

# Diagrid Structures: Innovation and Detailing

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**ABSTRACT:** Diagonalized grid structures have emerged as one of the most innovative and adaptable approaches to structuring buildings in this millennium. Variations of the diagrid system have evolved to the point of making its use non exclusive to the tall building. Diagrid construction is also to be found in a range of innovative mid rise steel projects. This paper will examine developments in the recent history of diagrid buildings to include the design and detailing. Images by author unless otherwise noted.

## 1 THE DEVELOPMENT OF THE DIAGRID

Modified diagonalized core system buildings – *diagrids* - only began to appear in contemporary steel design around the year 2003. All three of the initial examples – The London GLA, Swiss Re and the Hearst Tower – were in development in the offices of Foster+Partners at the same time and the engineering expertise of ARUP was integral to all three projects. Interestingly, all made use of unique variations of the system by virtue of their three dimensional geometry suggesting that the diagrid form could potentially support even more daring feats.

There are a number of structural advantages that can be attributed to the use of a diagrid system over a typical orthogonally framed system. Where the original “diagonalized core” or “braced tube” system used diagonal bracing members over a framed exterior support system as a supplementary stability system, the current diagrid system *often* uses an exclusive exterior frame comprised entirely of diagonal members, eliminating the vertical columns. Vertical columns are capable only of withstanding gravity loads and the diagrid is useful for both gravity and lateral loading. This type of structure carries lateral wind loads more efficiently, creating stiffness that is complemented by the axial action of the diagonal member.

The height of the building is divided into modules. The diamond shaped modules typically span 6 to 8 floors, tip to tip. Floor edge beams frame into the module to create triangulation. Major structural intersections occur at the nodes although the floor beams can also frame into the diagonal members. Much research is being conducted to determine the optimal dimensions of the base module. The primary university based research has been undertaken by Kyoung Sun Moon of Yale University with studies on building heights of 40, 60 and 80 floors, and more recently studies on diagrids for twisted towers. The sample study done of a 60 storey tall building, was based on a 1:6 ratio, measuring 36m x 36m with an 18m x 18m gravity core at the center with floor to floor heights of 3.9m confirmed 69° as the most effective angle for a uniform diagrid as it results in the least amount of steel by weight. (Moon, 2007, 2008, 2009, 2010, 2011) This angle changes as a function of the building height as well as its width to height ratio.

Other studies have concluded that a 20% savings in the weight of the structural steel is possible using a diagrid versus a braced tube. (Charnish, 2008)

This paper will not focus on these mathematically based studies but they are essential reading to gain a more complete understanding of the structural basis, actions and potential for optimization of the diagrid system. There exists a large lag between the published engineering research and the actual design and construction of diagrid structures. Most constructed diagrids do not resemble the optimization studies but rather tend towards extravagance in geometry, form and height. Methods of detailing and construction will be the focus of the paper.

## 2 CONSTRUCTABILITY AND NODE DESIGN

As with any deviation from standard framing techniques, constructability is an important issue in diagrid structures. Both the engineering and fabrication of the joints are more complex than for an orthogonal structure, and this incurs additional costs. The precision of the geometry of the connection nodes is critical, so it is advantageous to maximize shop fabrication to reduce difficulties associated with erection and site work. Some nodes are many tonnes and it is desirable to be able to lift and turn the elements with a crane to provide access for fabrication, welding and finishing.



Figure 1. (Left) A node for the Bow Encana by Foster+Partners in Calgary, Canada. The side of the elements facing towards the atrium in the double façade was finished to AESS 4. The backside was concealed so finished as Standard Structural Steel. (Right) The north façade of the Bow Encana uses a modified diagrid in a concealed fashion. The node-to-diaGRID connections are welded. Temporary bolted connections are used to secure the members prior to welding.

There are two schools of thought as to the rigidity of the construction of the nodes themselves. Technically, if designing a purely triangulated ‘truss like’ structure, the center of the node need not be rigid and be can constructed as a hinge or pin connection. (Moon, 2009) In the purest sense the diagrid tube is acting as a vertical cantilever and the elements themselves loaded axially. Moment resisting connections are not normally used in standard triangulated truss designs. Where this could work for symmetrical structures having well balanced loads, eccentrically loaded structures need rigidity in the node to assist in self support during the erection process. Constructability issues, particularly to enable quick erection without need for temporary bracing, are critical.

The module layout and angles also feed into erection concerns. Steeper diagrid angles are preferred to minimize the eccentricity in the loading on the diagonals. Deflection and deformation of the diagonals needs to be kept to a minimum in order to ensure that the subsequent node connection points will align.



Figure 2. The irregular diagrid structure of the addition to the Royal Ontario Museum by Studio Libeskind used angles that were shallow. The design of the nodes and the sizing of the grid elements were adjusted to ensure that no temporary shoring was required. At Left the ROM during construction. At Right the fabricator's digital image of the structure showing the variety of connection types that had to be detailed.

In many of the diagrid projects constructed to date, the nodes have been prefabricated as rigid elements in the shop allowing for incoming straight members to be either bolted or welded on site more easily. This moves the connection points away from the centroid of the node and to points that may be more than a meter away. This allows for easier access to complete the connections on the construction site. From a practical perspective, if using bolting, more than one ironworker can assist in completing the work at the node.

As this type of structure is more expensive to fabricate, cost savings are to be realized if there is a high degree of repetition in the design and fabrication of the nodes. Given the high profile nature of most diagrid buildings, this does not seem to have been made a priority as this would call for regular geometry in plan as well as uniformity over the height of the building. The Hearst Tower in New York is one of the few diagrid structures having a square plan and that also has a uniform plan for all floors. However the development of new BIM based detailing software has greatly changed the fabrication industry. The software is capable of dealing with highly differentiated geometries and also producing shop drawings for each element. If the fabrication method and surface treatments are relatively uniform, it is not difficult to customize the nodes.

### 3 THE IMPACT OF EXPOSURE ON DESIGN AND DETAILING

The choice to architecturally expose or conceal the frame has great impact on the design and detailing choices for both the member types and nodes. Exposure is not always an option. Fire codes vary by building type and jurisdiction, so although the desire may be to make the expression of the diagrid an integral part of the design, it may not be permitted. It is wise to ascertain this prior to assuming exposure is possible.

#### 3.1 *Concealed Structural Steel*

The primary concerns that will influence concealed steel diagrids will answer to loading and erection issues. Complete shop fabrication of the nodes has become the industry standard. As these elements are large and normally welded, overhead cranes are needed to move and rotate the steel for ease of access for welding. It will be more likely to use bolting to join the diagonals to the nodes as this can be done more quickly on the site.

However this does not preclude the use of welding the nodes to diagonal connections on site if the structural design determines it to be necessary. Where site welding is done the node and diagonals will arrive with connection tabs attached. These can be bolted to temporarily secure

the steel so that the crane can be disconnected. The tabs will be cut away once the welding is complete. (Boake, 2011)

In some cases where the diagrid is chosen purely for its structural efficiency and is not expressed, either at all or largely hidden behind gypsum board, the detailing will be less of a concern for the Architect. However, if the diagrid will be clad as part of the architectural expression (see Shelley Street, Fig. 8), then the connections must be made as discreet as possible to minimize the bulkiness of the members.



Figure 3. Capital Gate (Left) is able to expose its powerful diagrid, making the steel a vital part of the interior expression of the building. The Hearst Building (Right) must clad the members as is natural for a tall commercial building in New York City. This changes the feeling and apparancy of the steel in the space.

### 3.2 *Architecturally Exposed Structural Steel*

The decision to architecturally expose the diagrid will radically alter the decision making matrix for the project. An architecturally exposed diagrid is more likely to require fully welded connections – both within the node and for the connections between the nodes and the diagonals. This puts added pressure on the fabrication tolerances in order to ensure that the butt welds are closely aligned to ensure a seamless transition. Site welding may also require pre-heating of the material, so scaffolding and weather protection might also be required.

Most important if considering an AESS diagrid is to ascertain the impact of the local fire code. These vary substantially from country to country, and what might be permitted in China may not be in North America. The most common method of fire protection for exposed steel is the intumescent coating (with or without an additional fire suppression system). These coatings vary in thickness and finish as a function of the amount of protection required. Generally speaking, thinner steel requires thicker coatings. In all instances the finish has a texture much like an orange peel and will mask some of the finer welding and finishing details. (Boake, 2012)



Figure 4. The AESS diagrid of the Bow Encana uses welded joints between the node and the diagonal. As these surfaces are exposed within the atrium, they have been filled and ground after welding so that the transition is invisible once painted. The Left image shows the temporary bolted tabs used to secure the diagonal prior to welding. At Right the connection being filled and sanded to achieve a seamless appearance.

## 4 CLADDING AND FAÇADE TREATMENT

Diagrid buildings tend to set themselves apart from the balance of tall or Supertall buildings by virtue of their unique appearance. The current tendency in design is to express the use of the diagrid on the building, rather than ignoring the aesthetic potential of the structure as was historically done in tall buildings that relied on an orthographic structural system.

The treatment of the expression of the diagrid frame varies between projects as a function of the desired aesthetic for expression of the frame (or not). The size of the diagrid is often expressed in the cladding of the building. The modularity of the curtain wall normally will scale down the dimensions of the diamonds or triangulated shapes to suit the height of the floors and requirements for both fixed and operable windows. The decision to use a triangulated versus rectilinear curtain wall system is not consistent and seems to be a function both of the overall size of the diagrid structure as well as the form of the building itself. Buildings with more curvilinear forms tend to use triangulated windows as these easily adapt to the form. Larger module diagrids are easier to “fit” on the façade and can more easily accommodate standard rectilinear based curtain wall systems as infill. The expression (or not) of the diagrid in the curtain wall also varies from project to project. Again this is a function of the desired architectural expression.

### 4.1 *Triangulated Glazing*

Many diagrid buildings, in particular those with a curvilinear form, tend to subdivide the diagrid into triangulated glazing. The use of triangular geometry works like a “mesh” to allow for the approximation of the curved form through the use of non curved elements. This is far more economical than using true curves, even if the glazing system itself is more expensive.

Aldar HQ in Abu Dhabi, although covering the steel diagrid on the interior of the building with gypsum board, chooses to express the location of the grids on the exterior façade. Physically this was not required as the envelope is outboard of the steel. It was an aesthetic choice. This creates a prominent diamond pattern on the façade that clearly presents the diagrid module as an element of design. The curved face of Aldar requires customized window washing equipment. Curved façades require special window cleaning equipment to keep the platforms away from the building. A custom track and conveyance device was constructed to clean the “ends” of the building. The machine is able to track over the top and down the other side.



Figure 5. Aldar HQ in Abu Dhabi is the only circular diagrid tower. The diagrid has been constructed from standard structural steel (wide flange or universal column sections) and a spray fire protection used.

Capital Gate in Abu Dhabi also uses triangulated glazing but makes a more unobtrusive gesture on the façade regarding the location of the diagrid situated behind the glass. The very small 2 storey module size for Capital Gate, to support the 18° lean, has resulted in one of the smallest modules to date. The member sizes are large and to translate this to the façade would have been quite overbearing. Instead a slight color change at the grid is used to acknowledge the pattern. These sorts of twisted forms tend to subdue the reading of the module through to the façade.

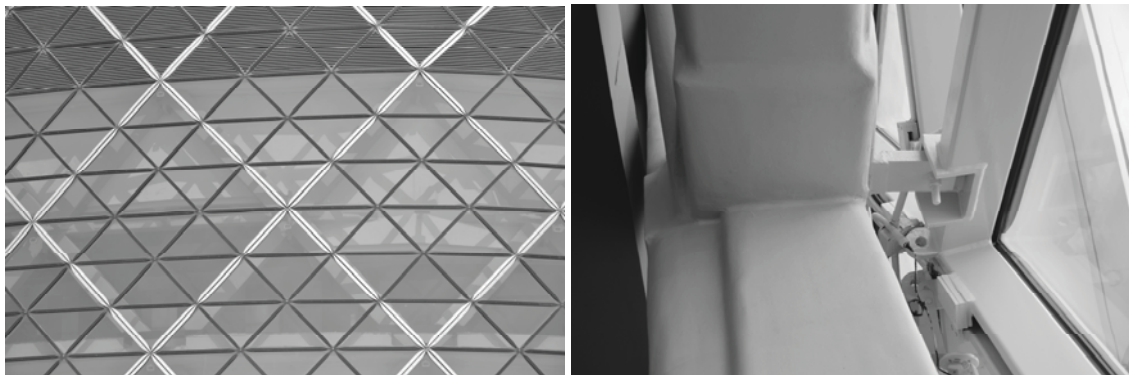


Figure 6. The modules on Capital Gate are almost square in proportion. The pressure caps that align with the grid are given a silver finish versus the black finish that surrounds the individual units. At Right is the connection of the steel frame that supports the glazing to the diagrid element. The clearance between the systems is tight.

Glazing choices will need to also consider the inclusion of operable windows as sustainability concerns increase. Operable windows have been incorporated into a number of the diagrid buildings using triangular windows. Awning types with the point down seem to be the choice.

#### 4.2 Rectilinear Glazing

Rectilinear curtain wall is often chosen for projects whose forms are more planar. It is typically less expensive than the customized triangulated option. For commercial office functions these windows are a practical solution for the provision of blinds and shades and also partitions if subdivision of the interior needs to extend to the perimeter of the building. Many of façade solutions for tall diagrid buildings will employ windows that are the same height as the floor to floor distance. This can be seen in both the Guangzhou IFC and Bow Encana (Fig. 7). Larger glazing units are more economical than systems comprised of smaller units. The designer can begin to play with the visual scale of the building in the choice of window proportion.

The frequency and nature of operable units is also important when selecting or designing the curtain wall system. Natural ventilation is seeing an increase, even in some high rise types. If operators are desired the size of the unit, nature of opening, and protection from fall hazard must be considered. Combined uses, such as office and hotel, might also infer differentiated glazing, both in terms of transparency as well as inclusion of operable windows.



Figure 7. (Left) The Guangzhou International Finance Center in China uses a very transparent glass, combined with a rectilinear curtain wall that does not acknowledge the diagrid behind by means of including a dominant system of column covers. The massive tubular round diagonals are clearly seen through the glass and are lit at night to enhance their expression. (Right) The Bow Encana uses enlarged covers on the exterior to highlight the locations of the diagrids. The infill glazing is rectilinear.

The bottom line with respect to the selection and the design of the curtain wall is that it is greatly impacted by the dimensions of the base module for the diagrid. Larger modules allow more flexibility in the choice of curtain wall. Smaller modules are more restrictive and invariably lead to more complex glazing systems that tend to be triangulated. This impacts labor costs as these tend to be more time consuming to install and maintain as they cannot be fitted with standard window washing equipment.

## 5 EXTERIOR DIAGRIDS

The majority of structural diagrids have been placed on the interior of the envelope. This is especially critical in cold climates where thermal expansion is significant and thermal bridges must be avoided. In highly corrosive environments exterior diagrids can also require ongoing maintenance due to oxidation and weathering of the finish. However diagrids have been used outside of the envelope in several instances to satisfy different programmatic requirements. This is more frequent in hot or temperate climates where thermal issues are less.

Perhaps the most notable exterior diagrid structure to date is for One Shelley Street in Sydney, Australia. The temperate climate has permitted the diagrid to exist outside of the curtain wall façade, effectively maximizing the internal leasable area. Although the designers were originally planning to construct the members from architecturally exposed steel, it was decided for economic reasons to instead use conventional universal column sections and clad these. As corrosion resistance is a great concern in Australia, this was likely a prudent decision. The triangulation of the diagrid is completed by the floor edge beams on the interior. This is always structurally necessary for stability, but normally this functionality is not separated by the placement of the curtain wall.

Exterior diagrids are also being used in double façade construction as a lightweight but stable means to support the outer layer of glazing. Although not structural in terms of the support of the building, they do take advantage of the structural attributes of diagrid design.

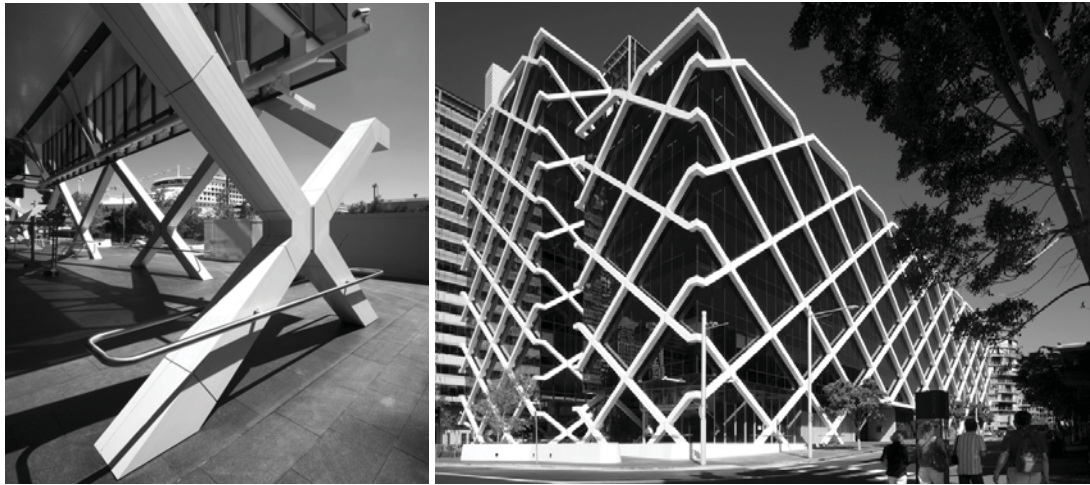


Figure 8. The exterior diagrid of One Shelley Street in Sydney, Australia creates a dynamic solution in part due to the choice of finish colors for the diagrid and façade, but as well from the innovative detailing as the diagrid wraps the corner. An innovative colonnade is created by the diagrid at grade. Rectilinear curtain wall sits behind the diagrid.

## 6 CONCLUSION

Diagrids, as they gain popularity and construction frequency are beginning to more clearly display a language of detailing and design that corresponds to choices in the size of the base module, building type and three-dimensional geometry of the project. They are demonstrating a dynamic and adaptable structural system that is more adapt at structuring contemporary architectural aspirations. There is still much to be explored in optimization from a structural perspective, but it is hoped that this paper has succeeded in introducing some of the primary architectural questions that need to be addressed as well as some possible avenues of design for exploration.

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### 7.1 Images

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- One Shelley St. <http://www.australiandesignreview.com/architecture/546-one-shelley-street>
- ROM diagram. Courtesy of Walters Inc.