The Case of the Disappearing Right Angle

Innovation in Architectural Steel

Castings and Curves

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Creating Curves

Wells Fargo Building, Salt Lake City, Utah

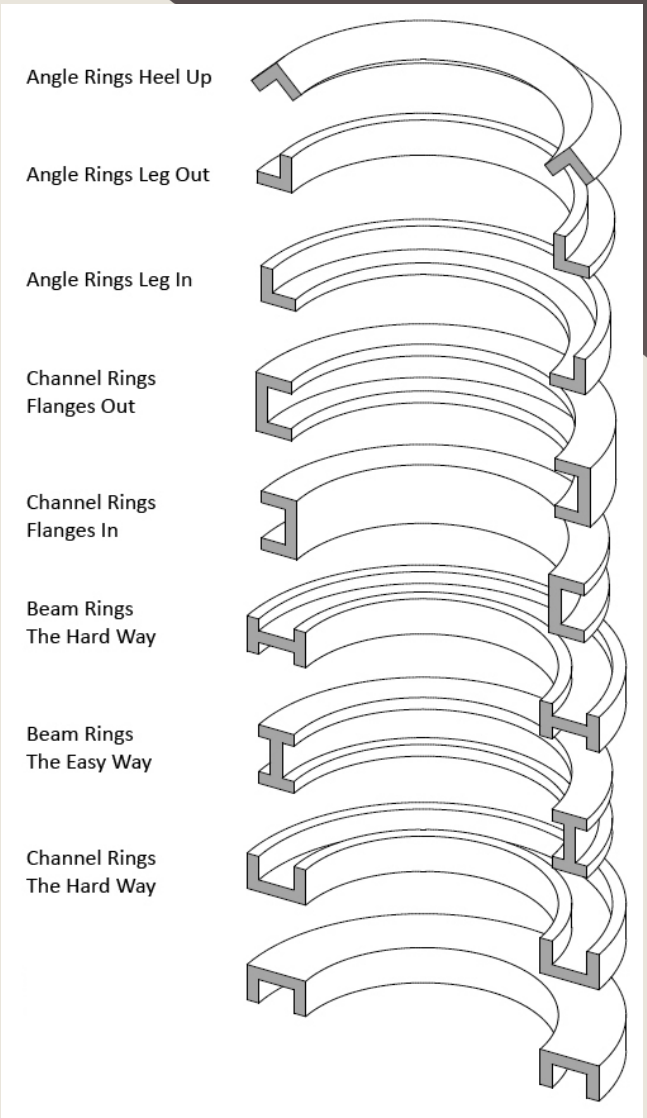
4 Ways of Tackling "Curves"

- bend the steel
  - Using a 3 point smooth bending machine
  - Using a brake press
  - Heat applied bending
- facet the building to give the appearance of curves while using straight members
- cut curved forms out of plate material
- induction heating

Bending Steel Issues

- Member type
- Orientation of member
- Length of member
- Shipping considerations
- Sourced out work
- Accuracy of curve
- Multiple curves
- Steel remains cold

Hard Way vs. Easy Way?



- Different shapes are more or less "easy" to bend
- Tendency for buckling on tighter curves
- Thin steel likely to buckle
- Heavier steel harder to bend

INDUCTION BENDING

For induction bending heat is applied sequentially to the specific portion to be bent. Used more for repetitive mechanical bending than for architectural bending.

BENDERS AND EQUIPMENT

Dies have to be tooled for each shape and changed between jobs. Smaller runs have higher costs. Bender must have the dies in order to do the job.

CORRECTNESS OF CURVE

The fabricator checks the accuracy of the curve against a wooden form as this section passes through the rollers.

STRAIGHT ENDS!

There is always a straight piece at the end as a result of the bending process that is cut off and recycled. So the length of “raw” member must be longer than the bent one.

TRANSPORTATION ISSUES

The straight steel that is shipped INTO the bending facility may NOT fit on the same truck for transport back to the fabricator. Detailing must account for this and include splices if required.

SIZE MATTERS!

These curved tubes for the Canadian Museum for Human Rights were to the limit for the bending facility. These will be AESS4 quality in the finished project as the "Cloud Rails" will be used to support the specialty glazing system.

SPLICING BENT STEEL

The curved stairs on the Art Gallery of Ontario were fabricated using round HSS. There were difficulties in ascertaining approval of the splices as unavoidable deformations happen when bending tubes, so guarantees on the welds were difficult.

SPLICING BENT TUBES

When splicing tubular steel so that the joins are not evident, it is typical to use an inset sleeve to form the backstop for the weld. Given the angular splice and deformation of the material, this proved to add a challenge to the splice.

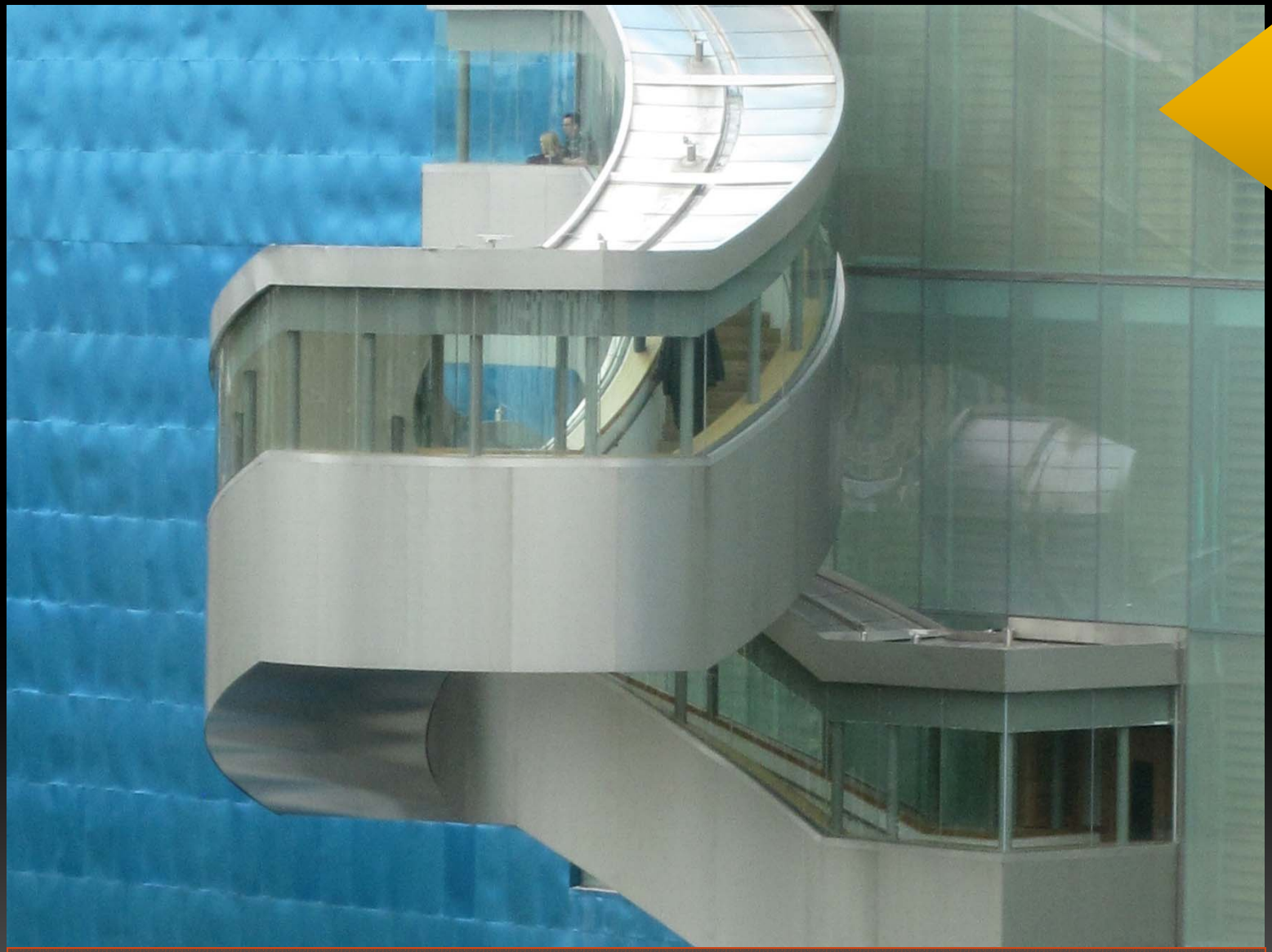
SPLICING BENT TUBES

Although workmanship was not a large issue in making the splices, the contractor could not use plates or bulkier methods as the cladding for the stair was to be very tight to the steel.

TIGHT CURVES AND TOLERANCES

Although the steel structure cannot be seen in the finished stair, keeping to tight tolerances and clean joints was necessary to ensure a sleek appearance of the finished wood cladding.

PARTIAL EXPOSURE



The rear curved stair of the AGO partially exposes the tubular structural steel frame. The cladding is again very tight to the structure, keeping the stair as light looking as possible.

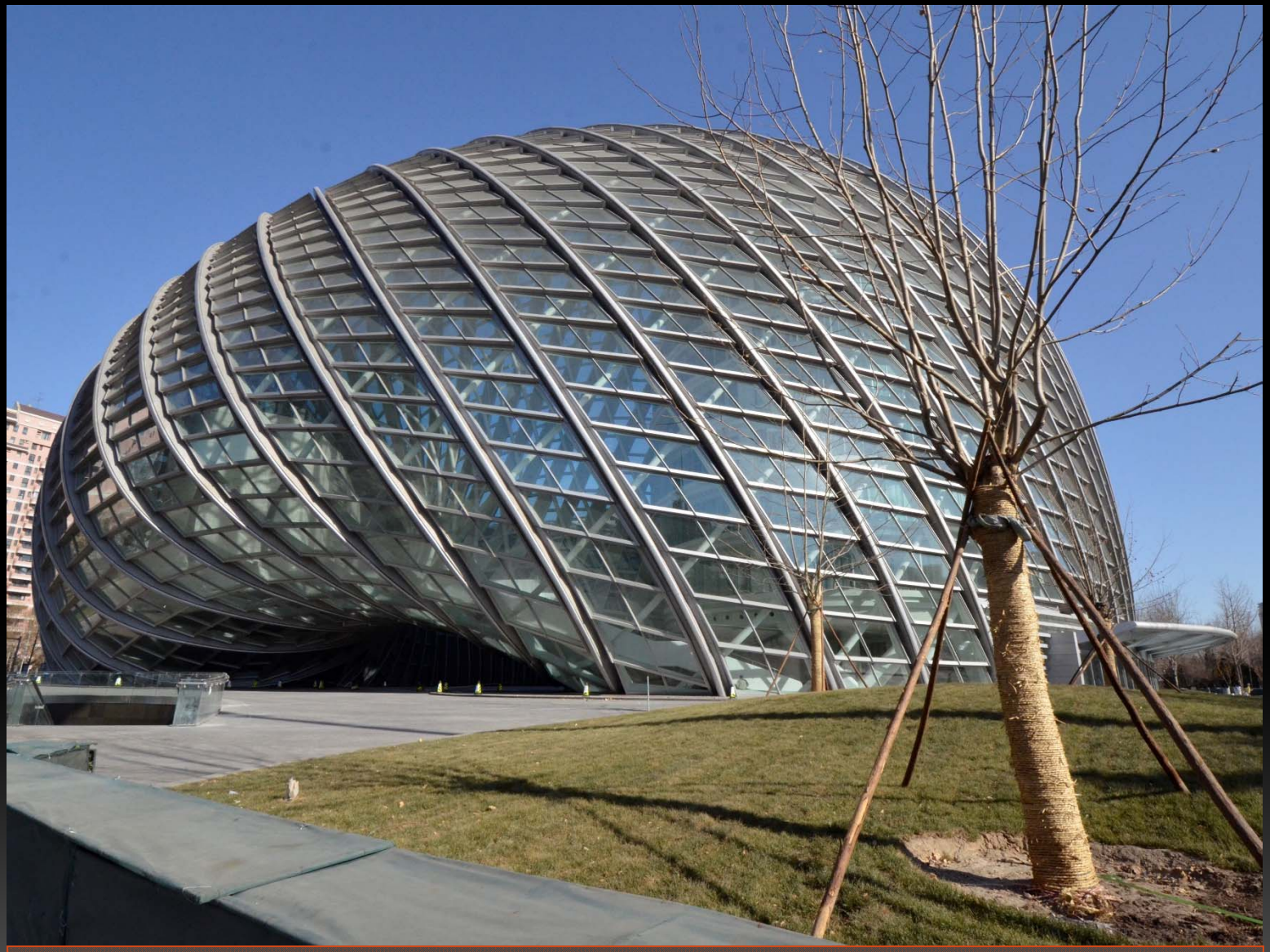
CURVED TRUSSES

The Abilities Centre in Whitby, Ontario, uses curved steel to create the top and bottom chords of these large, long span trusses over the rink area of the sports facility.

HIDDEN CONNECTIONS

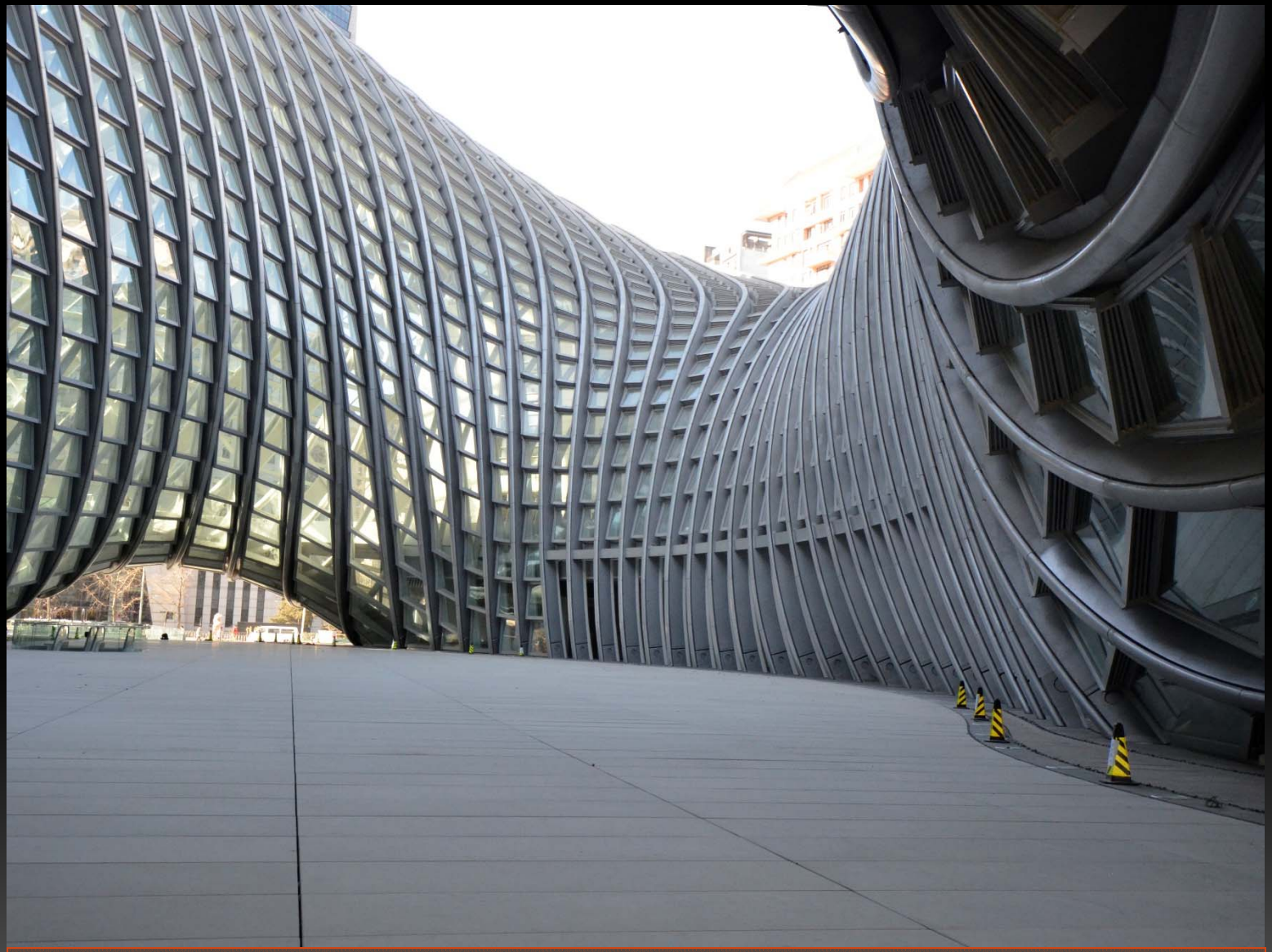
The connection between the curved “vertical” truss and the long horizontal members have been done as to be invisible. Although similar methods are used as in the AGO stair, the AESS4 level of this project requires impeccable workmanship.

MOST PARAMETRIC



The Phoenix New Media Center in Beijing, China is touted as the “most parametric” building in China.

PHOENIX NEW MEDIA CENTER



Hollow donut shape with multiple curves in action in all directions.

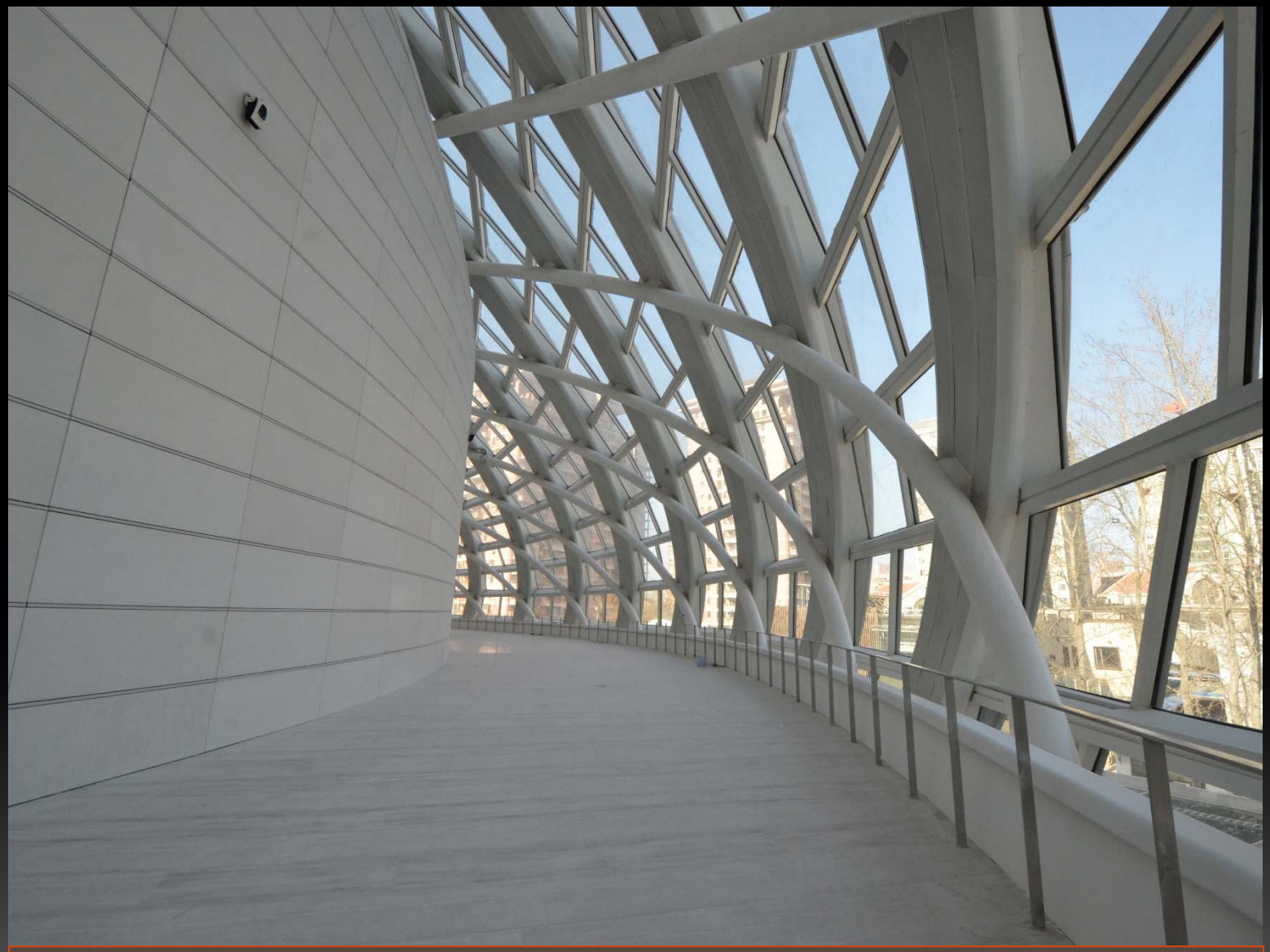
LAPPED CLADDING APROACH

The cladding system is lapped in a shingle fashion.

PIN CONNECTION

Simple pin connection to secure the bottom of the round member to the ground floor.

TWO SYSTEMS

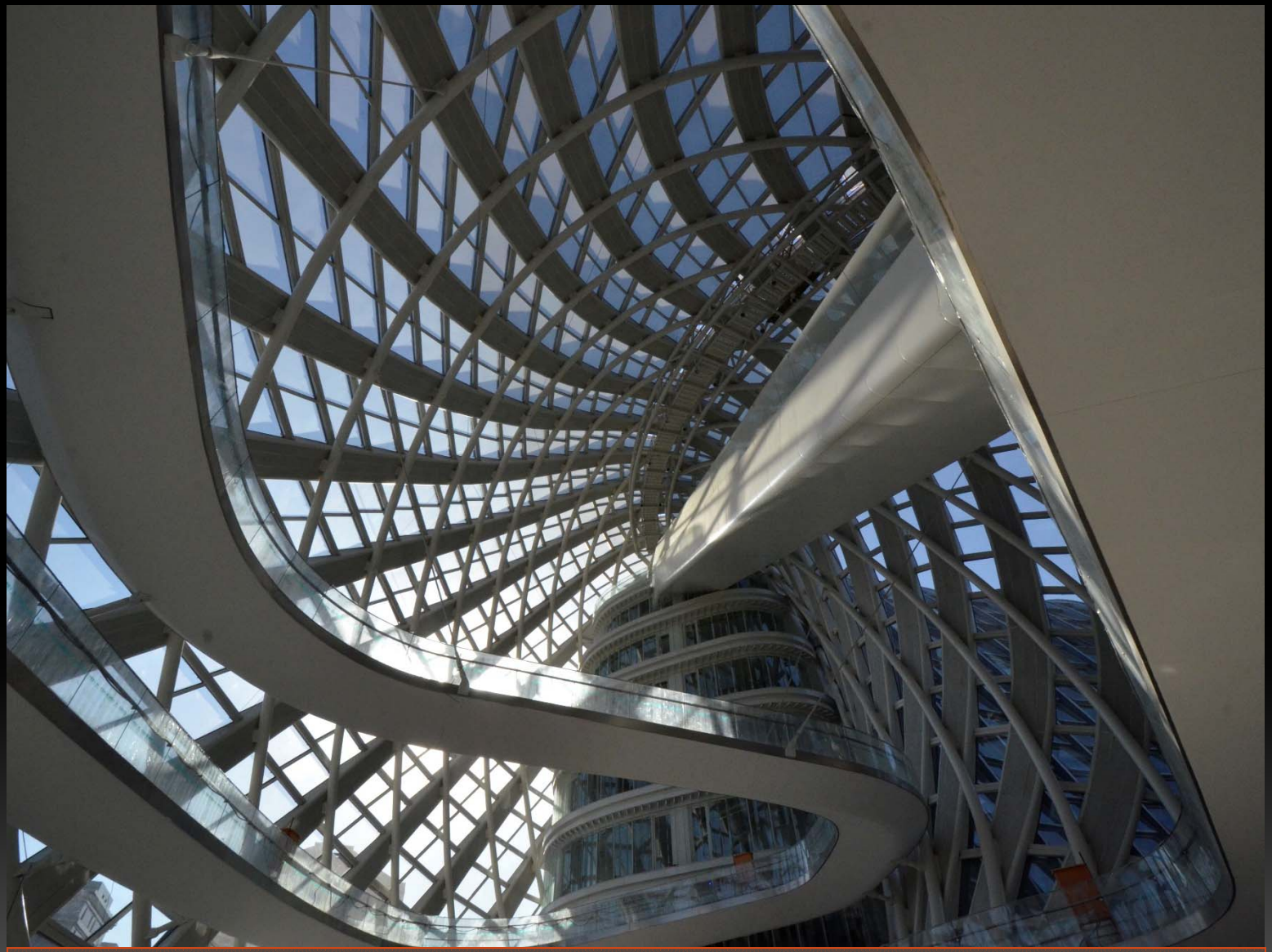


Tubular steel is used to create the AESS curves in one direction and concealed steel to support the exterior wall curvature.

SPIRALING RAMP

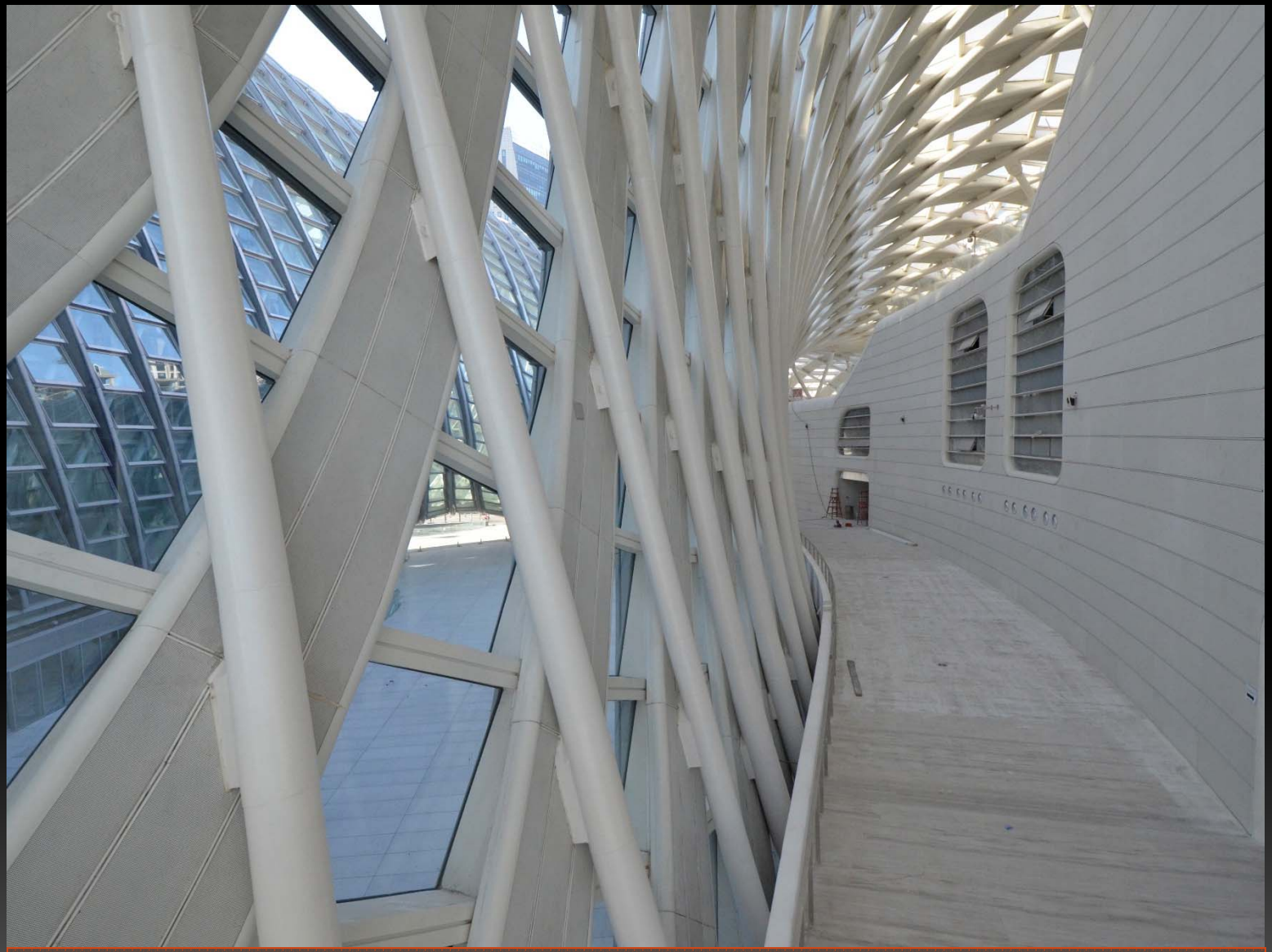
Spiraling ramp is a means of egress to the top levels of the theatre spaces.

SPIRALING RAMP



View up to the top of the lobby space.

CROSSING DIAGONALS



The round tubes are connected to the rectangular custom profiles through an interior finish layer.

STABILIZING THE RAMPS

The ramp system is tied back to the X points of the two structural systems via double ended pin connectors.

CONNECTION DETAILS

Butt welds that have been neatly done and not ground were used to splice the tubes.

PHOENIX NEW MEDIA CENTER

Ideas behind 3D shape.

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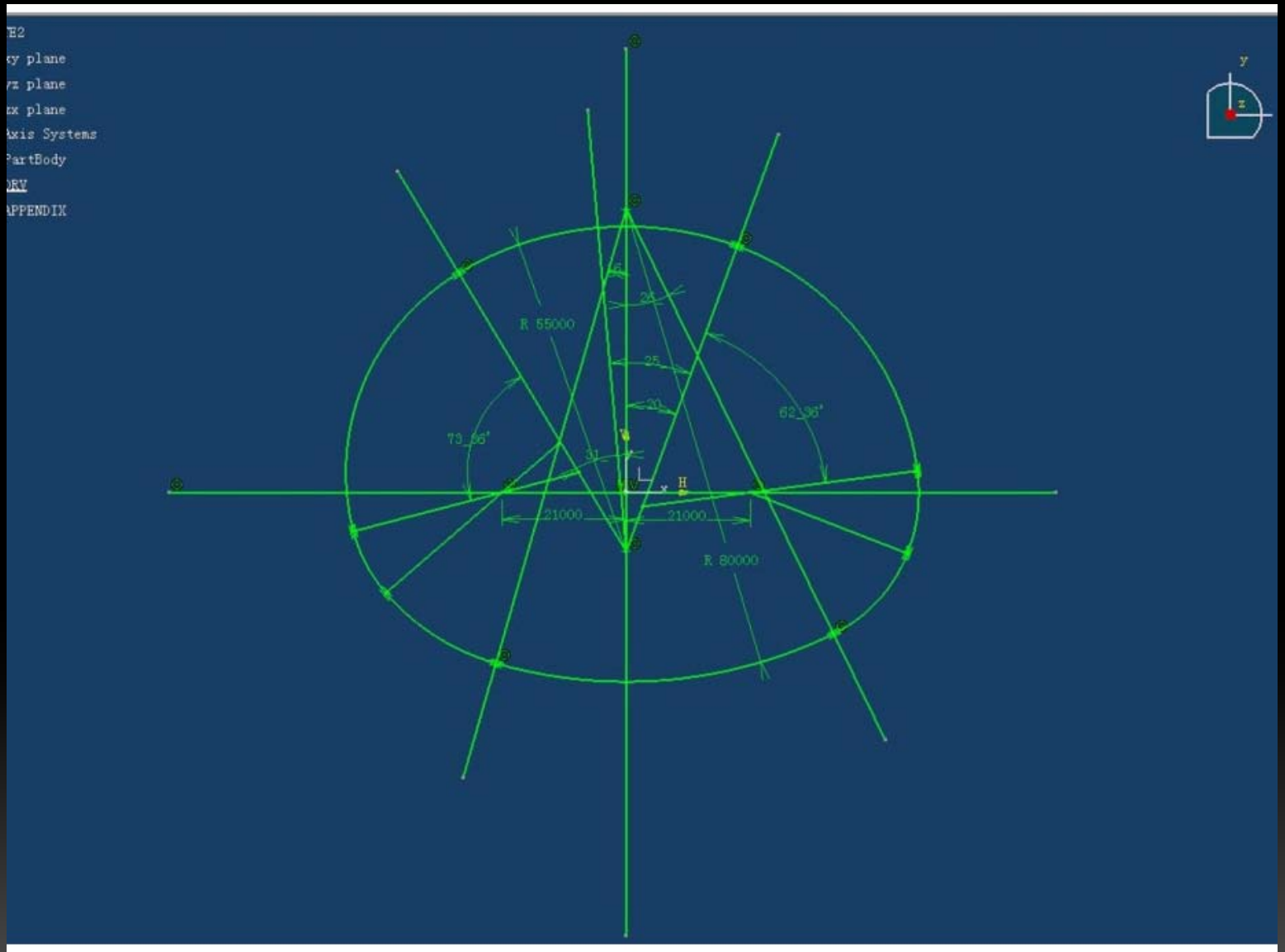

Working out the geometry. The complex looking curves are actually made from sections of a circle joined so that the tangents are smooth.

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View of major connector showing welded connections for exposed tubes and bolted connections for concealed structure.

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Ground floor support steel goes in. Use of tubes and welded connections.

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PHOENIX NEW MEDIA CENTER

Aerial view during latter stages of construction.

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Two contrasting shapes of steel for the exterior and interior systems.

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View of exterior during construction.

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Interior view of construction of spiraling ramp.

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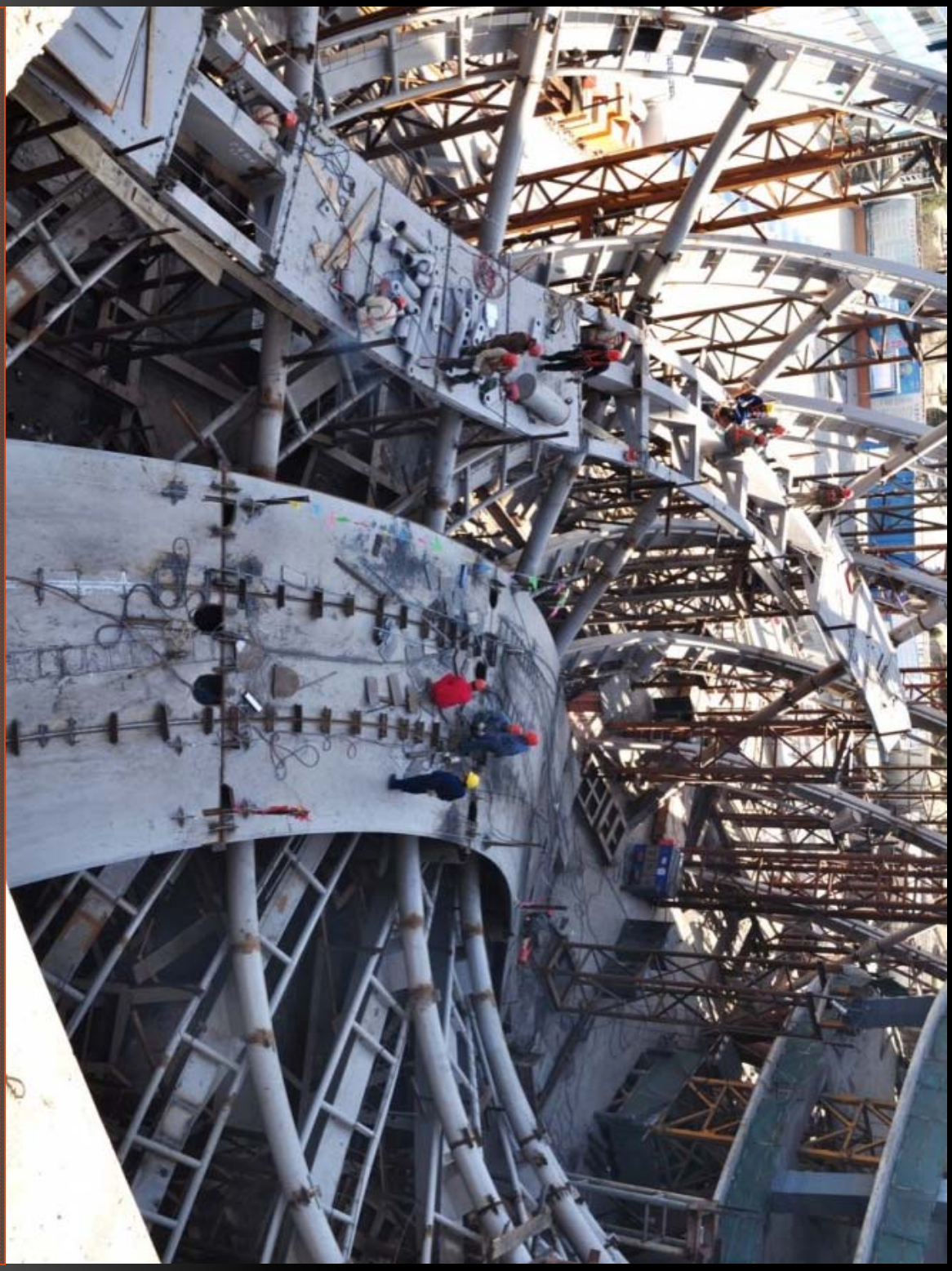
Ramp construction.



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Ribs constructed from custom plate with interior reinforcement.

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Installation of shingled glazing system.

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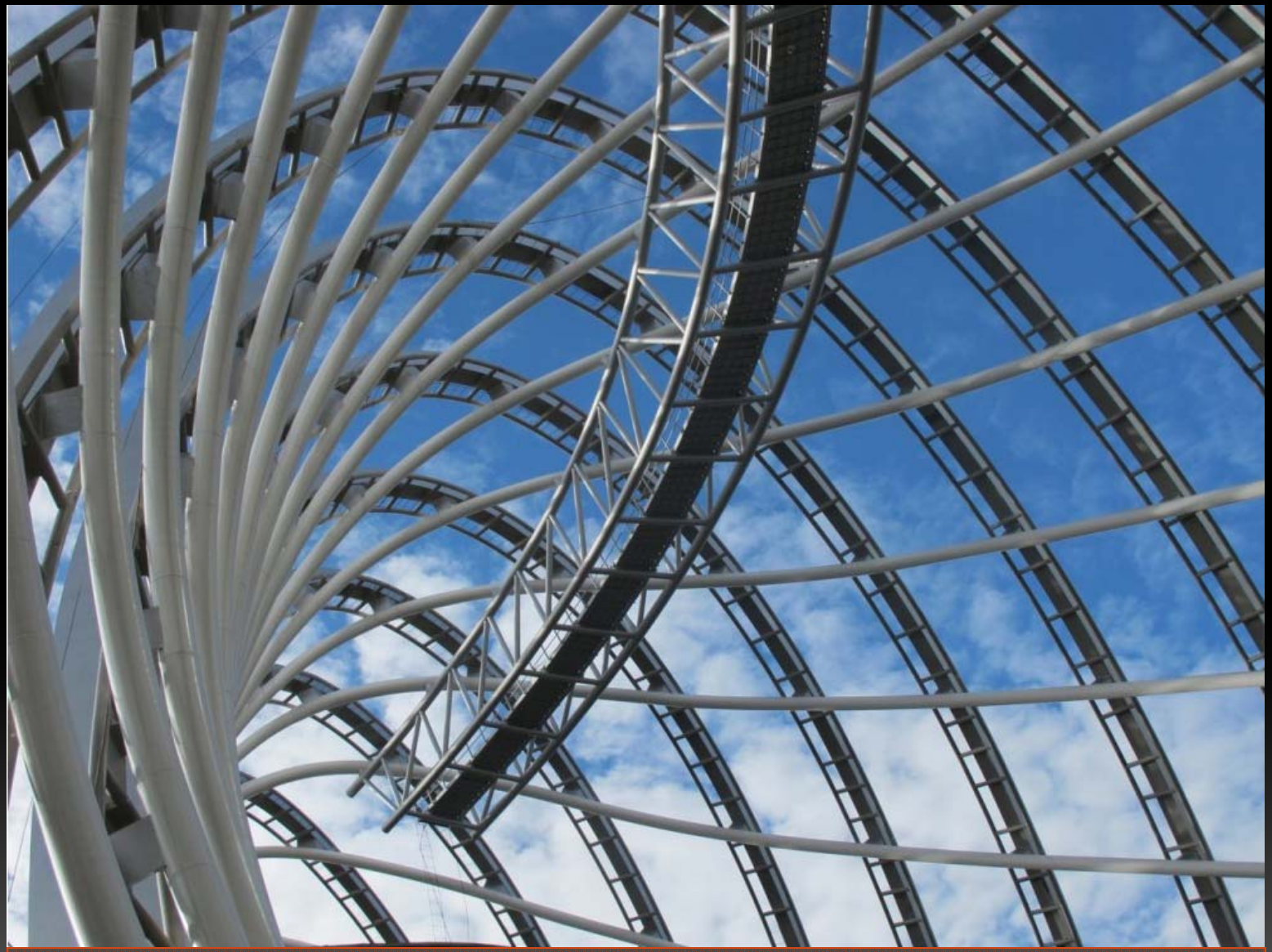

Interior view showing construction of upper spiraling ramp.

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Tell-tale signs of the welding platforms that reveal the locations of the major connections between members.

BRAKE FORMING

In brake forming, sheet steel is carefully marked with “lines” and then the brake press puts pressure on the lines to create creases. Much skill is required by the operator to determine the correct pressure and line placement.

MARKING THE PLATES

The plate is marked where the hits of the brake press are to take place in order to ensure correct geometry. Experience and accuracy are required as this is not as "scientific" a method and relies on the "feel" of the press operator for success.

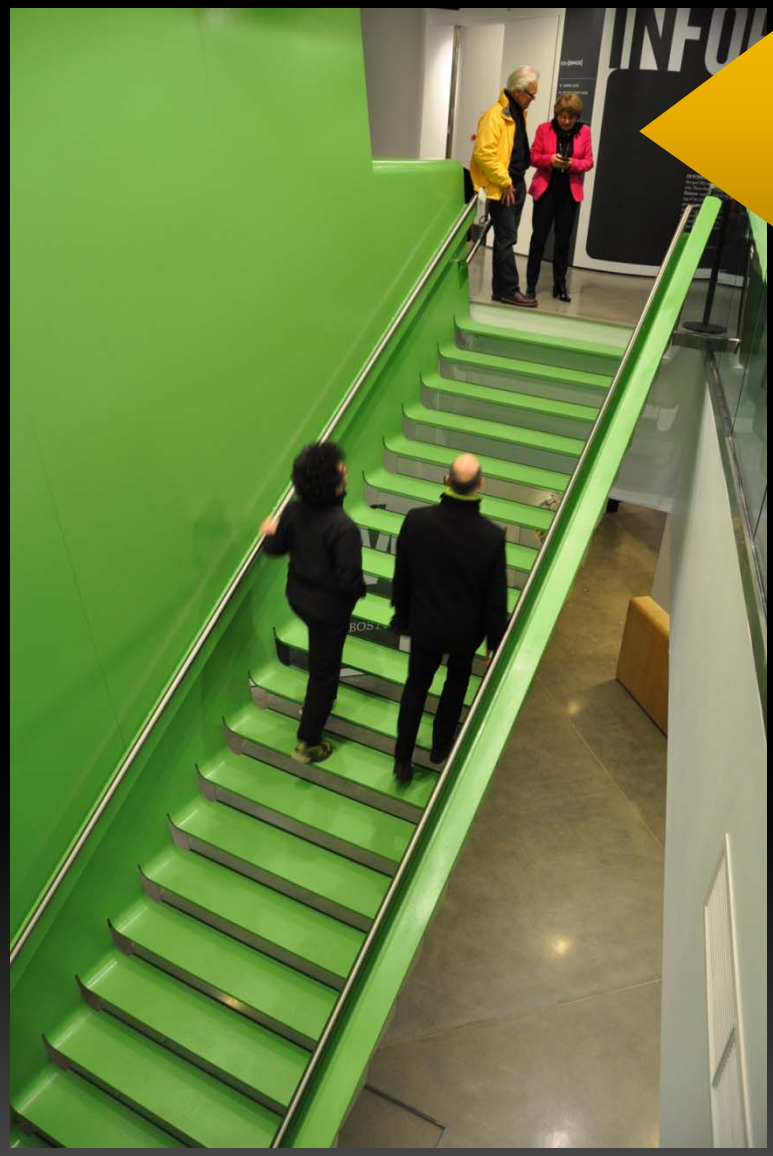
BRAKE FORMING

These oversized cylinders have been created using brake forming. The lines are evident on the interior but not the exterior. Brake forming is used for oversized members as well as plate that has complex or non uniform curves.

BRAKE FORMING PLATE

Here on the AGO, brake forming was used to form the large plate sections into the complex curves required for the stair. Weld seams can be seen to join the wedges of the large flat portion that will provide support for the steps.

BRAKE FORMED STAIR

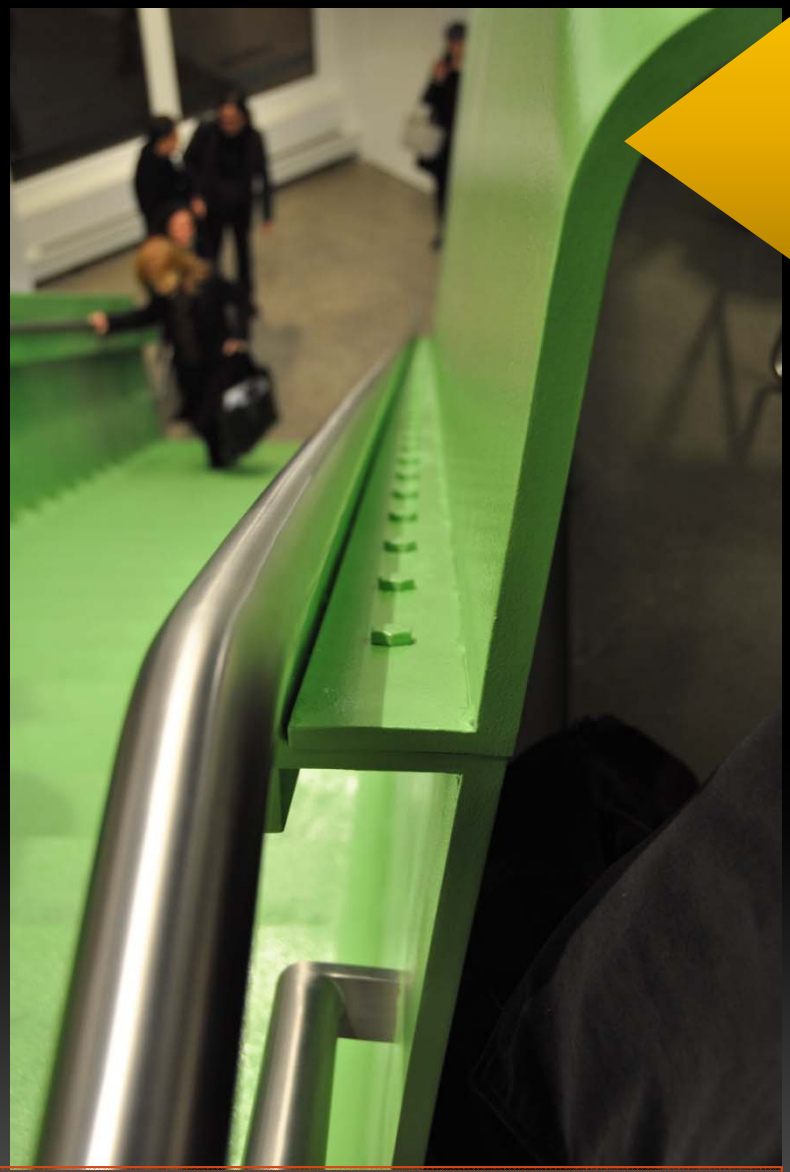


The grand stair at the Boston Society of Architects was created using brake forming. The stair (tread portion to handrail) was installed/shipped in one piece. The side piece/hanger is separate. Bolted joint visible at left.

HIDDEN WELDED CONNECTIONS

The treads were fabricated separately – brake forming used for the curves. The treads were then welded to the side panels and the welds completely concealed. This is AESS4 level workmanship.

COST SAVING DETAILS



In spite of the AESS4 level of the project, some cost saving measures were taken in the fabrication. Continuous weld s were avoided by making the welds align with the bolts. The bolted splice was “hidden” behind the handrail.

SCALE MAKES CURVES POSSIBLE

This concert hall in Boston, Massachusetts has what appears to be a curved triangular truss supporting its fabric roof.

SEGMENTED CURVES

Although the truss for this Boston Amphitheatre gives the impression of being curved, it is made from all straight segments. The bolted connections between the segments allow for easier assembly than welded connections.

REINFORCED JOINTS

The triangular plates that surround the tube to plate connection are used to provide additional stiffness to the joint. These type of end plate connectors (normally without reinforcement) would be more typical in tube to tube splices.

FACETED DESIGNS

The stadium designed by Peter Eisenman may appear to be curved, but is actually created from all flat sections. Faceting is used in the design to give the illusion of a smooth curve. This saves greatly on fabrication and erection costs.

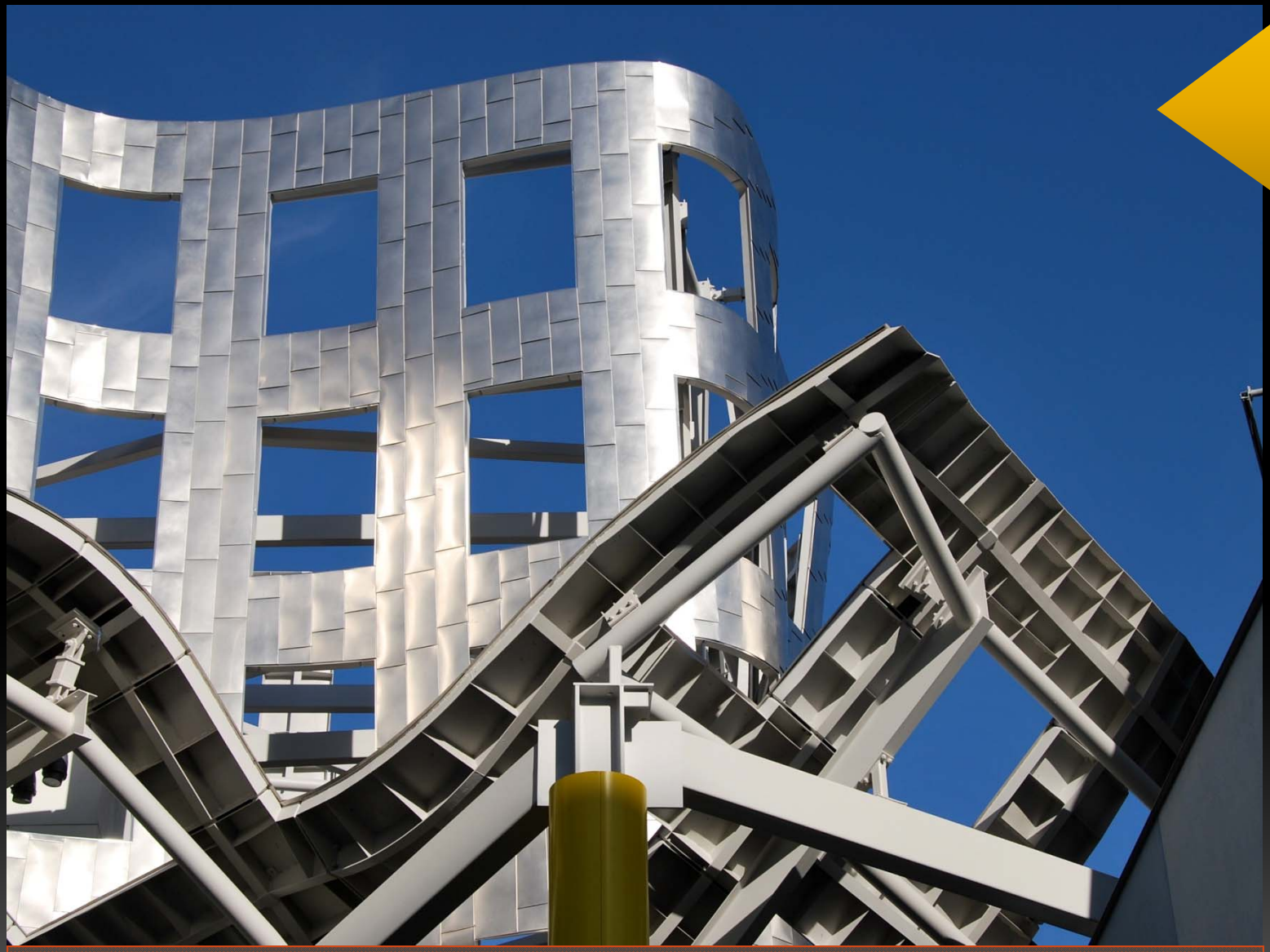
FACETED DESIGNS

It can be seen that the exposed members are quite straight, the curved geometry being resolved towards the exterior cladding by a sequential decrease in the span distance.

WILD ECCENTRICITIES

One might say that Frank Gehry has been singularly responsible for encouraging wild eccentricities and challenges in the fabrication and erection of structural steel!

CURVES AND STRAIGHTS



The sun shade canopy over the courtyard at the Lou Ruvo Brain Center combines curved steel cladding on a more rectilinear prefabricated framing system.

RECTILINEAR SUPPORTS CURVES

Here the prefabricated curved panels that form the sun shade for the courtyard of the Lou Ruvo Brain Center are in fact supported by straight W and HSS members using fairly simple connection types.

COMPLEX CURVES

Frank Gehry's Experience Music Project in Seattle, Washington used custom welded beams fabricated from plate to create the complex curves for the project.

SPLICING BEAM SECTIONS

Although the steel exposed, it is quite high up and the aesthetic might only call for an AESS2. Here more evident splices were permitted as they added to the rugged aesthetic of the interior.

GEHRY EMP

Steel web members have been cut from plate that economizes the use of steel via the “nesting” of the elements.

GEHRY EMP

Raw steel frame.

OTHER APPROACHES

The Chinese National Theatre in Beijing is a large “egg” shape. The exterior cladding is faceted. The interior structure uses cut sections of plate to create true curves.

CURVED PLATE TRUSSES

Each of the trusses that forms the amazing structure for the theatre is created from plate sections that have been cut to true curves and welded to create larger entities.

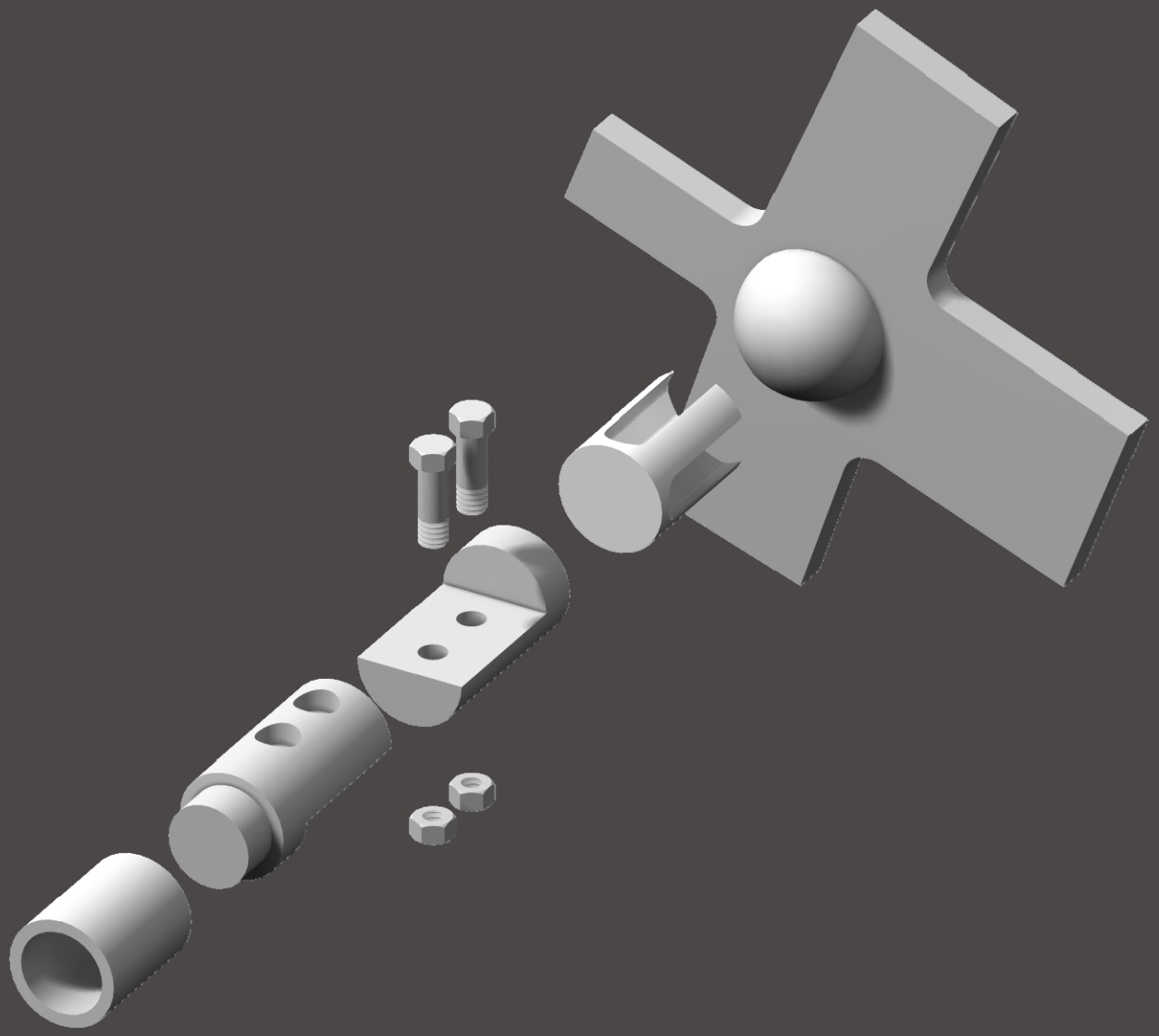
SEAMLESS WELDS FOR AESS4

The welds within the trusses have been cleanly done, carefully filled and sanded to AESS4 levels in order to provide a clean, seamless appearance. They are in close range to sight and touch.

NON UNIFORM JOINTS

The round bracing members that connect the plate trusses are attached via a “ball” joint as it most readily adapts to the continually changing geometry of the structure.

HIDDEN CONNECTIONS

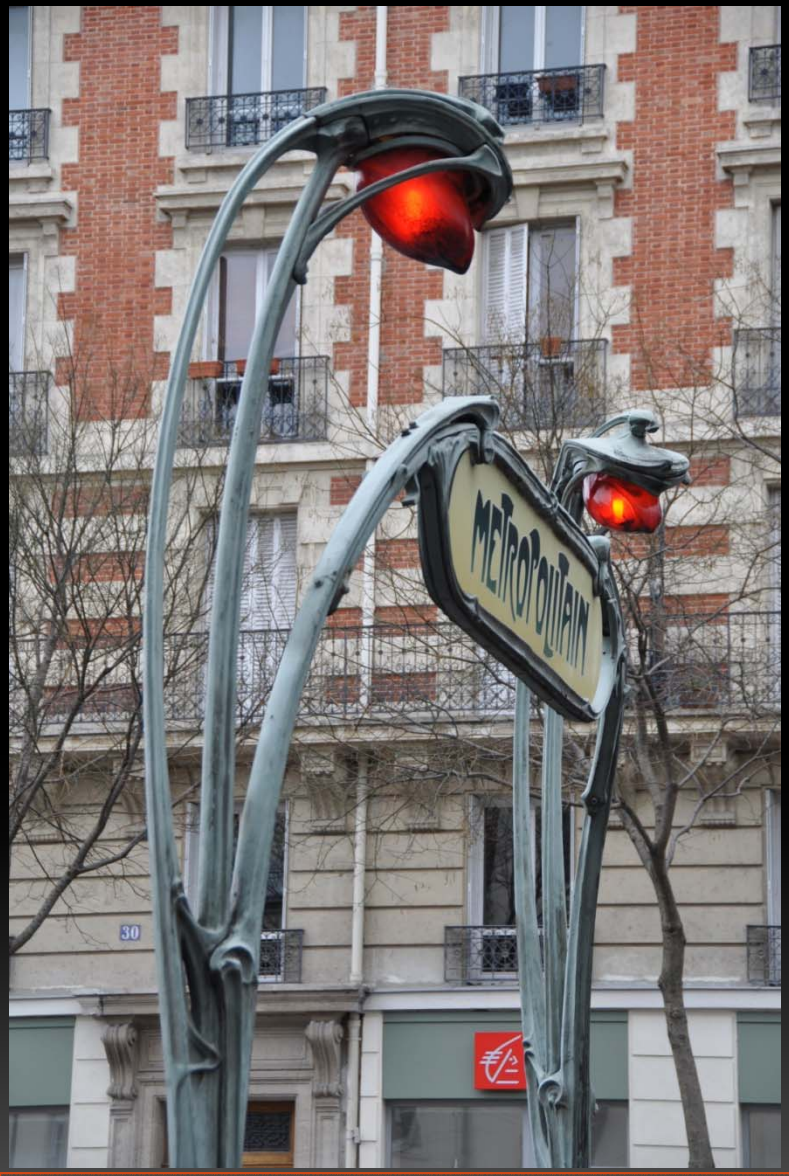


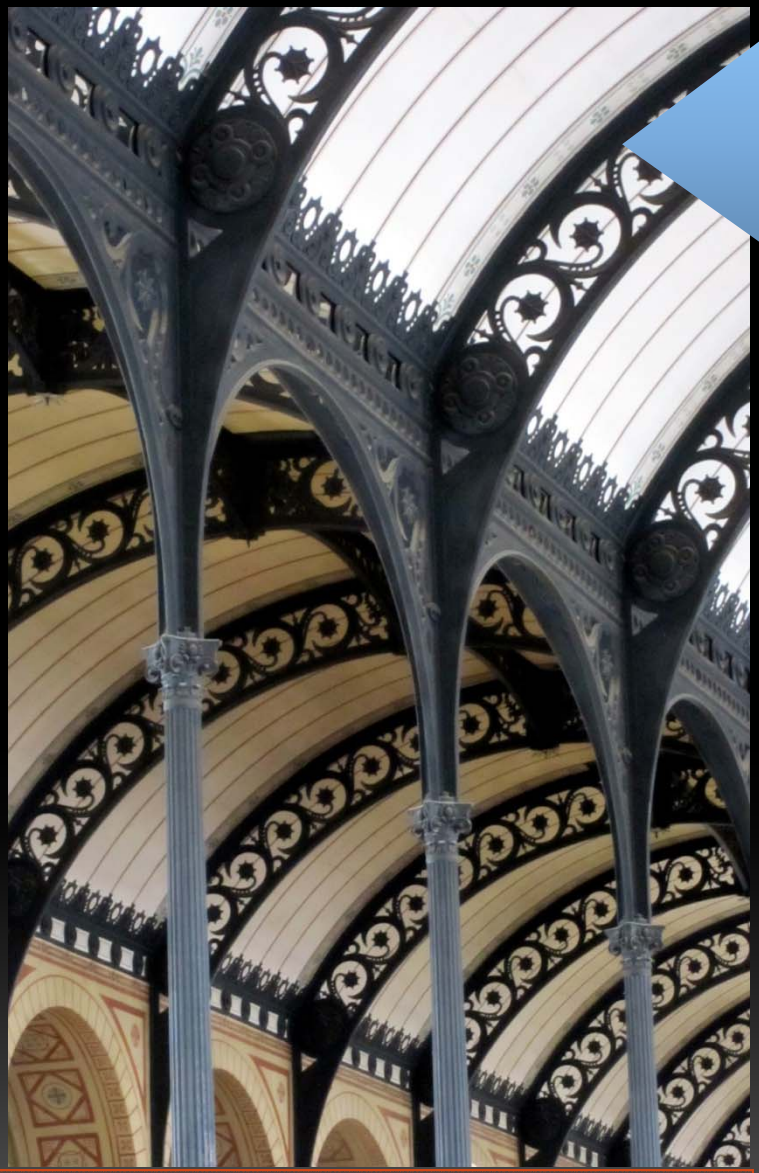
Here you can see the “secret” behind this joint! Here a fully welded “appearance” was desired, but a bolted connection has been used – subsequently covered with filler, sanded and then painted.

Castings and Cast Connections

University of Guelph | Young+Wright 2009

ORNATE NO MORE





Cast iron or steel used to be synonymous with the requirement for high levels of ornamentation, made cost effective through the use of articulate forms. This is no longer the case. Castings are now used to SIMPLIFY connections!

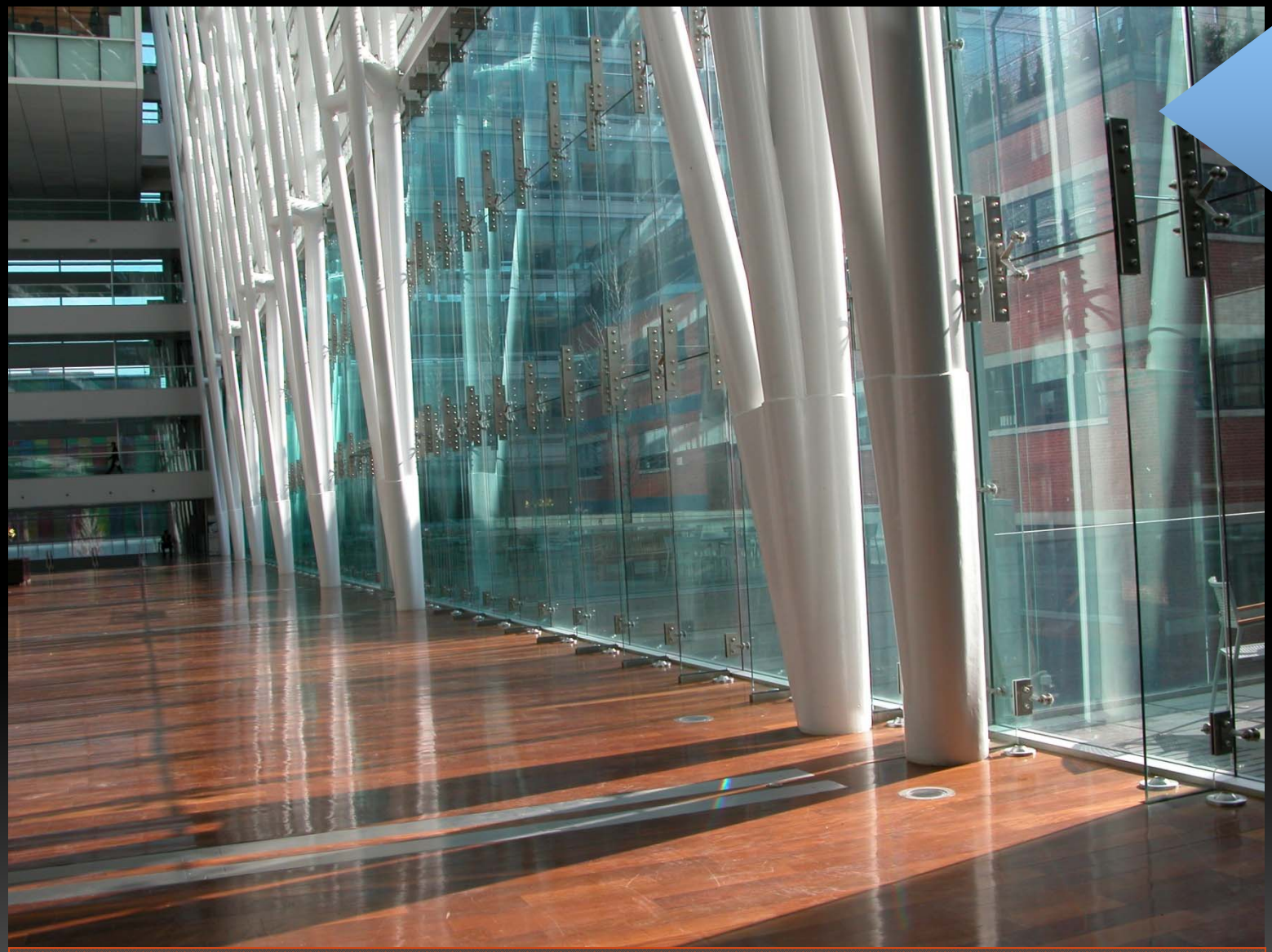
Castings

- Used for special connections
- Can be one-of large pieces formed with expendable molds (i.e. Structural)
- Can be smaller die cast pieces made in great quantity (i.e. glazing attachments)
- Can be solid or hollow depending on size and purpose

Structural Cast Connections

- It is said that when the fabrication costs for a connection become 4 times as expensive as the materials used to create the connection, then castings begin to make economic sense.

UNIQUE STRUCTURAL CASTINGS

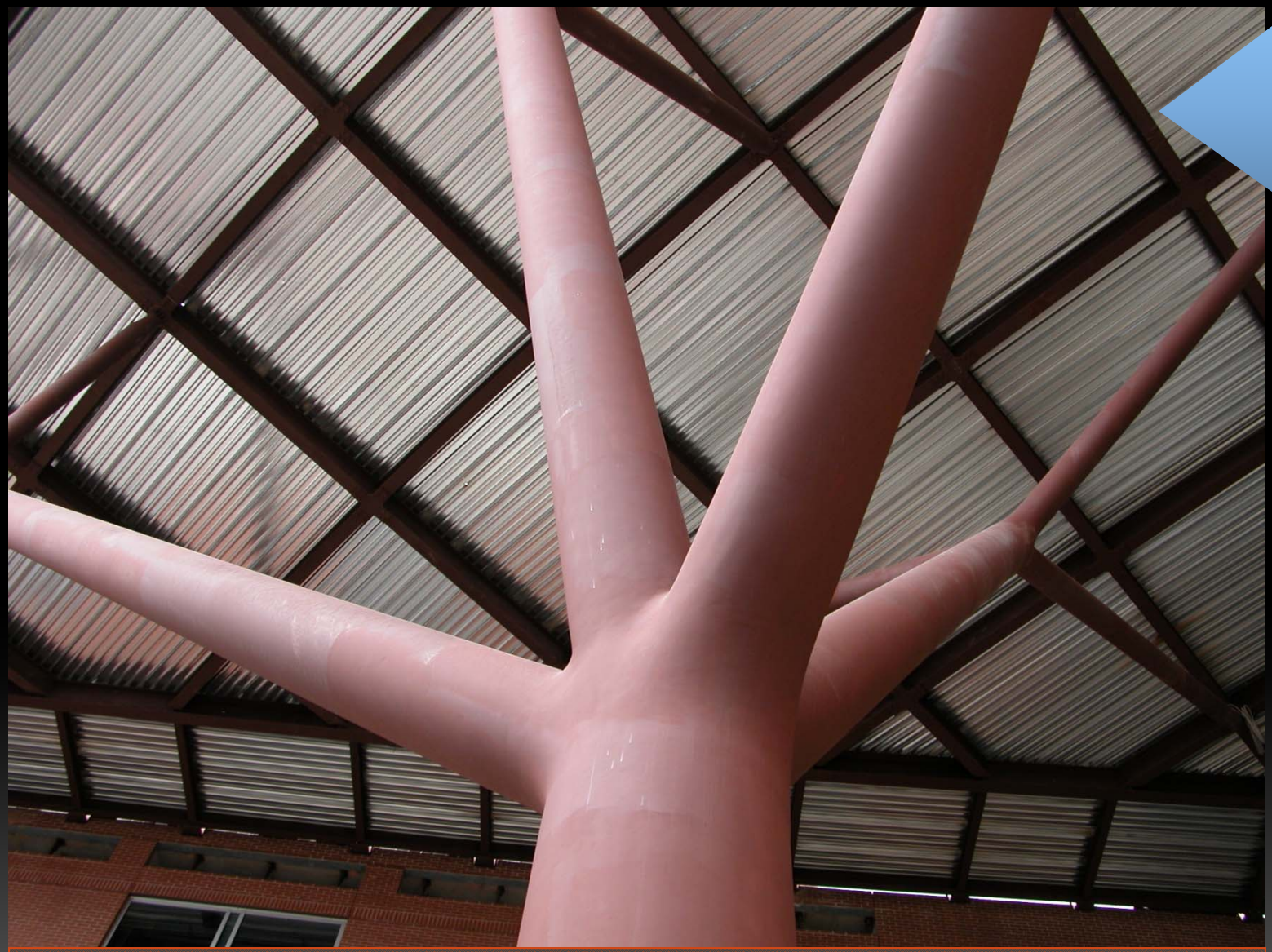


Some of the first large structural castings to be seen in Canada were used in the construction of the atrium for the Caisse de Depot et Placements in Montreal.

JOINING TO THE CASTING

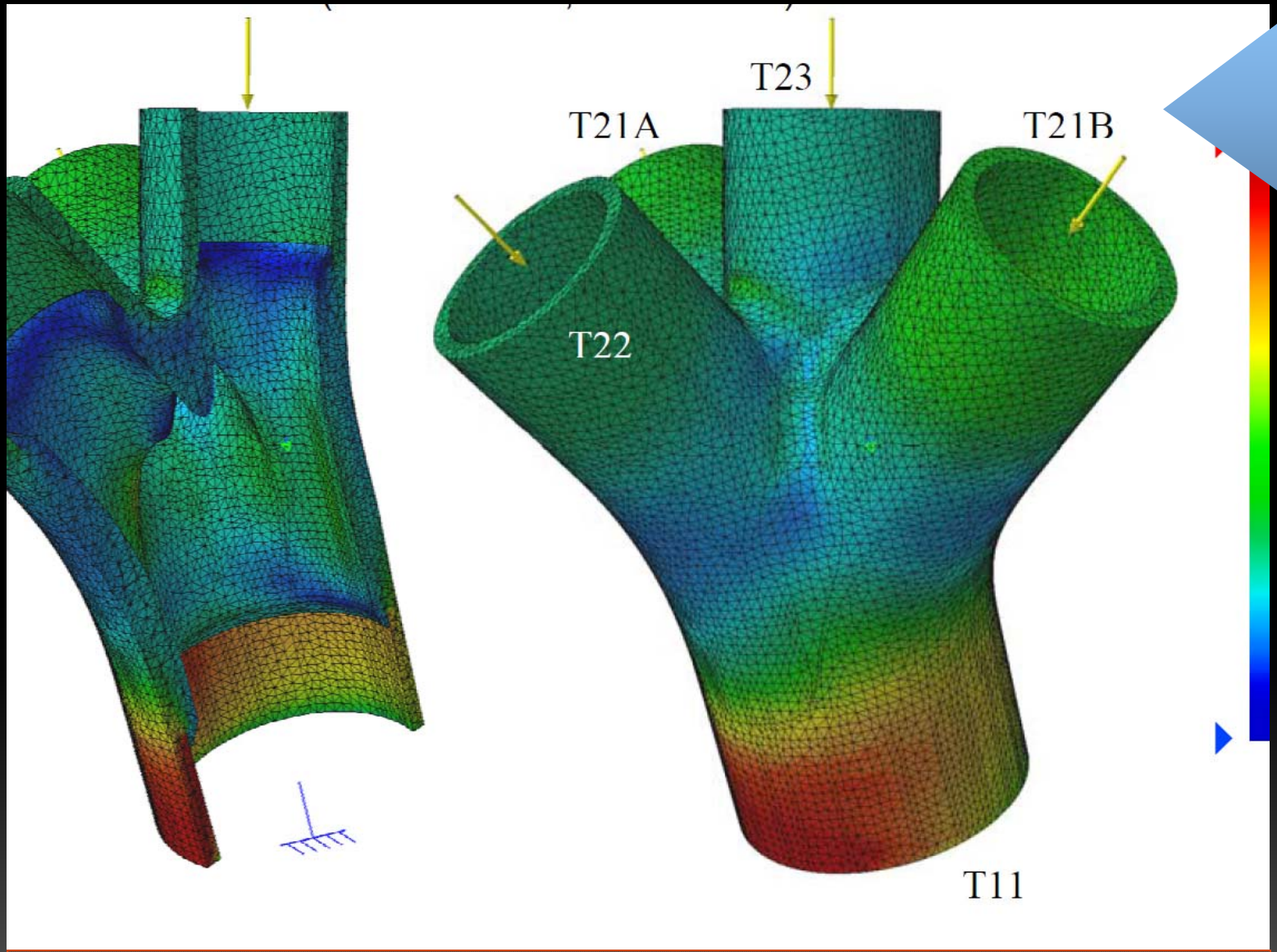
The castings at the CDP were connected to round HSS that comprised the balance of the vertical trusses using variations of non hidden welded connections or evident welded connections. There was no attempt to hide the connections.

A STEEL TREE



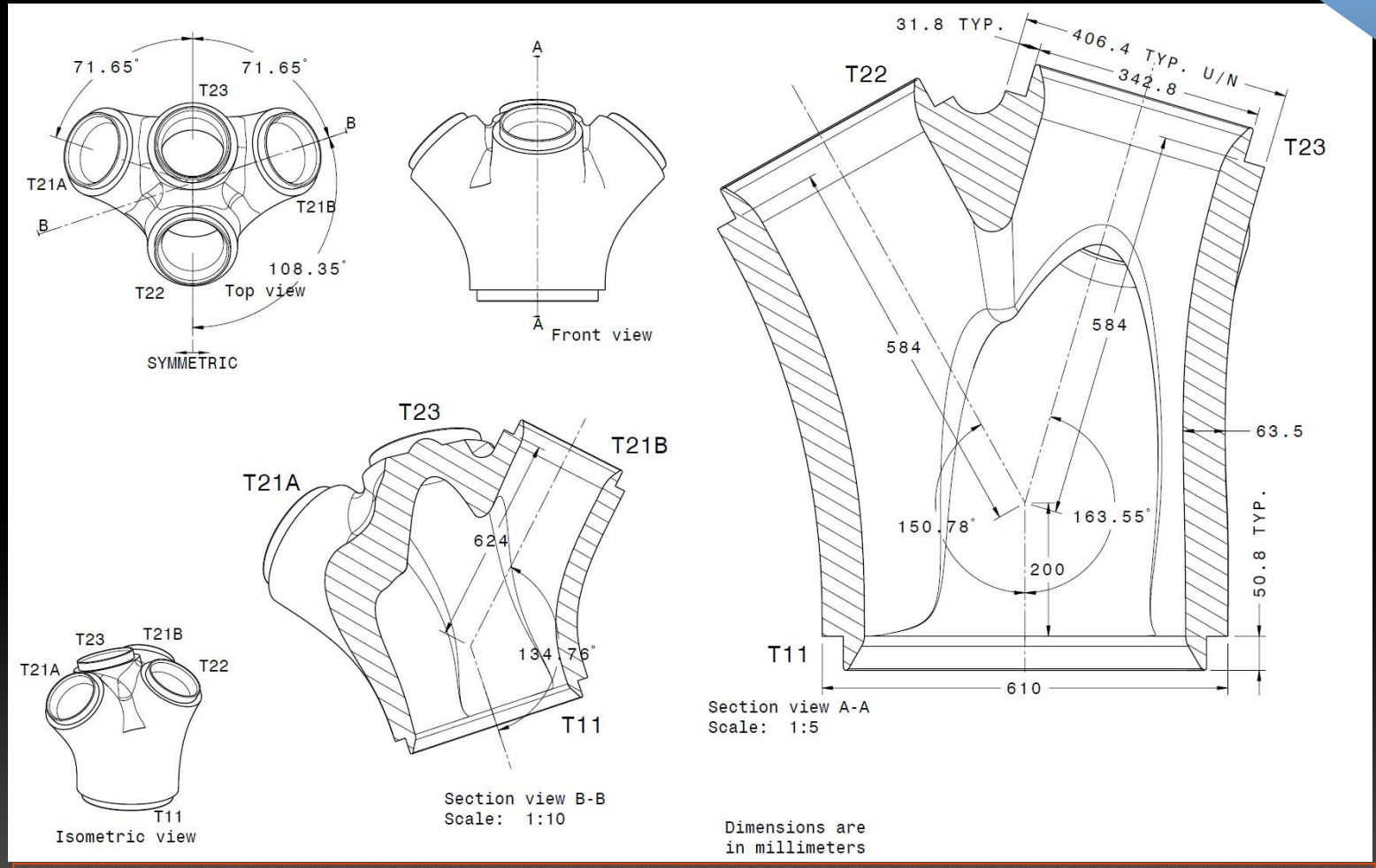
This steel “tree” at the University of Guelph was created using hollow castings to join the branches. The branches were made from mechanical pipe rather than HSS, for both structural and textural reasons.

TESTING IS NECESSARY



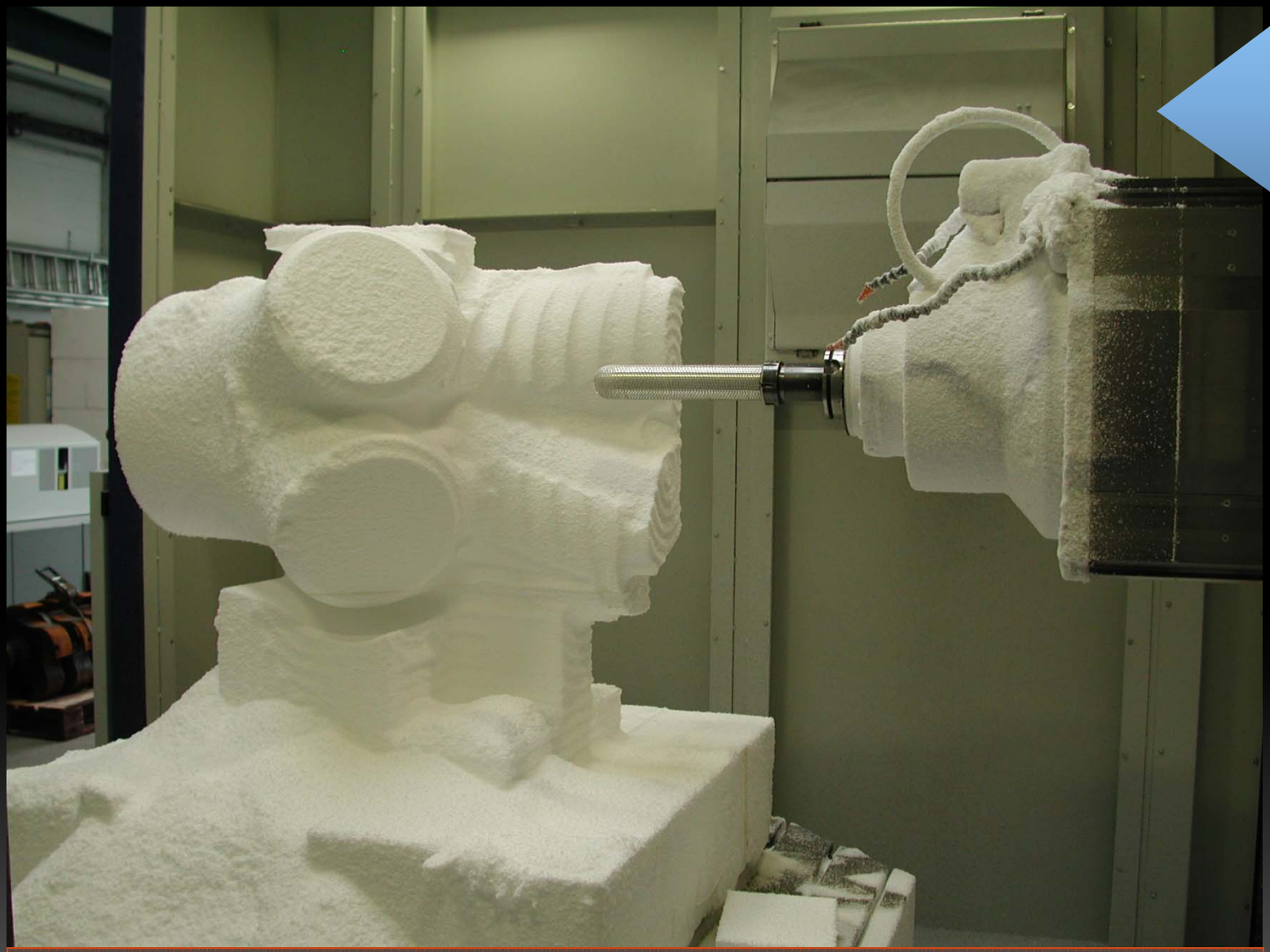
For these unique connections it is important that adequate testing be carried out. The steel must go through very controlled cooling in order to prevent the build up of problematic stresses in the material.

HOLLOW CASTINGS



The casting is hollow in the centre but the wall thicknesses are not uniform. They vary in order to locate the steel where the load transfer stresses require it.

MAKING THE CASTING



The expendable molds are often made from sand in resin, based on a form in this case driven by a CAD/CAM device. The casting technique leaves the surface of the casting with an orange peel like texture.

TEXTURED SURFACE

When the node comes out of the casting it requires remediation to the surface to remove burrs and in some cases make the surface of the casting more similar to the adjacent connecting materials.

THE CASTING SURFACE

This close view of the casting reveals the very different surface. In the case of the Guelph Tree, it was important that the connection between the casting and the branch was seamless, so this required extra care in fabrication and erection.

WELDED CONNECTIONS

The main casting node was attached at the shop as it is easier to have access for preheating. The connections are welded. Contemporary castings are quite weldable.

TREE BRANCHES

An upper branch is lifted into place. The steel support frame is there to allow for stabilization of the structure until the welds are fixed. In this case they did not use temporary tabs to provide an intermediate connection!

PREPARED FOR WELDING

The priming is held back from the welded connection. The rust will be removed prior to welding.

GENTLY NOW

Note the padded sling that is used as they ease this member into position so that they do not mar the surface.

PIN CONNECTIONS

The tops of the tree branches are fitted with custom pin connections to permit an easier erection. Pins are able to transfer vertical and horizontal loads but not moment/bending.

PIN CONNECTION

The finished pin connection at the top of the tree branch. The round plate is adjusted to accommodate varying alignments as the branched meet the top frame.

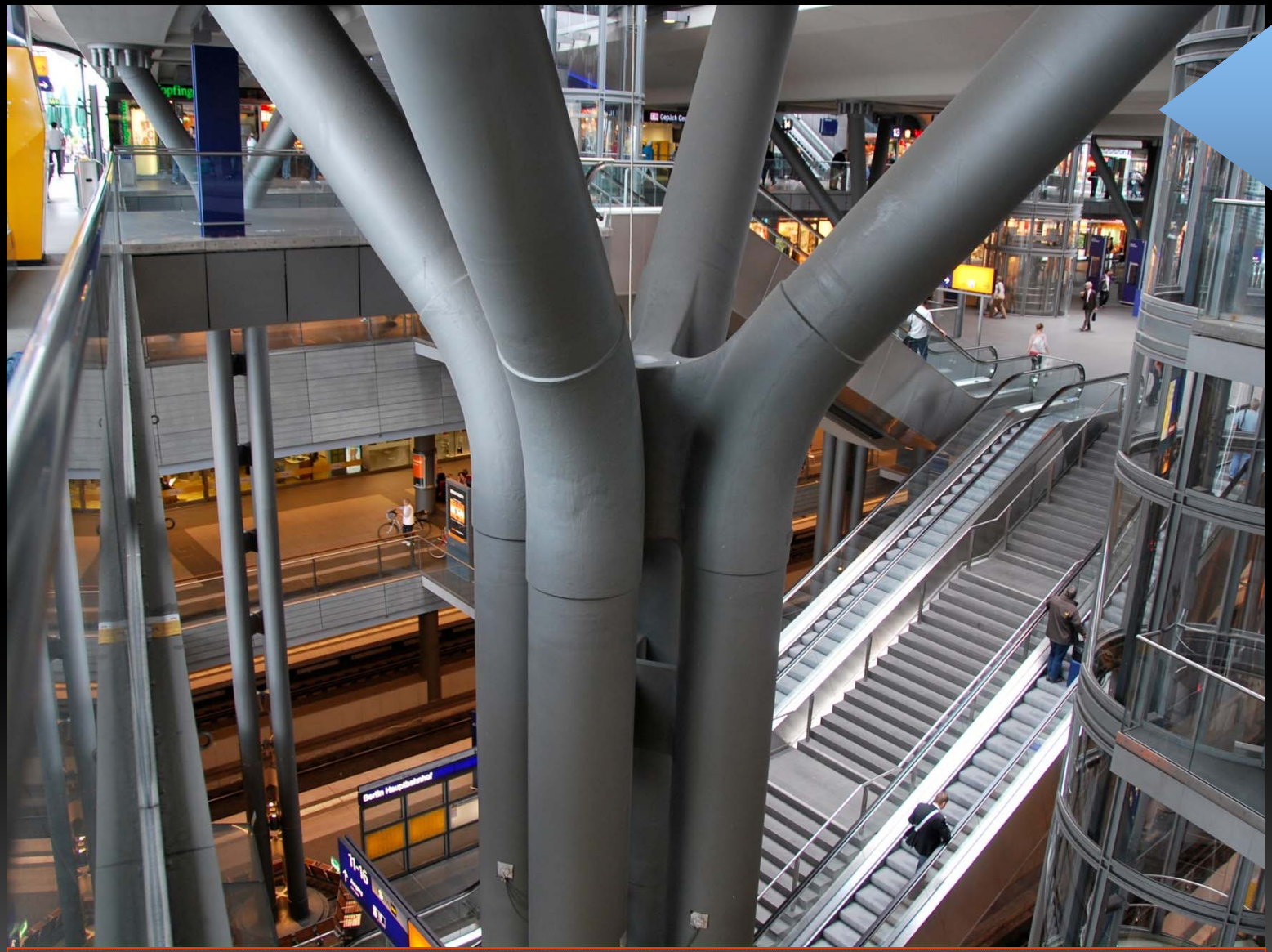
ALIGNMENT

The pin connectors allow for rotation in alignment between the diagonals of the tree branches and the steel grid of wide flange members the support the roof.

HIGH GLOSS FINISH

Understanding that the final finish was to be high gloss paint was important to know at the outset of the project. It helped to inform the detailing and finishing of this AESS4/Custom piece.

SHOWING THE JOINT



The cast connection used at Hauptbahnhof Station in Berlin does not try to hide the connection between the casting and the connecting HSS members. This reduces the cost and difficulty of site fabrication to an extent.

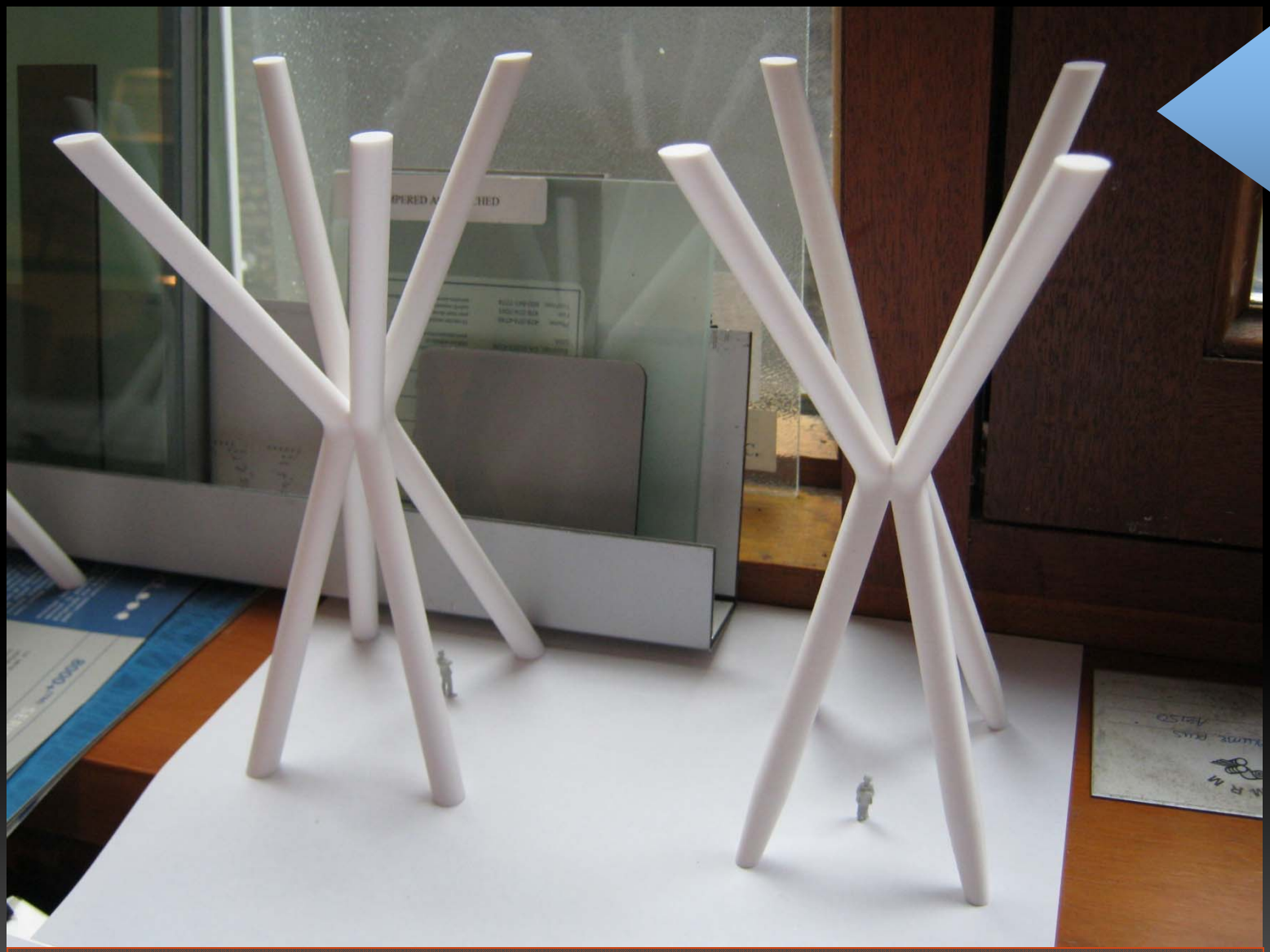
REPETITION MAKES ECONOMY

These tree like supports were repeated throughout the terminal. There is greater economy when producing repetitive elements as there are savings in fabrication as well as testing.

SPECIAL LEGS

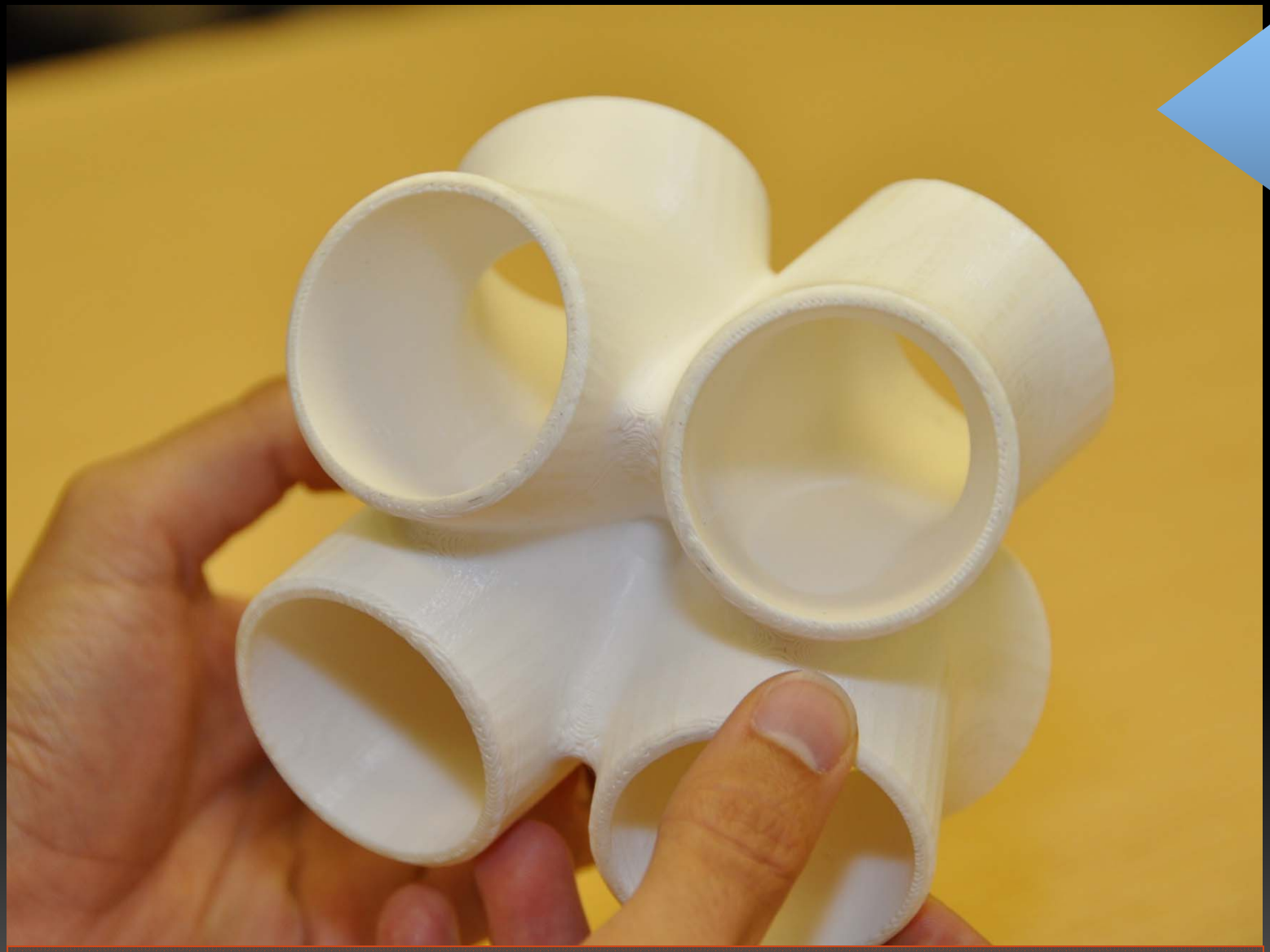
The ‘legs’ that will support the new office tower that sits over the older building at Queen and Richmond Streets in Toronto is set on very large legs created from hollow steel, connected with a large cast connector.

MODELING TO DESIGN



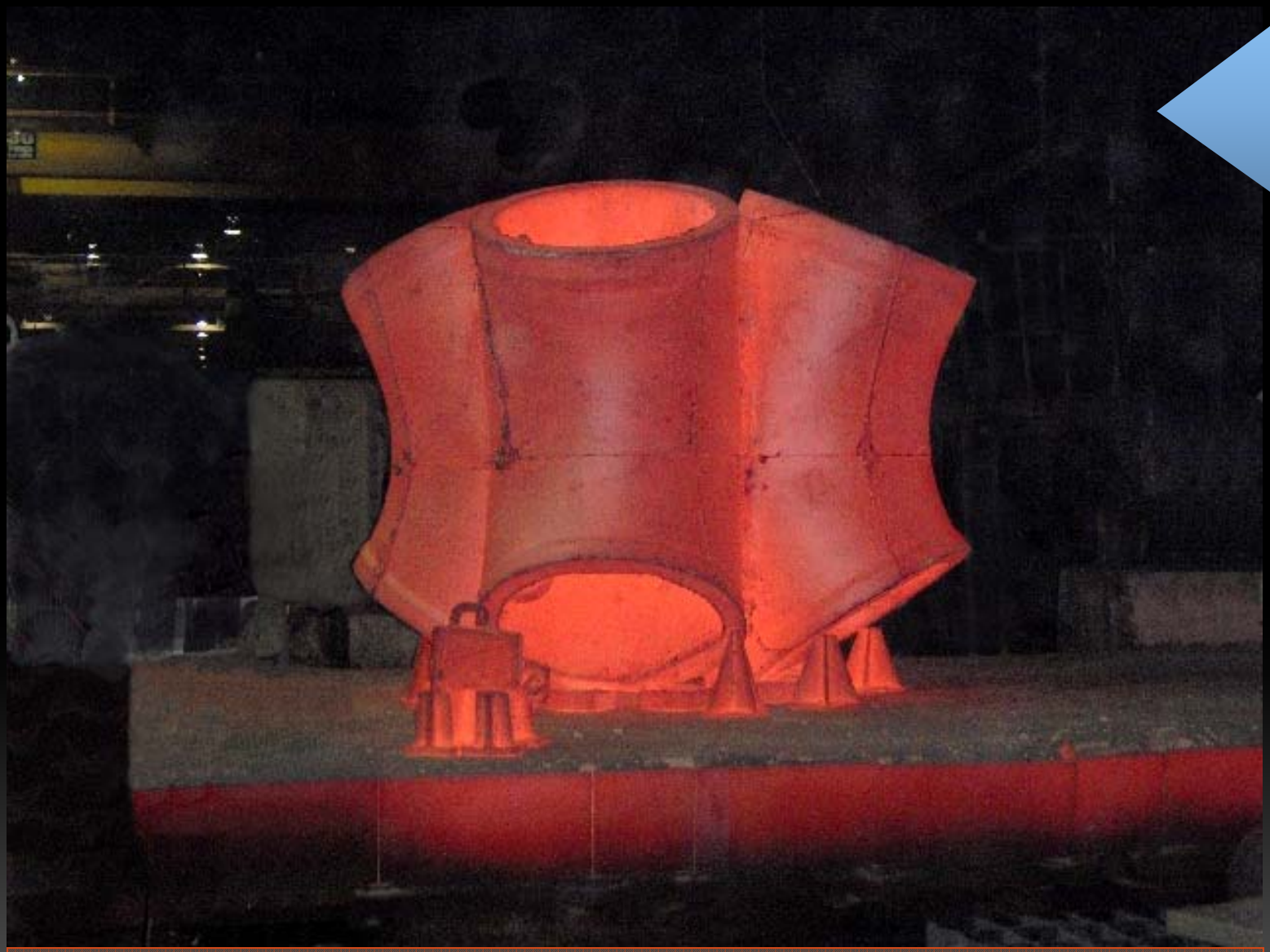
The decisions regarding the shape of the lower ‘legs’ were based on these models. The tapered ends were chosen.

RESIN MODEL



A resin casting of the node allowed better visualization of the connection and its curvatures.

CASTING PROCESS



The casting was done in Kansas as this facility offered the best quality and price.

CLEANED UP

Once the casting is cooled, it is cleaned up and rough edges removed. These were shipped from Kansas to Walter's Inc. in Hamilton for further work and preparation for attachment to the legs.

EXPENDIBLE MOULDS

This sort of node is created using an expendible mould. This means that it is broken in order to remove the casting. These are normally made from sand/resin casting.

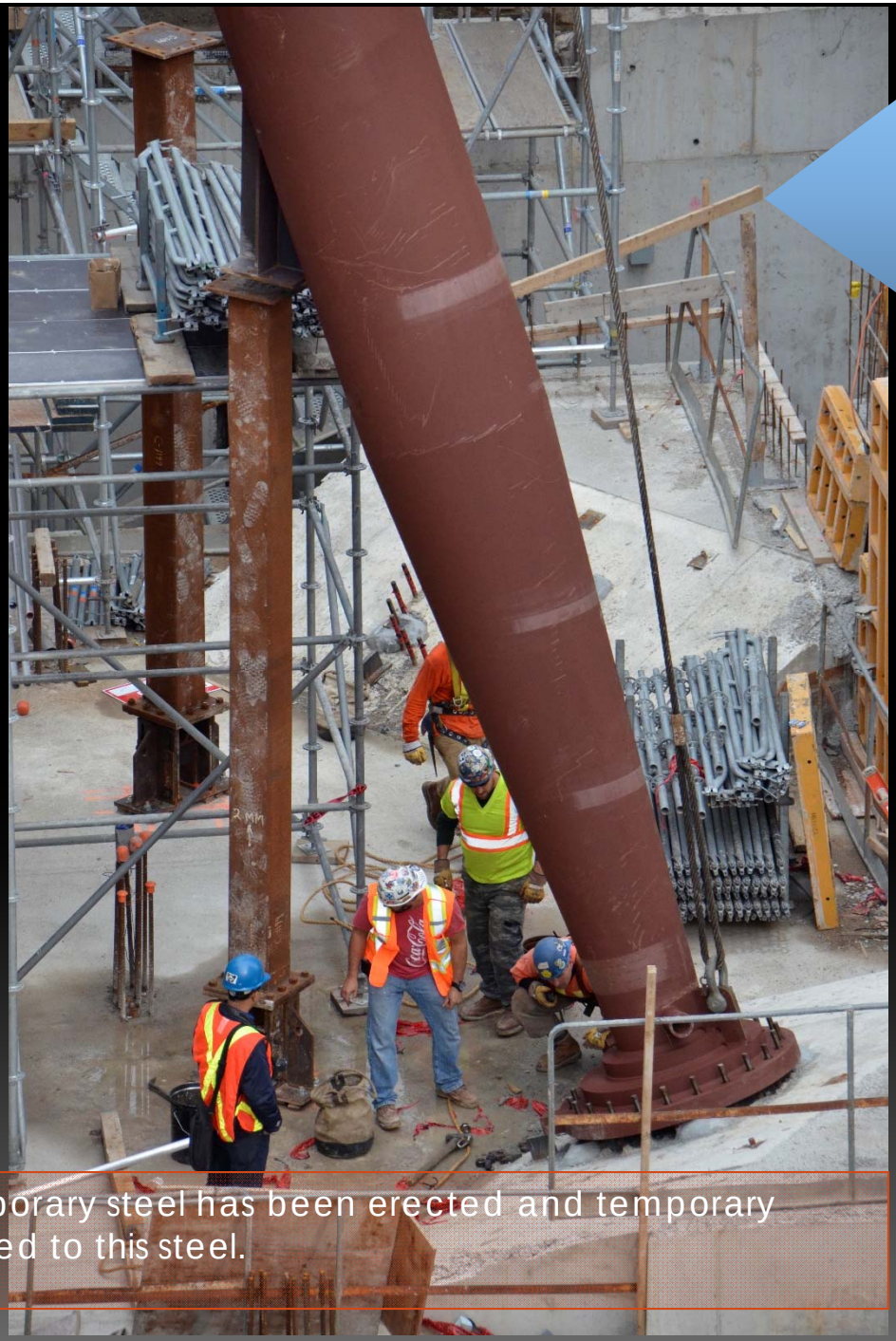
SHOP TESTED

To be certain of a fit on site, the legs are temporarily attached to the node in the shop.

LEG LIFTS

The legs are lifted into place. The holes in the thick base plates must line up with the threaded bolts in the angled concrete supports.

TEMPORARY SHORING



To align the sloped column temporary steel has been erected and temporary haunches on the leg will be bolted to this steel.

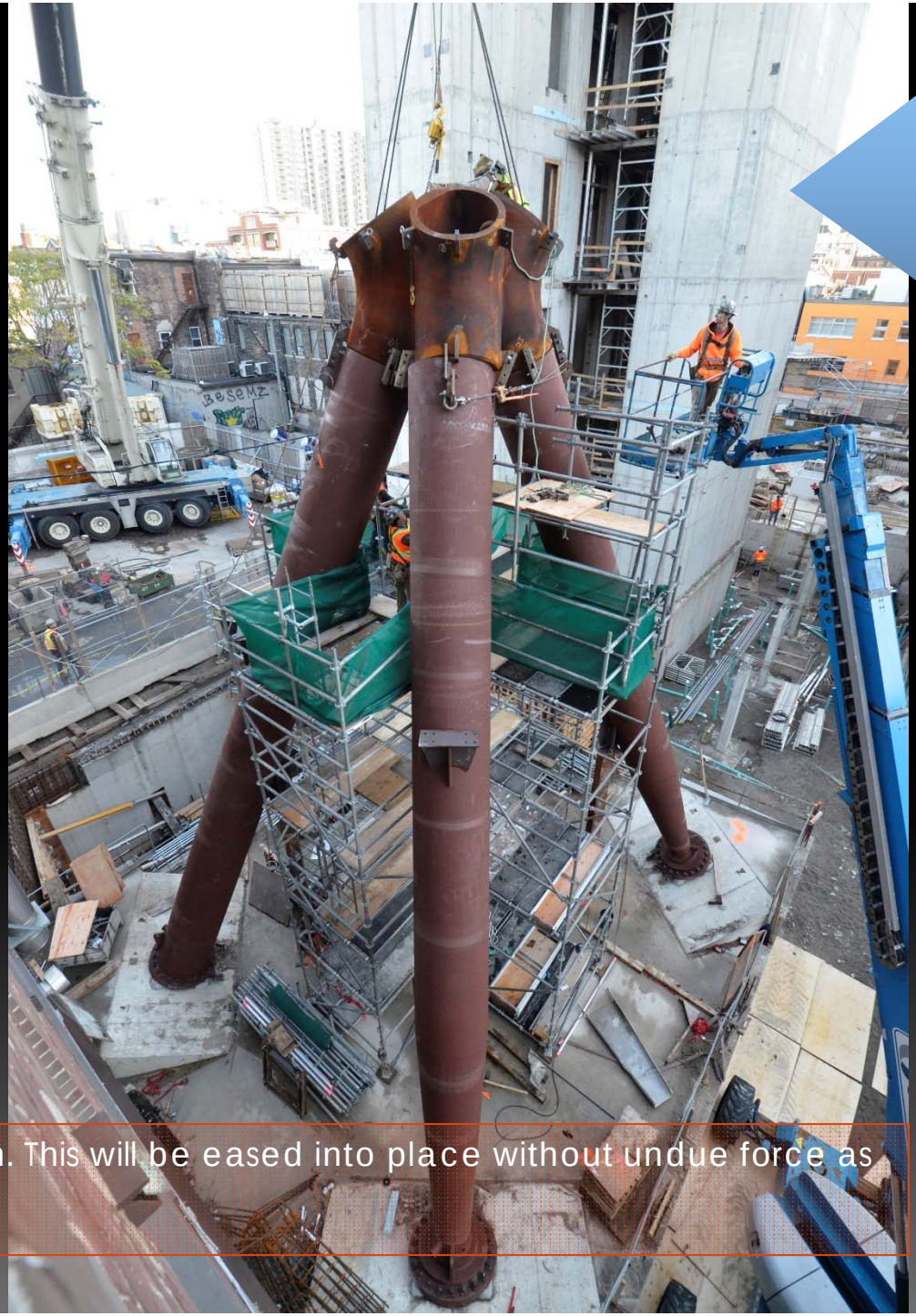
LIFTING THE NODE

Node ready for lifting at 8am.

TEMPORARY TABS

All of the temporary steel tables must be put into place to make the alignment correct. These are left there until the welding is complete.

NODE AND LEGS IN



The closest leg does not align. This will be eased into place without undue force as not to damage the steel.

UPPER LEG ARRIVES

The upper leg sections are topped with a complex custom steel element that must connect to the floor system that will support the multiple levels above.

UPPER LEGS

Different shoring is in place to support the upper legs as they are lifted into place. These include an adjustable element for alignment. Very tricky 3D installation.

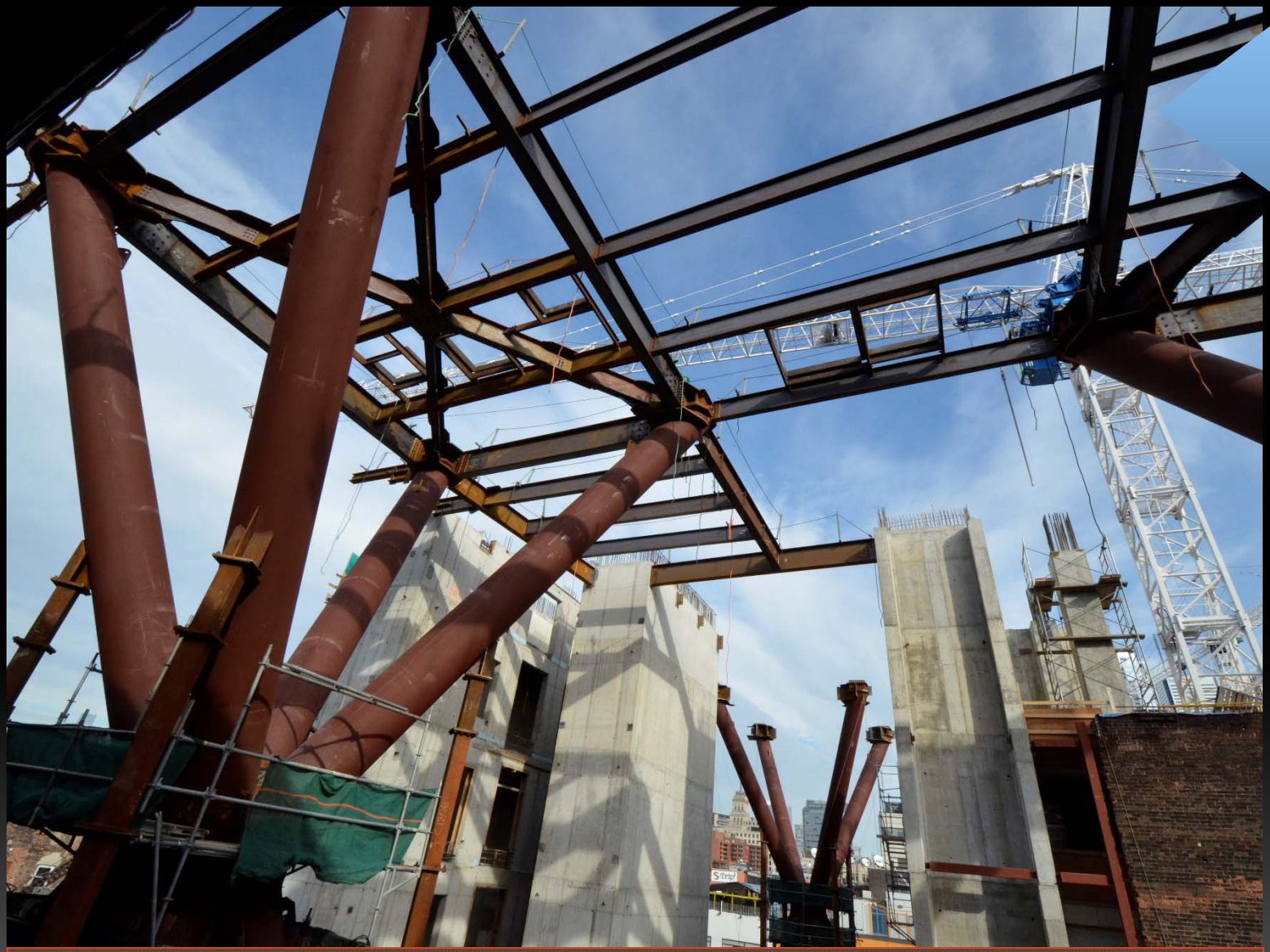
UPPER LEG

The priming is held back to allow for future welding. A safety platform has been erected for the ironworkers.

DAY AND NIGHT

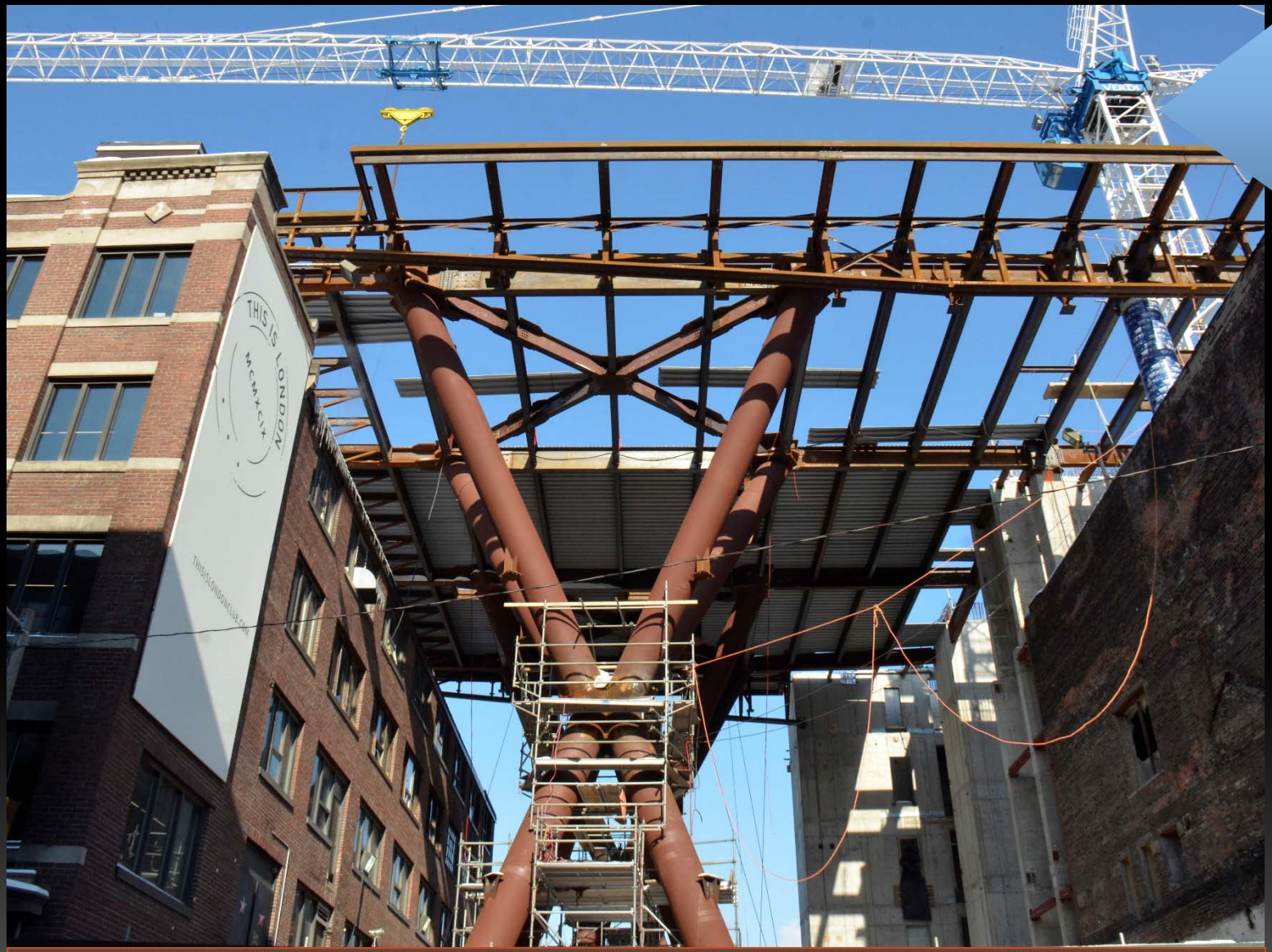
Many of the lifts had to happen at night as the downtown location did not allow for full street closure for the crane access on Richmond and Peter Streets during the day.

3 DELTA FRAMES



These three delta frames are joined with steel framing that will support multiple floors of office space above.

STEEL PLATFORM INSTALLATOIN



The delta frames are being connected with a steel framed floor which will in turn support multiple floors of office above. Note the X bracing that sits in the floor that connects the 4 upper legs of the frame.

WELDING AND GRINDING

The welding of the legs to the casting is complete. The temporary tabs have been removed and the surfaces ground smooth. This will be cleaned up further to prepare the surfaces for priming and painting.

KINGS CROSS STATION

Large AESS diagrid + lattice grid is supported on legs that use solid cast nodes to transfer the loads.

MORE TREES

The renovation to King's Cross Station in London uses tree forms as columns. Solid castings are used to attach the branches to the trunk. A reveal is used as the connection detail.

CAST NODES

The cast node in this instance has an unusual geometry and is not as smooth or uniform in its geometry. The level of quality in the project will depend on the quality of the translation of the geometry of the design smoothly into the casting.

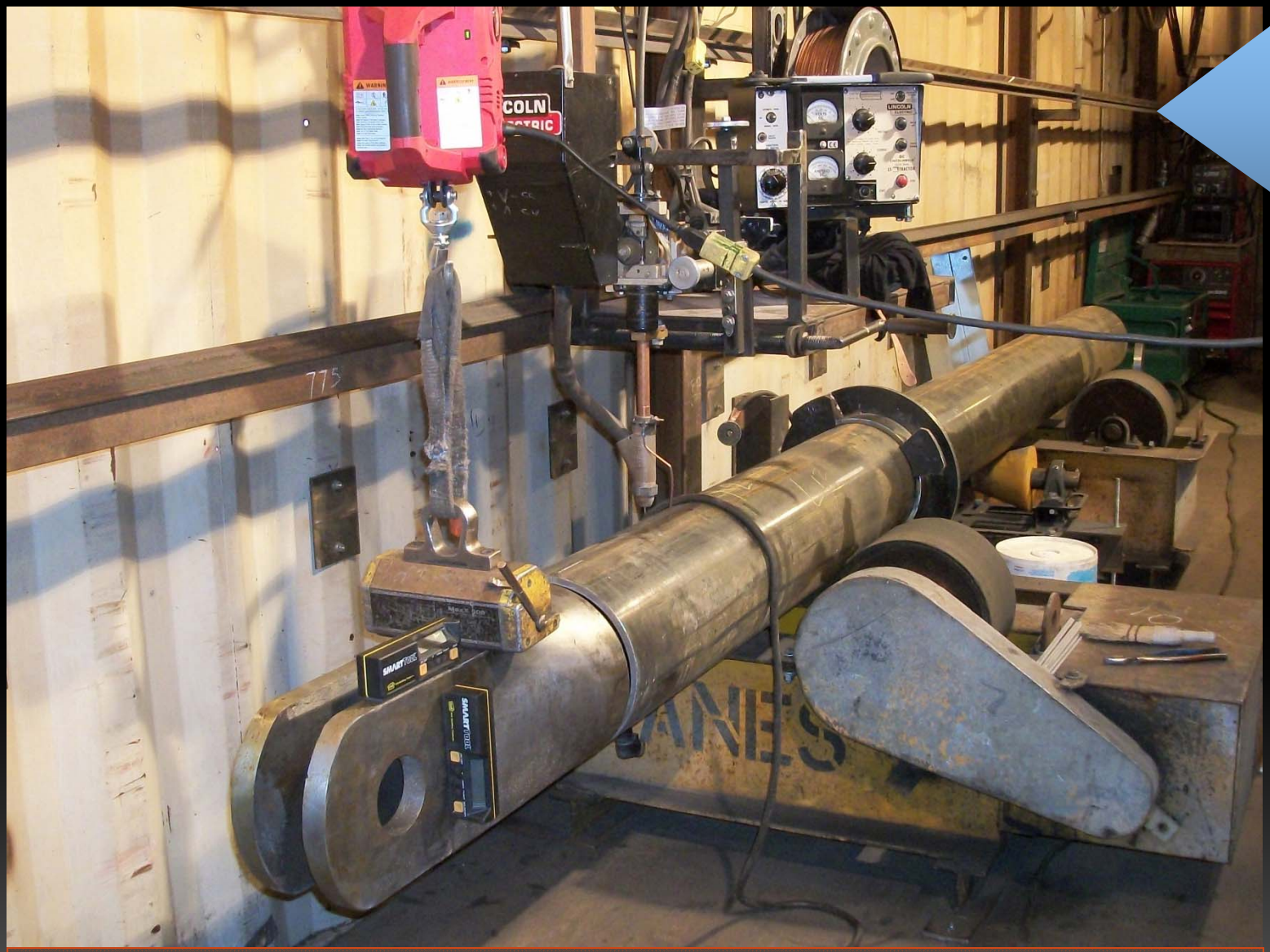
BRANCH FORMS

Renovations to Paddington Station in London are also using similar branch forms. Here braces are used on a column as the permanent lateral support system is not yet functional.

PIN CONNECTORS

These Universal pin connectors are manufactured by a Canadian company, CastConnex. These are made from solid steel. The surfaces are ground to remove the natural casting finish.

MECHANIZED WELDING



The connectors are attached to the HSS via mechanized welding. As this is an AESS project, the consistency of finish between the connector and the tube is important. The weld will be ground smooth and filled to be invisible in the final product.

EXPOSED BRACING

These connectors are being used as exposed bracing for the extension to the Whitney Museum in New York City.

UNIVERSAL PIN CONNECTORS

These large cast pin connectors will be used on the Trans Bay Terminal in San Francisco, designed by CastConnex of Toronto.

CASTINGS + CURVES

At Shanghai International Airport, Terminal 2, castings are combined with curved steel and tension trusses to create a vibrant structural system.

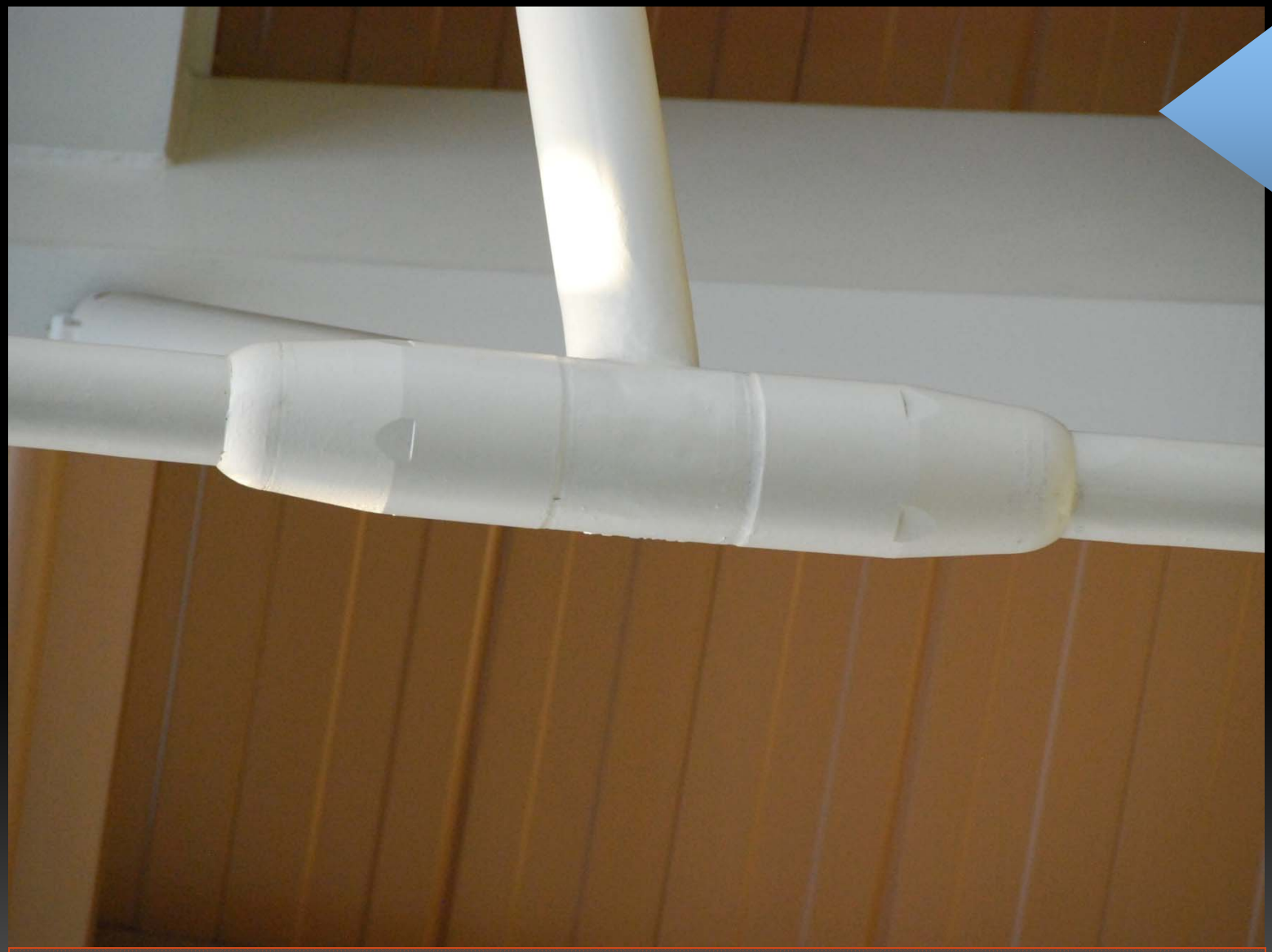
ACCOMMODATING GEOMETRY

The attachment of the diagonal to the roof member is achieved through a casting. This created a much smoother and better looking transition. The pin connection also improved constructability.

SMALLER CASTINGS

The tension truss for the airport also incorporates many smaller castings in the form of turnbuckle type variations allowing for the assembly and tensioning of the trusses.

TURNBUCKLE CASTING



This type of connection truly takes advantage of the compact nature of the casting to make a sleek connection. Welding or bolting would simply have been inappropriate.

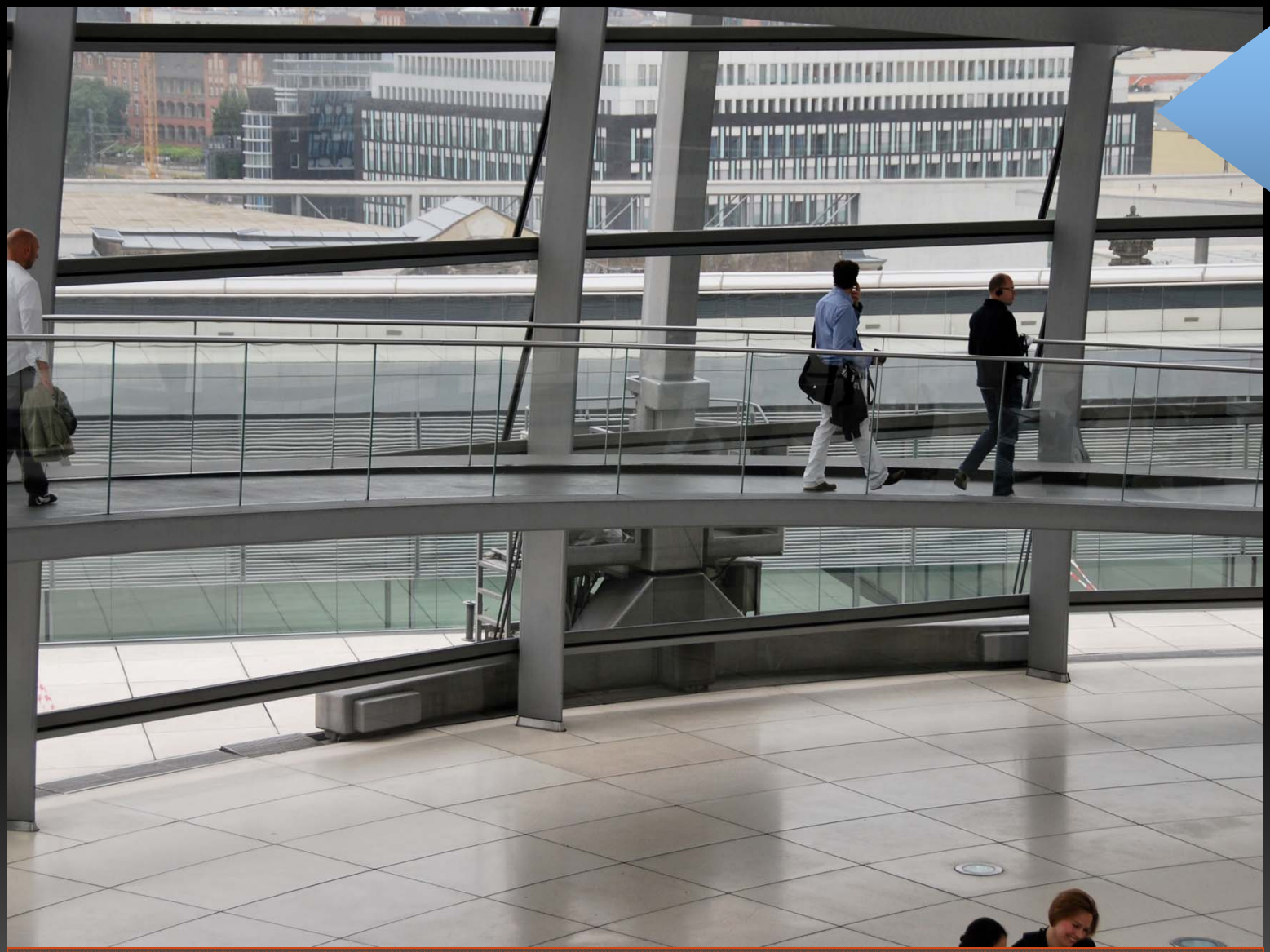
THE CHALLENGE OF A DOME

The Reichstag in Berlin, designed by Foster+Partners makes use of a number of innovative techniques in steel fabrication.

PLATE STEEL RAMP

The profile of the curving ramp is very thin, making use of plate steel that has been reinforced at its edges, and tied back to the ribs of the dome using cast connections and tension members.

STRENGTH IN GEOMETRY



The spiral form helps in strengthening the ramp, whose profile is very thin and unobtrusive.

DIE CAST CONNECTORS

Smaller die-cast connectors are used at the Reichstag in Berlin to attach the tension support system.

VARIETY IN CONNECTIONS

Three different cast connectors are used in the system. The one at the left that accepts two incoming members is quite innovative and the detail allows for a very tidy connection. This project also uses a significant quantity of bent plate steel.

RIB CONSTRUCTION

The ribs are made from plate steel that has been welded into triangular forms. The curve of the side members of the rib would have been cut from a flat piece of steel.