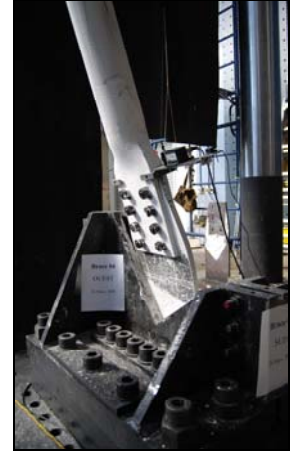


CAST STRUCTURAL CONNECTORS

Cast Connex Corporation



Submitter:

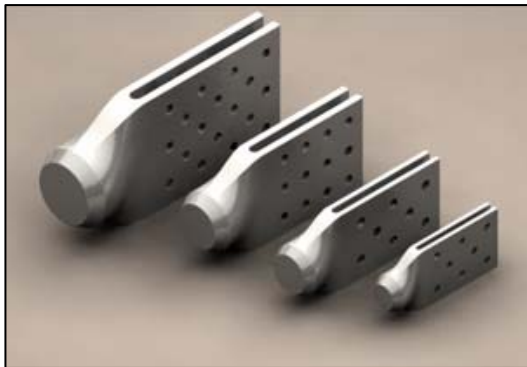
Professor Jeffrey Alan Packer

B.E., M.Sc., Ph.D., D.Sc., F.I.C.E., F.A.S.C.E., M.C.S.C.E., P.Eng., C.Eng.

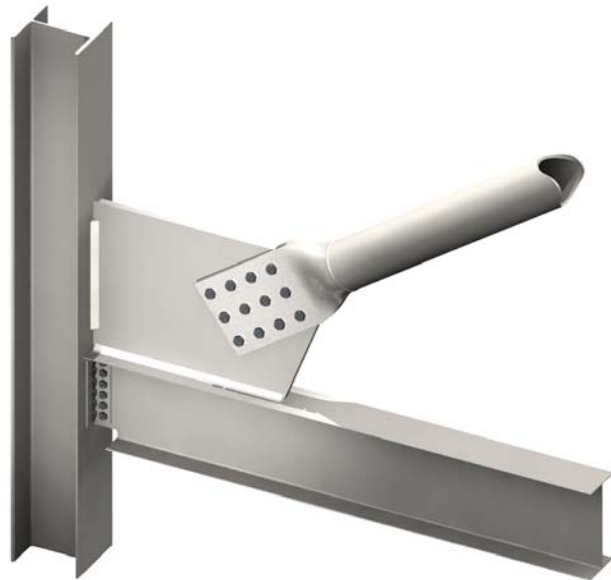
Summary of the Innovation

To withstand an earthquake, bracing connections in steel structures require complex engineering, detailing, fabrication, and site assembly. A research group at the University of Toronto developed cast steel brace connectors that leverage steel casting manufacturing's inclination towards mass production to provide the steel construction industry with standardized, pre-qualified, earthquake-resistant bracing connectors. The connectors are now commercially available through the Cast Connex Corporation, which was founded by the researchers and which is being nominated for the CSCE Innovation Award by the submitter.

Cast ConneX™ High-Strength Connectors



HSC-219 HSC-168 HSC-141 HSC-102
HSC-8.625 HSC-6.625 HSC-5.563 HSC-4.000



Highlights of the Innovation

Centrally braced frames (CBFs) are the most popular choice for the lateral force resisting system of low- to medium-rise steel structures in North America. CBFs work by transforming laterally applied forces (i.e. those induced by wind or by ground motion in an earthquake) to axial forces in the diagonal brace elements as illustrated in Figure 1.

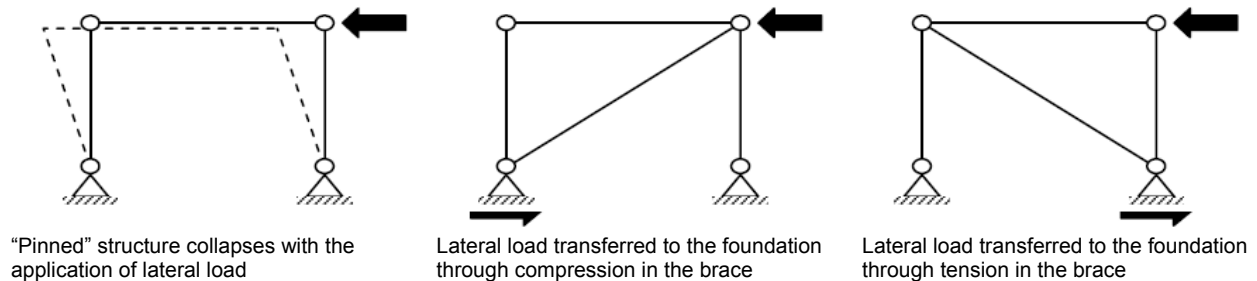


Figure 1: *The mechanics of concentrically braced frame structures*

As hollow structural sections (HSS) are the most efficient structural shapes for carrying axial loads, they are commonly selected as the bracing elements in braced frame structures designed to resist earthquake loading. The most common detail for connecting HSS bracing elements to the steel frame involves slotting the HSS member, fitting a gusset plate into the slot, and subsequently welding the plate to the HSS element (Figure 2a). Such a connection induces a phenomenon referred to as "shear lag" in the HSS member. Shear lag is acceptable in connections that are designed to resist load statically, however, in an earthquake, the bracing element will cyclically yield in tension and buckle in compression. As a result, the brace end connection must be substantially stronger than the brace member itself; otherwise the connection may fracture during an earthquake. The presence of shear lag makes achieving connection strengths that exceed the capacity of the connected member very difficult, particularly in cyclic inelastic loading. Figure 2b shows two shear lag-induced connection failure modes which are common in slotted HSS-to-gusset connections.

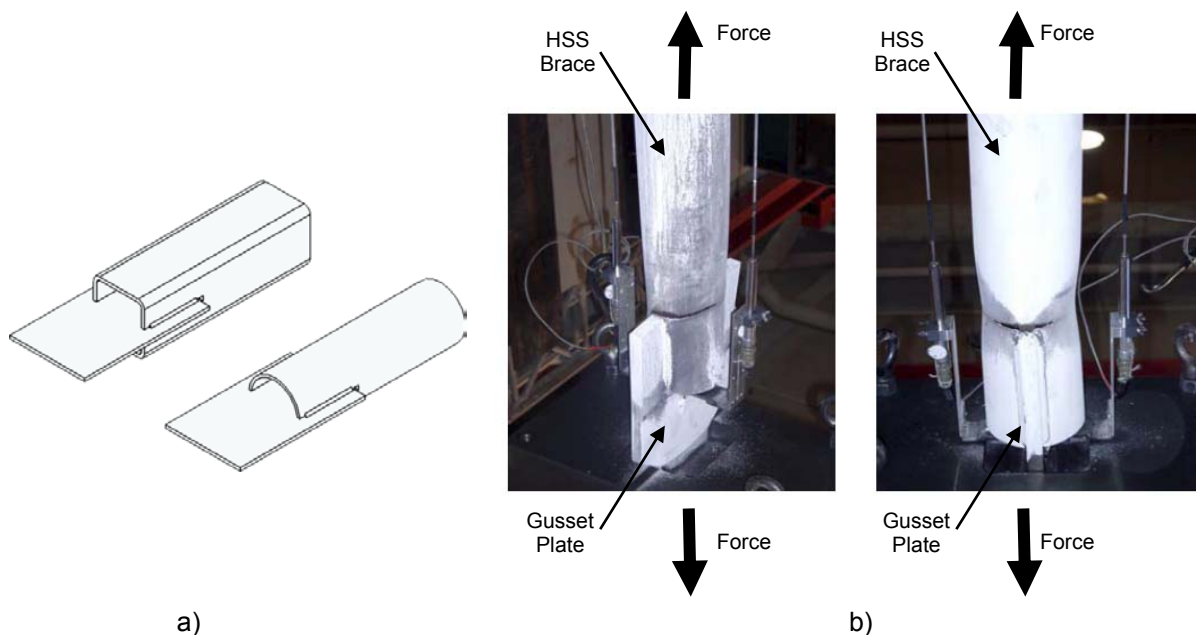


Figure 2: *a) Slotted HSS-to-gusset connections; b) Shear lag-induced failure modes for typical slotted HSS-to-gusset connections: gross section fracture (left), net section fracture (right)*

As a result of the undesirable cyclic response of HSS braces connected with slotted HSS-to-gusset details, North American seismic design standards require the use of connection reinforcement whenever slotted HSS bracing is used in buildings constructed in regions of moderate to high seismicity (Figure 3a). Each of these brace connections must be individually designed by an engineer to ensure that the brace elements they connect can safely dissipate seismic energy through inelastic yielding and buckling. Because the sizes of the bracing elements vary from storey to storey and frame to frame, each structure requires the engineering of a significant number of these complex connections. Furthermore, these reinforced connections require painstaking detailing, costly fabrication, and are cumbersome to erect.

A research group at the University of Toronto has studied and improved upon the current design and construction practices for seismic-resistant, HSS connections through the development of innovative cast steel connectors (Figure 3b). The group of inventors subsequently formed the Cast Connex Corporation – a University of Toronto spin-off company – and the technology they developed is the basis for Cast Connex Corporation’s High-Strength Connector line of products. This set of pre-engineered connectors is now commercially available for seismic-resistant bracing connections and had multiple patents pending in the U.S., Canada, and abroad.

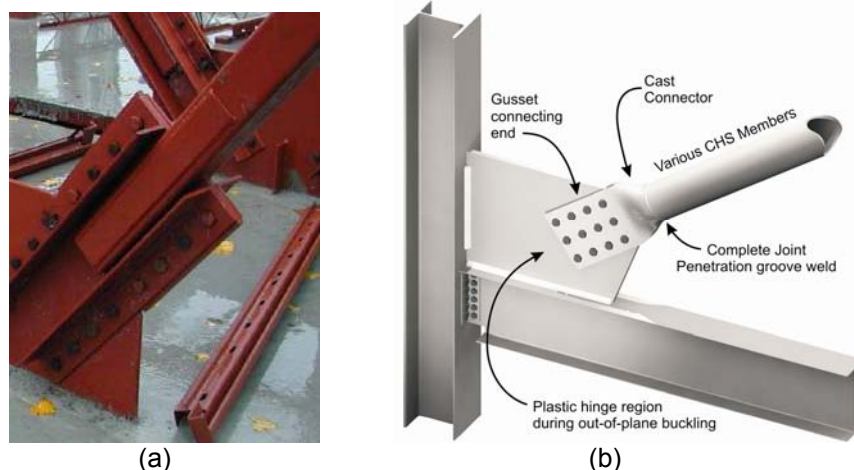


Figure 3: Conventional reinforced, slotted HSS connection in a seismic-resistant frame (left); Standardized Cast Connex seismic-resistant HSS connector in a frame (right)

At one end, the connectors are designed with a circular shape and preparation allowing for complete joint penetration shop welding to a range of tubular braces of a given outer diameter for the full development of their expected yield strength. At the other end, the connectors are shaped such that a double-shear bolted splice connection or longitudinal fillet welds can be used for connecting the shop-welded brace-connector assembly to conventional gusset plates secured to the beam-column intersection. The advantages of using the innovative cast connectors instead of standard fabricated connections are:

- connections designed using the connectors inherently satisfy North American seismic design provisions for energy dissipating braced frames,
- a single standardized connector works for all round HSS of a given outer diameter, regardless of the section’s wall thickness, vastly simplifying connection design and detailing,
- the double-shear bolted connection halves the number of bolts that would otherwise be required in a spliced, field-bolted connection,
- complex geometry is “cast in” to the components, reducing fit-up time in fabrication,
- the connectors eliminate the additional pieces that would otherwise be required for field-bolted, spliced connections, simplifying site erection and logistics,
- the more compact connection reduces the potential for interferences with other building elements,
- structural safety is improved through the use of pre-tested, standardized components and potential errors in connection design are avoided,
- round HSS members are accommodated, which provides a superior response over square HSS,
- and the connectors provide an improved aesthetic in comparison to the fabricated alternative.

Full Project Description



Image Courtesy of Les Architectes Odette Roy et Isabelle Jacques

Project Name:	Sandoz Canada Administration Building
Location:	Boucherville, Québec
Owner:	Sandoz Canada Inc.
Architect:	Les Architectes Odette Roy et Isabelle Jacques (St-Georges, Québec)
Structural Engineer:	Canam Group Inc. (Boucherville, Québec)
Fabricator:	Canam Group Inc.

Background

Canam Group was contracted to design and construct a four-storey structure that is to be expandable to a six-storey structure and which is to become the main administration building for Sandoz Canada Inc. The administration building is part of a large new development which includes 40,000 square feet of manufacturing space, 10,500 square feet of warehousing space, and 17,000 square feet for administrative support. The Sandoz Canada facilities are the largest small-volume injectable drug production site in Canada.

The site is located in Boucherville, Québec, which is near the St-Lambert region of Montréal. The National Building Code of Canada (NBCC) requires that structures constructed in this region be designed to endure a Peak Ground Acceleration of 0.43 g, which corresponds to a moderately high level of seismicity. For perspective, the region of highest seismicity in Canada is Victoria, British Columbia, for which a peak ground acceleration of 0.62 g must be assumed. By contrast, peak ground accelerations of 0.17 g and 0.059 g must be assumed for construction in the cities of Toronto and Edmonton, respectively, which are considered regions of low seismicity.

There are several options available to engineers for the lateral force resisting system (LFRS) of steel structures. Given the site's seismicity, the structure's height, and the code prescribed lateral drift limits, a concentrically braced frame (CBF) is the most economical LFRS in this particular situation. Engineers

have the option of designing a CBF to either remain predominately elastic during a seismic event or to dissipate seismic energy through the formation of a stable inelastic mechanism in the CBF (this type of CBF is designated a “moderately ductile” braced frame in the Canadian steel design codes). The latter provides a more robust design, given the uncertainty of earthquake-induced loading and the moderately ductile system’s ability to endure earthquakes of larger amplitude than that which the structure was originally intended to withstand. Additionally, the design of a moderately ductile CBF provides the opportunity to reduce the forces that the structure must accommodate, providing significant cost savings in the building’s structural elements.

In a moderately ductile concentrically braced frame, energy dissipation is provided through cyclic yielding and buckling of the diagonal brace elements of the frame, as illustrated in Figure 4 below.

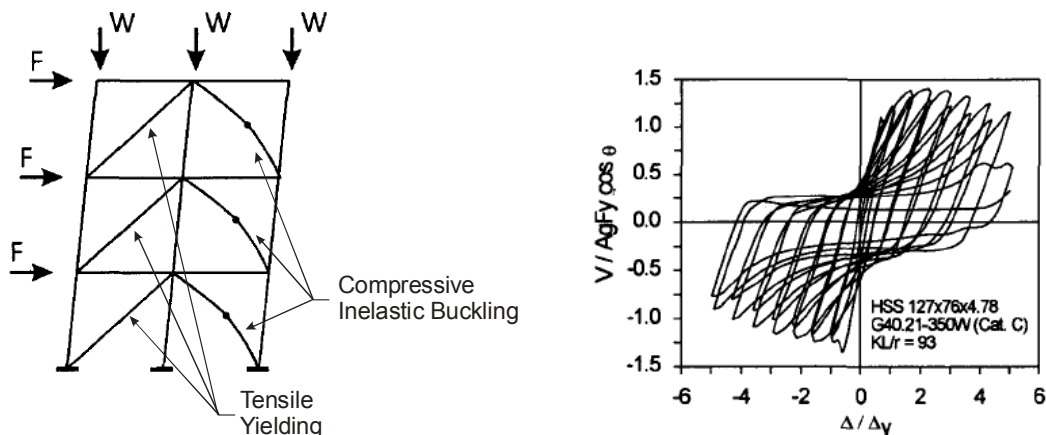


Figure 4: Seismic energy dissipation in a moderately ductile concentrically braced frame (adapted from Tremblay, 2003)

For the seismic design of the moderately ductile CBF, the diagonal bracing elements are selected such that they can carry the seismic design forces prescribed in the NBCC, given the seismicity of the region, the weight of each of the building’s storeys, and the braced frame’s geometry. The remainder of the elements in the braced frame (including the bracing connections) must then be designed to remain elastic during the formation of the stable plastic mechanism in the frame, as illustrated in Figure 5 below. The process of protecting the rest of the structure from damage during the dissipation of earthquake-induced energy through the formation of a stable plastic mechanism is termed “capacity design”. Capacity design is perhaps the most critical aspect of all modern seismic design codes.

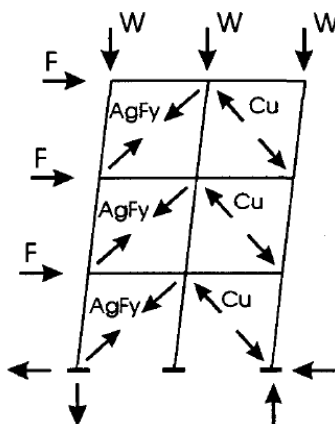


Figure 5: Forces developed during the formation of a plastic mechanism in the concentrically braced frame (adapted from Tremblay, 2003)

Seismic-Resistant Braced Frame

With the type of LFRS selected and the geometry of the braced frame established based on both structural and architectural requirements, the HSS bracing elements themselves were sized by the Canam Group such that the braced frame on each storey could resist the associated storey shear. Figure 6 below shows braced frame elevations for the structure, which provide the section designation of each of the brace elements.

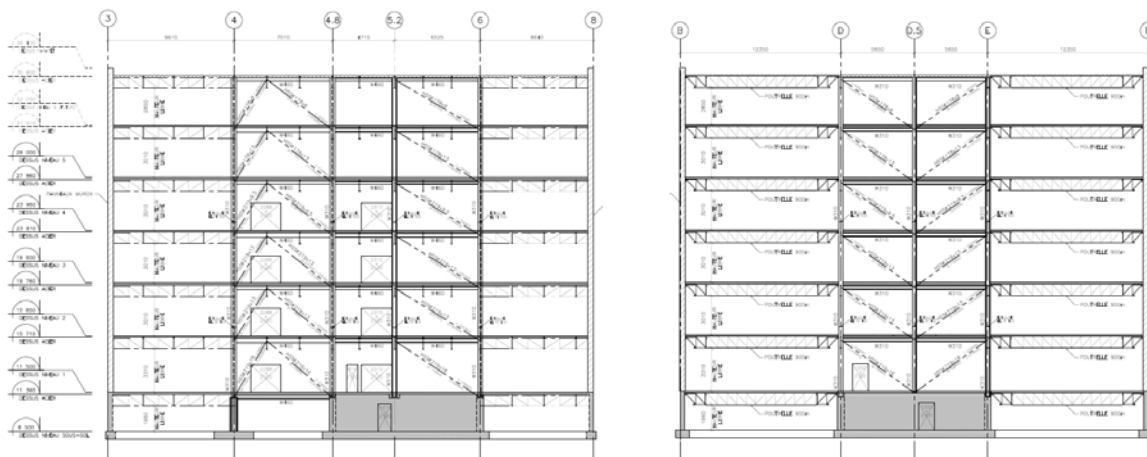


Figure 6: *Braced frame elevations for the Sandoz Canada Administration Building (courtesy of Canam Group Inc.)*

The brace members were specified as round HSS produced to ASTM A500 Grade C having outer diameters of 219 mm and 168 mm and wall thicknesses ranging from 16 mm to 8.0 mm, depending on their location in the frame.

Connection Design

Detailing of the connections at the ends of each brace must follow the principles of capacity design. Accordingly, each connection must be able to withstand the force transmitted during tensile yielding of the cross-section of the brace, including member overstrength, as well as the forces and deformations imparted during compressive inelastic buckling of the brace. The following example illustrates the simplicity in achieving a seismic-resistant connection using Cast ConneX™ High-Strength Connectors versus standard fabrication practices.

The heaviest brace member in the project (located in the ground level braced frame) is a round tubular section having an outer-diameter of 219 mm with a wall thickness of 16 mm (HSS 219x16). According to the Canadian Institute of Steel Construction, the seismic-resistant end connection associated with this element must be capable of resisting the section's yield capacity, $A_g F_y$, multiplied by an overstrength factor, R_y , which accounts for the difference between the minimum specified yield strength of the brace section (which in this case is 317 MPa) and the brace's actual yield strength. The American Institute of Steel Construction recommends a value of $R_y = 1.4$ for tube produced to ASTM A500 Grade C. Using this value, the end connection for the HSS 219x16 brace must be capable of resisting a total force of 4,210 kN. As the Canam Group decided to provide slip-critical bolted connections, 12 pre-tensioned 1-inch diameter ASTM A490 bolts were used with the HSC-219 standardized connector. Besides detailing the gusset's connection to the beam-column intersection (which must be done regardless of whether the cast connectors are employed), the calculations outlined above are virtually all that is required to design the brace connection using the High-Strength Connectors. In terms of detailing, a gap of twice the gusset thickness is left beyond the ends of each connector to accommodate the end rotations that will be induced during out-of-plane buckling of the brace. Figure 7 shows the connection detail associated with this brace as specified by the Canam Group.

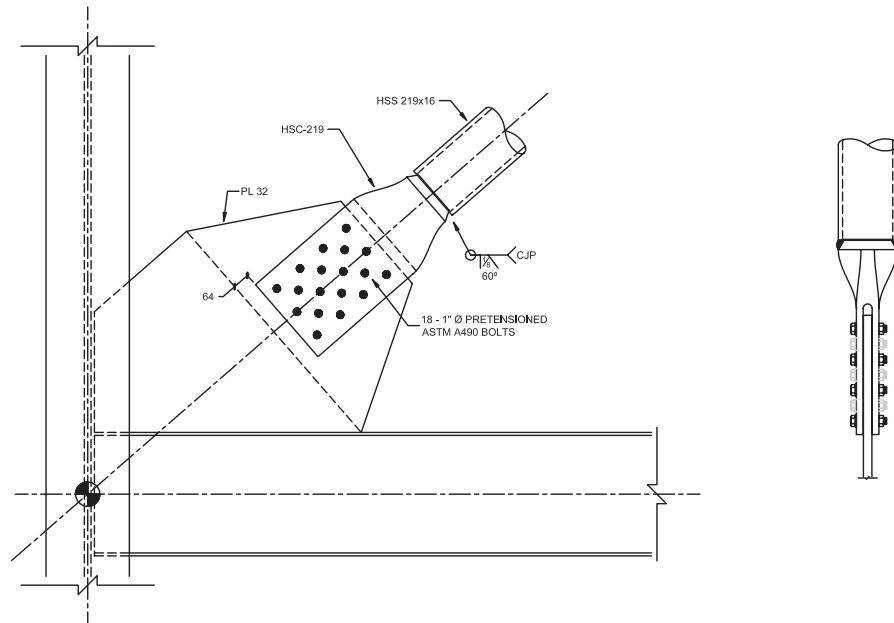


Figure 7: *Brace connection detail using Cast ConneX™ High-Strength Connectors in the Sandoz Project, as specified by the Canam Group*

Fabrication of braces equipped with the cast connectors is straightforward. The standardized connectors are first fitted to the ends of an HSS segment that has been cut such that the brace is the correct length (Figure 8a). After the connector is tack-welded to the HSS segment, the brace-connector assembly is mounted on a turning roll, the casting is preheated, and then the connector is fully welded to the HSS segment (Figure 8b). As the bevel preparation is a cast feature of the connector, no other weld preparation is necessary. The weld itself must be a complete joint penetration groove weld such that cyclic inelastic yielding of the brace can be accommodated in the event of an earthquake. Finally, after the brace cools and returns to its original length, bolt holes are drilled into the connector and the brace-connector assembly is shipped to site for bolted field installation of the brace (Figure 9).



a)



b)

Figure 8: *(a) Fitting Cast ConneX™ High-Strength Connectors to a tubular segment; (b) rotated complete-penetration welding of a High-Strength Connector to a tubular brace*

Cast Structural Connectors

Cast Connex Corporation

Canadian Society for Civil Engineering
Excellence in Innovation in Civil Engineering Award



Figure 9: Braces equipped with Cast ConneX™ High-Strength Connectors on site awaiting installation (left); braces installed in the steel frame structure (right)

By contrast, design of a slotted HSS connection that accommodates field bolting to an HSS 219x16 brace and which can resist a load of 4,210 kN is extremely involved. The design procedure necessitates first designing the connection between the plate that will be inserted into the slotted HSS element and the HSS member itself. The steps are generally:

- Determine the maximum fillet weld size such that shear rupture strength of the HSS does not govern
- Determine the minimum gusset size, based on shear rupture, that is capable of transferring the required force
- Determine the length of the weld required and detail the slot in the HSS segment
- Determine the reinforcement that is necessary at the net section of the HSS to ensure that the capacity of the connection, including the effects of shear lag, is sufficient. This will require iteration between selecting reinforcement, calculating the centroid of the built-up shape on either side of the gusset and quantifying the shear lag effects, and determining whether the reinforcement selected was sufficient.
- Design the weld between the reinforcement plate and the HSS, also accounting for shear lag in that connection

After having designed the reinforced slotted HSS connection, the splice connection between the gusset fastened to the beam-column intersection and the gusset welded to the slotted HSS brace must be designed. This splice requires complex detailing to ensure that the full force can be transferred between the brace and the beam-column gusset. Because the connection must maintain a concentric geometry, the number of bolts required due at the splice is double the number of bolts required in the connection designed using the High-Strength Connector.

To illustrate the connection complexity when the cast connectors are not employed for seismic-resistant HSS bracing connections, a preliminary design for a slotted-HSS to gusset connection that meets the seismic-design requirements for the same brace as shown above in Figure 7 was detailed and is shown below in Figure 10. Besides the added complexity in connection design in comparison to the connection detailed using the cast connectors, fabrication of the connection below requires tedious fitting, significant weld preparation, several stages of welding, and onerous installation of the multi-component connection. Additionally, the size of the connection is quite a bit larger, increasing the likelihood of interferences with other non-structural building elements, which for example may include wall openings or ductwork. Finally, and perhaps most importantly, if the connection shown in Figure 10 is not detailed correctly, the brace connections may fail abruptly in the event of an earthquake, which can lead to structural collapse with little to no warning. Conversely, the standardized cast connectors have been full-scale tested, which ensures that they can withstand a design level earthquake.

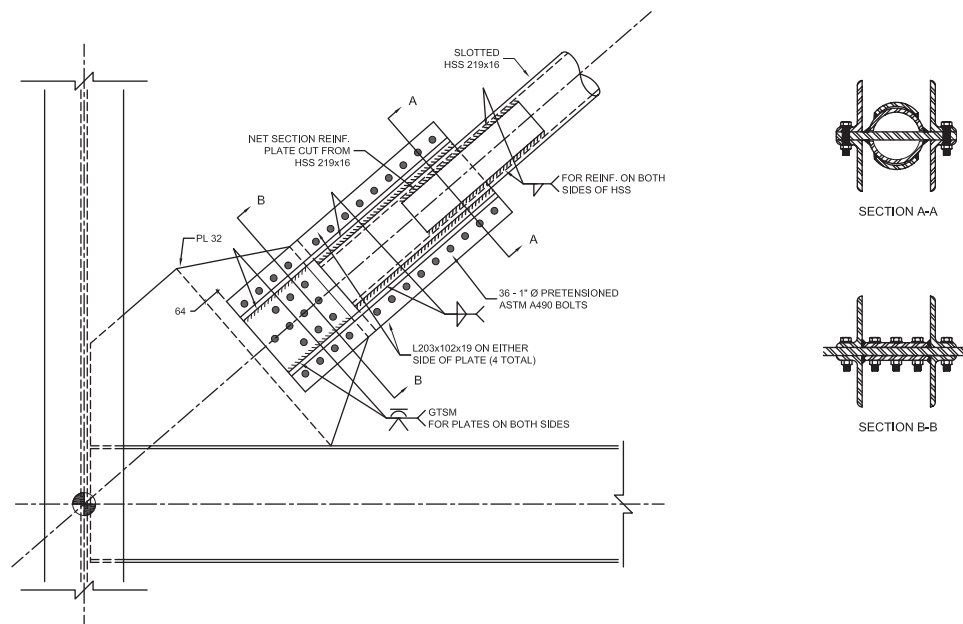


Figure 10: Example of a reinforced slotted HSS-to-gusset connection that accommodates field bolting. The connection was designed for the same brace as that which was detailed using the Cast ConneX™ High-Strength Connector shown above in Figure 7

Project Status

At the time of submission of this report, the Sandoz Administration Building was in mid-construction with the majority of the structural steel having been erected. As such, the Canam Group had fabricated and installed all of the braces that were equipped with the Cast ConneX™ High-Strength Connectors. Pierre Gignac, Vice-President, Engineering of the Canam Group, has offered to provide a Letter of Satisfaction in relation to the use of the innovative components, which the Canadian Society for Civil Engineering should be in receipt of in due course.

Development and Seismic Testing of the Cast Connectors

As the innovative connector technology was developed at the University of Toronto, a significant amount of research was involved in the development of the connectors (de Oliveira et al, 2006, 2008a, 2008b). The technology was first legally established in a U.S. Provisional Patent filed April 27, 2006, with subsequent U.S. and PCT International Patents filed on April 27, 2007. National Phase Patent Applications have now also been filed in Canada, China, Japan, Korea, India, and the European Union. Following the initial research, the technology was licensed to the Cast Connex Corporation, which subsequently developed a line of four High-Strength Connectors based on the U of T prototypes. Because each connector can accommodate a large number of HSS bracing elements (each of a given outer diameter but of any wall thickness), only the four connectors are needed to cover the wide range of brace capacities that may be required by an engineer sizing the bracing elements of a particular braced frame.

Following the design of the line of products, full-scale testing was carried out on braces equipped with the connectors at École Polytechnique de Montréal under the supervision of Professor Robert Tremblay and University of Toronto Professors Constantin Christopoulos and Jeffrey A. Packer (Tremblay et al., 2008). The images shown below were taken during the full scale testing, during which each brace was subjected to a loading protocol designed to simulate the axial deformations which would be applied to the brace in the event of a design level earthquake. A streaming video of a brace test can be viewed online at www.castconnex.com/HSCTesting.html.

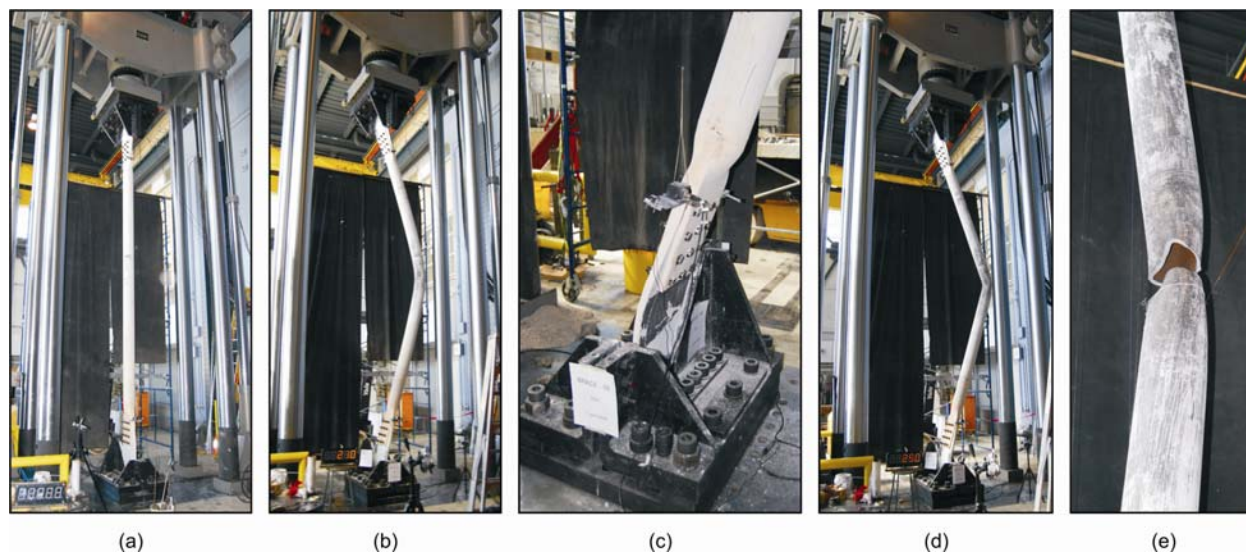


Figure 11: *HSS 219x16 brace-connector assembly being full-scale seismic tested: (a) undeformed; (b) experiencing inelastic buckling; (c) plastic hinge formation in free length of gusset plate; (d) localization of plastic hinge in CHS member; (e) fracture of brace at mid-length after the formation of a crescent-shaped snap-through local buckle*

Concluding Remarks

Given the potential impact of this innovative technology to not only vastly simplify the design and fabrication of seismic-resistant bracing connections, but to also significantly improve the safety of structures constructed in regions of moderate to high seismicity, the submitter strongly recommends that the Cast Connex Corporation be awarded the Canadian Society for Civil Engineering “Excellence in Innovation in Civil Engineering” Award.

References

de Oliveira, J. C., Willibald, S., Packer, J. A., Christopoulos, C., and Verhey, T. (2006). Cast Steel Nodes in Tubular Construction - Canadian Experience. Proc. 11th Int. Symp. and IIW Int. Conf. on Tubular Structures, Québec City, Québec, 523–529.

de Oliveira, J. C., Packer, J. A., and Christopoulos, C. (2008a). Cast Steel Connectors for Circular Hollow Section Braces under Inelastic Cyclic Loading. J. of Struct. Eng., ASCE, 134, 3, 374-383.

de Oliveira, J. C., Gray, M. G., Packer, J. A., and Christopoulos, C. (2008b). Standardized Cast Steel Connectors for Tubular Hollow Structural Sections. Proc. CSCE 2008 Annual Conference, Québec, QC, June.

Tremblay, R. (2003). Achieving a stable inelastic seismic response for multi-story concentrically braced steel frames. AISC Engineering Journal, 40(2), 111-129.

Tremblay, R., Christopoulos, C., Packer, J. A., de Oliveira, J. C. (2008). Quasi-Static Cyclic Testing of Individual Full-Scale Circular Steel Tubular Braces Equipped with Cast ConneX™ High-Strength Connectors. Joint École Polytechnique de Montréal and University of Toronto Publication.

Photographs for Submission

Enclosed with this package are five photographs of the innovation for official submission. Thumbnails of each of the enclosed photographs are provided below along with captions.



Caption: Full-scale seismic testing of a brace equipped with Cast ConneX™ High-Strength Connectors at the structural laboratories of École Polytechnique de Montréal. The brace pictured is experiencing out-of-plane inelastic buckling, as would occur during a design level seismic event.



Caption: Canam Group welder securing a Cast ConneX™ High-Strength Connector to a round hollow structural section brace member for the Sandoz project.



Caption: Sandoz Canada Administration Building: Rendering by Les Architectes Odette Roy et Isabelle Jacques.



Caption: Sandoz Canada Administration Building during construction.



Caption: Brace equipped with Cast ConneX™ High-Strength Connector installed in frame during initial structural erection phase.