The Hang Gang Arts Island, Structural Design of Free-Formed Roof

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Summary

This paper is expressed about structural design of Hang Gang Arts Island (HGAI) with dynamic and free-formed roof.

The HGAI is located on Nodul Island in Han River which flows across the city of Seoul. The HGAI will be an important cultural and iconic symbol of the Seoul Metropolitan City when it is completed. The centre of HGAI is consists of an opera theatre, studio theatre, symphony hall, HGAI tower and a food and beverage centre – Café Bird, all of which are grouped beneath a dynamic, free-formed roof with long length cantilever to be extend above the structure.

HGAI Roof Structural design process is presented in regard to free-formed shape and various loads such as Wind, snow and seismic load etc. in detail.

Keywords: *Free-Formed, Roof Structure, Hang Gang Arts Island (HGAI), Long Span*

1. Introduction

The proposed Hang Gang Arts Island (HGAI) is located on Nodul Island in Han River which flows across the city of Seoul. The HGAI will be an important cultural and iconic symbol of the Seoul Metropolitan City when completed.

Figure 1: Nodul Island, Han River, Seoul

Figure 2: Render of the HGAI Complex and Roof

The centre primarily consists of an opera theatre, studio theatre, symphony hall, HGAI tower and a food and beverage centre – Cafe Bird, all of which are grouped beneath a dynamic, free-formed roof with large cantilevered lengths extended above the building.

The overview of the project is as follows:

Site Location: 302-6, Ichon-dong, Yongsam-gu, Seoul, Korea

Occupancy of Use: Culture and Meeting Facilities

Gross Area: 99,102.23m^2

Size: Under-ground 2F, Over-ground 8F

Structural System: RC, Steel, SRC

This project was carried out with the following purposes:

1) Consider local terms characteristics and select a connected optimal structural system in the architectural plan

2) Examine the validity of the structure plan through three-dimensional dynamic analysis and secure structural safety
3) Consistently apply related laws, regulations and design codes authorized analysis program usage objectively
4) Apply usage material and design strength considering economics and workability
5) Select advantageous system for the shortening of construction period and the enhancement of workability through alternatives comparison
6) Structural plan so as to secure connected flexibility on the architectural plan

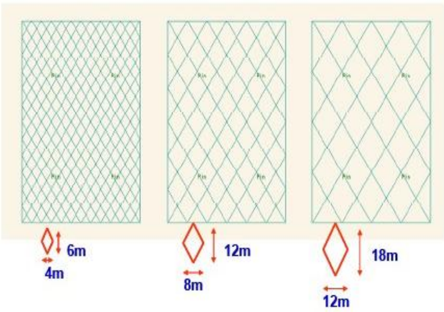
2. Overview of the advanced system

The complex form of the roof, with its free-flowing doubly-curved surface, poses major challenges to defining the geometry. Therefore, extensive studies were carried out in finding options and solutions for creating a rational and workable structural geometry. This study included ways of simplifying the double-curvature of the roof, and creating greater uniform and repetitive areas.

2.1 Roof Diamond Grid Size

The architectural design intent is to feature a relatively uniform diamond shape pattern across the roof surface.

The typical architectural pattern unit is 4m x 6m diamond. For matching the architectural pattern, three structural pattern dimension options were considered: 4m x 6m, 8m x 12m, 12m x 18m.



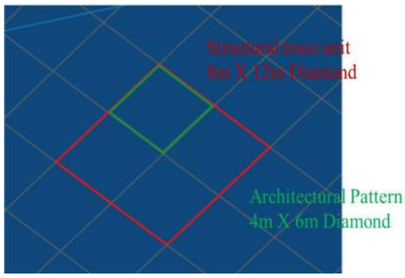
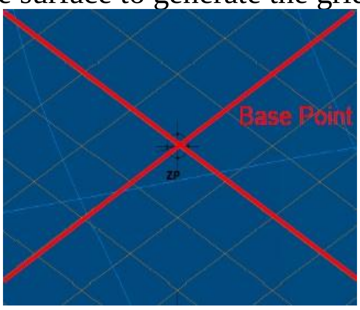


Figure 3: Structural Truss Grid Dimension Options *Figure 4: Chosen Structural Truss Grid*

Through consideration for design strength, cost, piece count and connection detailing, fabrication, and facade detailing and installation, it is decided the 8m x 12m unit is the most structural grid dimension. The structural grid dimension can be further sub-divided into the basic 4m x 6m unit when required, such as at support areas and areas of high stress and structural demand.

2.2 Architectural Grid Generation

The method adopted in generating the roof diamond pattern is by using Rhino command "offset curve on surface". The method works by firstly orienting two base lines to the desired diamond pattern. The base lines are positioned at the control point position here termed "Zero Point". The Zero Point is the anchor point for both architectural and structure to position the diamond grid. The base lines for generating the architectural grids all cross through the zero point. Then the base lines are offset on the surface to generate the grid lines covering the entire roof.



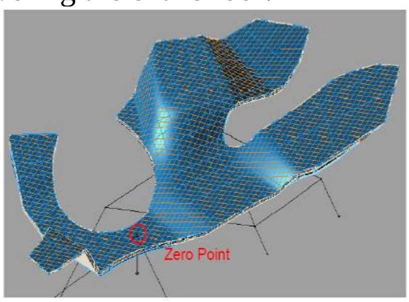


Figure 5: Base Point for Grid Generation *Figure 6: Generated Architectural Grids*

The following image shows the generated gird architectural grid of the roof (at 4m x 6m subdivisions). The structural grid generation described next follows the same procedure (with offset allowing for the depth of cladding finishes) in producing a structural geometry.

Note in the architectural grid generation, due to the organic and double-curvature of the roof surface, the size of final grid units cannot be uniform (not definitively 4m x 6m) because of the geometry issues discussed above. There are slight differences in dimension between each diamond shape.

2.3 Roof Structural Geometry Generation

For the HGAI roof covering over 25000m^2 in area, modeling all the structural truss elements can be very tedious and time consuming.

An automatic modeling process has been developed to handle this problem, through developing a script in "Grasshopper"-a Rhino plug-in. Once the architectural grid lines and the depth of the truss are determined, the script can generate the roof truss 3D geometry quickly and accurately in Rhino. The generated 3D model can then be exported to structural analysis software as well as using in design coordination with the architectural and other design disciplines.

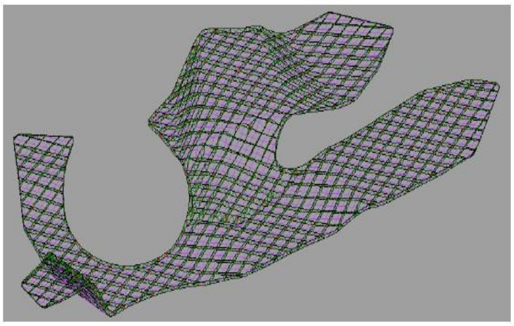


Figure 7: Structural Truss Generated from Architectural Grids

The following steps and setting out dimensions have been adopted to form the roof structural geometry
1) Obtain architectural top surface with diagrid. Note that structural geometry generation relies on the architectural top surface only. The bottom architectural surface is not referenced at all.
2) Offset 700mm from architectural top surface to locate the centerline of the top chord. The direction of offset is perpendicular to the surface
3)_Offset the required roof truss structural depth, as determined and agreed in the design development (2.5m, 3.5m, 5m), to generate the centerline of the bottom chord. The direction of the offset is perpendicular the surface.
4) Offset he edge 500mm from the architectural edge surface. This generates the structural edge line which is separate to the architectural edge line.

3. Roof Structural System

3.1 Roof Structural System

The roof for the HGAI is a free-formed curved surface reflective of the dynamics and movements of the intended activities in the centre. Geometrically it is made up of plane, curved, and doubly-curved surfaces folded and connected to create the fluid movement shape of the roof. The long spans and cantilevers of the roof mean the use of singular elements such as girders is structurally not feasible. The free-formed shape of the roof rules out the use of shells and grid shell systems. Tensile and membrane structural systems, with their use of mast and membranes, are also not applicable.

Thus the appropriate structural system for the roof is a truss system. The desired architectural diagrid patterning on the roof also lens to the use of a truss system.
1) Roof is formed by planar trusses replicating the diamond architectural grid patterns
2) The trusses are of warren-type framing
3) The trusses are at 8m x 12m grids, with allowance for subdivision to 4m x 6m grids

4) The diamond orientation is arranged with the long diamond directions running in the east-west direction

The chosen roof structural system has the following vantages.

1) Structural efficient solution matching the architectural form and geometry facilitates the architectural patterning and facade/cladding strategy
2) Minimized piece count in structural elements – simplifies fabrication and connection detailing, and erection
3) Facilitates ease of secondary steelwork arrangement for roof cladding and services
4) Facilitates integration of services and maintenance within the structural zone
5) Roof is light weight – kept to within 100kg/m^2

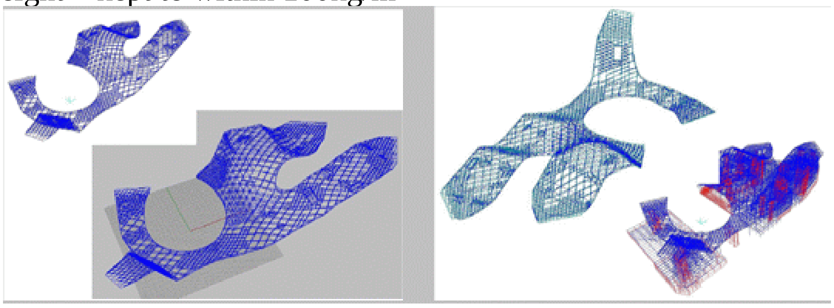


Figure 8: Structural System of Roof

The long span member of the roof structure is designed with steel pipe truss, and with some lower circular column, it is designed with steel pipe member which is not general H-steel, and the reason is that architectural requirements of the exposed member and its structural merit which can express the same property without the division of the main axis to all directions against the combination stress of the multiple forms acting on the members.

In addition, to the material of all steel pipe members, structural steel (STKN Steel KS D 3632) applies, and the reasons for the adoption are as follows:

1) Realize structural performance purpose through securing the member's deformation capacity
2) Secure required property upon the production and processing of steel pipe member
3) Secure structural member's welding joint property

3.2 Roof Support System

The roof to the Hang Gang Arts Island covers over the different complexes of the centre, including the opera house, symphony hall, auditorium, the tower and the cafe area. The supports of the roof are provided by the superstructure of each complex. Depending on the location and supporting superstructure condition, the supports of the roof extending from the buildings below range from columns, shear cores, to trussing elements.

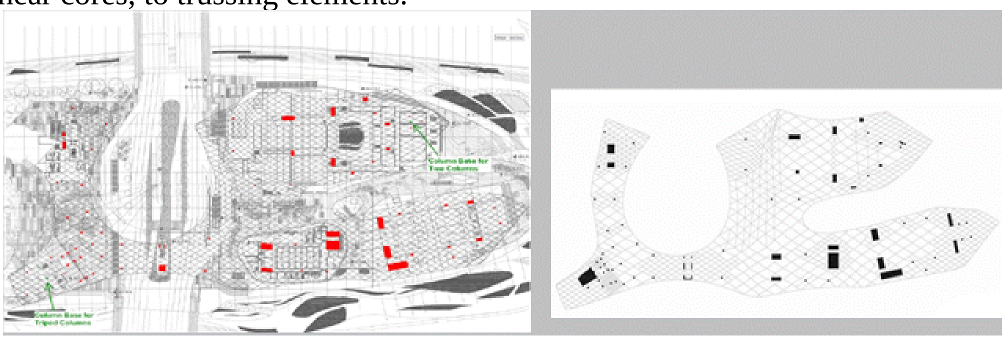


Figure 9: Roof Supports Layout

Lateral stability of the roof is provided by connecting the roof to lift and stair cores, and other stiff elements in the superstructure below. At the HGAI tower end, the shape of the roof folding over the back of the tower leads to the roof connecting into the side of the tower for support (more details provided below). The roof support columns are very tall and slender, and therefore their structural role is restricted to carrying axial load in support of the roof.

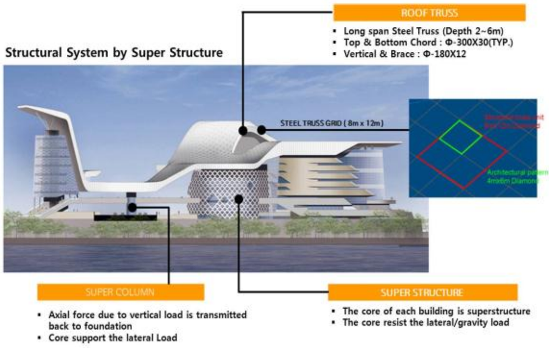


Figure 10: Structural System by Super Structure

4. Structural Plan for Each Building

4.1 Opera Theater Structure Plan

The opera theater is formed of eight stories above ground and two beneath ground level, and load by the installation of various devices in close consultation with stage machinery area and other areas including architecture was considered, and mutual examination for space composition necessary for stage management and maintaining management was carried out.

For the second floor above ground, slab structure on the base with a relatively patterned slab module by basic module, suitable RC structure was applied, and for higher than the second floor above ground, since properties such as long span, high floor and free-form space (stage and the audience, etc.) are shown, considering structure usefulness and workability, etc., appropriate steel system was applied.

For the long span, basically steel truss structure was applied and for some space, displacement and serviceability were examined and the built-up singular steel was applied. The truss's depth was determined considering structural reasons and minimum depth necessary for the maintaining management for the stage machinery and equipment.

This structure's slab diaphragm was not formed continually, and compared to the core wall, the stiffness of the moment frame is relatively small, and it cannot be clearly defined as a basic seismic force resist system as defined in the standard since the whole building is connected as one space in complex behaviour property and roof floor by free-form, In particular, R factor is one that was defined first by the consultation of California architectural engineers in the late 1950s, which does not have a complete theoretical or test base even in the present. In other words, for the clear selection of lateral load resist system and accordingly the selection of R factor, the impact of strength by frequency (excess strength) and the structure's tensile capacity and system redundancy should be understood; however, at the step of design, it is very difficult to identify these, so according to the engineer's experience and judgment, as a seismic force resistance system, other structural system (R=3.0) was applied.

The core wall and part of the column supported the roof structure. In particular, the core was planned to support lateral load (earthquake, wind load) and the column to support the vertical load.

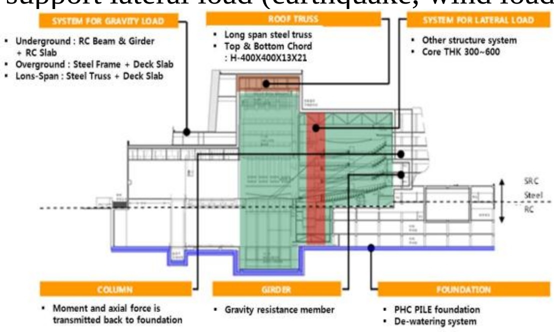


Figure 11: Structural Design of Opera House

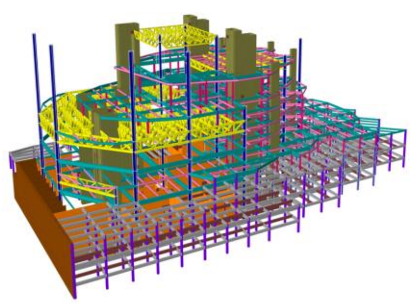
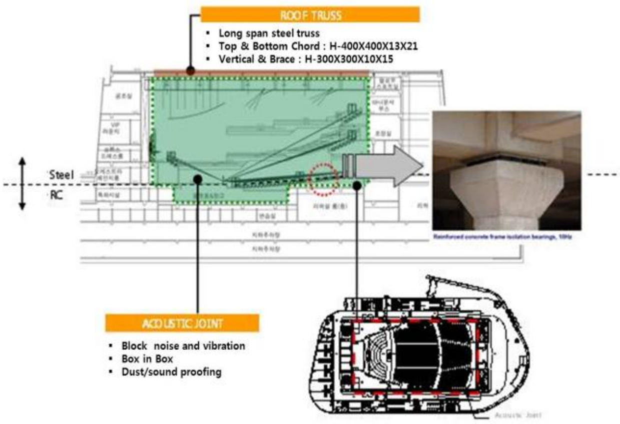


Figure 12: Modelling of Opera House

4.2 Symphony Hall Structure Plan

To the structure plan of the symphony hall, the same structure concepts as that of opera theater were applied.

As a significant abnormality, completely blocking external vibration and noise, it was planned to meet high levels sound terms (PNC-15 and above). Architecturally, through acoustic analysis, sound wall's material and thickness were closely examined and applied, and structurally, the internal space consisting of a stage and seats was composed as an independent space (Box In Box style).



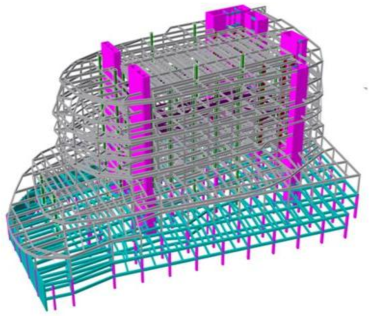


Figure 13: Structural Design of Symphony Hall *Figure 14: Modelling of Opera Symphony Hall*

At the third floor above ground and the lower eighth floor above ground, double slabs were installed and here, a vibration-resistant sliding seismic isolation device to block external vibration and noise and vibration-resistant leed rubber bearing to resist against the occurrence of an earthquake were installed together. Since the eighth floor above ground was a restaurant hall and it had to block slab vibration and noise from being delivered to lower seats, and the impacts of lateral displacement by earthquake load is not great, only a vibration-resistant sliding seismic isolation device was installed there.

The stage and seats space were composed by external space and double column system on the surface and the in-between space (sound joint, acoustic joint) was planned in an independent structure to use architecturally and for sound.

4.3 Multi-purpose Theatre Structure Plan

To the structure plan of the multi-purpose theatre, the same structure concepts of the opera theater were applied.

As a significant abnormality, an external elevation facade was planned as an architectural design element and structure element supporting the slab on each floor. Many parts such as architectural requirements for wavy form, the restrictions of member size, the considerations of finish, correlation with structural member on each surface, and joint details according to free-form shape had to be concerned and resolved.

As an initial H steel, initial cross section was selected, and as a result of the examination of the architecture shape according to the installation of finishing materials, it was found that structural member should be distorted, and the structure was planned changing to steel pipe (Φ350, STKN 490) for the structure.

For the successful design and construction of this free-form structure, a closer analysis on the joint should precede. For this, splicing angle on each member's surface and elevation scheme at the joint node was analyzed, and the joint was composed in 4 types in total. Each joint should be a form cut fitting with an architecture shape from a globe, and this is a shape that cannot be produced by welding or monotone, and in particular, since the quality of the joint depends on the total property of this structure, it should be produced with the steel casting that can secure the same quality.

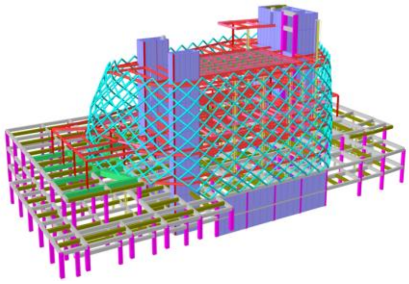


Figure 15: Modelling of Opera Symphony Hall

5. Structural Wind Tunnel Loading Test and Water Tank Test

5.1 Structural Loading Wind Tunnel Test

Over its design life the roof structure of the Hang Gang Art Island will be exposed to continually varying fluctuating pressure distributions arising from the unsteady nature of the incident winds. Historically, large span roof structure designers would have used only the peak pressures from boundary layer wind tunnel tests in conjunction with design code procedures. However, with the advancement of computational technology there are now more realistic options for applying wind loads on large span roof structures.

The most common current practice is to measure pressures simultaneously across the roof surface and area average them using ‘influence surface’ depending on the critical structural action. For some structures, depending on complexity, it can be very difficult to identify a limited number of critical influence surfaces and for such structures, where the wind loading is important to the cost of the structure, it is possible to apply the simultaneously measured wind tunnel pressures as a time-history to dynamic mathematical models of the structure.

If the primary modal frequency of a large roof structure is less than about 0.8Hz it has an increased susceptibility to dynamic actions caused by wind. Wind tunnel testing of highly dynamic structures requires different methodological approaches than wind tunnel testing of near static structures. In case of both flexible and lightweight structures, aero-elastic model studies are often recommended.

The sensitive areas of the performance arts centre’s roof have modal frequencies in excess of 1.0Hz and therefore it was recommended that a simultaneous pressure

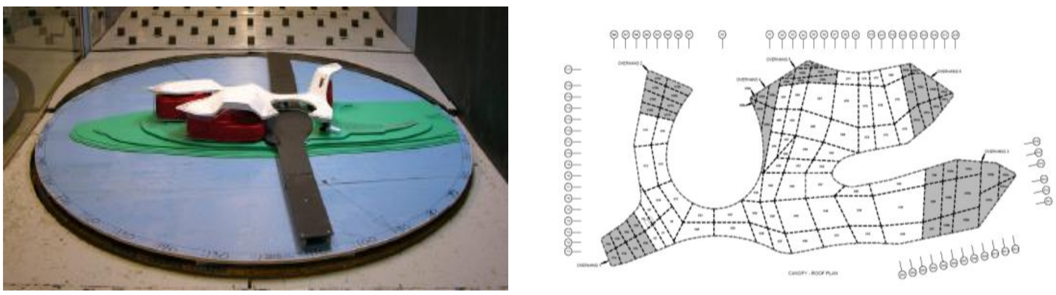


Figure 16: Wind Tunnel Loading Test

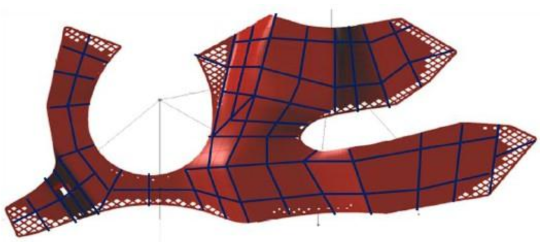


Figure 17: Top Surface Pressure Panels

5.2 Water Tank Test

Wind load acting on the roof structure was obtained on the basis of Korean Standard and ASCE7-05, and from the results through Seoul's local weather center data and water tank test, the results of snow pattern were estimated.

The purpose of this test is to evaluate imbalanced wind load by snowing phenomenon according to the shape of the roof. The scale models of the building and surrounding environment are made in a water tank inside a RWDI test room, which was a model of building rigid form. Evaluation by spraying in the water tank was based on Korean Standard and ASCE 7-05, and the load combination was considered as follows:

1) The case of wind load by Korean Standard was referred to, and snow was considered sliding down when the roof incline was over 45°.

2) It was considered that when the roof incline was over 50°, snow slid and gathered to the nick of the sloping plane.

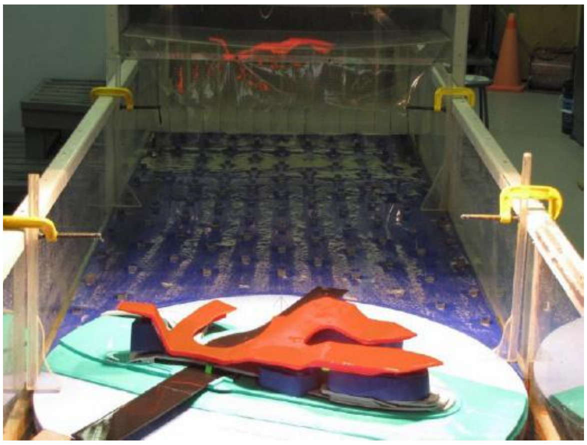


Figure 18: Water Tank Test

6. Conclusion

In this paper, which consists of a free-formed surface with respect to the roof structure was introduced. In addition, structural plan of each buildings, structural wind tunnel loading test and water tank test

This paper corresponds to participate in this project for the structural design engineers widened the breadth of understanding, there has been a better offer is the opportunity to receive.

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