DIAGRIDS, THE NEW STABLITY SYSTEM: COMBINING ARCHITECTURE WITH ENGINEERING

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Abstract

Diagonalized grid structures – "diagrids" - 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, detailing, fabrication and erection issues.

The structural and architectural design of diagrid buildings falls cleanly between the typical education or experience of the architect and engineer. The approach to the current study and design of diagrid buildings is very different if looked at through the eyes of the Architect vs. Engineer vs. Fabricator/erector. The decision to express or conceal the structure impacts the design of the building in very unique ways given the angular nature of this new geometry. It is the intention of this paper to provide a comparative understanding of the design requirements and detailing of these structures via an examination of significant recent examples.

Keywords

Steel, Diagrid, Stability Systems, Architecturally Exposed Structural Steel

INTRODUCTION

The evolution of the form and expression of the tall building is only slightly more than 100 years old. As a building type it has been the subject of much debate, in terms of its structure, materiality, form and environmental impact. Early tall buildings typically relied on an all steel structure based on a portal frame with reinforced connections to resist wind and other lateral loads. Later structures separated the gravity and lateral loading systems, using additional bracing in the form of overlaid diagonals, to take the lateral loads.

The design of the structural stability system of early tall buildings was clearly the job of the Engineer. Architects responded with façade designs that reflected trends of the period. Early curtain wall design typically used glazed terra cotta tiles with punched (operable) windows. With the invention of aluminum curtain wall systems, these were replaced with significantly higher proportions of glazing. No matter what the interior structural system, the façade design was based on a rectilinear aesthetic. Architecturally these towers tended towards a visual “sameness” as they were optimized and constructed across booming North American cities.

As building heights were increased and subjected to higher wind loads, new types of bracing systems were needed to reinforce the structure which in simple terms had to perform as a very tall cantilever. Where moment resisting beam to column connections were insufficient, K and X bracing was added. This was typically located internally, near the core, in order to make it as unobtrusive as possible; i.e. having no impact on the design of the façade or the flow of traffic in the building. As requirements for mechanical systems increased, these were often relegated to designated floors at intervals over the height of the building. Truss structures were used at these floors as a stabilization method. From a design perspective, these truss-band floors could easily be incorporated into the façade planning, while still supporting the use of a standard curtain wall. It was only with the design of the iconic 100 storey John Hancock Building in Chicago in the late 1960s, and the introduction of braced tubes, were Architects challenged to incorporate the bracing into their façade designs, thereby pushing an engineering choice into the architectural design.

FROM DIAGONALIZED TUBE TO DIAGRID

Although the first building to use a diagrid was constructed around 1965 in Pittsburgh, the method was not really used again until several high profile projects were in their design phase around the year 2000. The IBM Building integrated the diagrid with the glazing system resulting in oddly shaped windows. This would have created a far more expensive option than the balance of curtain wall clad office buildings of the same period, and was likely the reason for its brief use.

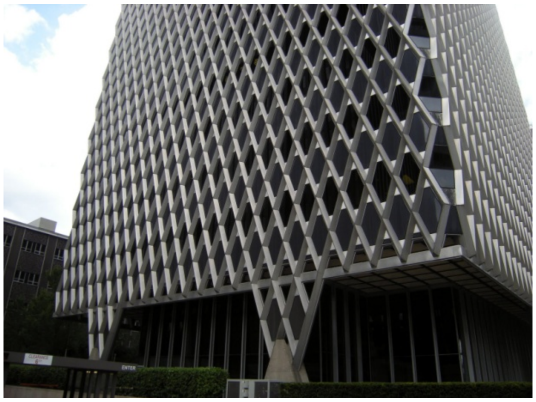

Fig. 1: The IBM Building in Pittsburgh (now called United Steelworkers Building), designed by Curtis and Davis and engineered by Leslie Robertson, is the first example of a steel diagrid expressed in a façade.[1] The steel diagrid exoskeleton assists in stability and is not a classic curtain wall system.

The primary idea behind the development of the diagrid system was the recognition of the savings possible in the removal of (most of) the vertical columns. The vertical columns were only engineered to carry gravity loads and were incapable of providing lateral stability. The diagonal grid, if properly spaced, was capable of assuming all of the gravity loads as well as providing lateral stability due to its triangular configuration. As the exterior diagrid tube is comprised of diamond shapes, triangulation is achieved where the floor edge beams tie into the grid.

> "Compared with conventional framed tubular structures without diagonals, diagrid structures are much more effective in minimizing shear deformation because they carry shear by axial action of the diagonal members, while conventional framed tubular structures carry shear by the bending of the vertical columns."[2]

Where the original diagonal bracing members were laid over a regularly framed exterior support system as a *supplementary* method of support, the current (standard high rise) diagrid system uses an exterior frame comprised exclusively of diagonal members as the *primary* means of support. If properly engineered, such systems can use less steel than conventionally framed tall buildings.[3] Where early conventionally framed office towers did not necessarily strive for a column free interior, most diagrid towers work towards the elimination of columns between the exterior structure and the core. This supports a sustainability-motivated move towards increased daylight effectiveness and LEED™ credits. This supports the choice of the structural diagrid by the Architect over the Engineer.

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. Numerous studies have been conducted towards the optimization of the module size as a function of the building height and angles of the inclined members.[4] 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 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 towards minimizing their frequency and simplifying the connection between the node and the diagonal to speed up erection.

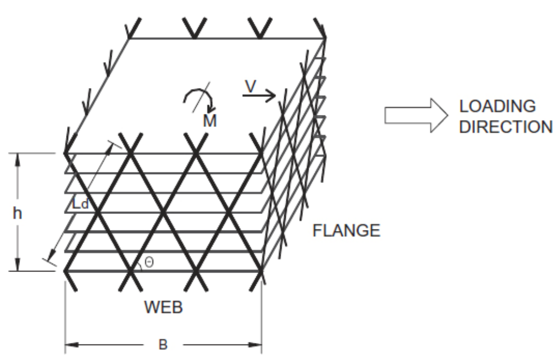

Fig. 2: Current exploration into the best geometry for diagrids is based on this Figure as established by Kyoung Sun Moon from Yale University in his research.[5]

SELECTING THE MODULE

Much engineering research is underway to establish the optimal module size, which directly impacts the “shape” of the diagrid, window size and placement as well as the amount of resources used in the project. The impact of “shape” is viewed differently by Architects and Engineers – structural concerns also being impacted by wind and vortex shedding issues.

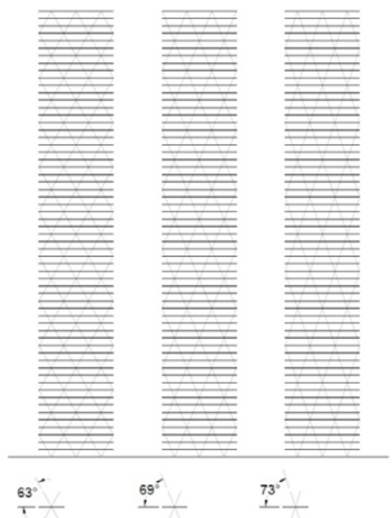

Fig. 3: This sample study done of a 60 storey tall building, based on a 1:6 ratio, measuring 36m x 36m with an 18m x 18m gravity core at the center with floor to floor heights of 3.9m confirmed 69^{o} as the most effective angle for a uniform diagrid.[6] This value changes as a function of the building height as well as its width to height ratio.

As a tall building functions as a vertical cantilever, the taller and more slender the building, the greater will be the differentiation between the function of the diagrid elements at the base to those towards the top. This has suggested that a variation in the inclination angle of the diagonals can be used to reduce the amount of steel and provide needed resistance in the structure. The members and connections at the base of the building must be designed to resist moment while those at the top to resist shear.

The triangulation of the diagrid “tube” itself is not sufficient to achieve full rigidity in the structure. Ring beams at the floor edges are normally tied into the diagrid to integrate the structural action into a coherent tube and connect the same to the floors, and back to the core. As there are normally multiple floors intersecting with each long diagonal of the grid, these intersections will occur at the nodes as well as at several instances along the diagonal. The angle of the diagonals allows for a natural and direct flow of loads through the structure and down to the foundation of the building.

Where orthogonally framed towers conformed to International Style architecture of the times, diagrids have challenged the norm and are creating new expressions that question standard methods of design and construction. Although structural optimization might be central to discussions from the engineering perspective, many high profile constructed diagrid towers bear little similarity to optimization diagrams which would suggest architecturally driven influence.

The size of the diagrid is normally expressed in the cladding of the building. The modularity of the curtain wall will usually 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 because it is a function of the overall size of the diagrid structure as well as the form of the building itself. Buildings whose diagrids support more curvilinear forms tend to use triangulated windows as these more easily adapt to the shape. Larger diagrids have less impact on the façade and can more easily accommodate standard rectilinear based curtain wall systems that may fit within the diagrid. The choice to express the location of the structural diagrid in the curtain wall varies from project to project. This is driven by the architecture and not the engineering.

Fig. 4: Capital Gate, Abu Dhabi (left) has a small module and uses a triangular window system that accommodates operable windows. Aldar HQ, Abu Dhabi (center) has a larger module and also employs a triangular system. Bow Encana, Calgary (right) has the largest module and the faceting of the structure allows for the use of a rectilinear glazing system.

CONSTRUCTABILITY

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 incurring 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 site work and erection of the odd geometries associated with the design of the nodes.

There are two schools of thought as to the rigidity of the construction of the nodes themselves. In theory, 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. Where this may work well for symmetrical structures having well balanced loads, eccentrically loaded structures will need some rigidity in the node to assist in self support during the construction process. In many of the diagrid projects constructed to date, the nodes have been prefabricated in the shop as rigid elements allowing for incoming straight members to be either bolted or welded on site, more easily, and without need of temporary supports until the next node is attached. 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. Reductions in site labor also lowers cost and time.

If the structure is to be clad or concealed, as in the case of the Hearst Tower, the diagrid elements can be bolted on site for speed of erection. In cases where the diagrid is able to be left architecturally exposed, the connections have been welded. This adds significantly to the cost of erection as more scaffolding is required for welders to access the nodes. It is more difficult to get high quality site welds due to access angles.

Fig. 5: The nodes on the Bow Encana are of two types. The diagrid on the south façade (left) is expressed as part of the double façade atrium and has been designed to AESS4 standards.[7] The node-to-diagonal connections were welded. The diagrid on the north façade (right) is concealed so although the connections have also been welded, the system is constructed of different section types and to a Standard Structural Steel level of finish.

THE POSSIBILITIES OF DIAGRID SYSTEMS

Where early applications of expressed diagonal bracing tended not to significantly modify the basic rectilinear shape of the tower, current applications of the diagrid are exploiting the ability of the triangulated “mesh” to more easily distort and create both curved and more random geometric forms. The term “mesh” makes direct reference to the mapping techniques of 3-D modeling software and the means to make fairly direct translations from design investigations and through BIM to fabrication detailing software. The more striking examples also tend to strive for effective daylighting and use a small floor plate. This works well with the diagrid typology as the intention of the system is to eliminate interior columns between the exterior wall and the core.

Diagrid based buildings began to appear in contemporary steel design around the year 2003. All three of the initial examples – 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 part of all of the projects. Interestingly, all three make use of unique variations of the system by virtue of their three dimensional geometry. The Hearst Tower is perhaps the most normalized given the rectangular shape of the tower – modified slightly as the corners are indented in places. The Swiss Re tower alters the design by creating a building that is not a cylinder but whose shape bulges at mid-height and tapers to a virtual point at the top (hence its nickname, Gherkin). Both Hearst and Swiss Re have eliminated vertical columns, create a column-free interior and use the diagrid as the primary stability system.

Where recent Supertall buildings such as the Burj Khalifa and the proposed Jeddah and China Broad Group towers increase the size of the building base to resist moment, most diagrid towers have not. Some, such as Swiss Re and Guangzhou IFC have even narrowed the base and relied on the diagrid for stability. The geometric explorations and structural success of Swiss Re as an early example of the diagrid type has served to fuel the imagination and ambitions of subsequent designs – most notably Capital Gate with its 18^{o} backwards lean (Fig. 6).

What is incredibly intriguing with diagrids as opposed to previous Modernist structural strategies for tall buildings is that a "basic" typology does not exist. Unlike the skyscraper designs that reflected the International Style or Modern Movement, contemporary diagrid buildings all strive to be unique, reinforcing the idea that the architectural ambitions are pushing the engineering technology in these structures. Whether in terms of height, shape/profile, node design or the length of the diagrid member, each and every diagrid structure is very different, *almost in defiance of current research looking for optimization.* This can likely be attributed to advances in computing and modeling that have run parallel to their development, if not slightly ahead, easily supporting curvilinear geometries from structural design through to detailing, the creation of shop drawings and fabrication.

RECENT ARCHITECTURAL APPLICATIONS OF THE DIAGRID

Currently the most challenging use of the diagrid structural model is in the creation of "twisted forms". These can be seen in numerous tall buildings presently under construction, particularly in Asia and the Middle East. The steel diagrid, in its ability to create a "mesh" is capable of conforming to almost any shape that can be created using modern 3-D modeling software. The diamond shaped grids are easily further subdivided into triangulated patterns for curtain wall manufacture. Typically the building will try to use a substantial vertical concrete core that can provide straight run elevator access through the building, and arrange the offsets to hang from the core. This requires extra engineering to ascertain the structural integrity of the building. There is also a substantial increase in fabrication and erection cost as a result of the decrease in repetitive design of the nodes.

Capital Gate by RMJM Architects in Abu Dhabi uses the strength of the diagrid to create an 18^{o} backwards lean on the tower. The importance of the concrete core in stabilizing the building is quite different than is required by other diagrid towers whose geometry is more symmetrical in its loading. Here the base module of the diagrid has been reduced to two floors (from the usual 6 to 8) to increase the stiffness of the tube.

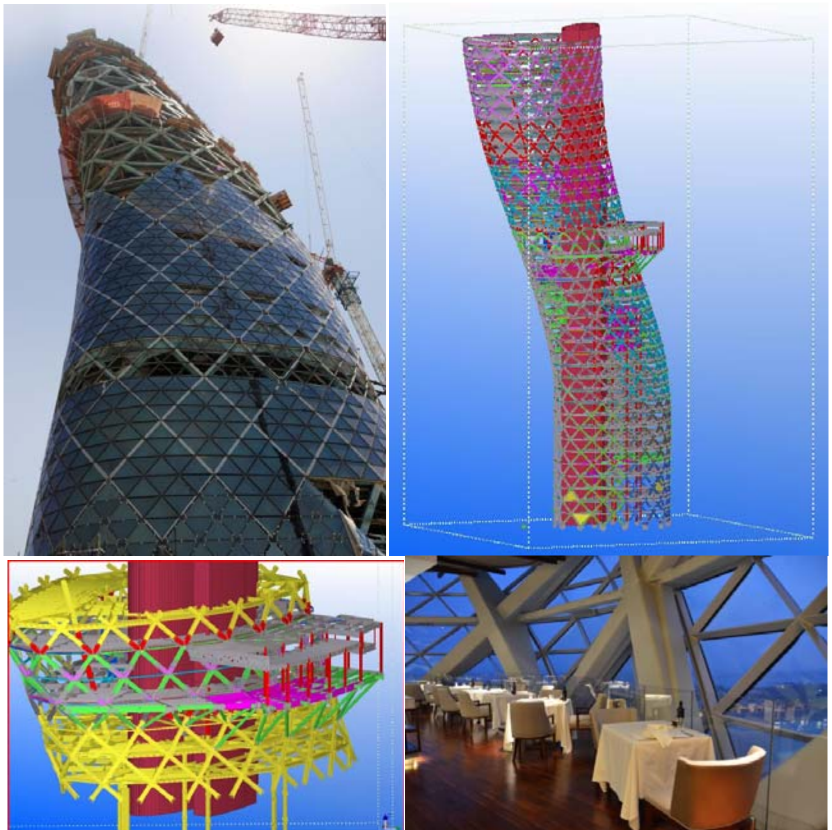

Fig. 6: Capital Gate: The construction of the tower (top left)[8]; Tekla diagram of the entire tower revealing the concrete core (top right)[9]; Tekla drawing of the structure at the 18th floor, restaurant level and pool projection on the 19th floor (bottom left)[10]; interior view of the restaurant on the 18th floor illustrating the presence of the architecturally exposed welded steel diagrid frame.

As the top half of the tower is used as a hotel, operable windows have been incorporated into the triangular pattern. Where the overall scale of building gives the impression of multiple curves, this has actually been resolved through the use of triangulation into straight elements. Each diagrid has been resolved into a custom triangular steel window frame that is tied back to the diagrid and supports the glazing modules. Fire regulations in the UAE have permitted the exposure of the steel on the interior through the use of an intumescent coating. Guangzhou IFC also uses exposed intumescent coated steel. Exposure has permitted a remarkable experience of the diagrid on the interior of the building. These regulations vary greatly by jurisdiction so it is necessary to ascertain local fire regulations before designing for architecturally exposed structural steel.

Aldar HQ in Abu Dhabi (Fig. 7) is able to use the larger 8 floor base module, which is capable of forming to the curves required by the circular disk design of the tower. Again a concrete core is used, although in this case the building is quite symmetrical and so not for obvious reasons of stability due to eccentric loading.

What becomes increasingly apparent is the critical role that developments in BIM and specialized steel detailing software have played in these structures. While not making the task simple by any means, the software does allow the fabricator to extract each connection detail as a unique drawing in order to create shop drawings for fabrication. Given the incorporation of requirements for thermal expansion and movement due to temporary eccentric loading during construction, it is reasonable to expect that the final structure be identical to the drawings. In fact it must be or the pieces will not fit. Diagrids are constructed to considerably tighter tolerances than Standard Structural Steel.

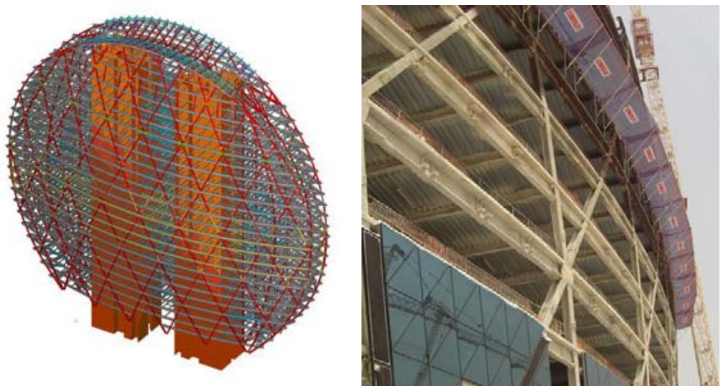

Fig. 7: Aldar HQ: The Tekla BIM model showing the pair of concrete cores and steel diagrid (left); a construction image showing the way the floors tie into the diagonals of the grid as well as the spray fireproofing (right).[11] The triangular glazing modules are also evident. Although UAE Fire codes permit exposing the steel, the tenant desired an alternate fit out and finish on the interior. The grid is nonetheless clearly expressed on the façade so an important part of the architectural expression of the structure.

Fig. 8: A comparison of the detail drawing and final structure illustrating the similarities.[12]

Detailing software played a significant role in the design of the diagrid elements for the Addition to the Royal Ontario Museum by Daniel Libeskind (Fig. 8). Although angular crystalline forms like the ROM use the principles of diagrid construction – those being taking the load path on an angle as a means to eliminate vertical columns and solve bracing issues at the same time – their structural resolution is quite different from diagrids used in towers or other more regular forms. To date most crystalline applications of the diagrid have been used to create larger aggregated volumes, often with complicated intersections of their volumes. This has meant that much of the expression and formal impact of the angular steel supports can be seen on the interior of the building. Eccentricities and large cantilevers also require more strength in the nodal connections. In order for these structures to be self supporting during construction, either temporary support towers or cable stays are necessary before the concrete floor systems are poured to provide the necessary diaphragm action.

DIAGRID RESEARCH AND FUTURE POTENTIAL

Diagrid stability systems hold great potential for future buildings that wish to *merge Architecture and Engineering* in a compelling way as their execution, as described in this paper, requires a carefully integrated design process due to the impact of the geometry of this structural system on the spaces within the building as well as the façade and fenestration design. However, little in the way of prescriptive or proscriptive material has been published to date that might assist Architects or Engineers in the task. The majority of the published research has been conducted within the University setting (Ref. 2, 4, 5, 6) and has focused primarily on *idealized optimization*, leaving the applied *realities* of the practising professionals, hidden or internalized. Professionals involved in built projects tend to internalize their detailed findings in support of their specialization in this emerging methodology. This is likely understandable given the newness of diagrid design and the competitive global economic climate. Most significant published engineering papers on diagrids are included in the references for this paper. To date a comprehensive text has not been published. It is the intention of this author to publish such a text or handbook based on detailed personal visits and investigations of a wide range of built diagrid projects.[13]

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