International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 05, May - 2017

Constructablity of Diagrid Structures

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Abstract— **"A Diagrid is a type of structural system that is designed for constructing large buildings with steel that creates triangular structures with diagonal support beams."**

This paper explores the skill of diagrid structural system from the basic of materials, component of such structural system, structural behaviour of diagrid design methodology, diagrid constructability.

Keywords*— *Diagrid; Structural system; environment ;Construction ; tall structures ;nodes ; parametric architecture .

INTRODUCTION

The diagrid (a portmanteau of diagonal grid) is a framework of diagonally intersecting metal, concrete or wooden beams that is used in the construction of buildings and roofs. The number of tall building developments has been rapidly increasing worldwide and these developments involve various complex factors such as economics, aesthetics, technology, and policies.

Advancements in structural engineering and technology have significantly pushed the height limit of high-rise buildings. For several years, many countries and companies have been constantly pursuing ownership for the title of the tallest building in the world. Until now, tall buildings have been built in an angular, round, or slightly modified form, with their technology focused on height, rather than shape. The current trend, however, is to design buildings that are aesthetically pleasing and more sophisticated and there is involvement of parametric architecture which has changed the scenario seamlessly.

These buildings can now be designed and constructed in twisted, tilted, or tapered forms. As the height of the building increases, the lateral resisting system becomes more important than the gravity system. The structural efficiency of the diagrid structure stems from its triangular configuration, which resists both gravity and lateral load by axial stresses of its members. Some of these systems include tube structures, bundled tubes, shear cores, outrigger trusses, shear walls, and diagrid structure.

WHAT IS A DIAGRID?

The word "diagrid" is a blending of the words "diagonal" and "grid" and refers to a structural system that is single thickness in nature and gains its structural integrity using triangulation. They can be planar, crystalline or take on multiple curvatures and often use crystalline forms or curvature to increase their stiffness.Z

This differentiates a diagrid from any of the three dimensional triangulated systems such as space frames, space trusses or geodesic structures, braced frame systems, lamella structure.

Diagrid systems are also being used as roofs to create large column free clear spans. The steel detailing of the lattice grid system is significantly different from that of the perimeter structural diagrid for larger buildings. A diagrid structure is a type of structural system consisting of diagonal grids connected through horizontal rings, which creates an elegant and redundant structure that is especially efficient for high-rise buildings. Though the construction of a diagrid structure is challenging due to its complicated nodes, its constructability can be enhanced by appropriate prefabrication methods. We can see the examples of diagrid structures in Shukov Towers (various) Russia by Vladimir Shukov, London City Hall London, England, Swiss Re(St. Mary Axe) - London,England by Norman foster In 2004 ,CCTV Beijing, China by Rem khoolhas in 2012.

I. DIAGRID STRUCTURE COMPONENT AND MATERIAL .

A. Diagrid material

Material selection for a Diagrid construction is based on the following factors
a) Unit weight of the material. b) Availability of the material, c) Lead-time, d) Erection Time, e) Flexibility, f) Durability, g) Labor cost, h) Fire resistance.
Materials those are majorly used are:
a) STEEL (Wide Flanges, rectangular and round HSS), b) Concrete c) Precast Concrete, d) Cast-in situ Concrete, e) Timber/Wood.

B. Diagrid Component

Diagrid comprises of the component which constitutes the structure and responsible for its composition and structural stability are

- Jointed nodes,
- Diagonal support beams,
- Horizontal beams &
- Floor plates.

These component's behaviour with each other hold the structure to its extent and develops a profile with its own language of design which are aesthetically appealing. To define their role independently is like providing the half information.

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ISSN: 2278-0181
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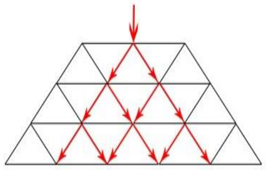

Fig1 . Point load Transfer diagram

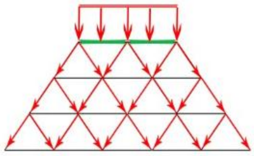

Fig2 . Uniform distributed load Transfer diagram

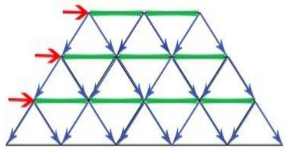

Fig3 . lateral force loaded on simple grid

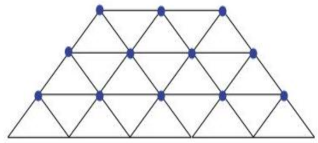

Fig4 . Arrangement of nodes in diagrid

II. DIAGRID-STRUCTURAL BEHAVIOUR

A. Foundation

When dealing with diagrids the first and most important thing to remember is that everything simplifies back to triangles (the strongest and most efficient shape) like in a normal truss. By removing all the columns and replacing them with diagonal supports, you get a much more efficient and redundant structure. But, because vertical loads still move to defined points at the bottom just like a normal framing system, there is no limit or change needed in foundation design for diagrid systems.

B. A Vertical Point Load and Distributed Vertical on A Simple Diagrid

This ability to handle gravimetric load types (such as dead, live, and snow & rain) so effectively, is why diagrids are so greatly valued. Its good efficiency allows it to handle static loads without much need for overdesign while its redundancy helps keep dynamic loads in check.
(Refer Fig 1 & fig.2)

C. A Laterally Loaded Simple Diagrid.

The horizontal members receive the load and transfer it into the vertical members by shear forces before eventually reaching the foundation. This is the reason as to why diagrids tend to have thicker horizontal members than diagonal members.
(Refer Fig 3)

D. The Nodes of a Simple Diagrid.

So, while handling vertical loads is improved and there is virtually no gain or lose in handling horizontal loads, there is a catch to diagrid system, the joints. Just like a triangle, what determines the overall strength are the nodes which are used to connect all the members together Because of the nature of the diagrid, most nodes have at least 6 members to which they are attached. This means the nodes must be very strong and leaves very little flexibly for anything other than a fixed connection or, rarely, a hinged connection as the node must be able to take and apply forces on at least 3 axes' simultaneously.(fig.4)

E. Cyclic Behaviour Of Diagrid Nodes With H Section Braces And Its Experimental Investigation.

An experiment conducted by Young-Ju Kim; In-Yong Jung; Young-Kyu Ju; Soon- Jeon Park; and Sang-Dae Kim. The results of the study show that the combined mechanism of axial force and additional moment from the two axial forces governs the failure mechanism of a diagrid node. When the node is under tension, the crack initiates the side of the flange at the end of the side stiffener and, at ultimate state, the node fails by fracture due to the stress concentration resulting from the abrupt geometrical changes and the metallurgical notches at the end of the side stiffener, resulting in a reduction in stiffness, strength, as well as ductility.

III. DIAGRID DESIGN METHODOLOGY

A. Established Numerical Values- A Simple Design Methodolgy:

B. Derivation Of Numerical Values-Stiffness Based Design Methodology:

A stiffness based design methodology for determining preliminary member sizes of steel diagrid structures for tall buildings. The methodology is applied to diagrids of various heights and grid geometries to determine the optimal grid configuration of the diagrid structure within a certain height range. There are design methodology design by K. Moon (2008) by deriving via the equations and later concluded that Bending beams and shorter buildings behave more like shear beams Based on the design studies, it is suggested to use a varying angle diagrid structure for a very tall building with its aspect ratio bigger than about 7 as is the case with the Lotte Super Tower in Seoul, and a uniform angle diagrid for a tall building with its aspect ratio smaller than about 7 as is the case with the Hearst Tower in New York, to save structural materials and, in turn, to create more sustainable built environments.

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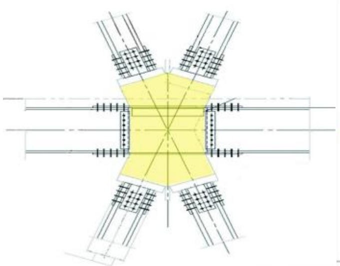

Fig7 . Typical arrangement of members in nodes

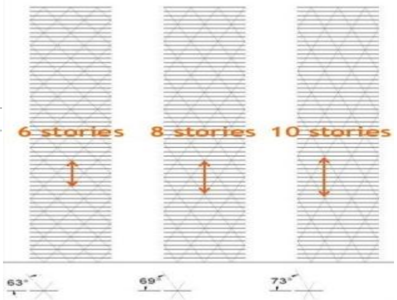

Fig5 . modules expressing stories and angles

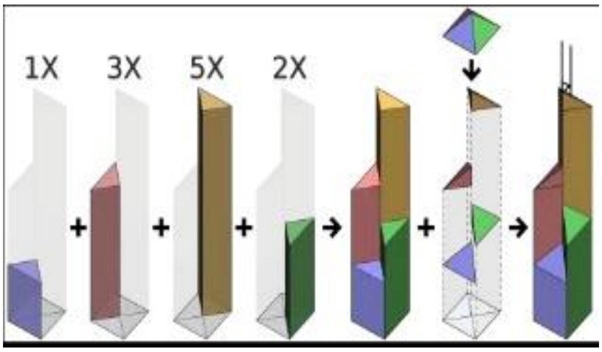

Fig6 . Permutation and combination of different scales of same module

C. Diagrid Node Design:

The diagrid segments are planned to minimize onsite butt welding and the welding locations. The load path can be divided into two main scenarios, vertical load and horizontal shear their combination. The vertical load will be transferred in the form of an axial load from the diagrid members above the node to the gusset plate and stiffeners, then to the diagrid members below the nodes. The horizontal shear will be in the form of axial loads in the diagrid members above the node with one in compression and one in tension to the gusset plate and stiffeners. The force will then be transferred as shear force in the gusset plate and then to the other pair of tensile and compressive forces on the diagrid members below the node. From this load path, the shear force at the location of bolt connections is high under lateral loads. Because this may create weak points at the node particularly during earthquakes, the strength of the bolts should be designed carefully.

D. Diagrid Modeules And Modularility

Module and modularity are the creation of the composition with the different standard modules of the different shape and size. Once the module is finalized then the composition of the module generates the different form. This modularity of the structures is results in the fast construction and easy and save material and save on wastage in enormous items of construction. The permutation and combination of the prismatic form that is used in the different modules for the composition and language of different scales of diagrid can be used. Proportion is a correspondence among the measures of the members of an entire work, and of the whole to a certain part selected as standard. (Fig.5 and Fig.6)

IV. DIAGRID CONSTRUCTABLITY

Constructability is a genuine issue in diagrid structures because the system is relatively new and nodes or the joints of diagrid are more complicated and tend to be more expensive than those of conventional orthogonal structures. One strategy to overcome this disadvantageous characteristic of the system is to shop-fabricate the complicated joints. In fact, this strategy has been used for conventional steel tubular structures, which involves many rigid column–beam connections due to the substantial number of perimeter columns required in general to make the system work as intended. Due to the triangular configuration of the diagrid structural system, rigid connections are not necessary. Pin connections at the complicated joints for diagrids work well. When designed using a prefabrication strategy, constructability will not be a critical issue for diagrid structures.

When moving from the conventional to the Diagrid structures, thorough use of material leads to ability to express organic form in a new structural language. Most forms that can be created with a triangulated form can be assumed possible. Floor plates may not be regular - they can change from one level to the next as long as the structural skin employed in a Diagrid is mostly continuous the structure can rather safely be assumed acceptable.

A. Concrete systems.

In concrete construction, there is a major emphasis on two key points. Efficiency of the use of the materials and, in relations, a focus on converting loads into compressive forces rather than tensile. In these department, the diagrid excels greatly. As was previously stated, Diagrids make great use of their materials for efficiency allowing for much lighter structures and, consequently, less need in the foundations to support the extra weight. Also, a diagrid 's simple organic nature allows for a great multitude flexibility of overall design shapes allowing for a designer to easily consolidate forces into compression rather than tension.

B. Steel systems.

It is in steel systems where a diagrid truly shines. Besides its more efficient use of materials (it was estimated by Sir Norman Foster that the Hearst Tower took 21% less steel to create than a standard design), inherent redundancy and ability to form complex shapes, a diagrid is essentially a single gigantic truss. This means that the diagrid can act like a shear wall in all directions, which removes the need for any interior columns or supports (with the except of the building core, where elevators, utilities, and staircases tend to be) making allowing for completely open floors. This allows for a great deal of flexibility in interior design besides increased floor area as the interior designers do not need to worry about structural columns or walls in their work space.

Because a diagrid is simply a system of supports, combining it with other building structural styles (such as 3D compression, pneumatic, or tensile construction) is possible and could lead to interesting and potentially powerful constructions. It should also be noted that the diagrid's ability to form organic shapes, regardless of the material, could lead to unusual and interesting shapes that one would not normally expect from the material (such as concrete forming long span cantilever arches) .

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C. Prefabrication structure

Various strategies to improve constructability of diagrids through prefabrication of the nodes. Construction of diagrids is more challenging compared to conventional structural systems for tall buildings because the system is relatively new. As a result, construction workers are unfamiliar with how to construct the system and small parts are often done incorrectly. The joints of diagrid structures are more complicated than those of conventional orthogonal structures. To reduce jobsite work, prefabrication of nodal elements is essential. A significant amount of work is being done to developed improved techniques for diagrid construction.

D. Cosntruction of steel structures

The choice to architecturally expose or conceal the frame has significant 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.

E. 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. In some cases where the diagrid is chosen purely for its structural efficiency and is not ex- pressed, either at all or largely hidden behind gypsum board, the detailing will be less of a concern for the Architect.

F. 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 put added pressure on the fabrication tolerances 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. 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. 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.

G. Node construction

If considerately designed using appropriate prefabrication strategy, constructability will not be such a limiting factor of the diagrid structures. Prefabrication of diagrid nodes for conventional rectangular shape buildings can be done relatively easily and economically because many nodes of the same configuration are required in this case. As building form becomes more irregular, generating appropriate construction modules is critical for better constructability. 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 tones and it is desirable to be able to lift and turn the elements with a crane to provide access for fabrication, welding and finishing.

H. Erection of diagrid nodes:

During construction, the stability in the in-plane direction can be provided by the modules themselves and in the out-of-plane direction can be provided by the tie beams at the node. The temporary restraint to the diagrid and the construction may be minimized. The various steps in the Diagrid erection process include are a) In-place steel shop welding, b) Lifting up piece by piece, c) Trial shop assembly of parts with high strength bolts, d) In-place welding e) High strength bolts assembly f) Setting up perimeter girders.

I. Welding methods:

Two welding methods, the FP weld and PP weld were adopted for the fabrication of nodes to investigate the effect of the welding method on the structural performance It can be expected that the adoption of the PP weld, particularly satisfying the structural safety requirement, would significantly contribute to reducing the amount of weld material needed, moreover even in thick plate nodes the side stiffener end is the critical region of the nodes.

J. Façade construction.

Façade construction is the issue of the beauty that relates with the common people in terms of the precision to the beauty and quality sustaining issues. The geometry of the façade will be impacted by the size of the module, shape of the form, desire to include natural ventilation placement of the structural diagrid (inside or outside the envelope), function of the building (use and partitions), Double Façades, Intermediary Structures, use of lattice grids to span or complement diagrid structural systems, washing and maintenance. There are two types of glazing which are reasonable in terms of cost and fit them self into the mesh form to allow approximation of the curves and operable.

K. Exterior diagrids

Most 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

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programmatic requirements. This is more frequent in hot or temperate climates where thermal issues are less. 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.

V. BENEFITS OF DIAGRID SYSTEM OVER CONVENTIONAL STRUCTURAL SYSTEM

a) The Diagrid structures have mostly column free exterior and interior, hence free and clear, unique floor plans are possible.
b) The Glass facades and dearth of interior columns allow generous amounts of day lighting into the structure.
c) The use of Diagrids results in roughly 1/5th reduction in steel as compared to Braced frame structures.
d) The construction techniques involved are simple, yet they need to be perfect.
e) The Diagrids makes maximum exploitation of the structural Material.
f) The diagrid Structures are aesthetically dominant and expressive.
g) Redundancy in the Diagrid design is obvious. It is this redundancy then that can transfer load from a failed portion of the structure to another. Skyscraper structural failure, as it is such an important/ prominent topic, can be minimized in a DiaGrid design. A DiaGrid has better ability to redistribute load than a Moment Frame skyscraper.
h) Load paths are continuous and uninterrupted.

VI. LIMITATIONS

a) Lack of availability of skilled workers. Construction crews have little or no experience creating a DiaGrid skyscraper.
b) The DiaGrid can dominate aesthetically, which can be an issue depending upon design intent.
c) It is hard to design windows that create a regular language from floor to floor.
d) The DiaGrid is heavy-handed if not executed properly.

VII. 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. The selection of a diagrid system is often based on architectural choice rather than structural directive, however there are several functional and economic advantages that underlie the system increased stability due to triangulation diagrids. Hence, the need for a team approach given the complexity of the design and visual impact of the structure on the building design - a high level of cooperation between the architect and engineer - a higher freedom of expression possible given the innate stability of the frame - requirements of expertise and specialization from both architects and engineers.

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