections are NOT coupling beams

- Effect of axial force
- Additional confinement around column flanges
- 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
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

![Graph showing the comparison between different models and their ratio of test-to-predicted moments. The graph includes data points for generic details with and without reinforcement, and with or without stirrups. The proposed model is indicated by a dashed line.](image)
Rotational stiffness of embedded bases

![Graph showing rotational stiffness](image-url)
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
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

Uncertain component demands

$P_u, M_u$

$M < \phi M_{plate}$

$T < \phi T_{rod}$

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

Blockout connections and overtopping slab
Blockout connections and overtopping slab
Blockout connections and overtopping slab

Work done at BYU (Paul Richards) and UC Davis
Potential proposals

A look to the future

“Resolved” issues

Ongoing work

Unresolved issues

• New (3rd) Edition of Design Guide One (~2024) – in progress

• AISC 341 – Next code cycle

• Seismic Design Manual
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

“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

Still an exciting area with many opportunities

A look to the future

“Resolved” issues

• Resilience and remaining life

• Design to minimize damage

• Design for repair

Ongoing work

Unresolved issues
Thank you!

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