Suitability of Steel Hollow Sections for Seismic Design with Solutions for Connections

Santiago, Chile, May 27, 2014

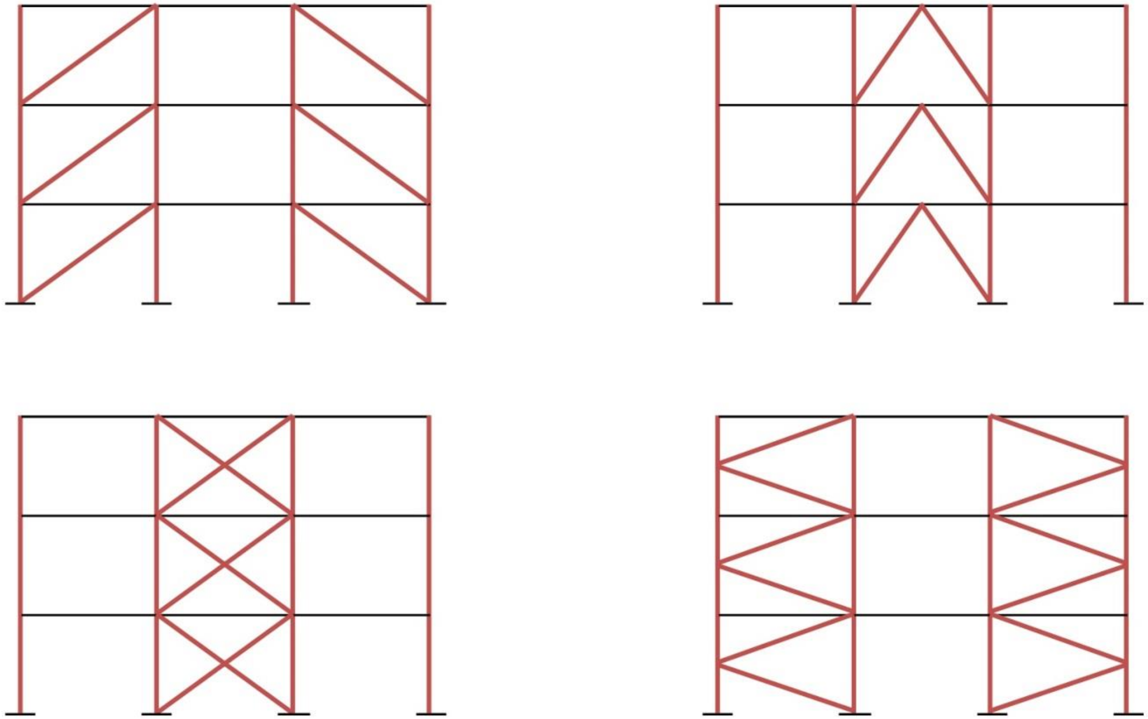
Professor Jeff Packer

Department of Civil Engineering, University of Toronto, Canada

VELUT ARBOR ÆVO

Braced Frames or Moment-Resisting Frames?

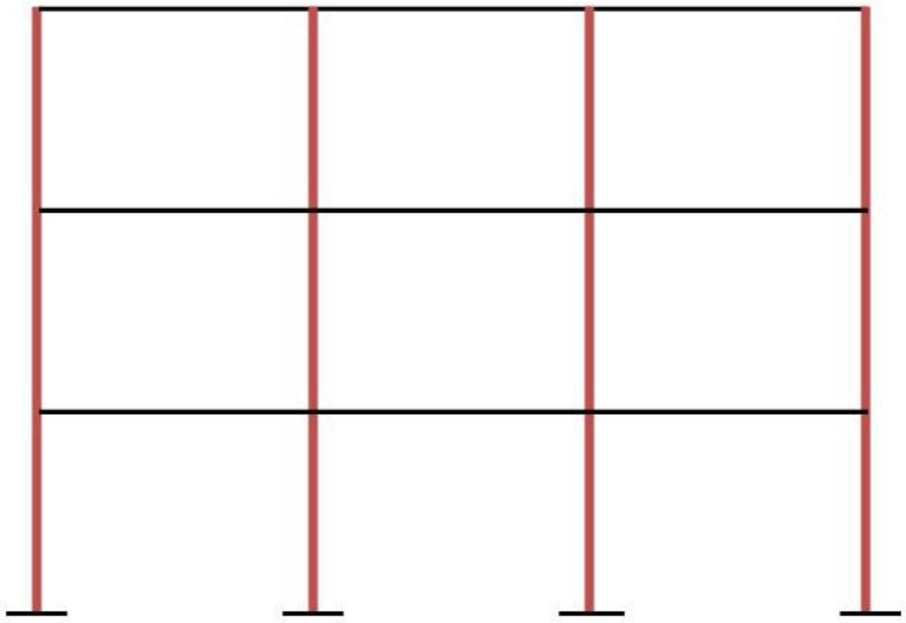
- **Braced steel frames have become increasingly popular as a seismic lateral force-resisting mechanism in North America, since the Northridge (California) and Kobe (Japan) earthquakes of the 1990s.**



Hollow sections are ideal for the Columns and the Bracings

Braced Frames or Moment-Resisting Frames?

- **Moment frames are ideal for offering bays without diagonal members. Detailing techniques have overcome any brittle fracture problems**



- **Less stiff than braced frames**
- **Generally more costly and more complex connections than braced frames**
- **Very popular in Japan**

Hollow sections are ideal for the Columns

Hollow Sections in use in Santiago, Chile

Cold-Formed Hollow Sections for Columns

- **Square or Circular Hollow Section columns:**
  - → **Ideal for *all* compression members. They have no weak axis for overall (flexural) buckling, unlike open sections**
  - → **Are torsionally stiff, unlike open sections**
  - → **Result in lighter sections (less weight) than open section columns**
  - → **Result in cheaper columns (despite cost per tonne of hollow sections > cost per tonne of I-sections)**
  - → **Result in lighter buildings: advantageous for seismic design; advantageous for foundation design; using less steel has sustainability benefits; etc.**
  - → **Hollow section columns can be easily concrete-filled: advantageous for composite strength design; advantageous for fire protection**
  - → **Hollow sections have less surface area than I-sections: advantageous for surface protection (painting, coating)**

Cold-Formed Hollow Sections for Columns

As an example, let us design the optimum (least mass) column – according to the Canadian steel design standard CSA S16-09 Clause 13.3 – which is very similar to all other international limit state steel design codes – and compare the best designs for hollow sections versus I-shape sections.

Effective Length (KL) = 5.0 metres; Factored axial compressive load = 450 kN

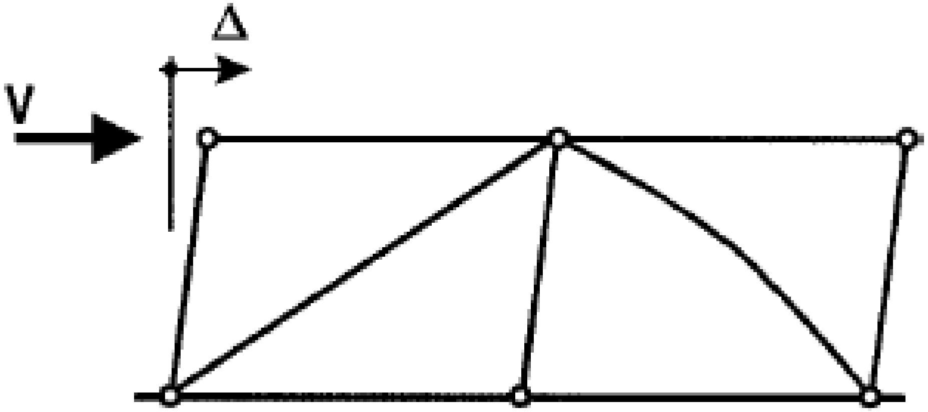
Column Type	I-section	Circular (CHS)	Square (SHS)
Member	W200x36	HSS168x6.4	HSS152x152x4.8
Material	ASTM A992 / A572 Gr. 50 F_y = 345 MPa	G40.21, 350W F_y = 350 MPa	G40.21, 350W F_y = 350 MPa
Compressive resistance C_r (kN)	452	514	463
Mass (kg/m)	35.6 (100%)	25.4 (71%)	21.7 (61%)
Surface area (m^2/m)	1.05 (100%)	0.529 (50%)	0.593 (56%)

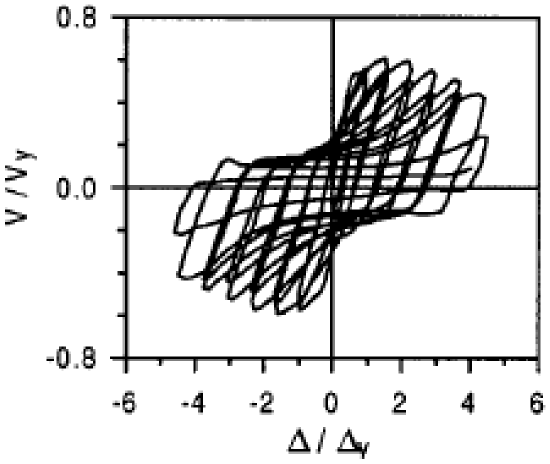
Cold-Formed Hollow Sections for Bracings

What hollow section is optimal for diagonal bracings?

- **For energy-absorbing, dissipative bracings in "seismic braced frames", circular hollow sections (CHS) are VERY popular.**

- **During an earthquake, bracing members *absorb* seismic energy input by cyclically yielding in tension and buckling in compression**

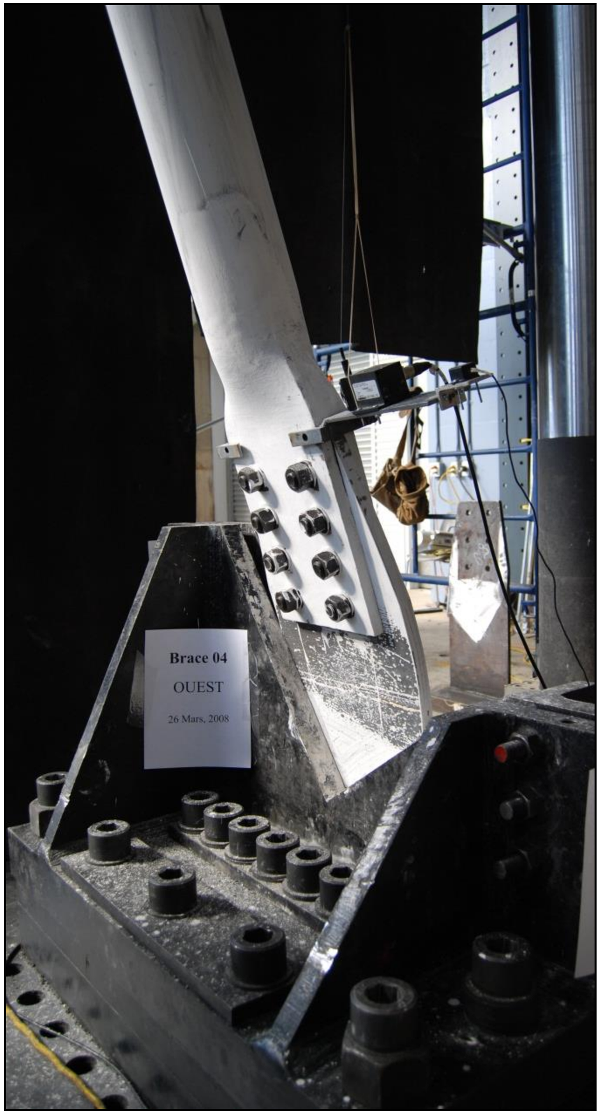




- **Specially-made Buckling Restrained Braces (BRBs) also available**

Cold-Formed CHS Bracings in Large-Scale Tests

Excellent Response demonstrated by laboratory testing in Canada

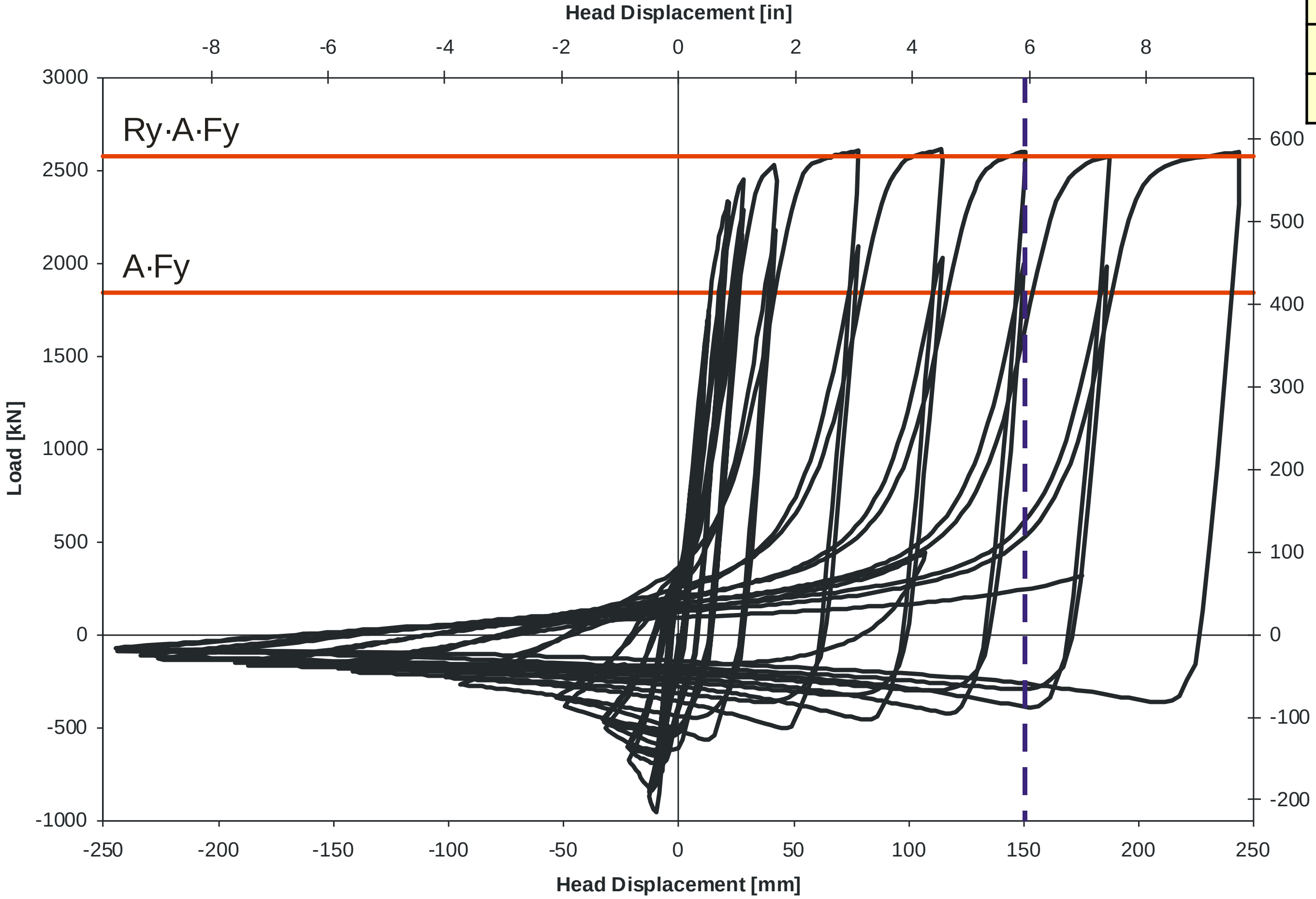


Cold-Formed CHS Bracings in Large-Scale Tests

Brace-Connector assemblies tested, using:
CHS 102 x 8.0, CHS 141 x 9.5, CHS 168 x 13, CHS 219 x 16

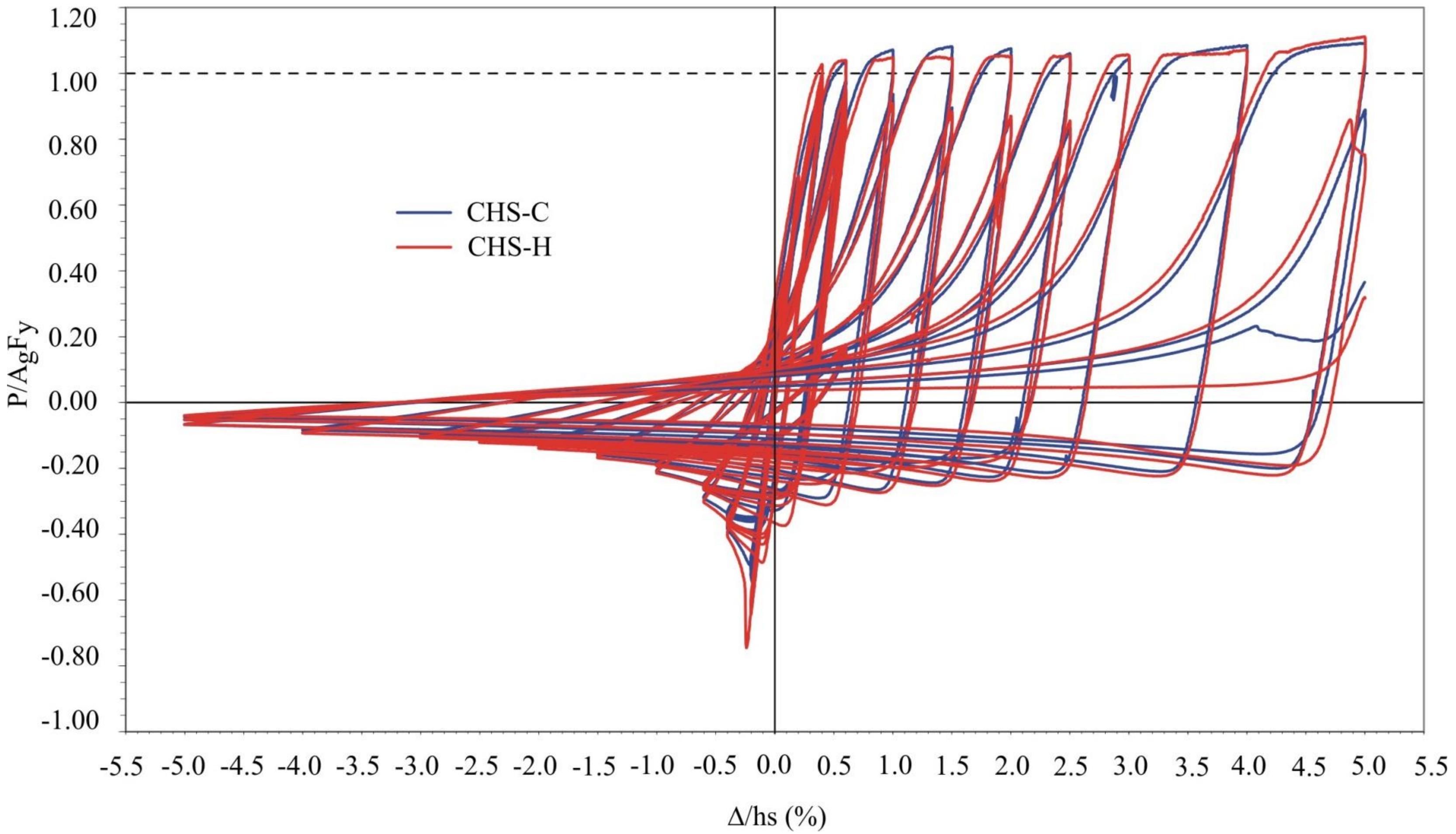
Brace Member	CHS 6.625x0.625 ASTM A500a Grade C Equivalent
Connectors	HSC-6.625
Gusset Plate	1“ (25 mm)
Unbraced Brace Length	20’-2” (6.150 m)
KL/r_{design}	111.0 (110.6)
D/t_{design}	14.25 (14.72)

CHS 168x13 with HSC-168



Stress-Relieve CHS Bracings? → Not worthwhile

Cold-formed versus (Cold-formed + stress-relieved) (D/t ≈ 14)



- **Extremely similar (non-dimensionalized) hysteretic response – stress-relieving just provides a higher <u>initial</u> buckling load**

CHS Bracing Cross-Section Slenderness

- ***Heat-treating a cold-formed brace is of no real benefit;*** ***the hysteretic response is very similar, brace failure occurs by cracking at brace mid-height, and both CF and CF+SR can reach the same inter-storey drift (~5%). This inter-storey drift exceeds the required 4% typically assumed for the "maximum considered earthquake" demand.***

- ***Tube D/t trumps material as the prime pre-requisite.*** ***Tubes must have a low D/t that satisfies the ANSI/AISC 341-10 seismic provisions ($D/t \leq 7600/F_y$).***

Failure Mode

Connections

Steel is generally "over-strength", relative to its nominal (design) strength, F_y, which means that energy-dissipating members – which must yield – impart very high forces on the connections.

Expected yield stress = $R_y\,F_y$
where R_y = 1.4 for all ASTM A500 hollow sections (ANSI/AISC 341-10 Table A3.1)

Expected ultimate tensile strength = $R_t\,F_u$
where R_t = 1.3 for all ASTM A500 hollow sections (ANSI/AISC 341-10 Table A3.1)

Thus, for example, bracing member end connections must resist a tension force of $A_g R_y F_y$ where A_g = member gross area.

Connections in Braced Frames

Special Concentrically Braced Frames (SCBFs)

– frames designed with detailing provisions to accommodate energy dissipation and inelasticity

– to accommodate brace buckling during the compression loading cycles the connections can be designed to be either:

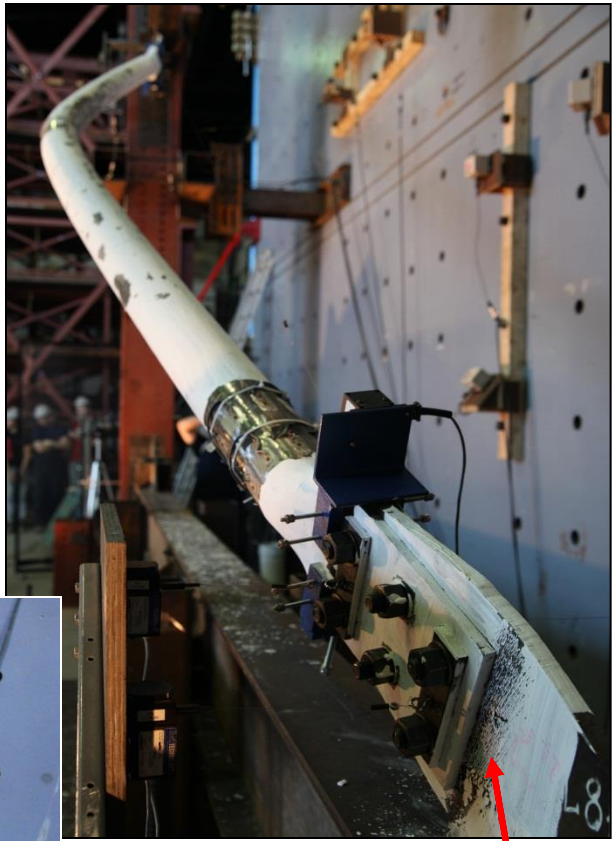
(a) strong and rigid enough to force all plastic hinges to occur in the bracing member, ***or***

(b) to have plastic hinges in the gusset plates (causing out-of-plane flexure of the gusset plates) at the bracing ends, and at mid-length of the bracing. ***Preferable method.*** **This is usually achieved by a clear gusset plate distance of $2t_p$ for a “fold line”.**

Connections in Braced Frames

Special Concentrically Braced Frames (SCBFs)

(b)



Plastic hinge

Further Validation by Brace Testing within a Full Frame

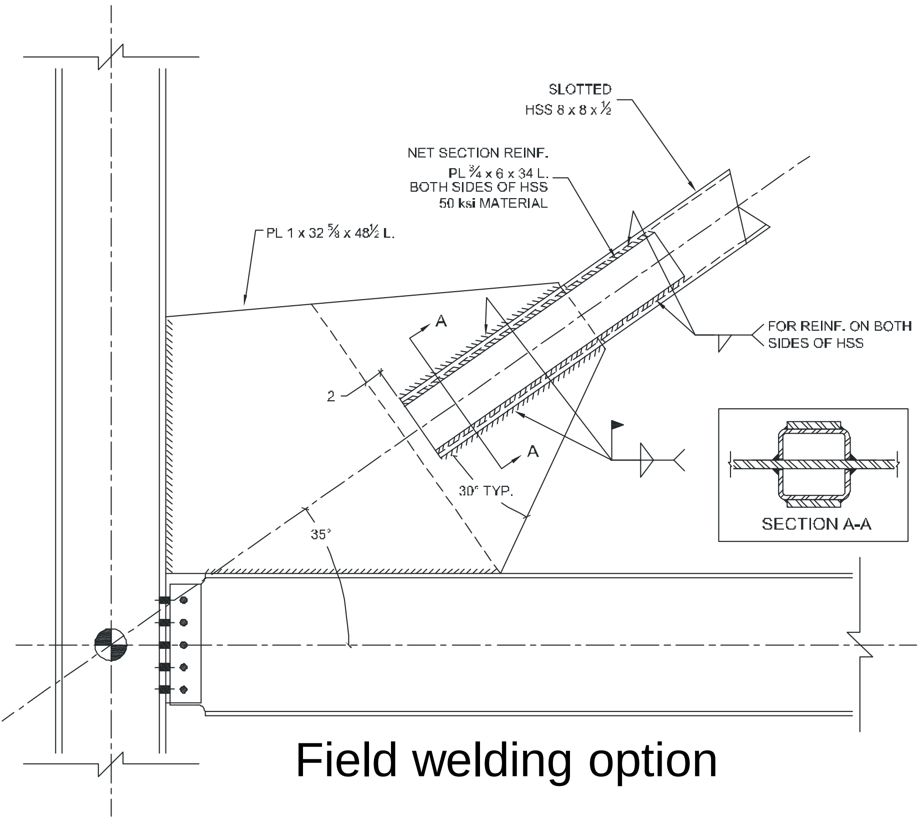
Fabricated Connections at Brace Ends

Special Concentrically Braced Frames (SCBFs)

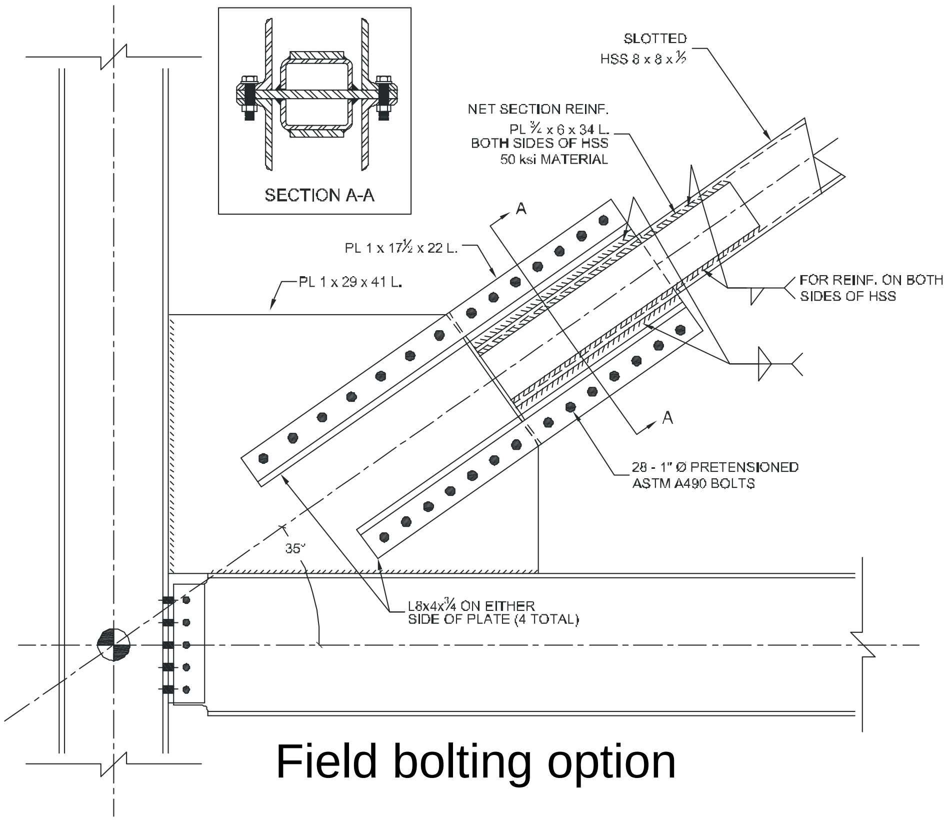
– *fabricated* bracing-to-gusset connections frequently require steel reinforcement, especially if some of the bracing cross-sectional area is removed at the connection, resulting in a net area $A_n < A_g$ (Recall that $A_g R_y F_y$ must be resisted in tension)

– these connections then:
- **require careful design**
- **require much, but easy, fabrication**
- **can be large**
- **are likely not aesthetic**
  (not ideal for Architecturally Exposed Structural Steel)

Fabricated Connections at Brace Ends



Field welding option



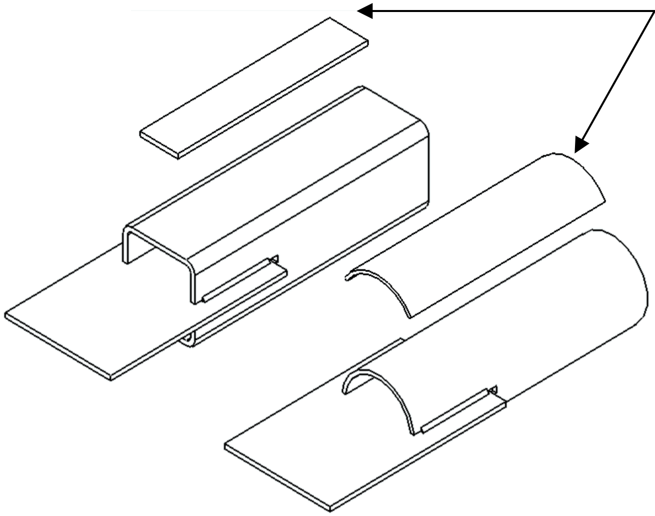
Field bolting option

Current Connection Details for Special Concentrically Braced Frames: with such connections the gusset plate is aligned with brace center-line

Fabricated Connections at Brace Ends

Special Concentrically Braced Frames (SCBFs)

Net Section Reinforcement

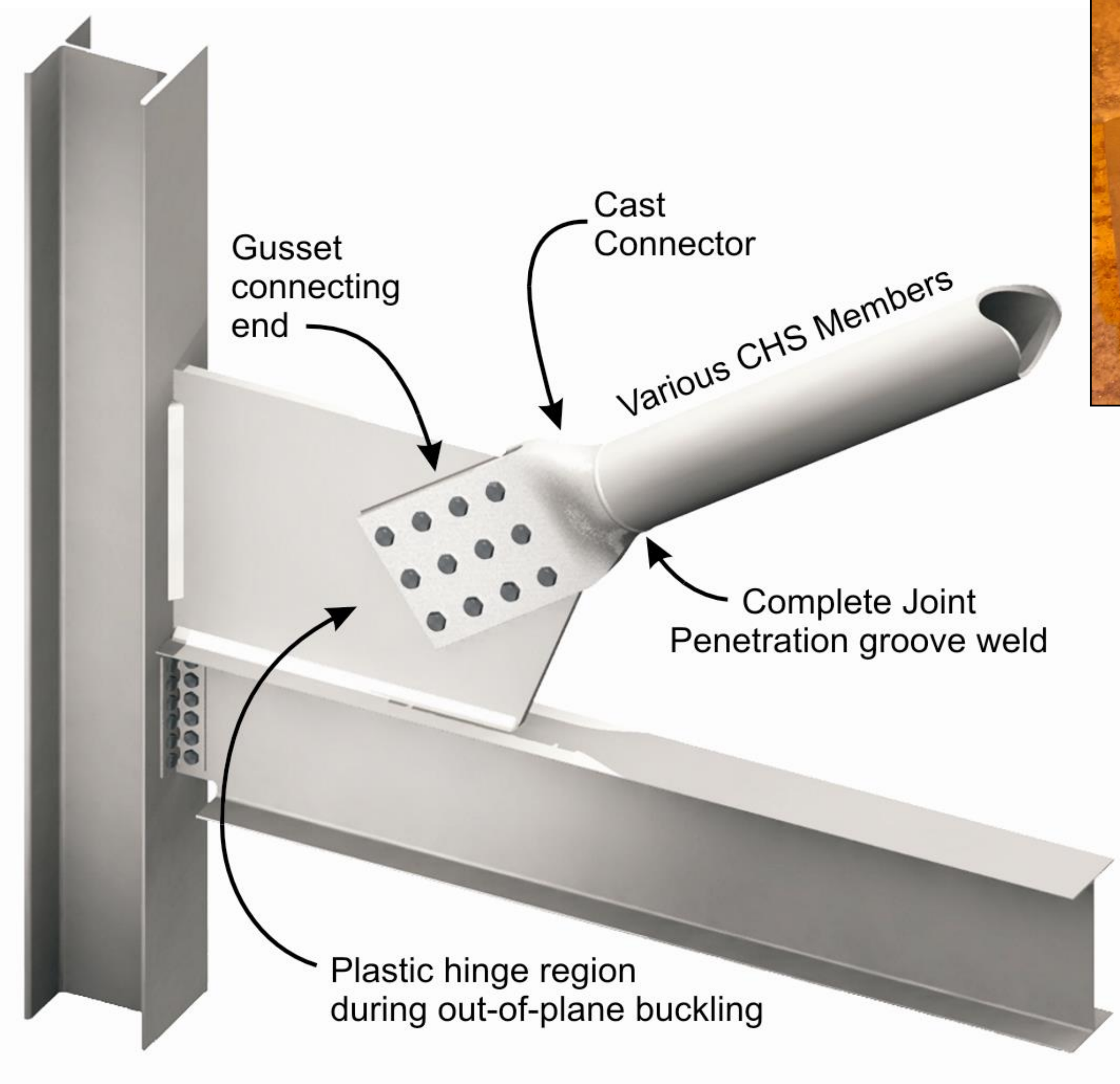


Net Section

Net Section Reinforcement plate

Example: Slotted-end hollow section connection

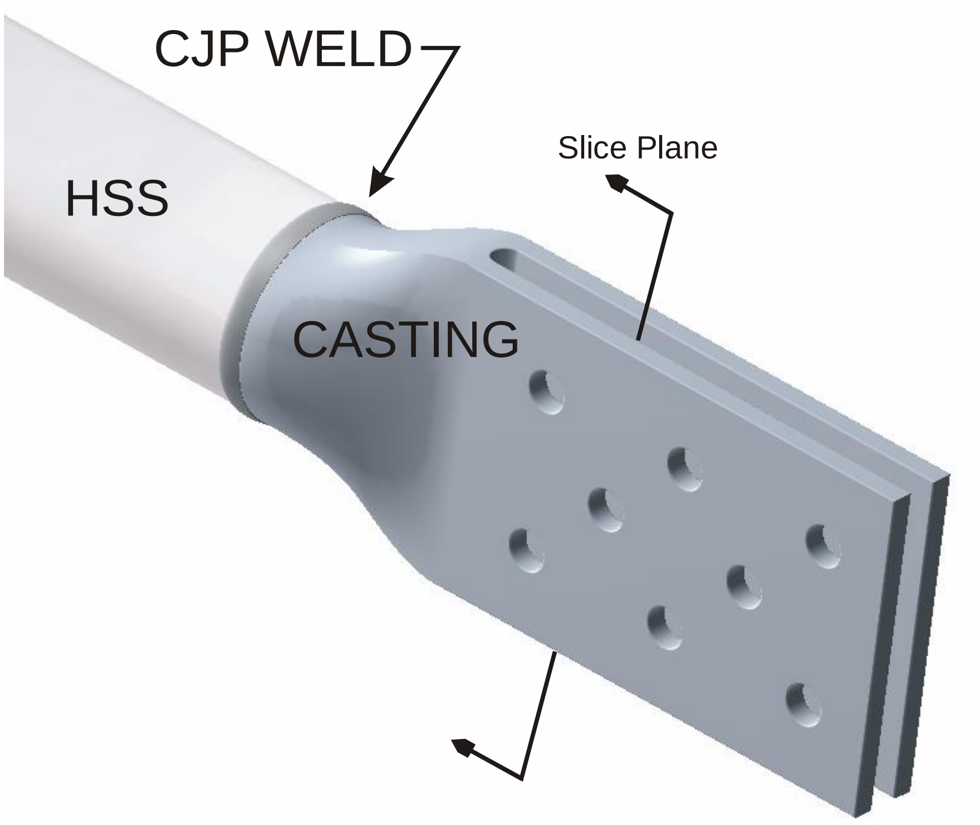
Proprietary Connectors at Brace Ends



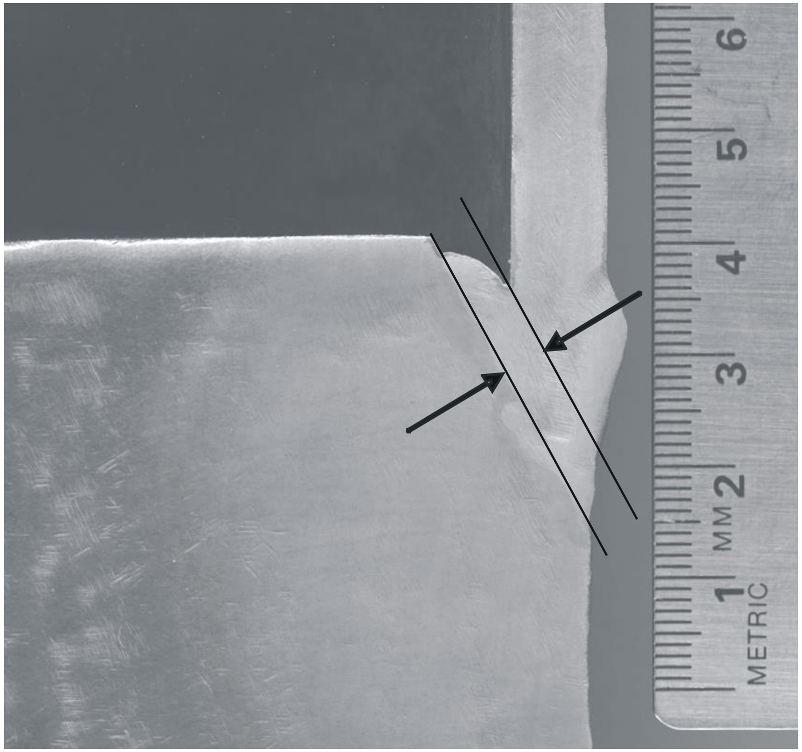
Standardized pre-engineered connectors, made from cast steel, are available off-the-shelf to fit into a tube of specific outside diameter, but variable wall thickness.

These connectors remain elastic under extreme seismic loading.

Cast Steel (Elastic) Connectors at Brace Ends



Complete Joint Penetration shop welding, while tube is rotated



Section cut through casting, tube and weld

CASTCONNEX®

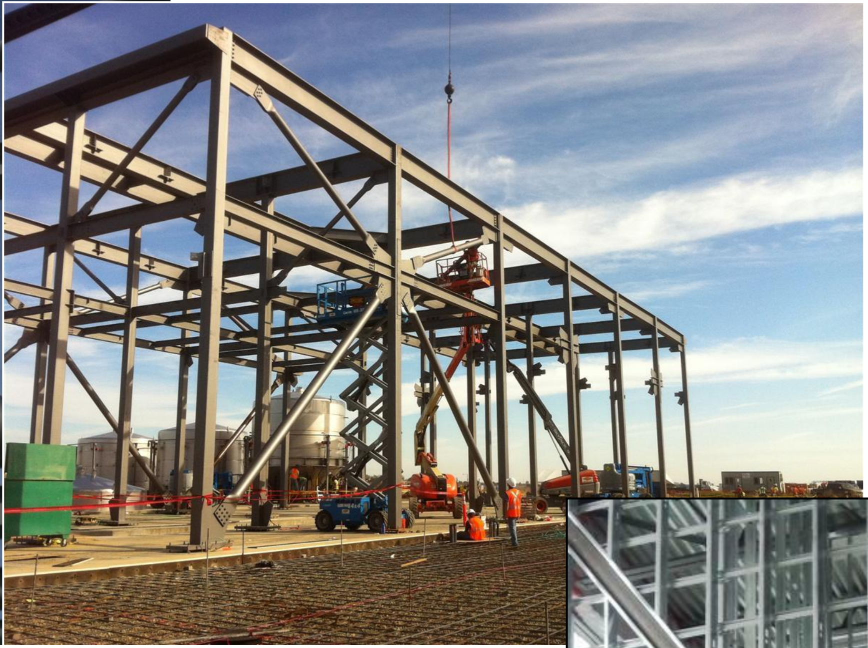
www.castconnex.com

Casting nose protrudes into the tube, providing weld backing

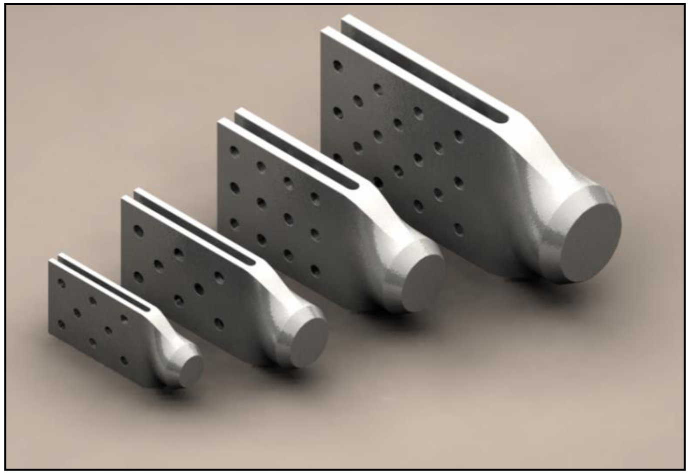
Connectors fully tested and patented

Cast Steel (Elastic) Connectors at Brace Ends

Gallo Winery, California, 2011



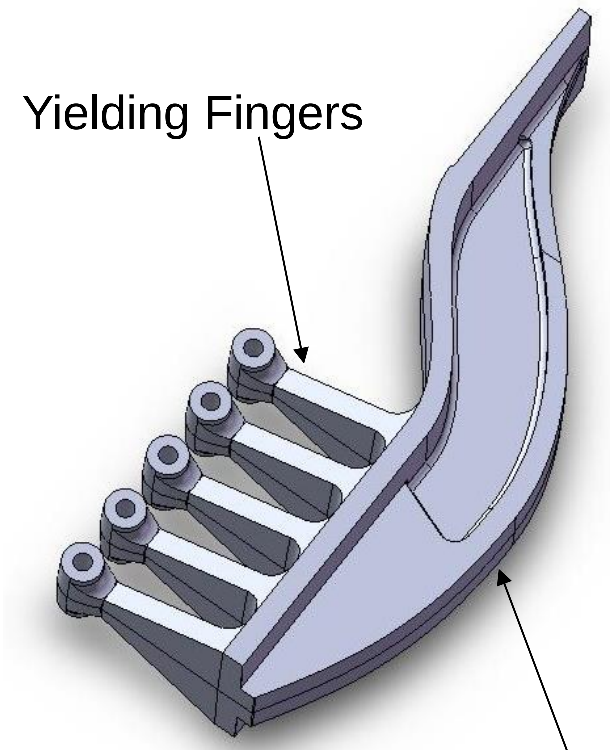
Pre-engineered, off-the-shelf, High Strength Connectors (HSCs) for seismic-resistant, braced steel frames



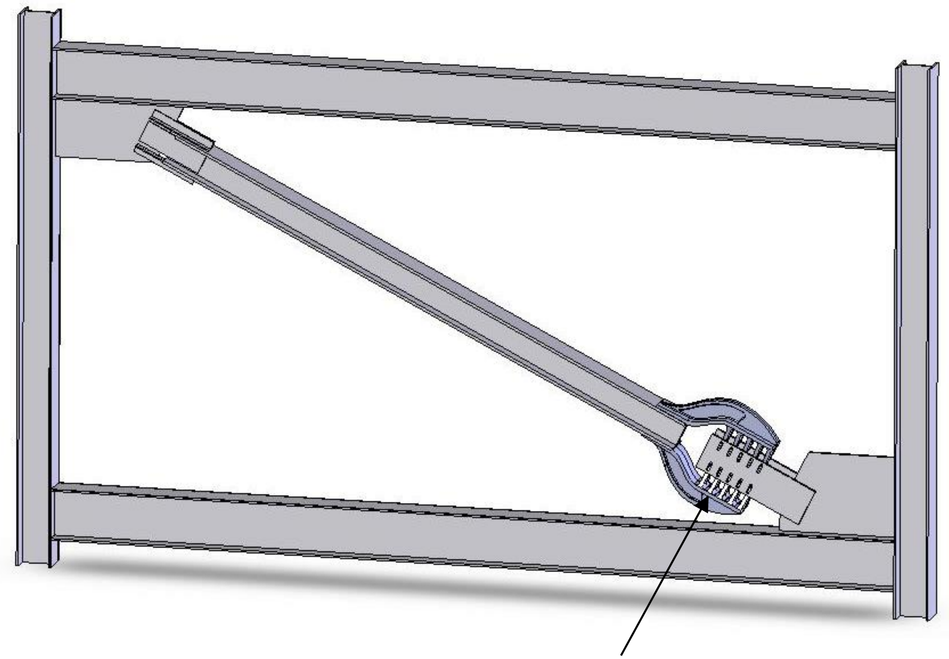
CASTCONNEX®

www.castconnex.com

Cast Steel Yielding Connector at Brace End



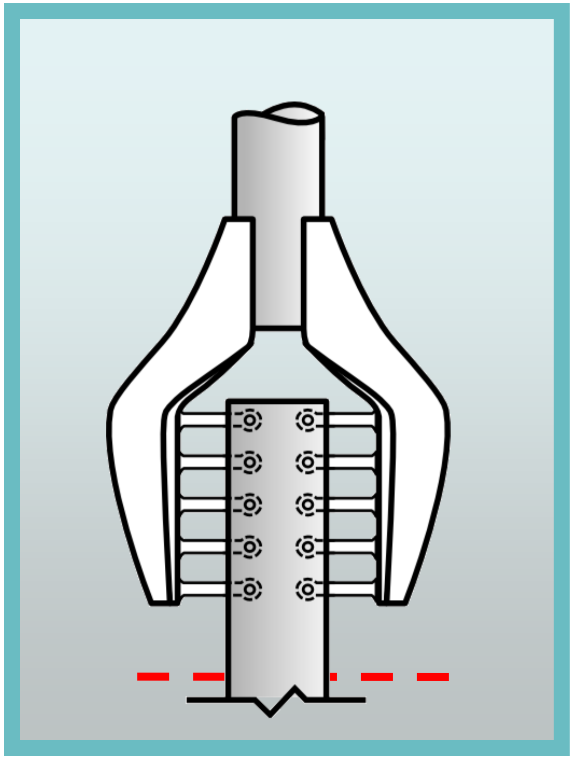
Cast Steel Yielding Fuse (CSF) Concept



Cast Steel Yielding Fuse at only one end absorbs all seismic energy – the brace can be any structural shape (square hollow section is ideal) and remains elastic

CASTCONNEX®

Cast Steel Yielding Connector at Brace End



Cast Steel Yielding Fuse (CSF) Concept

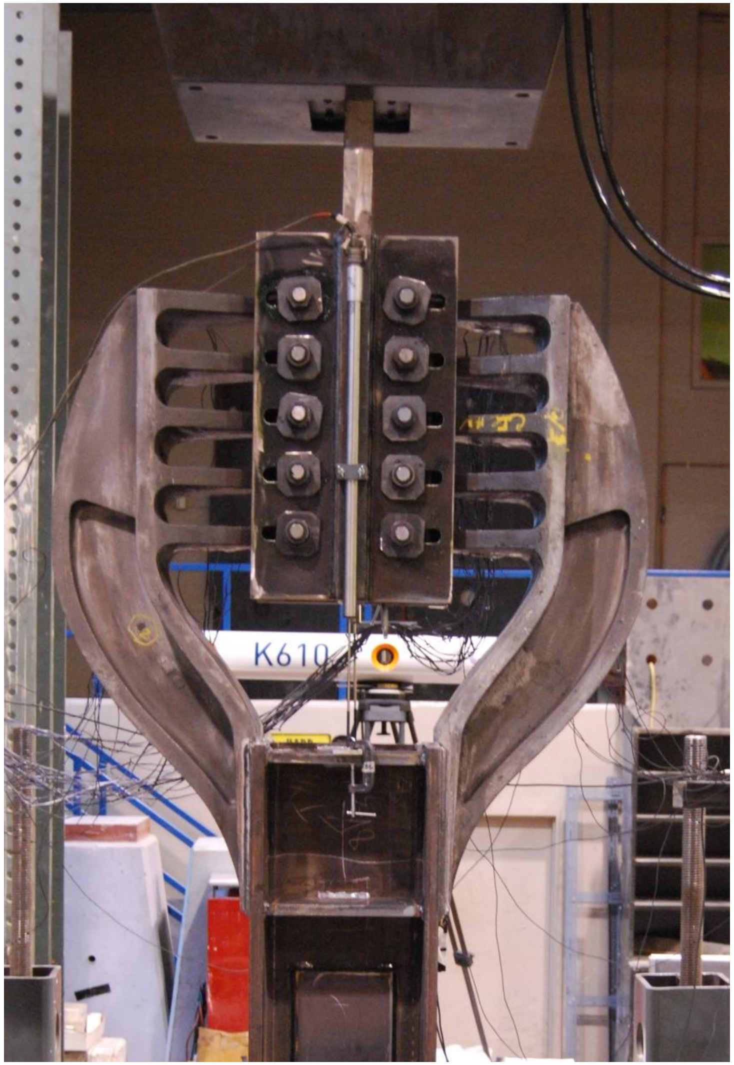
Yielding Fingers:

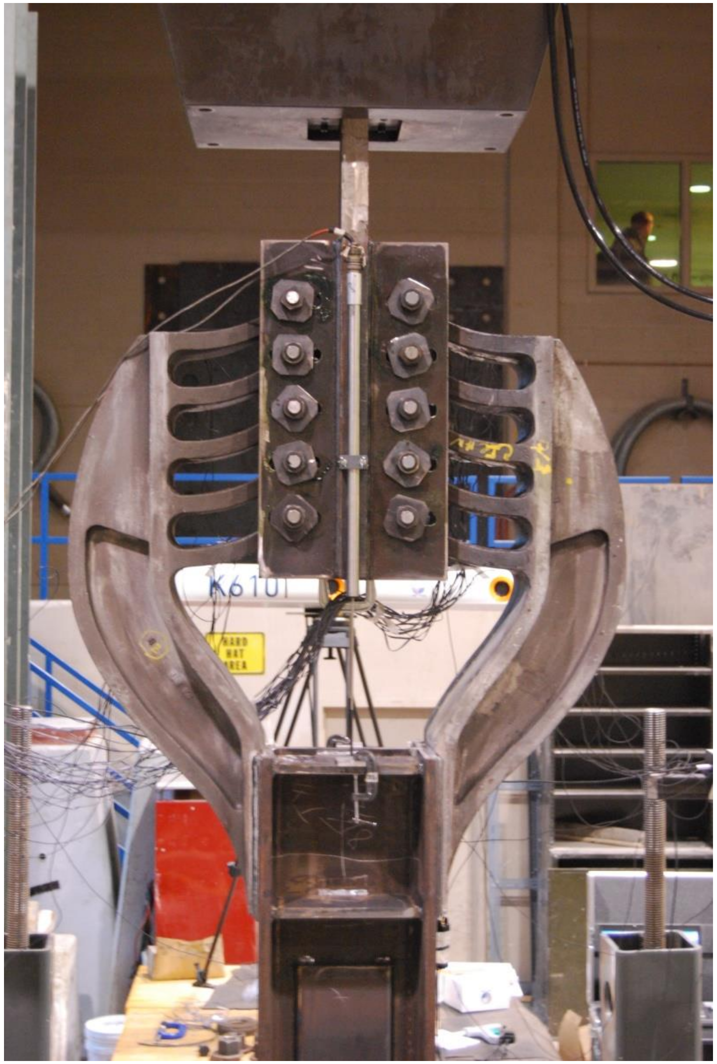
- **Triangular in plan to provide constant curvature/strain**
- **Slotted end detail reduces the axial forces that develop in the fingers due to P-Δ effects**
- **Similar in concept to the fabricated ADAS and TADAS devices but pre-engineered**

CASTCONNEX®

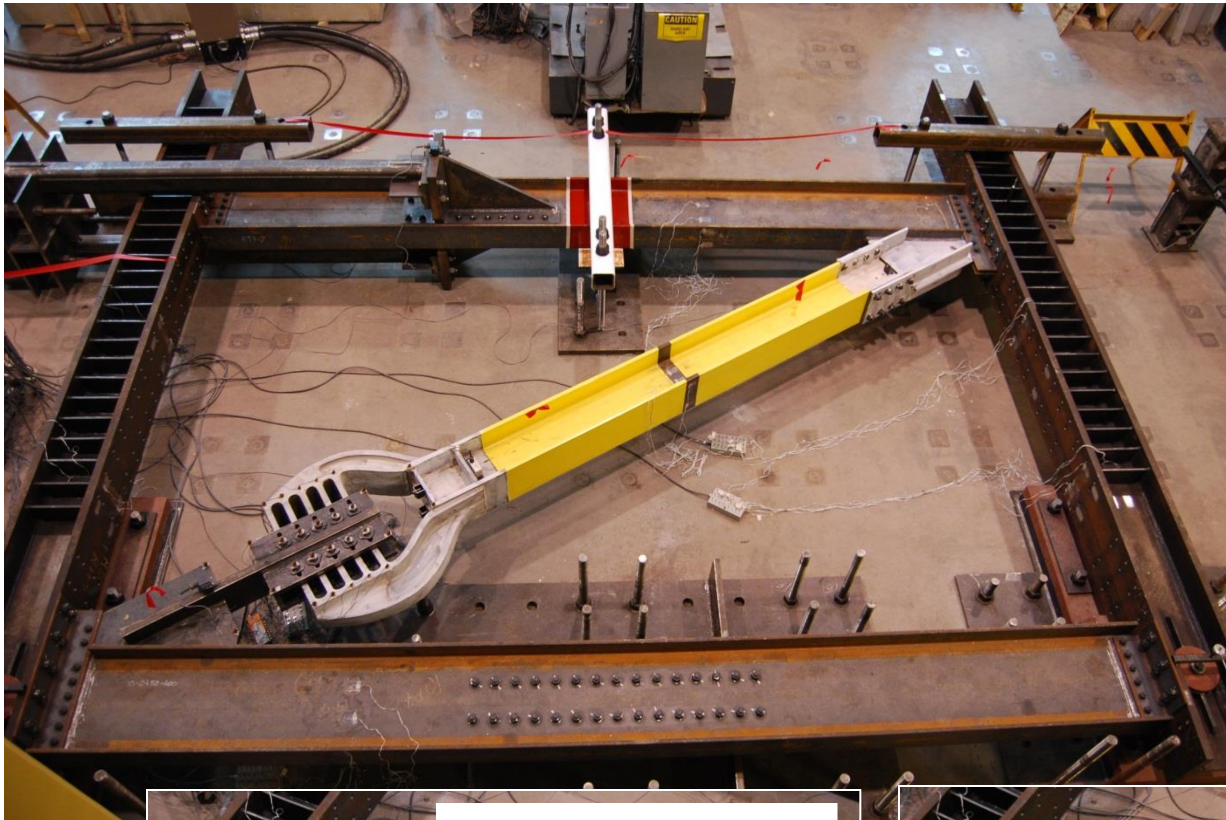
Cast Steel Yielding Connector at Brace End

Laboratory validation: Deformations under inelastic cyclic loading

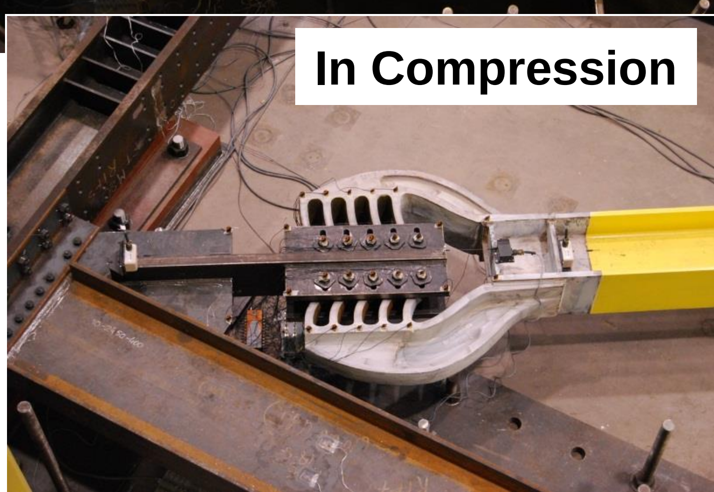


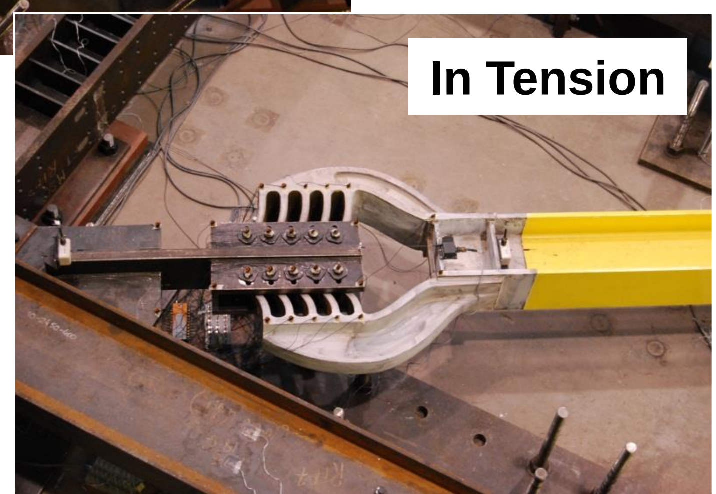


Cast Steel Yielding Connector at Brace End

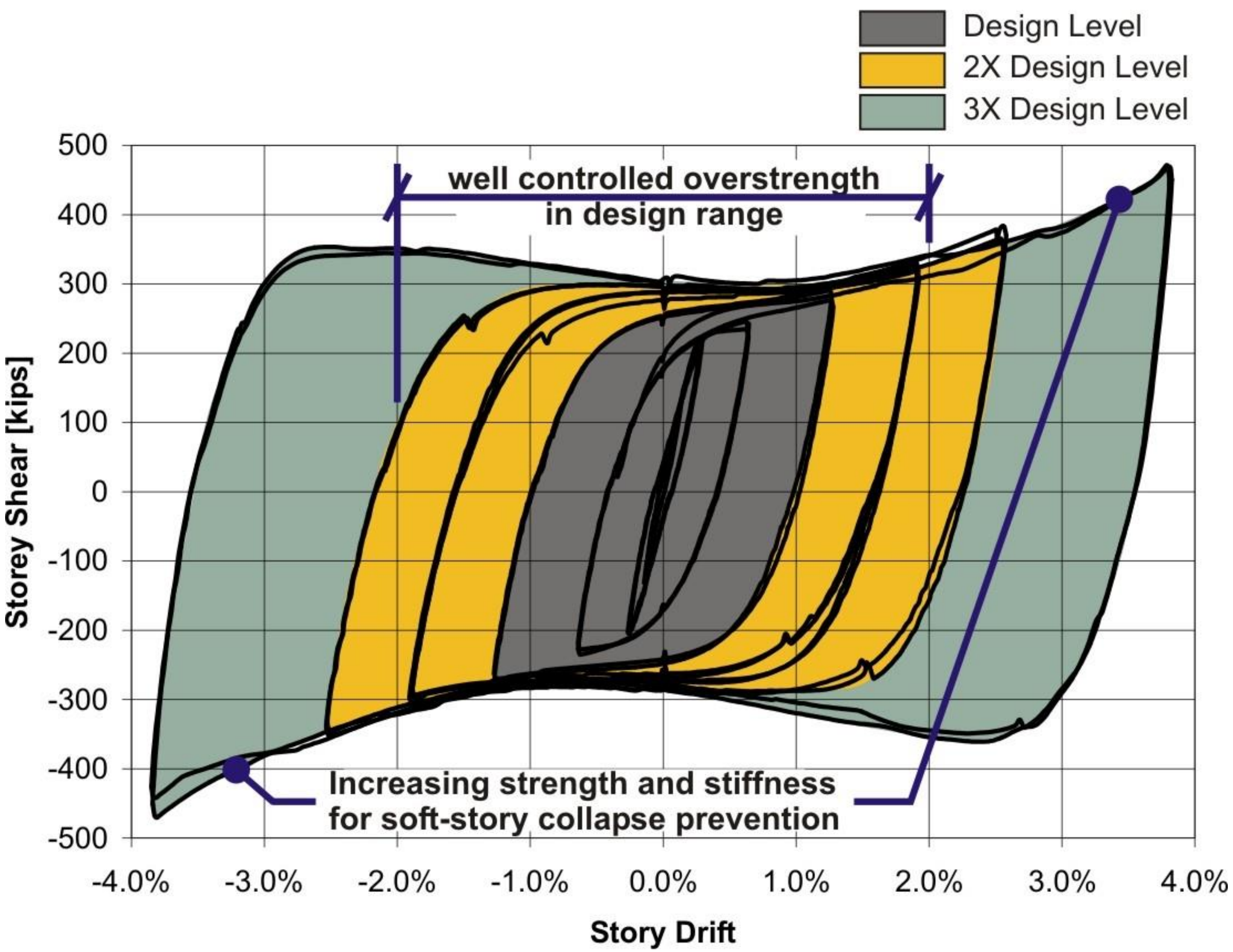


Full-frame testing





Cast Steel Yielding Connector at Brace End



Full-frame testing

Redundancy:

Each casting is made of several specially designed yielding fingers. In the event of an extremely large earthquake the loss of a single finger would not result in complete loss of lateral strength.

Now manufactured and marketed as the "Scorpion" Yielding Brace System by

CASTCONNEX® ***www.castconnex.com***

Connections in Un-Braced Frames

Rigid, Moment-Resisting Beam-to-Tubular Column Connections under High Seismic Loading

Diaphragm Approach

Using a strong-column-weak-beam design procedure, to achieve full moment capacity transverse column stiffeners are usually needed to transfer axial loads in the beam flanges.

These 2 stiffeners can be:

(i) internal diaphragms, *or*
(ii) through diaphragms, *or*
(iii) external diaphragms.

Design procedures, developed in Japan are available in *CIDECT Design Guide No. 9* Chapter 8 (Kurobane et al., 2004). This is available in Spanish, as a free download from: *www.cidect .com*

Diaphragm Connections in Un-Braced Frames

Through Diaphragm Approach

- **The most popular diaphragm connection type in Japan, particularly using square hollow section columns**

- **Requires excellent fabrication details; achieved generally by robot welding in Japan**

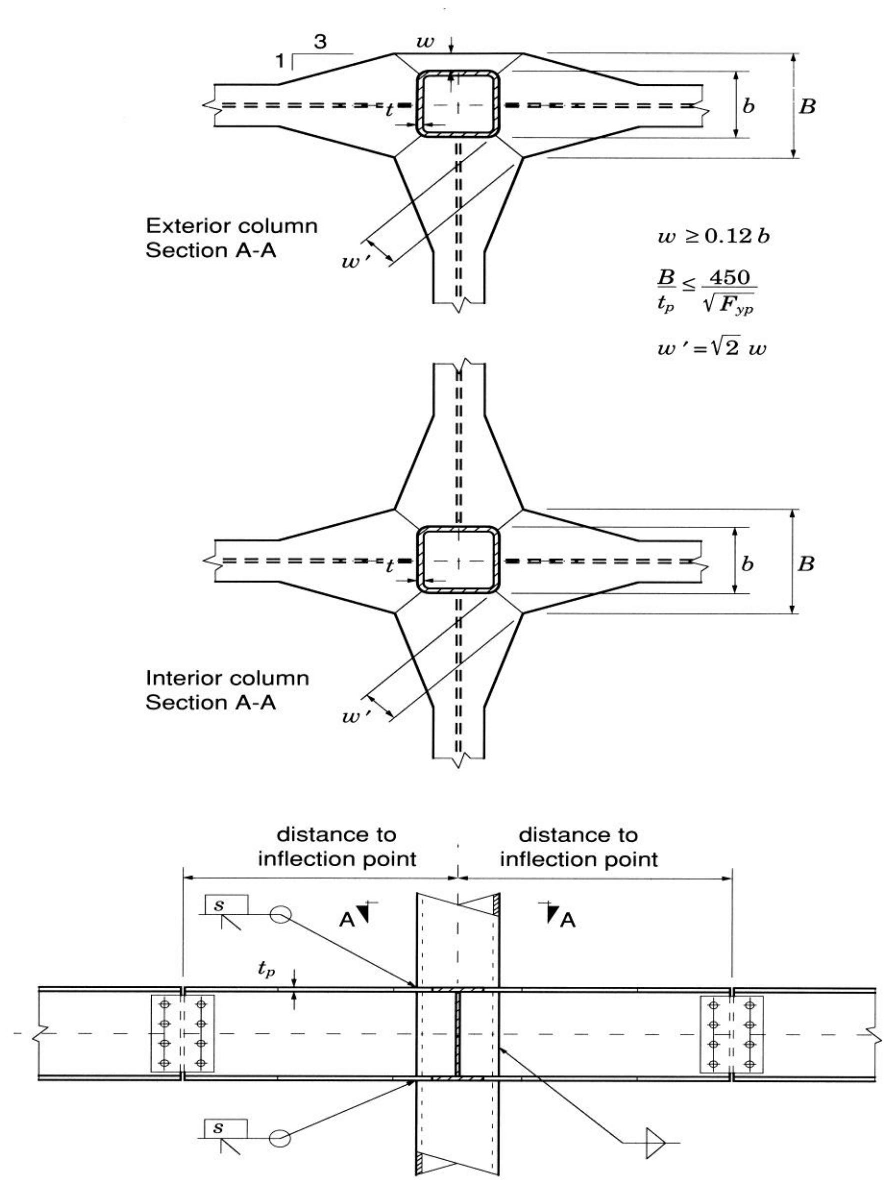
- **Column is protected; plasticity occurs in the beam**

Diaphragm Connections in Un-Braced Frames

External Diaphragm Approach

- Achievable by any fabricator
- Plate collars fit around circular or square columns
- Permits concrete-filling

Auckland Airport, NZ

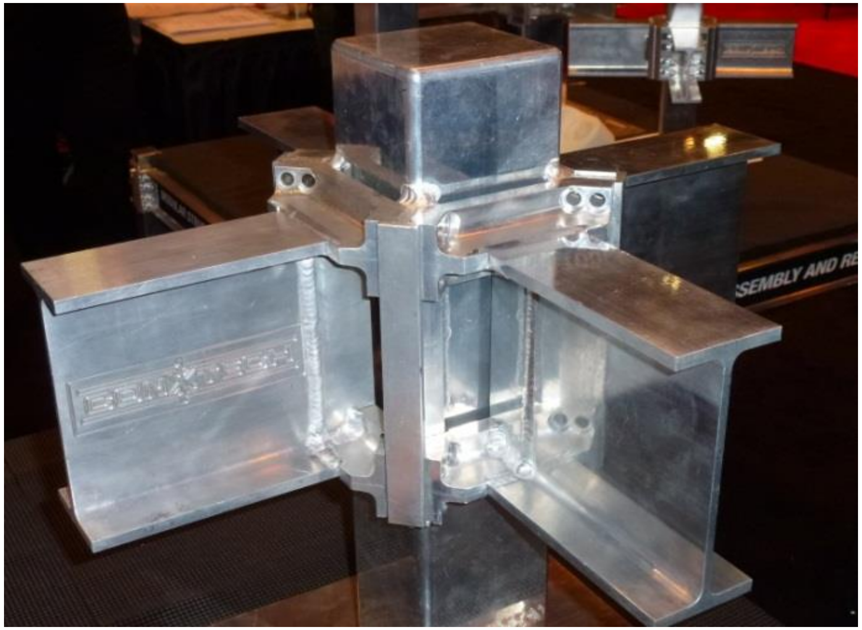


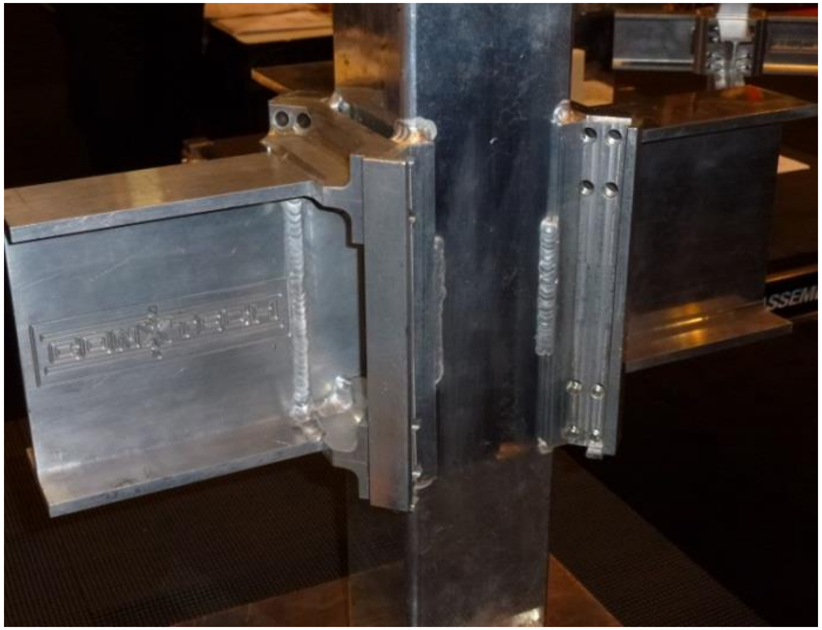
Proprietary Connections in Un-Braced Frames

ConXtech® ConXL™ Moment Connection

- **Consists of collar assemblies that form a compression collar around a square hollow section column, when fastened on site with high-strength pre-tensioned bolts.**

- **Rigid bi-axial fixity is achieved between the column (concrete-filled) and up to 4 I-section beams, with no field welding.**





Proprietary Connections in Un-Braced Frames

ConXtech® ConXL™ Moment Connection

- **Column collars (with a 3D taper) are shop-welded to the column**
- **Beam collars (also tapered) are shop-welded to top and bottom beam flanges**
- **The forged and machined collars remain elastic**
- **Patented framing system**
- **System developed only for 406 x 406 concrete-filled square hollow sections**
- **Only prequalified moment connection in AISC 358 for hollow section columns**

www.conxtech.com

Proprietary Connections in Un-Braced Frames

SidePlate® Connection

• **Consists of a series of welded-on plates to create a rigid, fixed planar connection between the column and I-section beam(s)**

• **In the shop, flange cover plates are welded to the top and bottom of the beam(s) and side plates are welded to two sides of the column**

• **On site, the connection can be completed by welding or bolting (to angles protruding from the column side plates)**

Proprietary Connections in Un-Braced Frames

SidePlate® Connection

- **Patented connection "technology"**

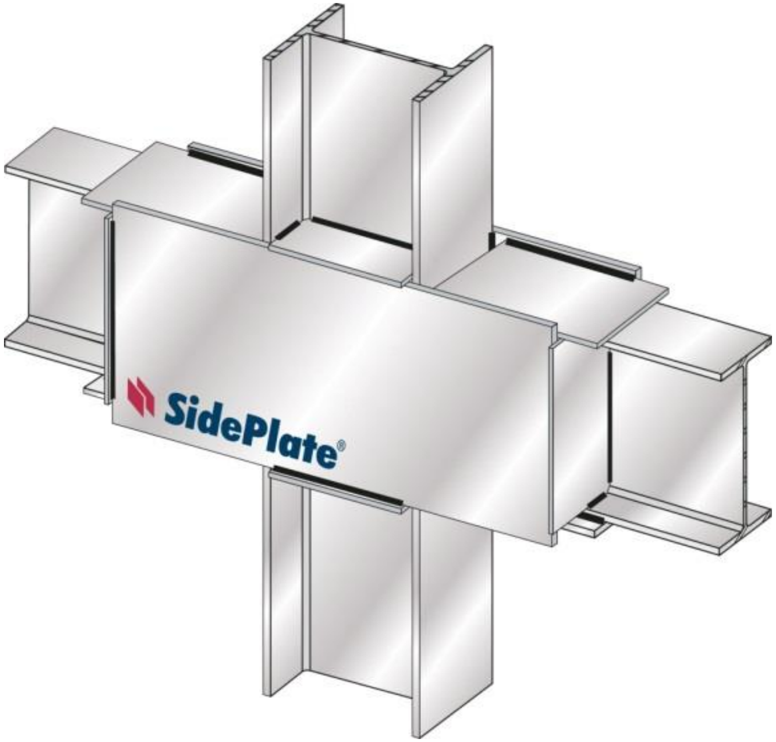
- **Sideplate's own engineers work with the consulting structural engineers to provide a complete lateral load-resisting system**

- **No "anti-seismic" products need to be bought or stocked**

- **Invented for I-section columns, but applicable to all square and rectangular hollow section column sizes**

- **Nearing pre-qualification status with AISC 358**

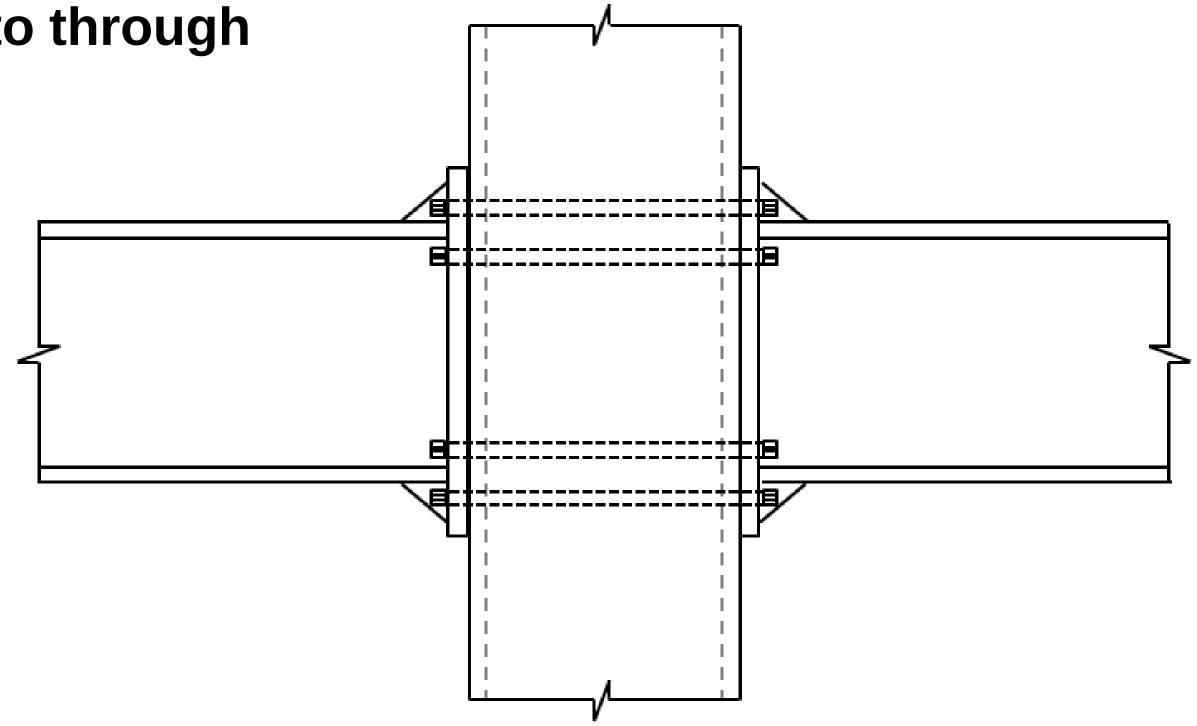
www.sideplate.com



Generic Connections in Un-Braced Frames

Rigid Moment Connections with Long Bolts

- **Requires the square/rectangular column to be concrete-filled**
- **Could use beam end-plates (as shown) or T-stubs welded to beam flanges**
- **Potential problem with bi-axial moment frames, due to through bolts interfering**



Generic Connections in Un-Braced Frames

Rigid Moment Connections with "Blind" Bolts

- **Concept used principally in Japan**
- **Column walls must be reinforced to achieve full rigidity + moment over-strength**
- **Column can be strengthened by the addition of collars or collar plates, or the hollow section can be "locally thickened"**

CIDECT Design Guides (9) and Books

- **Free downloads – *in Spanish* – from: *www.cidect.com***

Publicaciones del CIDECT

La situación actual de las publicaciones del CIDECT refleja el creciente énfasis en la divulgación de los resultados de las investigaciones.
A continuación se enumeran las Guías de diseño del CIDECT ya publicadas, dentro de la serie "Construcción con perfiles tubulares de acero". Estas guías de diseño están disponibles en inglés, francés, alemán y español.

1. Guía de diseño para nudos de perfiles tubulares circulares (CHS) bajo cargas predominantemente estáticas (1991)
2. Estabilidad estructural de perfiles tubulares (1992, reimpresa en 1996)
3. Guía de diseño para nudos de perfiles tubulares rectangulares (RHS) bajo cargas predominantemente estáticas (1992)
4. Guía de diseño para columnas de perfiles tubulares estructurales sometidas a fuego (1995, reimpresa en 1996)
5. Guía de diseño para columnas de perfiles tubulares rellenas de hormigón bajo cargas estáticas y sísmicas (1995)
6. Guía de diseño para perfiles tubulares estructurales en aplicaciones mecánicas (1995)
7. Guía de diseño para la fabricación, ensamble y montaje de estructuras de perfiles tubulares (1998)
8. Guía de diseño para nudos soldados de perfiles tubulares circulares y rectangulares sometidos a solicitaciones de fatiga (2000)

Gracias

jeffrey.packer@utoronto.ca