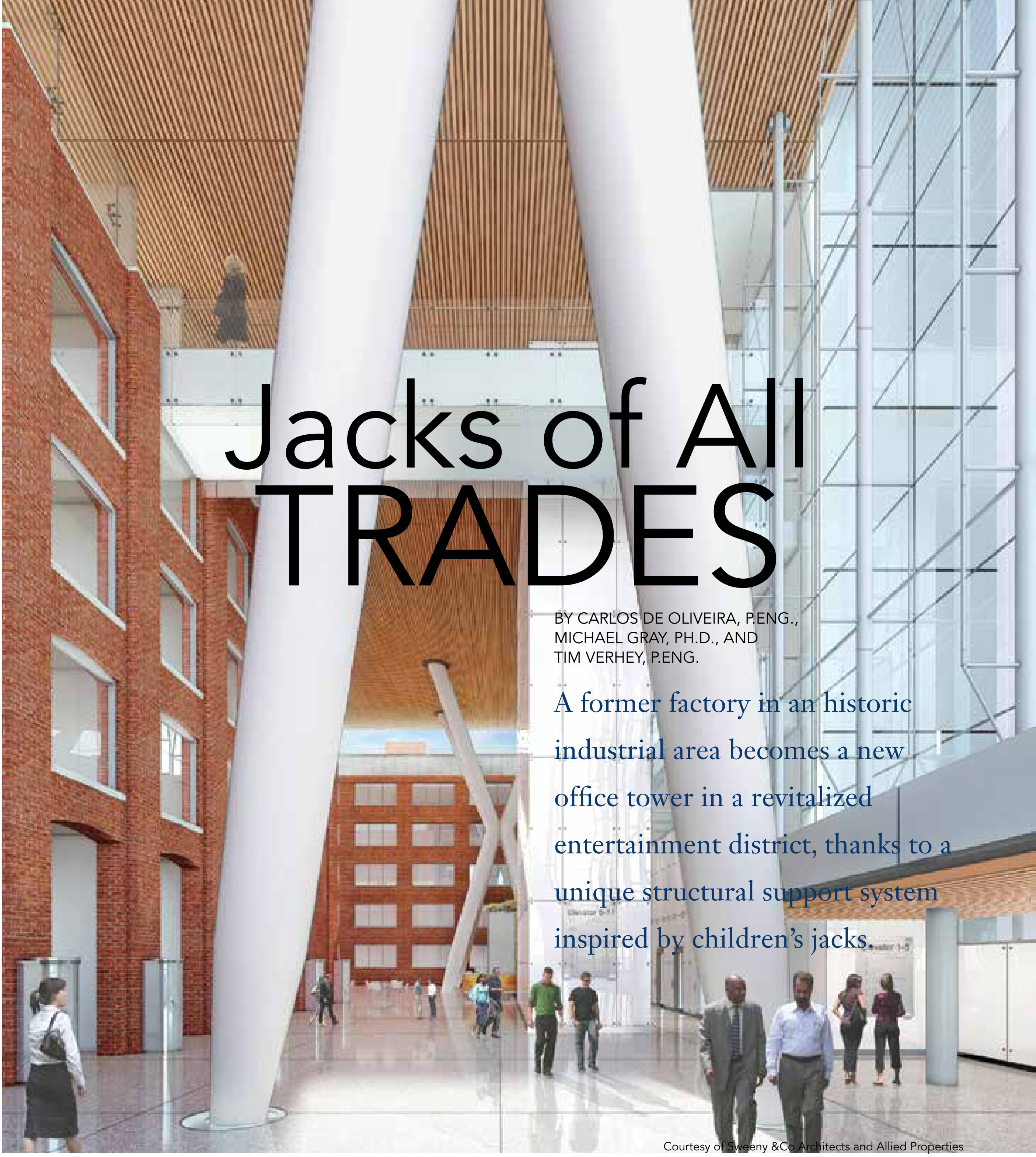
# Jacks of All TRADES

BY CARLOS DE OLIVEIRA, P.ENG., MICHAEL GRAY, PH.D., AND TIM VERHEY, P.ENG.

A former factory in an historic industrial area becomes a new office tower in a revitalized entertainment district, thanks to a unique structural support system inspired by children's jacks.



Courtesy of Sweeny &Co Architects and Allied Properties

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**IT ALL BEGAN** with biscuits.

Constructed in 1915, the four-story brick-and-beam building at the northwest corner of Peter and Richmond Streets in Toronto was originally home to a biscuit factory owned by Weston Bakery—a company that would ultimately become a Canadian food processing and distribution empire.

At the time, the neighborhood was characterized by sparsely spaced warehouses and factories. Today, the area as an entertainment district for the city, thanks in part to the versatility of these types of old structures, which often have the character and layout that are ideal for being repurposed into shops and restaurants as well as offices and lofts.

In 2003, Allied Properties REIT acquired the building along with two other adjacent buildings and, with the help of Sweeny &Co Architects, Inc. (Sweeny) prepared a plan to revitalize the block. But rather than simply retrofitting and repurposing the buildings as they have done in the past, Allied Properties decided to construct a new building amongst the old ones, as well as make use of the empty spaces between the structures. And instead of just incorporating one or two faces of the heritage building's façade onto a podium for the new structure, as is so often done, their plan called for an 11-story office tower to spring from above the old bakery. In this layout, the tower's midair footprint would span north and west of the intact century-old structure to become the ceiling of a 70-ft-tall publicly accessible atrium converted from what was once an empty, L-shaped lot wrapping the old factory. The development, which would also include the repurposing of the other two existing buildings, was dubbed Queen Richmond Centre West.

## Tabletop Tower

Designed by Sweeny with structural consultants Stephenson Engineering, the scheme called for the creation of a "tabletop" platform seven stories in the air from which a conventional office building could be constructed. The existing building, whose ground floor level had to be lowered, as it had initially been half-a-grade above street level to accommodate horse-and-buggy loading, would be fitted with new foundations and internal structure including columns protruding through what was once the building's roof level to support a portion of the 11-story building above. A new elevator core would be constructed to the north of the existing building, and the remainder of the gravity and lateral load from the tower would have to be supported with structure that would pass through the atrium space.

Although the design team opted for a reinforced concrete structural system for the 11-story tower, structural steel was the material of choice for the tabletop framing, and architecturally exposed structural steel (AESS) was used for the tabletop-supporting structure in the building's atrium. All other significant structural and architectural advantages aside,

A view of the atrium from the Peter Street entrance.

Two of the building's three "delta frames."

Terri Meyer Boake

Eleven stories of office space commences 70 ft above the street.

Courtesy of Sweeny &Co Architects and Allied Properties

Peter Kurkjian

▲ A rapid prototype (3D print) of a full delta frame at 1:100 scale.

▼ A Revit model view from Richmond Street showing two delta frames.

Courtesy of Stephenson Engineering

constructing the tabletop and its support from structural steel eliminated the need to shore the tabletop 70-ft above street level during construction.

The design of the tabletop-supporting structure was a significant challenge, considering the enormous loads involved; the need for lateral stiffness given the eccentric location of the elevator core; the more than 75-ft unbraced height from the top of the foundation level to the underside of the tabletop; and the architectural desire to support the building above with a structure that wouldn't clutter the atrium.

The first solution developed was a mega-moment frame comprised of 12 vertical space frame columns, each of which would have the appearance of a tower crane's mast. However, Sweeny pressed for other options as the mega-moment frame congested the atrium with a forest of heavy columns. Inspired by children's jacks, the design team developed an alternative support concept based on the use of three "delta frames." Each delta frame is an hourglass-shaped frame comprised of steel pipes—four rising from the foundation, meeting at approximately the mid-height of the frame, and continuing through to the tabletop to frame directly below the centerlines of the tower's columns, which are placed on a 9-m by 11.25-m (29.5-ft by 37-ft) grid. This configuration halved the unbraced length of the inclined pipe columns, significantly reducing their required member size to provide a slim aesthetic. The result was a support concept that was far less obtrusive to the soaring atrium and which would be a distinctive feature of the iconic development.

Each delta frame carries a maximum factored load of approximately 90,000 kN (20,250 kip), with the heaviest loading on any single leg being 27,500 kN (6,200 kip). Stephenson Engineering opted to use concrete-filled, 1,000-mm-diameter (nearly 40-in.) steel pipes with a 50-mm (2-in.) wall thickness for the legs. Filling the legs was achieved by pumping the concrete through a 100-mm-diameter (4-in.) port located at the base of each leg all the way to the tabletop frame. Infill was a high-slump, 45-MPa (6.5-ksi) concrete with a low-shrinkage additive and having a maximum aggregate size of 10 mm (3⁄8 in.). Each delta frame sits atop of a 1.8-m-deep (6-ft) mat foundation, which in turn rests upon 6-ft-diameter caissons. The pipes are intumescent-coated for fire resistance.

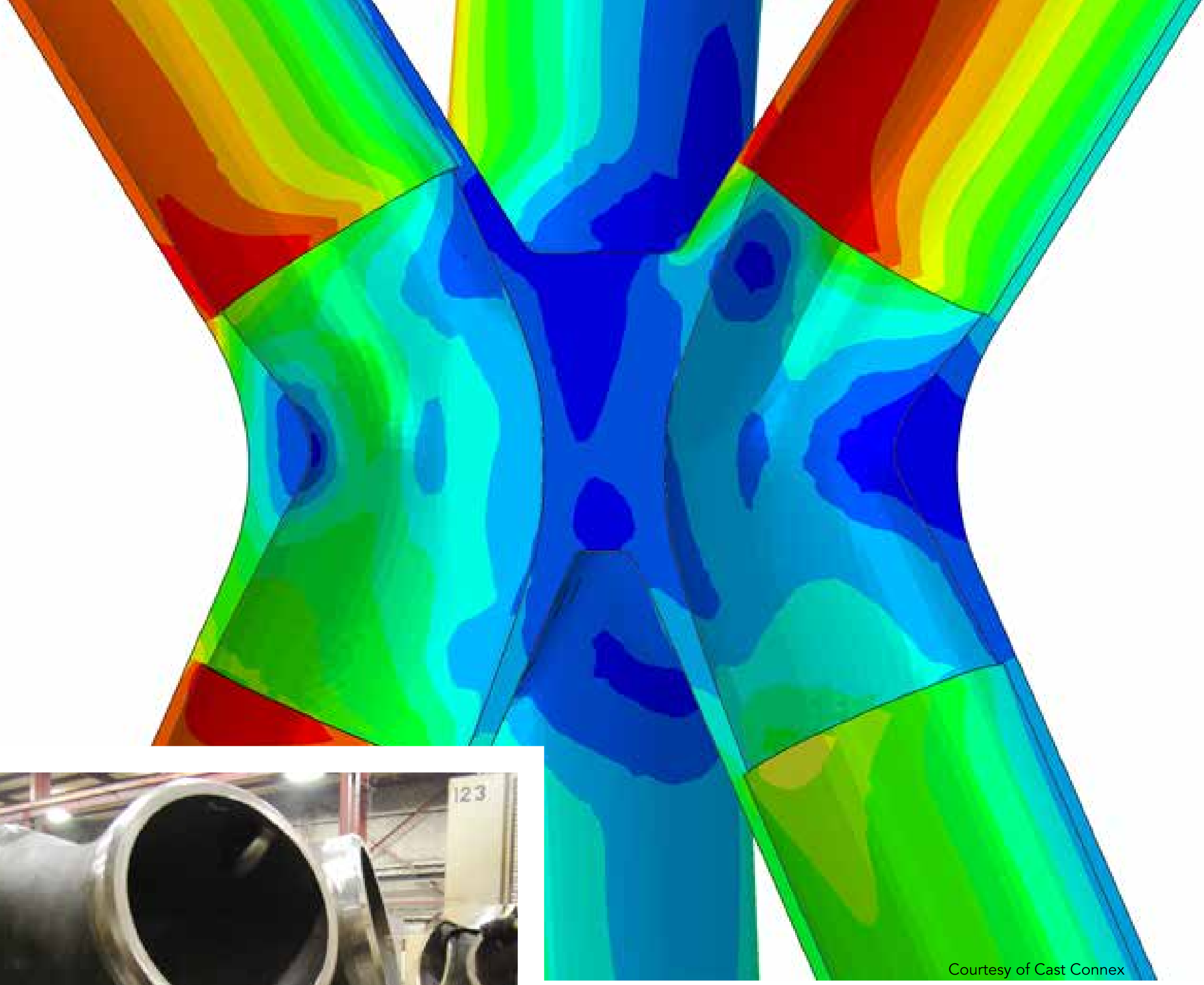
## Design-Assist

With the complexity of the proposed structural steel, the project's GC/CM, Eastern Construction, began reaching out to local steel fabricators. Given its expertise with highly complex steel structures, Walters, Inc., was selected through a competitive forum to provide design-assist services in relation to the delta frames and the tabletop, and to ultimately detail, fabricate and erect the structural steel. Additionally, Cast Connex was engaged to engineer, detail and supply cast nodes for the delta frames.

The design-assist process took place during the late construction documentation phase of the building's design. During this process, Walters and Cast Connex worked collaboratively with the design team, with Walters reviewing all aspects of the structural steel, addressing design and constructability in shop and field, and Cast Connex assisting Stephenson Engineering with incorporating the node into its ETABS building analysis model and iteratively optimizing the node geometry and updating the design team's model.

## Delta Frames

The delta frames posed a significant challenge from a constructability perspective. After studying the frames, Walters recommended the central junction point of the frame (the "node") be detailed independently from the frame's lower and upper legs such that each leg and the node could be shipped to site separately and with the pipe members and node to be welded together in place in the field. The decision to make use of a cast steel node at the central junction of the delta frames, rather than fabricated nodes, came about through an evaluation of cost and aesthetics.


Courtesy of Cast Connex


Courtesy of Cast Connex

Finite element analysis of the cast node—equivalent stress results for a load case.

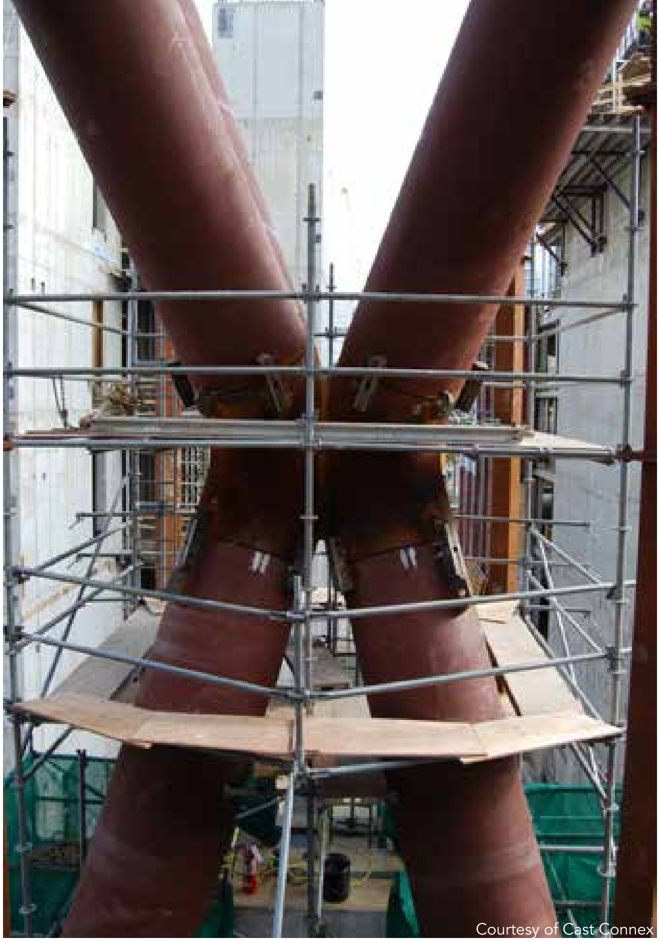
A finished, machined cast steel node.

The design team's original concept for a fabricated node called for all of the pipe members of the delta frame to align concentrically at the central junction. This would have required the node to be stitched together from various profile-cut segments of large-diameter, heavy-walled pipe, as well as required significant internal stiffening to ensure the reduced section was capable of transferring the forces. To simplify node fabrication, Walters recommended pulling the legs away from one another at the kernel point of the delta frame such that a heavy, 200-mm-thick (8-in.) steel plate could be used at the "waist" of each node to which relatively short segments of miter-cut pipe could be welded in the shop.

In parallel, Cast Connex prepared a preliminary feasibility and cost study on the use of cast nodes. Concentric delta frame geometry resulted in a cast node over 3-m-tall (10-ft) weighing somewhere in the neighborhood of 37.5 tons. During their study, Cast Connex carried out a preliminary geometric optimization of the cast node where eccentricity was incrementally increased thus reducing casting size. Ultimately, the most compact cast node resulted from the use of eccentricities, which were about half of those proposed in the fabricated node concept, resulting in a better balance of visual aesthetic and cost.

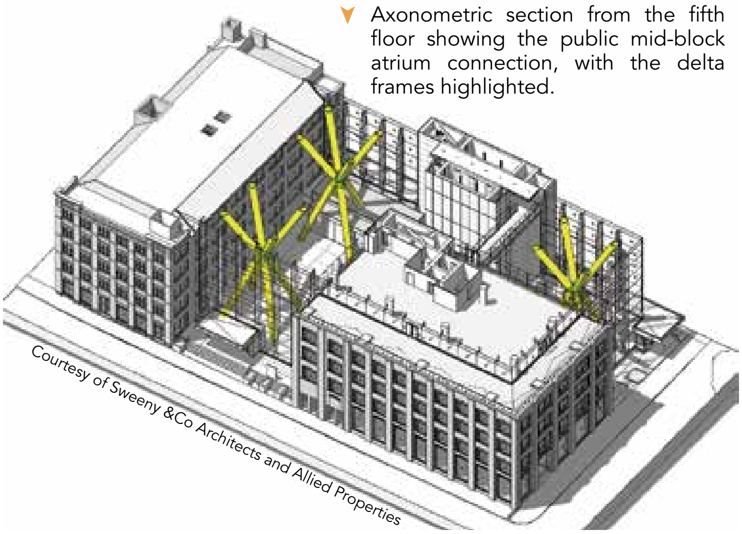
The cast node concept that Cast Connex developed also featured a cellular design, allowing concrete infill to be continuous from each lower leg through the node and into each upper leg of the delta frame. Prior to design-assist, it was thought that perhaps rebar would be required to reinforce the concrete infill at the junction points between the node nozzle ends and the pipes. Additionally, the design team was calling for complete joint penetration welding between the node nozzle ends and the pipes due to high bending forces which existed in the delta frame members. Walters recommended eliminating a significant vertical eccentricity that had been designed into the steel framing at the top of the delta frame to reducing bending moments in the legs. This simplification removed the need for rebar and shear studs within the delta frame legs and castings, as was confirmed by Cast Connex's sophisticated finite element stress analysis of the composite system under nearly 400 unique load combinations. Walters further confirmed the joints between the node and the pipes could be achieved with combination bearing and partial joint penetration groove welds—design-assist improvements that resulted in significant cost savings to the project.

While the interior shaping of the cast steel node was optimized by Cast Connex to accommodate the severe loading from the building above, the exterior shaping of the node was




Northwest delta frame installed, with temporary supports still in place.

Axonometric section from the fifth floor showing the public mid-block atrium connection, with the delta frames highlighted.




The steel "tabletop" framing over the existing building, supported by the delta frames.

developed collaboratively with Sweeny to deliver the delta frame's resulting aesthetic, one where each of the legs appears to effortlessly curve while subtly merging with each of the neighboring legs.

Walters also collaborated with the design team on the design of fabricated tapers for the ends of the lower legs of the delta frames. The tapers were built-up from an internal tapering cruciform built from 127-mm-thick (5-in.) plates and exterior formed 50-mm-thick (2-in.) conical shells. The legs tapered from 1,000 mm (39 in.) at their widest down to 500 mm (19.5 in.) at their base over a 3.5-m (11.5-ft) length. From there, the tapered ends were fitted with a built-up base plate arrangement consisting of three, 100-mm-thick (4-in.) stacked plates, each increasing in diameter with the final plate drilled to accept the anchor rods. Concrete fill ports and vent holes at the base of the delta frame legs were located in the tapered ends, but below the finished ground floor slab so as to be out of sight in the completed building.

When dealing with doubly inclined steel columns, of utmost importance is placing the anchor rods in the correct location and orientation. Walters thus designed (and positioned on-site) sophisticated steel alignment frames, which were embedded in the reinforced concrete foundations at the base of each delta frame.

## Tabletop Steel Framing

The design-assist process also focused on the steel framing of the tabletop. Of particular concern were the junctions where the topsides of the delta frame's upper legs mated with the tabletop steel and the concrete column above. In these locations, significant drag/diaphragm forces had to be resolved and the concrete column had to be sufficiently developed to behave integrally with the steel tabletop frame.

Walters developed a built-up box detail at the topside of the delta frame legs, which would be fitted with rebar and filled with concrete to integrate the concrete columns above with the structural steel tabletop.

Walters carried out all steel connection design and detailing and fabricated the structural steel in its shop in Hamilton, Ontario. Cast Connex prepared all casting specifications, engineered and detailed the cast nodes and oversaw their production in a U.S. steel foundry. The nodes were then machined in Ontario and delivered to Walters' shop, where they were fitted with temporary erection aids and trial assembled to the legs.

With the anchor rod locations precisely set within the foundations on site, erection could proceed with the team's full confidence. The erection of the delta frames was carefully pre-planned to minimize site duration and street closures. Walters installed a custom temporary shoring system to provide structural support and allow geometric adjustment of the system to ensure tight contact at each of the 24 milled bearing joints between castings and pipe legs, while ensuring the tops of the legs at Level 7 also remained within allowable tolerances. Level 7 was ultimately fully erected to within ¼-in. of the theoretical plan coordinates and elevations.

➤ The lower portion of one of the delta frames, with the node installed.

Courtesy of Cast Connex

The tops of the delta frames were then tied back to the elevator core, and a field-welding crew welded out the partial-joint penetration groove welds between each of the pipes and the cast nodes, and all temporary erection aids were removed. Simultaneously, the infill members of the tabletop framing were installed, spanning from the tops of the delta frames back to the elevator core and the columns protruding from the top of the heritage structure, and once all of the steel was in place, including the concrete on metal deck on the tabletop level, the legs of the delta frames were pumped full with concrete. (A time-lapse video showing the site installation of the three delta frames can be viewed at **http://bit.ly/1bvC0vi** .)

A mixed-use development featuring the adaptive repurposing of three heritage buildings and the construction of an innovative new office structure, the Queen Richmond Centre West is a model of urban intensification and an iconic addition to the city of Toronto. The building's soaring atrium extends the public realm indoors, while passers-by often stop to marvel at what is clearly a structural feat. The inspired design was enabled through a collaborative design-assist process, which not only enhanced constructability and reduced costs, but also resulted in an improved architectural design with the use of steel castings, effortlessly creating an AESS assembly of unparalleled strength and elegance.

A tour of Queen Richmond Centre West will take place the Wednesday of NASCC (March 26); the project is located just a few blocks from the Metro Toronto Convention Centre, NASCC's home in Toronto. Visit **www.aisc.org/nascc** for more information. ■

**Owner**
Allied Properties REIT

**General Contractor/Construction Manager**
Eastern Construction

**Architect**
Sweeny &Co Architects, Inc.

**Structural Engineer**
Stephenson Engineering

**Steel Fabricator, Erector and Detailer**
Walters, Inc.

**Steel Casting Engineer and Supplier**
Cast Connex (AISC Member)

➤ The delta frame assemblies were inspired by children's jacks.

Courtesy of Cast Connex