NANYANG TECHNOLOGICAL UNIVERSITY SPORTS HALL – SINGAPORE

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1. INTRODUCTION

Nanyang Technological University (NTU) is known as a global leader in sustainability research, attracting more than SGD$ 1.2 B in research funding.

The new Sports Hall is designed with sustainable features, in line with NTU's decision to achieve a 35% reduction in energy, water and waste consumption by 2020.

The sports hall, also called "The Wave", spreads over an area of 10.000 m2 and is able to accommodate 1.000 spectators. Mechanical seats are retractable so that the central field can house 13 full-sized badminton courts or three basketball or volleyball courts and a netball court.

1.1 Engineered wood system

The sports hall is the first large-scale building in Singapore adopting an engineered wood system (EWS) in a completely new construction process for the country. The building is constructed combining different structural systems.

The superstructure is an EWS that sits on a reinforced concrete foundation system. Glue laminated timber is largely used for beams, columns and the long column-free three-hinged arch roof. Cross laminated timber (CLT) is adopted in large scale for the main roof bracing system and for the slabs at the interior levels.

A special care has been given to the durability. The Singapore climate is quite severe due to a high level of constant humidity throughout the year. The durability of the superstructure is achieved with a combination of adopted solutions such as sacrificial layers and endgrain metal capping. Water proofing and prevention of water stagnation have been one of the major issues in terms design of durability.

Figure 1: *NTU sports hall won the Green Mark Platinum Award by Building Construction Authority AWARDS 2015 (courtesy of The Magazine of The Institution of Engineers, Singapore).*

1.2 Natural ventilation and passive air-conditioning

The Wave has been designed analysing sun and wind patterns of the construction site. The goal was to optimize the need of energy and has been achieved by designing an efficient air-conditioning system based on passive induction cooling effects. Each external wall has two layers with a pocket of air between them that insulates the heat on hot days. The walls have special metal coils installed with chilled water flowing through them. This cools the wind that enters the hall allowing warmer air to escape through convection.

This necessity has forced the structural design towards a free-standing façade, with main columns spanning from the base up the top and with a special connection to the arches that let them move under vertical loads without additional axial compression force.

2. CHOICE OF THE STRUCTURAL SYSTEM

The column-free arches span for 72m between the side supports. The total length measured along the curvature of the arches is 105m including the portion that span on top of the main entrance and that is supported by a system of slanting steel columns.

The design is based on the concept of the three-hinged arch. The choice has been driven by several reasons including shipment and erection sequence and has become the most adequate system to get a slim and elegant profile in general. A deep investigation of the system was necessary to restore the full capacity of the cross section of the elements.

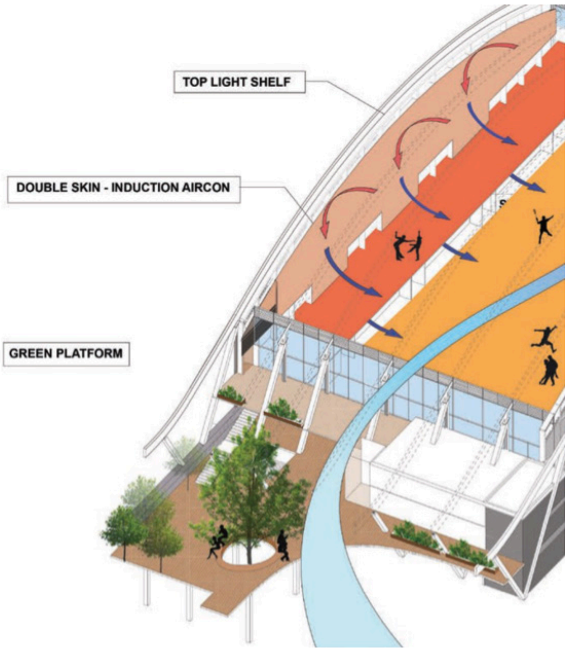


Figure 2: *Double skin concept and natural ventilation.*

2.1 Shallow glulam arches

The big challenge was represented by the shape of the shallow arch: over 72m in free span, the top hinge is placed 9.5m above the ideal lower chord line only. This condition heavily increases the magnitude of the axial compression force N acting through the arches, despite relative low values of superimposed dead loads and live loads.

Axial force flow along the arch is shown in the scheme aboard. Compression acting through the arches is transferred down to the foundation piles through 2 so-called steel A-frames, as shown in Figure 6.

2.2 Lateral steel supports

The arches are supported by 2 lateral steel A-frames working in tension (vertical column) and compression

Figure 3: *Cross section view of the sports hall.*

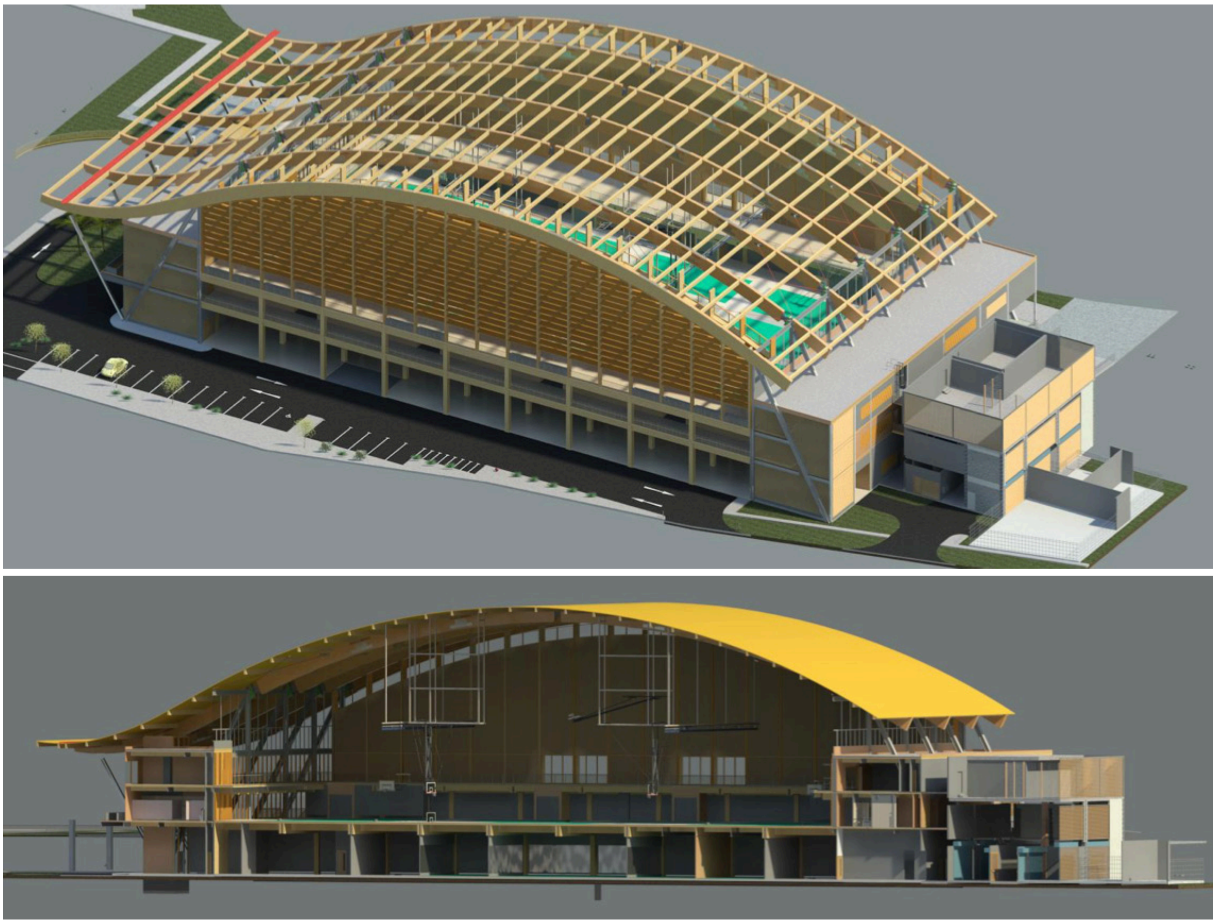


Figure 4: *Three-hinged glulam arches spanning across the long direction.*

Figure 5: *Elevation view of the shallow shape of the arches of the Wave.*

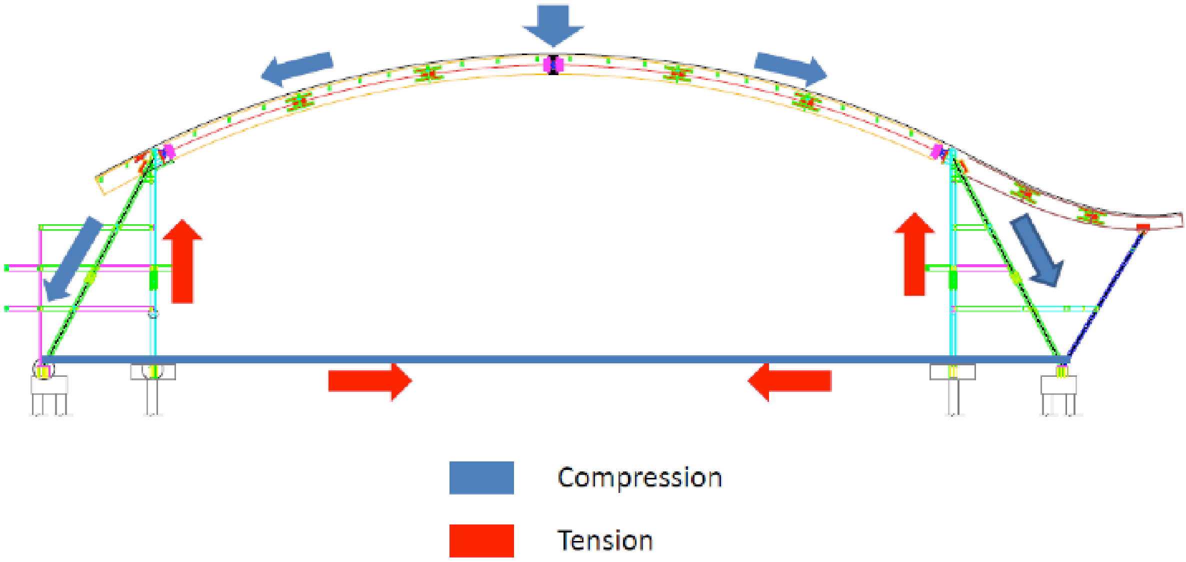


Figure 6: *Axial force flow along the single arch.*

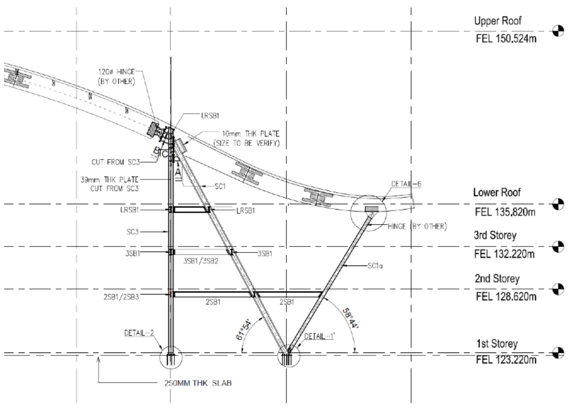


Figure 7: *Steel A-frames providing support for the side hinge of the arches.*

Load Comb.	Axial Load (kN)	Shear (kN)
ULS31	3226.3	103.9

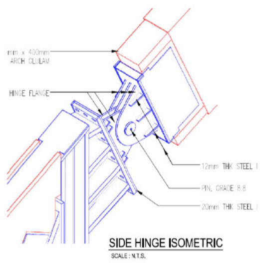


Figure 8: *Axial force magnitude at the side hinges.*

(slanting diagonal). The magnitude of the axial compression force being transferred through the hinge is A_{ax} = - 3220 kN.

The steel A-frame has been designed considering a top displacement limited to H/500, being H the distance of the pin from level 0. With that being the leading combination, a certain ratio of over strength for the bolted connections has been considered to achieve the required axial and lateral stiffness.

2.3 Spitting, shipment, jointing of arches

One of the major issue of the project has been represented by the necessity of jointing the single portion of the arches to restore the capacity of the glulam section. Shipment from overseas was done using regular 40’ and 45’ shipping containers (12,2 m and 13,7 m long respectively). The semi-arch was split into 3 portions each; therefore, each arch of the seven in total, was split in 6 symmetric elements.

Moment resisting connections have been placed approximately at the thirds of each semi-arch. Shape of bending moment, for a three-hinged arch under symmetric and not symmetric loads is shown in picture 10. The higher magnitude of the bending moment acting through the main arches happens under non-symmetric conditions. Values are approximatively symmetric; therefore, all the connections are symmetric about the neutral axis of the arches.

Moment resisting connections have been designed

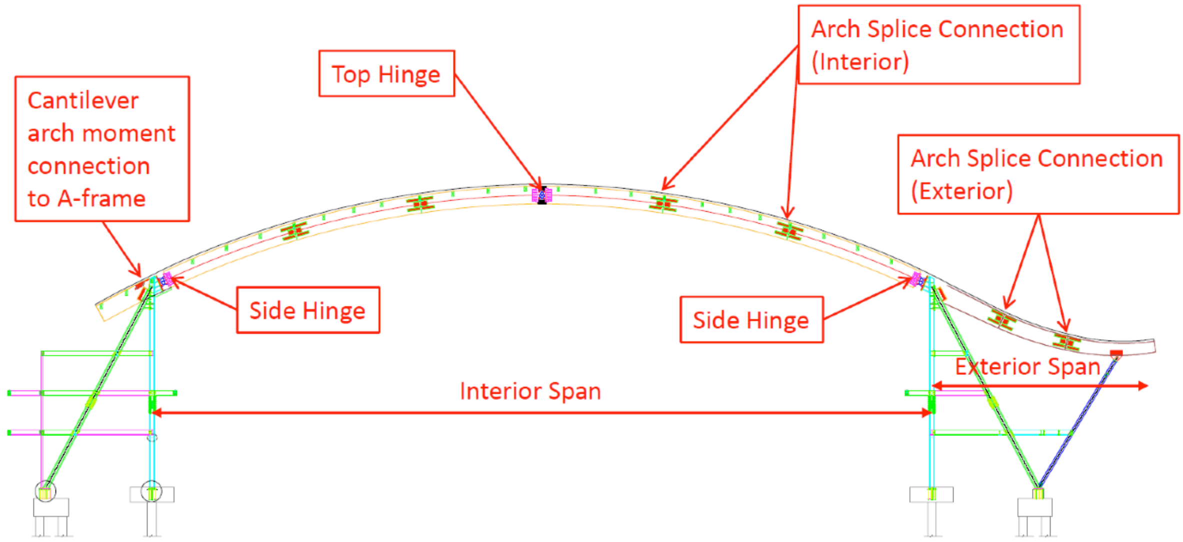
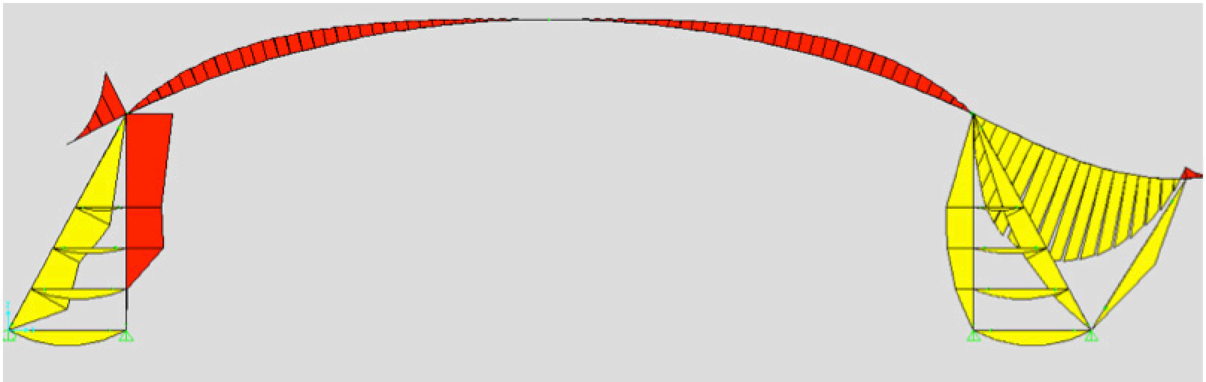


Figure 9: *Cross section of the arch and position of the moment resisting connections.*



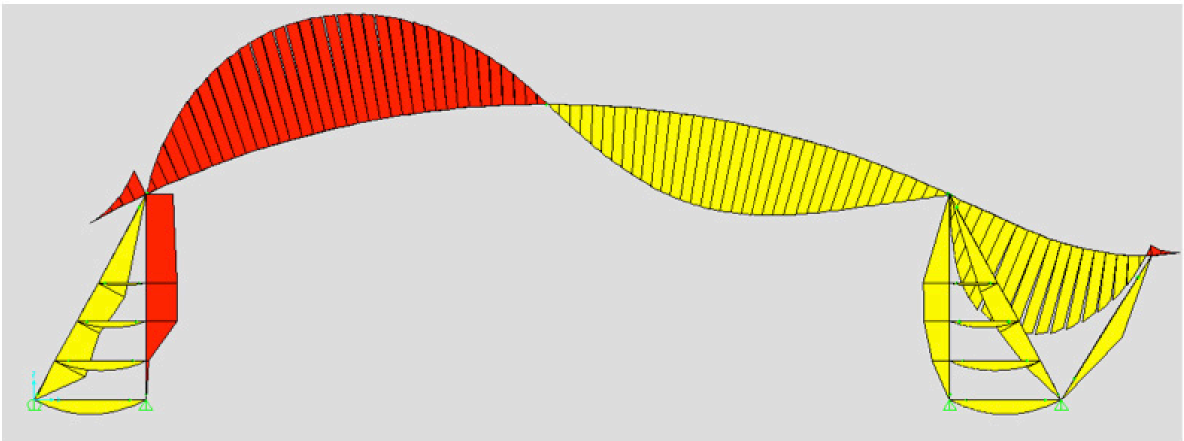


Figure 10: *Bending moment flow under symmetric and not symmetric uniform loads.*

with a configuration where top and one bottom plates develop axial tension to resist against moment, and symmetric central plates, each side, provide strength against shear. Image 11 indicates the plates working in tension to provide equilibrium.

These plates connect the ends of the semi-arch segments through a set of fully threaded screws installed at 45° from the vertical. The horizontal projection of the withdrawal tension gives the capacity in shear required to have to plate develop axial resistance. Connections are symmetric throughout each arch and do not differ depending on the location.

Each plate is 3800 mm long and 280 mm wide and is provided with slot holes to accommodate the 45° washer where fully threaded screws go through.

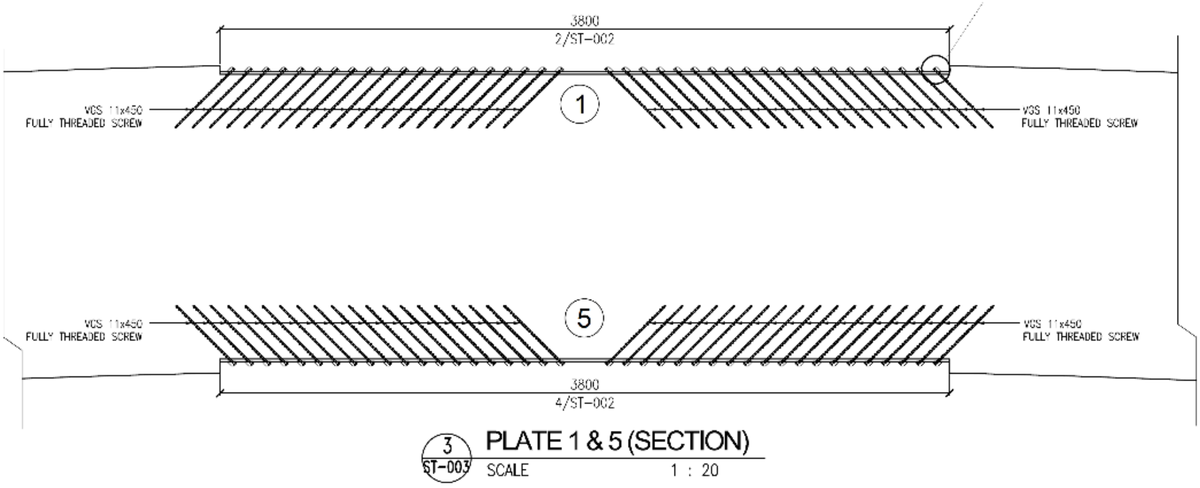


Figure 11: *Moment resisting connection with steel plates and fully threaded screws.*

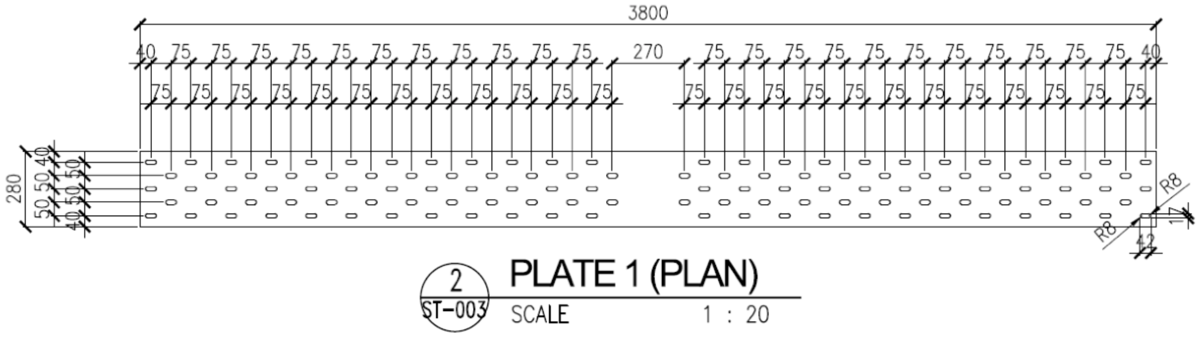


Figure 12: *Top and bottom plates of the moment connections.*

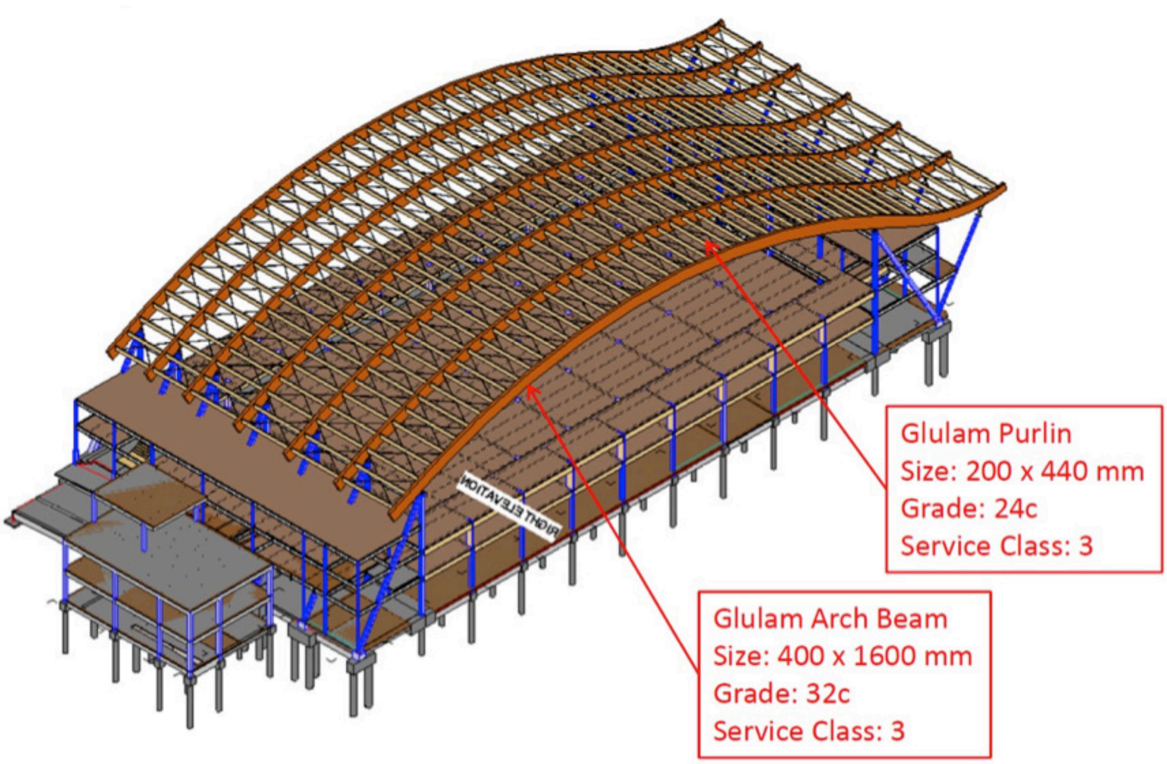


Figure 13: *3D view of the main glulam structural system.*

2.4 Design of the cross section of the arch

A 3-d finite element analysis has been carried out to size the timber and steel structural components. Buckling analysis has been carried out to check on the capacity of the arch to resist against out-of-plane deformation due to axial forces.

Cross section of the main arches is 400 mm wide and 1600 mm deep, with GL32c strength grade. Purlins are spanning across in between the arches and provide supports for the CLT roof diaphragm.

2.5 CLT stiff diaphragms

The whole arch system has been braced by using an in-plane rigid thin diaphragm made out of cross laminated timber panels. Thickness of these panels has been set at 60 mm in order to have them bent throughout the span of the arches and guarantee a perfect degree of adjustment to the curvature. CLT panel have been screwed to the top of arches and staggered in plan in order to achieve the maximum stiffness ratio possible.

3. ERECTION SEQUENCE

3.1 Ground assembly and test

Each semi-arch has been jointed at ground level by using a temporary adjustable bracing system provided with portable hydraulic jacks in order to get the exact shape of the system.

3.2 Launching of main arches

Main arches have been launched following a precise strategy and sequence. After the first two semi-arches have been jointed, they were lifted up and side hinges were secured on top of the steel A-frames.

Then semi-arches were lowered down to adjust the position of the lifting cables, then lifted up and the top hinge finally secured by inserting the steel pin.

The first main arch pair, standing alone without lateral restraints, were braced by using steel adjustable cables connected to concrete temporary plinths at the ground.

3.3 Interior structure

After the erection of the glulam arch system was completed, the interior structure and double façades were constructed.

The sports hall is provided with 2 interior stories where gyms and mechanicals are located, besides a portion used for general training activities.

Figure 14: *CLT stiff diaphragm on the roof.*

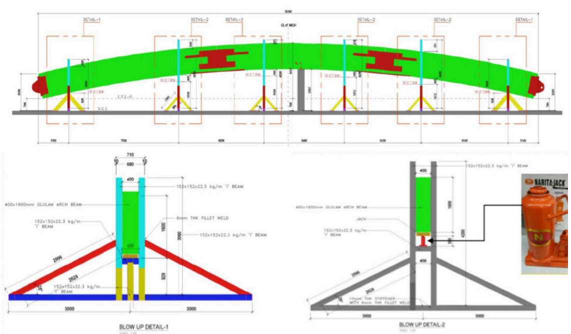


Figure 15: *Schematic view of the ground testing system.*

Figure 16: *Launching of arches.*

Figure 17: *Following phases until completion of the arch system.*

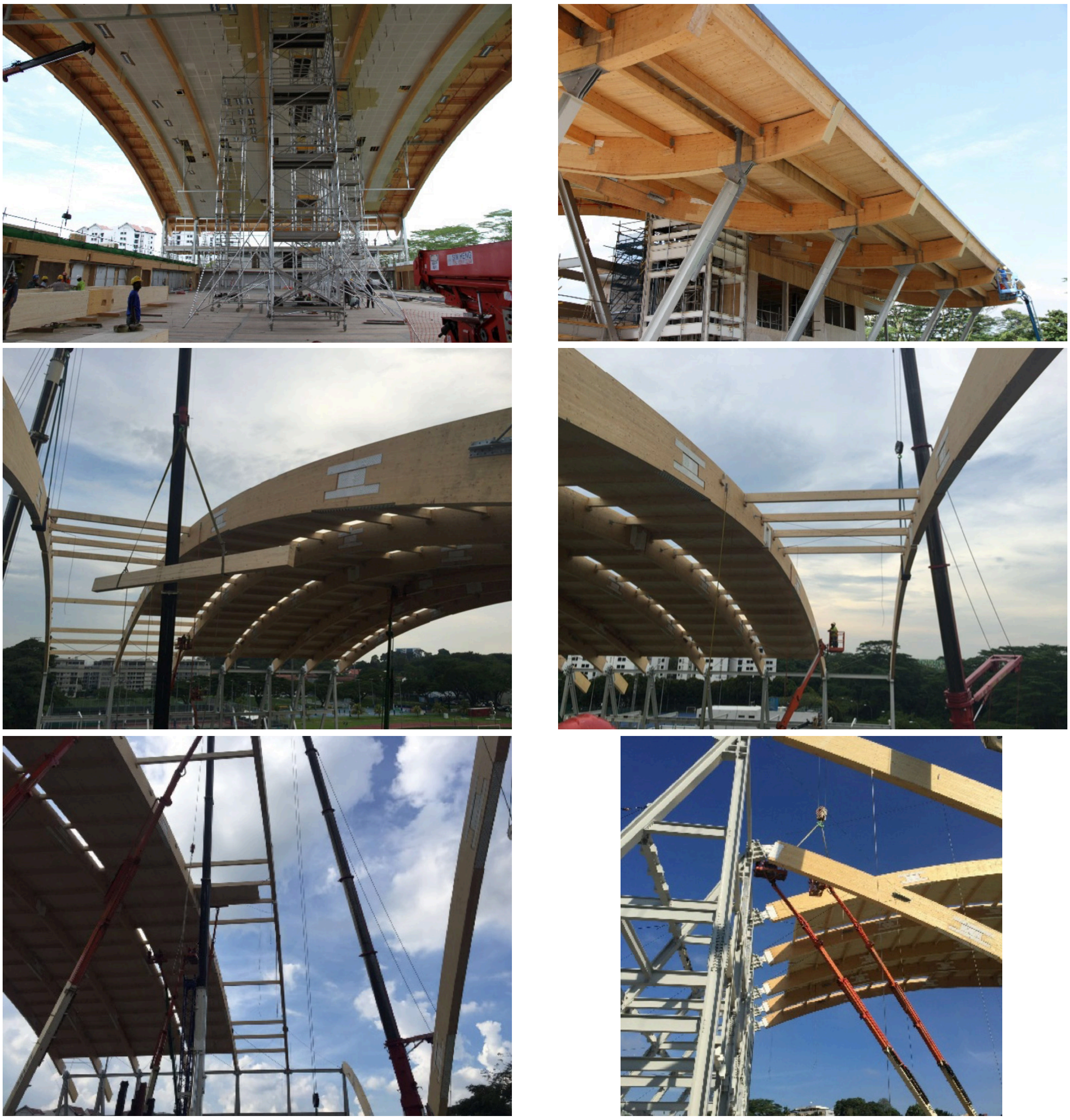


Figure 17: *Following phases until completion of the arch system. (cont'd)*

Figure 18: *Phases of the erection sequence of the interior stories.*

Figure 19: *Main glulam coupled beams on the exterior façade.*

Figure 20: *Working on the inside of the Wave.*

4. CONCLUSION

The Wave has been officially opened on April 24th 2017 by the Minister for National Development of the Republic of Singapore.

The building has been recognized as a milestone in Singapore's hard push to be more productive and efficient in construction. The successful delivery and completion of the Wave has been the result of a strong technical culture shared by the team design members. The Wave is now a real component of NTU's campus master plan and witnesses the strong commitment of the university towards sustainability and efficiency.

All this is pushing NTU of Singapore to become one of the greenest and most efficient university campuses in the world within the next years.

CREDITS:

i) The Magazine of the Institution of Engineers, Singapore

ii) Nanyang Technological University, Singapore

iii) Binderholz GmbH

Figure 21: *The Wave being opened. (photo Wee Teck Hian/TODAY)*