International Journal of High-Rise Buildings
December 2016, Vol 5, No 4, 293-304
http://dx.doi.org/10.21022/IJHRB.2016.5.4.293

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

The Emergence of the Diagrid - It's All About the Node

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Abstract

The diagrid structural system for constructing tall buildings is a recent invention. Debuting in 2004 with the construction of the Swiss Re Tower in London, this aesthetically driven structural system has centered the perfecting of its technology on the development of the nodes that form its innovative deviation from standard steel tall framing methods. The paper examines variations in node design, understanding the linked dependence the modularity and the choice to expose the steel in the building, as well as on advances in digital modelling that allow an increasingly seamless line of communication from the engineering design through to the actual fabrication of the nodes. This advanced design and fabrication technology will be seen to have resulted in the expanded use of the technical term "node" to inform the design and construction of a range of other applications in the structuring of tall buildings, including the use of steel castings.

Keywords: Diagrid, Node, Steel structures, Cast steel

1. Introduction

node /nōd/

Noun. A point at which lines or pathways intersect or branch; a central or connecting point.

Reflect on the introduction on the term "node" in the history of structural design. Although in a looser sense the terms "joint" or "connection" might be considered synonymous, the term "node" conjures a very different visual idea of the aesthetics and functional requirements of a 3-dimensional connection. Nodes first appeared in conjunction with spaceframe technology, and were critical in the creation of a heavily prefabricated system that could permit easy assembly on site. The members were fairly light and the geometries, though relatively regular, required the resolution of a high number of angled components at a point. The size of the node was directly related to the number of connecting members and the ability to accept their cross sectional areas. There was significant uniformity in their design. These were quite unlike the angled connections in 2D or 3D trusses, which were normally shop fabricated and could afford some structural continuity of the chord members through the joint, providing stiffness, although in theory, moment resistance at panel points is not required. Nodes tend to be fabricated as discrete elements to which other members connect. For larger nodes the connection to the incoming members is usually done on site.

Where the nodal connections used in spaceframes were part of a 3-dimensional system, often used to carry relatively uniform roof loads, the adoption of the nodal connection type to the diagrid system required significant modifications as a result of the type and size of loads to be carried. The 3-dimensional depth of the spaceframe and its planar applications were transformed into a single thickness system, most often oriented vertically, that also was subjected to extreme forces of wind given its application in tall buildings.

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2. The Emergence of Diagrid Structures

Diagonalized grid structures – *diagrids* – have emerged as one of the most innovative and adaptable approaches to structuring buildings in this millennium. Based on the revolutionary structural concept for towers invented by Vladimir Shukhov in the late 1800s, the use of diagrids as a contemporary formal structural language for tall buildings only started in the 2000s, examples being Swiss Re (2004), in London, the Hearst Magazine Tower (2006) in New York City and the Mode Gakuen Cocoon Tower (2008) in Tokyo.

Diagrids are a structural design strategy for constructing buildings that combines the resistance to gravity and lateral loads into a single thickness, triangulated system of members that can eliminate the need for vertical columns. The system is comprised of diagonal members, normally fabricated from structural steel, that are joined at nodal points. For tall buildings this typically forms a tubular perimeter support system. As a function of the height and loading on the building, this can also remove the requirement for a reinforced concrete core to assist with lateral stability. To date Swiss Re at 179.m is the tallest diagrid skyscraper to be constructed without a lat-



Figure 1. Nodal connections are the basis for the fabrication of 3-dimensional spaceframes. (Left) a typical prefabricated ball node connection joint. (Right) the fully welded spaceframe for the Mandarin Hotel in Beijing, China.



Figure 2. In a short period of four years the understanding of and adeptness with the design of diagrid structures leads to its use in less regular and more complex geometries. From left to right: Swiss Re (2004), Hearst Tower (2006), Mode Gakuen Cocoon Tower (2008).

erally reinforcing core. The tallest diagrid tower, Guangzhou International Finance Center (2010) stands at 438.6 m and uses a reinforced concrete central core to the 70th floor that then splits to 3 smaller cores set at the corners of its rounded triangular shape to permit a central atrium space.

The term diagrid is somewhat misleading. The diamond shape of the "diagonal grid", although often presented as the dominant visual feature in the design of the façades of diagrid buildings, is by itself unstable. The diamond shaped system requires triangulation in order to create sufficiency in the structure. A system of horizontal hoops that are typically located at the floor levels (allowing them to be visually suppressed) is essential to triangulate the structure. The diagonal grid, if properly spaced, is capable of assuming all of the gravity loads as well as providing lateral stability due to this triangular configuration.

2.1. Optimization versus Aesthetic Drive

Over the last 13 years, applications of diagrid structures have evolved as the system has proven to be highly adaptable in structuring a range of building types and forms.



Figure 3. The diagrid within a diagrid is used to create the central atrium spaces for the Capital Gate Tower (left) and Guangzhou IFC (right). This permits the floor system to span between the diagrid tubes. Both towers use reinforced concrete cores to assist with stability due to eccentric loads in the case of the 18° lean of Capital Gate, and the extreme height in the case of Guangzhou IFC, also contending with seismic and wind loads. Note the contrasting thinness of the horizontal ties in the Capital Gate Tower.

Although significant research effort has been put into the optimization of the structural system to reduce the use of steel (Moon, 2008, Baker et al., 2010) diagrids have tended to instead be aesthetically driven. What is attractive to designers and what sets diagrids apart from traditional framing systems is the ability of the diagrid to provide structural support to buildings that are non-rectilinear, adapting well to highly angular buildings and curved or twisted forms. For tall buildings in particular the diagrid system has enabled some very unique deviations from structural types that are more fully dependent on the core for lateral stability. Both Guangzhou IFC (2010) and the Capital Gate Tower (2011) in Abu Dhabi have exploited this ability to manipulate the core to create central atriums at their top floor levels. In each case the central atrium is supported by an additional diagrid structure to provide the interior support for the floor system. In both cases the upper levels of the towers function as hotels, with this use of the diagrid useful in creating spectacular focus spaces for these multi-use towers. In most skyscrapers this central zone is occupied by the stability core, relegating the usable space to the perimeter of the tower as is typical on most floors.

3. The Developments of the Node

In terms of influence on the concept, structure and detailing of diagrid structures, the invention and development of spaceframe and geodesic structures was important as an overlay to Shukhov's hyperbolic paraboloid towers. Where Shukhov allowed the long, slender members of his hollow diagrid towers to simply overlap and often be continuous through the "theoretical nodes", geodesics and spaceframes introduced the technique of the nodal connection, thereby making the members discontinuous through the connection point. Many changes were also necessary to adapt Shukhov's system for hollow parabolic lattice-like towers to one that could support significant floor loading. This introduced issues of increased loading and scale to the design of the frame. Nodal connections were introduced to connect the floor beams to the node for a clear distribution of loads to promote axial load paths. Member sizes increased to match the loads and the nature of the nodal connection revisited. Typical orthogonal framed connections required significant modifications due to the presence of typically 4 incoming large diagonal members at each nodal connection, in addition to the required



Figure 4. On the Poly International Plaza Tower the choice of concrete filled steel tubes and the resultant node design responded to the elliptical plan of the tower. This type of system requires all welded connections both for stability as well as to seal for leakage.

horizontal bracing ring and often a major floor beam.

4. Differentiating Diagrids from Traditional Framing Techniques

Diagrid structural systems as they are applied to tall buildings deviate significantly from traditional structural framing methods in several significant ways. Traditional steel framing systems are based in orthogonal geometries. Diagonal components, if included, exist as a secondary support system to create lateral bracing leaving the columns to assume the gravity loads. In this way the connection strategy for the diagonal elements in the system tends not to dominate the overall design of the structure. Diagonal braces are often concealed and therefore do not consistently influence the expression of the structure on the façade, although they may be pushed to the exterior and form an important part of the architectural expression in the façade (Bank of China, Hong Kong and Hancock Tower, Chicago). The majority of the beam to column connections are based on variations of standard "right angle" framing details. This allows for relatively straightforward engineering design, fabrication and erection based on tried and true methods. The creation of the node has been used to address the need to invent new ways of creating complex connections that were not suited to typical framing methods for concealed steel structures and that can respond well to the need for the diagonal connections to dominate the overall structural design.

4.1. Differing Angles and Modules

Being aesthetically driven, the resulting unique nature of each diagrid project tends to result in different combinations of member types and angles in the design and modules. Angles range from less than 40° in One Shelley Street (2012) in Sydney and the Poly International Plaza Tower (2015) in Beijing, to the recommended optimal angle of approximately 69° (Moon, 2008) for Hearst Tower and many others. The overall massing, height and shape of the tower, as well as the desired scale and expression of the diamond pattern in the façade treatment will drive the choices in the modularity and therefore the angles in the design. It is a generally well accepted fact in the design of trusses, that angles shallower than 45° will exaggerate the forces on the web members. Steeper angles are better to accommodate gravity forces in the case of the tower applications of diagrid "column" members.

The desire to create a "paper lantern like appearance" drove the structural choices in the design of the Poly International Plaza Tower in Beijing, resulting in a very shallow angle. In the case of this building the loading on the concrete filled hollow steel tube frame was even more exacerbated by the decision to hang alternate floors from the structure in the creation of a double façade system. The choice to fill the tubes with concrete allowed the thickness of the steel walls of the tubes to be reduced from 60 mm to 30 mm. (BIAD, 2013) The concrete fill also provides fire resistance in addition to stiffness. The choice to concrete fill tubes puts additional demands on the design of the nodes as they too must be hollow and allow for an ensured full fill when the concrete is pumped. Guangzhou IFC (2010) and the Canton Tower (2010) all employ this system.

Many iconic diagrid towers use varying geometries, so that the modules and thereby the nodes are purposefully inconsistent throughout the project. The most extreme



Figure 5. Continuity of the void is necessary to permit the pumping of concrete through the node. At left the node is seen to be site welded to the incoming diagonal members. Custom tapered tubes are fabricated to resolve the connection between the tube and the plates at the intersection. At right the node in the fabrication shop. Reinforcing at the connection of the node to the tube permits the passage of concrete. (Image right, BIAD).

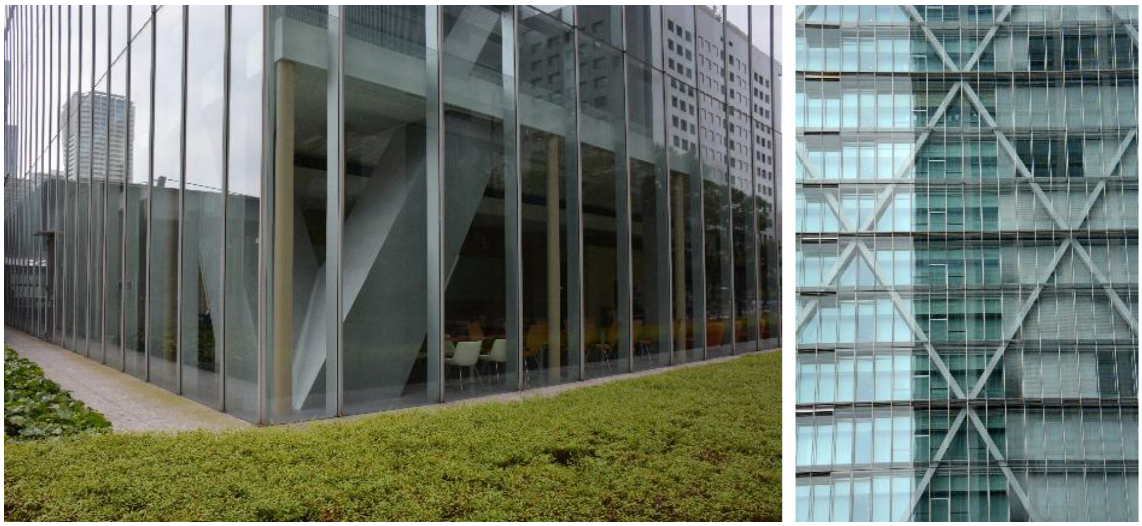


Figure 6. Sony City (2006) in Tokyo used custom fabricated square hollow sections in conjunction with castings to create this innovative double façade diagrid project.

example of this is the case of the Capital Gate Tower. The plan shape is somewhat elliptical and the leaning curved form of the tower resulted in more than 800 unique node connections. (Schofield, 2012) According to the architect in charge, Jeff Schofield, the client wanted an iconic building. Hence the choice to use the diagrid and the complex curved shape were quite intentional – optimization was not a concern. Given the extremely small two storey module used, the hollow steel tubes remain unfilled, with an intumescent coating system used to address fire protection and permit the structure to be architecturally exposed. The relatively small cross section of the tubes and the frequency of the nodal conditions would have made pumping near to impossible.

4.2. Concealed versus Architecturally Expressed Steel

Where the majority of skyscrapers that use more functionally driven orthogonal methods for construction will tend to conceal the structural steel behind fire protective coverings or concrete, diagrid buildings will often choose to express the steel – resulting in a higher level of aesthetic expectations on the appearance of the steel. This can translate into member choices as well as node design. The nodes in particular may become a feature of the aesthetic expression in the project. The application of tubular material in the Poly Plaza International Tower versus Ca-

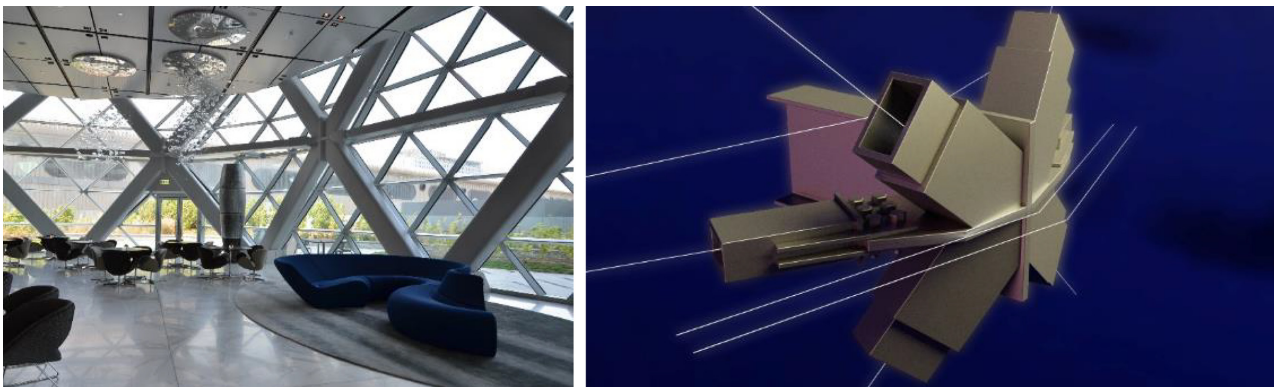


Figure 7. The square tubular frame for the Capital Gate Tower drove a node connection that employed a crossing fabricated from plate steel to accommodate the multiple angular variations in the many nodes, while keeping the design aesthetic consistent. (Image right, Jeff Schofield)

pital Gate highlights the contrast between steel that will be concealed versus architecturally exposed. In the Poly Tower there is no requirement for weld remediation, greatly simplifying erection. In Capital Gate all welds needed to be remediated (ground) prior to the application of coating systems. These welded site connections between the node and members will necessitate the construction of platforms at each connection to provide a safe space for the ironworkers. Welds also require heat pre-treatment. The thicker the steel the longer the preheat time required. This needs to be taken into account during pricing and scheduling.

The choice of member type for AESS projects can be seen to vary worldwide due to preferences in steel structural systems. Where North American and European tall building projects in general will tend to be more accustomed to the use of Wide Flange (Universal) sections on concealed steel tall building projects (with an associated preference for bolted connections), concrete filled steel tubes and fully welded connections are quite common in Asia and the Middle East. (Boake, 2016) The majority of diagrid structures have been constructed in Asia and the Middle East, and so the adoption of concrete filled steel tubes in these AESS projects has been fairly natural. The exceptions for AESS would be The Leadenhall Building (2015) in London with its custom plate fabricated expressed frame with the *appearance* of a Wide Flange type, set within the double façade for the buildings.

4.3. Gravity Defying Erection

In particular, gravity forces are not adversarial when it comes to the erection of orthogonal steel framed buildings. Gravity forces naturally pull the columns into position during lowering. Ascertaining lifting points for the members is less of a challenge as there is more uniformity and symmetry. In diagrid structures the angled elements can pose challenges during erection and the connections between members need to be designed to accommodate this. Lifting points will require more careful determ-



Figure 8. In order to address the great variety of loading conditions on The Leadenhall Building (the pure diagrid only positioned on the street face pictured at left) plate steel was used in varying thicknesses and configurations to create the nodes. Bolted connections were used on site. Cover plates were welded over the exposed connection boxes to tidy up the appearance of the connections.

ination, particularly for asymmetrical assemblies.

The size of the node will depend on the determination of the overall module for the tower. The larger the module, the longer the diagonal members and the greater the capacity of the node. Smaller modules will permit the pre-assembly of the node and two incoming diagonals in the staging area, the lift taking place as an inverted V shape. This decreases the number of connections that must be made at height. The overall inverted V assembly must be stiff enough to resist gravity induced deformations, or the connections made at height (permanent bolts or temporary bolts prior to welding) will not fit. For larger modules the nodes and members are usually lifted separately. For tall buildings this means that the node and members must have an extra stiffness to maintain dimensional stability and resist deflection during the erection process. It would be expensive and impractical to provide a temporary support or shoring system for the diagonal members during the erection process. Lower diagrid projects like the Denver Art Museum have required substantial support towers to maintain the geometry of the partially erected structure. This is absolutely not done on tall building projects, therefore the engineering of the structure must size members accordingly.

5. Understanding the Diagrid System

Much of the following section is reflective of my research in the writing of "Diagrid Structures: Systems, Connections, Details" published by Birkhäuser in 2014.

5.1. The Relationship Between the Module and the Node

A diagrid tower is modeled as a vertical cantilever. The size of the diagonal grid is determined by dividing the height of the tower into a series of modules. The diamond shaped modules typically span 6 to 8 floors, tip to tip although shorter modules are used for buildings with irregular geometries or tighter curves and larger modules have been used for much taller towers. Normally the height of the base module of the diamond grid will extend over several stories. In this way the beams that define the edge of the floors can also frame into the diagonal members providing both connection to the core, support for the floor edge beams, and stiffness to the unsupported length of the diagonal member. As a significant portion of the expense of the structure lies in the fabrication of the nodes versus the steel that comprises the diagonal element, efforts are often towards minimizing their frequency and simplifying the connection between the node and the diagonal to ease erection issues. Fully optimized a diagrid tower structure can see a 20% reduction in the requirement of steel over a standard framed building. (Charnish, 2008, Rahimian, 2006)

The diamond shaped modules must be braced at the very least at their widest point using a node to node connection to complete the basic structurally necessary triangulation. Depending on the overall geometry of the building, the horizontal bracing or rings can be required to act in tension, where the gravity loads would cause the diagrid to deflect outwards, or in compression where the slope of the diagrid would push inwards on the building. Bracing rings acting in tension can naturally be of a thinner, different cross section than the diagonal members that are resisting compression forces, if not also acting as the floor edge beam. However the horizontal brace is often formed by the edge beam of the floor structure which will frame into the node to complete the triangle. An additional



Figure 9. The four storey diagonal members of the Hearst Tower must resist deflection while awaiting their connection to the node.



Figure 10. The floor edge beams frame into the diagonal members on Aldar HQ, Abu Dhabi (left, photo, William Hare). At right the same condition is seen on Guangzhou IFC (photo, Arup). Where Aldar HQ will have its steel concealed, Guangzhou IFC is an AESS project. This does not really impact the connection between the edge beams and the diagonals as this portion of the structure is concealed in both cases.

expressed structural steel member could alternatively be fixed between the nodes which is done in double façade applications to accommodate the required void between the pair of façades as in the case of Swiss Re. The major structural intersections occur at the nodes although the floor beams that subdivide the height of the module can also frame into the diagonal members. If the overall module size of the diagrid is very large, the floors are often required to brace the diagonals at each floor level, thereby restraining the diagonal and reducing its effective unsupported length (Hearst Tower, Guangzhou IFC, Aldar HQ).

5.2. Dimension Requirements for Nodes

Swiss Re and the Hearst Magazine Tower provided early precedents for subsequent designs of diagrid structural systems. Swiss Re tackled curves and therefore elected to use round tubular structural members to solve its geometries. Hearst adopted a rectangular plan and used hot rolled wide flange sections, which is typical for New York tall building projects. Neither system was designed as Architecturally Exposed Structural Steel (AESS), however the aesthetic demands of the cladding systems required that the connection designs be very "tight" in order to diminish the bulk of the clad members. In Swiss Re the rectangular protective column enclosures were set on an angle to the face of the building, allowing the façade mullions to be very narrow. In Hearst Tower, the cover plates on the curtain wall are quite wide, making more of an expression of the size of the diagrid in the cladding. In both cases the design of the façade and expression of the diagrid in the curtain wall design impacted the design of the nodal connections, requiring them to be tightly designed to minimize their bulk while creating clear load paths.

Architecturally exposed systems have even more pressure on the design of the nodes as they can become a very real part of the expression of the structure as in the instance of the double height public spaces at Capital Gate and Guangzhou IFC. Many AESS diagrids have tended to use variations of hollow structural members as they tend to provide cleaner lines. This can infer the need to use concrete filled steel tubes in addition to an intumescent fire protection system to satisfy code requirements, plus a durable top coat system to maintain the appearance.

6. A System Enabled by the Evolution of Digital Design

Advances in digital software over the past 15 years can be seen to have enabled a general heightening in the complexity of architectural design. When Swiss Re and the Hearst Tower were in the development and detailing stage, BIM based steel detailing software such as Xsteel (now Tekla Structures) had only recently become available. Advances in this type of software were critical to the dev-

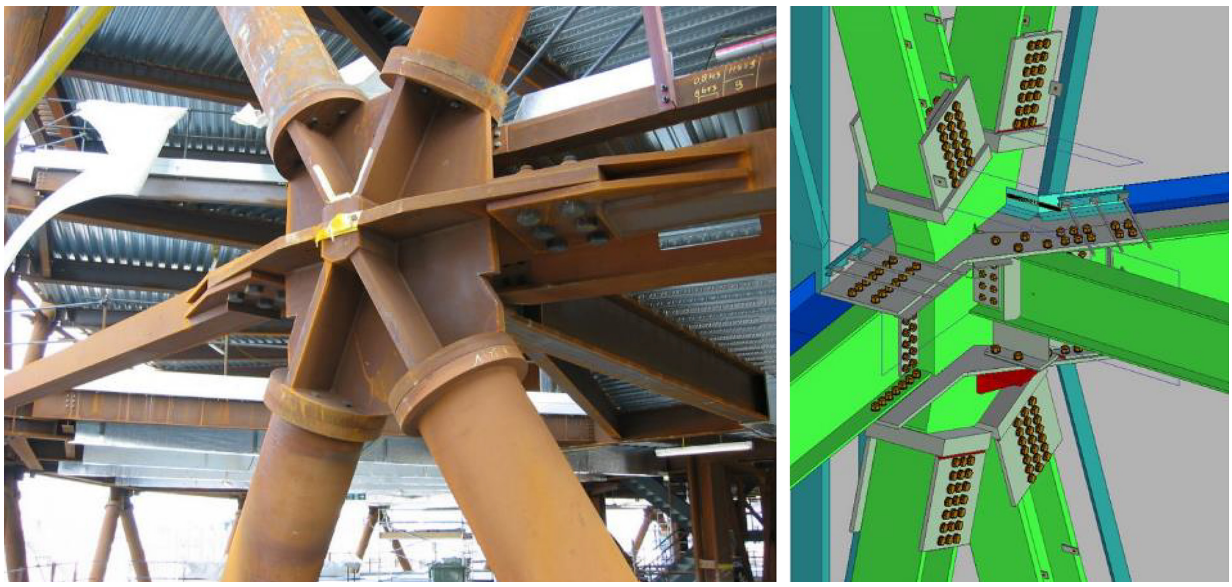


Figure 11. The tubular node for Swiss Re (left, photo Arup) and the wide flange connection for the Hearst Tower (right, photo WSP) served as precedents for subsequent node designs. The lines of force transfer through the Swiss Re node are geometrically clear. The double façade allows for a more slender horizontal ring as this member does not support the floor. The bolted connections used on the concealed node of Hearst required innovation to keep the profile tight to serve the requirements for the exterior curtain wall diagrid member covers. The horizontal bracing rings also act as the floor edge beams.

elopment of diagrid systems. Earlier methods of the structural design and detailing of steel structures would have precluded the natural complexity presented in detailing and fabricating a diagonal node based system of this scale. Complexity in architecture, engineering and construction is constantly increasing due to our present ability to design, calculate *and fabricate* an increasing range of geometric shapes. Where traditional 20th century architectural design was forced to reasonably limit form-based architectural expression in steel to simplified calculation-based design – resulting in buildings and structures that could be largely be reduced to 2D force systems – the 21st century has stepped beyond those boundaries. This is clearly evidenced in the rapid evolution of diagrid structural systems, with particular emphasis on the design of the nodes, over a very short time. From the time of the construction of Swiss Re (2004) to Capital Gate (2010) software advances allowed for a tremendous increase in the number of variations of node types.

What was clear in the early approaches of Swiss Re

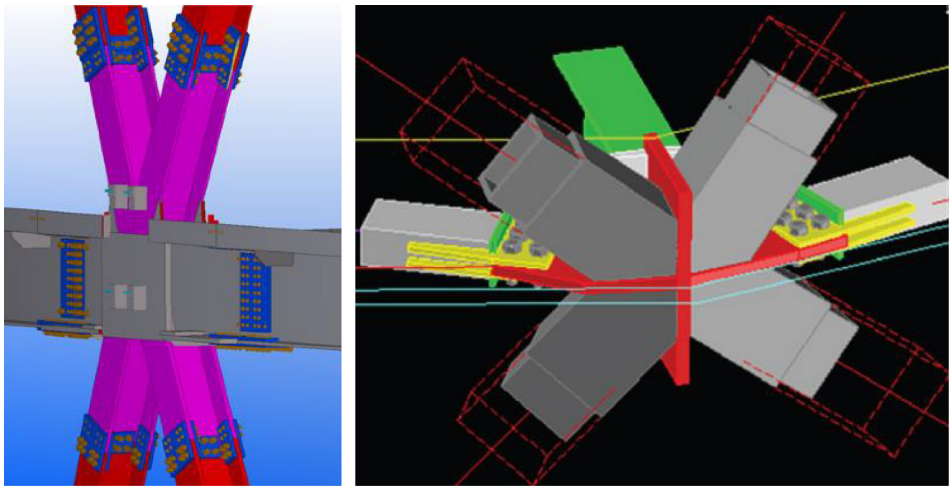


Figure 12. Tekla models for the nodes at Aldar HQ (image, William Hare) and Capital Gate (image, Jeff Schofield).

and Hearst was the need to shop-fabricate the nodes and diagrid members so that they could be more easily erected on site. The connections within the nodes themselves were fully welded. All of the site connections were achieved through bolting. Shop fabrication allows the effective use of jigs to ensure that the alignment and positioning of the steel elements is accurate. The shop is also equipped with cranes and other innovative devices that can lift, turn and rotate the members so that there is easier access for welding and remediation operations such as grinding and milling, resulting in a higher quality final product. Although Swiss Re and Hearst were not to be AESS, when the diagrid system is to be exposed, the quality control of the shop environment for welding is essential. Quality control on site welding is also important as the splices between the node arms and the diagonal members will often occur at viewing level. If specifying a fully welded connection on an AESS project it is essential that the viewing distances be taken into account in determining the approach to finishing the connections (Boake, 2015).

7. The Influence of the Node: Technology Transfer

A structural development can be seen as significant if it transforms design thinking. This can certainly be said of the node system of connection that is central to the concept of the diagrid system. Although not all diagrid structures are conceived of using the node and connecting member system (some structures will fabricate the node an integral part of the long diagonal members to reduce site welded connections), it does represent a significant proportion of diagrid structures. This methodology isolates the geometrically articulated nodal pieces, placing the challenge of their exacting fabrication in the fabrication shop. This allows for ease of fabrication, tighter dimensional controls and access to better conditions for welding – all critical to ensuring ease of erection.

The large structural nodes that were first developed for diagrid structures have begun to create a general transformation of structural design for a wider range of "non-diagrid" buildings. This, of course has been additionally fueled by advances in BIM modeling technologies and the interoperability possible from engineering to fabrication software for steel design, detailing and eventual fabrication and erection. *Node* has become a widespread structural term used to describe large, typically steel, connections that must accommodate a number of incoming angled members. Nodes are now commonly used to handle the construction of a wide variety of geometries, both regular and irregular. The surge in the use of these eccentric geometries that are taking advantage of the structural abilities of node design also parallels advances in digital modeling and the more direct transfer of information from engineering to fabrication.

7.1. Cast Nodes

Although the use of castings by Sony City (2006) in Tokyo to create the nodal connections for its 22 storey,



Figure 13. The narrowing of the base of One Manhattan West in New York City is facilitated by the use of steel nodes. The tower floor plate will increase in overall dimension above the fifth floor level. The nodes accommodate the branching of steel out to receive the loads from the perimeter columns of the tower. The node pictured here weighs 51.3 metric tons. The final height of the tower will be 303 m.

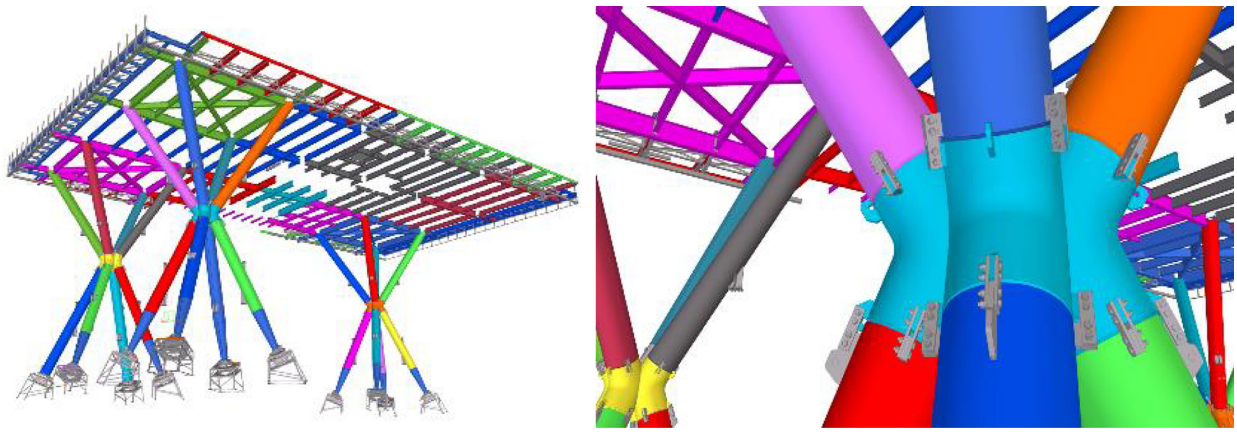


Figure 14. The Tekla models for the diagonal frames at the Queen Richmond Center (2015) in Toronto illustrate the ability of this system to provide the visualization of the project as well as the creation of the shop drawings essential to fabrication. In this instance the node has been created as a large hollow steel casting. The frame is filled with concrete and given an intumescent coating. The steel delta frames and floor support an 11 storey reinforced concrete office tower. (Images, Walters Inc., castings by CastConnex).

AESS, double façade project has not been widely adopted in diagrid towers, the use of cast steel nodes in general has greatly increased. Again this use can in part be attributed to the wider acceptance of nodes in structural systems as well as addressing the increasing geometric complexity in architectural design, fueled by digital design tools. Castings are being seen by many as a very viable alternate solution to the standard fabrication of complex steel nodes from (predominantly) plate steel (de Oliveira, 2008). Particularly in architecturally exposed conditions where the lines perhaps need to be cleaner while keeping good load paths, castings have proven to be quite effective. The ability to keep good control of the outer geometry of the node, while increasing the amount of steel that is structurally required by varying the size of the void on the interior, has been effectively used on a number of extremely large projects.

Given the technological advances in software and the increased experience level in the design and application of cast nodes to a wide variety of structures, it is not incon-



Figure 15. Steel castings create smooth angular load paths when solving the convergence of large tubular members. The Transbay Transit Center (2016) in San Francisco (left) incorporates 304 cast steel nodes produced from 74 unique casting geometries which range in weight from 2 to 20 metric tons each. Queen Richmond Center (2014) in Toronto employs cast steel nodes weighing 14.3 metric tons at the intersection of its large steel tube support frames. Castings designed by CastConnex.

ceivable to imagine that a cast solution may more widely applied to a diagrid tower in the near future. Were the Transbay Transit Center, which extends to cover 4 city blocks, be turned on end, its sheer size and high number of large cast nodes could easily comprise a tower type.

8. Conclusions

The use of the diagrid as a structural system for tall buildings is expanding in ways that tend to be increasing the variety and uniqueness of a typology that has tended to be selected for its value as a means of iconic architectural expression, rather than for is potential in optimization and reductions in the use of steel. Some of the most significant developments in the design of diagrids have laid in the creation of the node as a key structural connection strategy. This invention and technology is being transferred to the greater application of steel structures, creating buildings that while not being of a "pure" diagrid type, are taking advantage of the advances in the development of diagrid technology to respond to the design potential that has been introduced by advanced digital modeling. Although the majority of node connections in diagrid buildings to date have been constructed using custom plate steel fabrication, advances in casting applications may soon see the adoption of this node technology to diagrid towers.

Acknowledgements

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