The Singapore Flyer And Design Of Giant Observation Wheels

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Introduction

Completed in 2008, the Singapore Flyer is now the largest Giant Observation Wheel (GOW) of its type in the world. Arup built upon design knowledge gained during the design of the London Eye to develop a 'next generation' rim structure. The resulting two dimensional 'ladder truss' rim structure of the Singapore Flyer is both larger and lighter than its predecessor. This paper describes some of the engineering principles behind the design of GOW's and in particular the design of the Singapore Flyer.

Figure 1: Singapore Flyer, Perspective looking North West (Image courtesy DP Architects)

Great Observation Wheel's : A Short History

GOW's represent one lineage of a family of visitor attractions known as Iconic Viewing Platforms, (IVP's). They are characterised by their size and advanced engineering nature. The most well known of all GOW's, and arguably the founder of the lineage is George Ferris' original Ferris wheel (see Figure 2). The Ferris wheel was designed and built as the principle engineering attraction for the Chicago World Fair of 1893. The intention was to create an engineering marvel to rival the spectacular success of the Eiffel Tower, the centrepiece of the 1889 Pars Exposition. The structure had a diameter of 76 metres and had 35 cabins attached, each with a capacity to carry 60 people.

A number of large GOW's have been commissioned and built since then around the world including:

- 1896 Vienna Riesenrad – 60m diameter, 14 cabins of approx capacity 15 person capacity
- 1900 La Grande Roue Exposition, Paris – approx 80m diameter, 36 capsules with 8-10 person capacity
- 2001 London Eye (Millennium Wheel) – 135m diameter, 32 capsules, 25 person capacity per capsule.

Figure 2 : Original Ferris Wheel, 1893 Chicago world Fair

Alternative fig 2 with better resolution

The Singapore Flyer

The largest Giant Observation Wheel (GOW), of its type when constructed the Singapore Flyer wheel is 150m in diameter. Passengers board via access gantries and loading platforms two stories above ground in the terminal building located at the base of the wheel.

The Singapore Flyer is located on Marina Bay in Singapore and is orientated to look out over the new downtown around Marina Bay and existing CBD, in one direction (and over the East Coast and Singapore Straits in the other.

As well as housing all of the passenger flow infrastructure required for the wheel, the Terminal Building at the base of the wheel, also contains 15,000 m^2 of prime retail shopping space. In order to add to the visitor experience a tropical rainforest attraction has been built into the courtyard space immediately below the wheel. A 300 space car park building has been provided across Raffles avenue and linked at high level through a pedestrian bridge to the main Terminal building. The Singapore Flyer is in close proximity to the future Millennia MRT Station, and forms part of what will be a ‘string of pearl’ series of attractions around the new waterfront at Marina Bay.

The Singapore Flyer is a development led project originally initiated by Melchers Project Management. Arup worked with Melchers from a very early stage to develop concepts and establish feasibility. The design was prepared to scheme and tender stage by Arup under a traditional form of contract. The detailed design was then prepared by Mitsubishi Heavy Industries with Arup acting in a novated role as the engineer of record.

Foundations

The geology of the Marina Bay area is typically recent marine and fluvial sediments of the Kallang Formation, varying from unconsolidated to normally consolidated. These materials overlay the Old Alluvium present at 15-30m depth. The site was reclaimed using fill over the existing strata approximately 30 years ago.

The foundations for the buildings and wheel are bored piles between 600mm and 1500mm in diameter penetrating up to 52m in depth, socketed into the Old Alluvium. The piles were fully cased through the extent of the reclaimed fill and soft marine clays.

Supporting Structure

The wheel is supported by two 2,850mm diameter columns founded in the courtyard of the terminal building below and stabilised at the spindle level by 4 cable stays. Each cable stay consists of a group of 6 x 100mm diameter locked coil cables prestressed to 17MN.

The lateral components of the stay pre-tensions are resolved through the spindle structure connecting the tops of the columns at the high level, and through the ground floor (level one) of the building structure acting as a compression annulus, at the low level (Fig 3).

The result is a stiff closed structural system that distributes and balances the lateral components of the permanent pretension forces within the structure. The piles in essence are then only required to resist the vertical uplift and downwards reactions, and the net lateral force arising from wind loading etc.

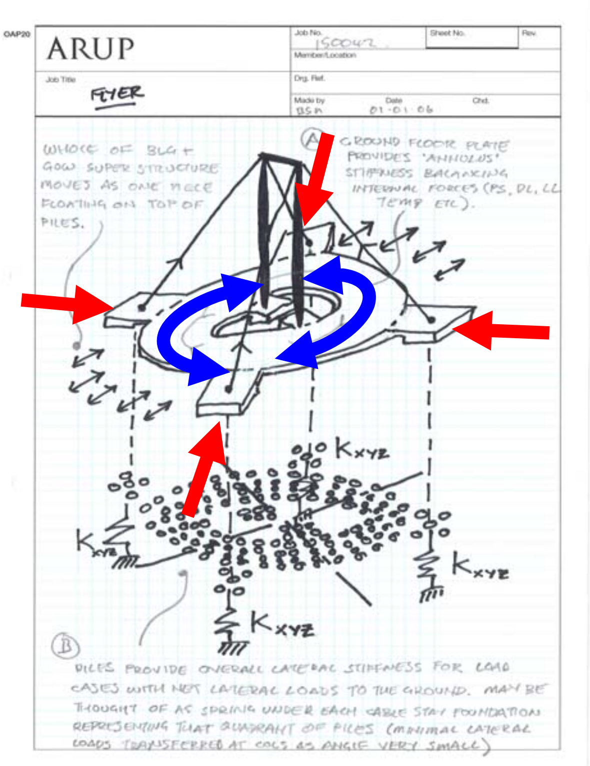

Figure 3 : Design Sketch Showing Supporting Structure Force Resolution

Rim & Spoke Design

The rim and spokes are the components that differentiate wheels from all other types of structure, and which pose some of the principal engineering challenges in designing GOWs.

Three external load cases generate significant forces in the rim and spokes. These forces are described assuming that the spokes can resist compression. Firstly, gravity causes tension in the lower spokes and compression in the upper ones, along with compression in the lower half of the rim and tension in the upper half. Secondly, wind causes tension in spokes attached to the windward side of the hub and compression in those attached to the leeward side. Thirdly, temperature differentials between the rim and spokes cause spoke tension and rim compression, or vice versa.

The Flyer uses cable spokes that need to be prestressed to resist compression. The prestress is set such that under factored loads none of the cables go slack, so they remain effective in controlling the displacement of the rim. While the prestress is necessary, the compression it induces in the rim dominates the rim design. Achieving an efficient design requires the prestress to be minimised (Fig 4).

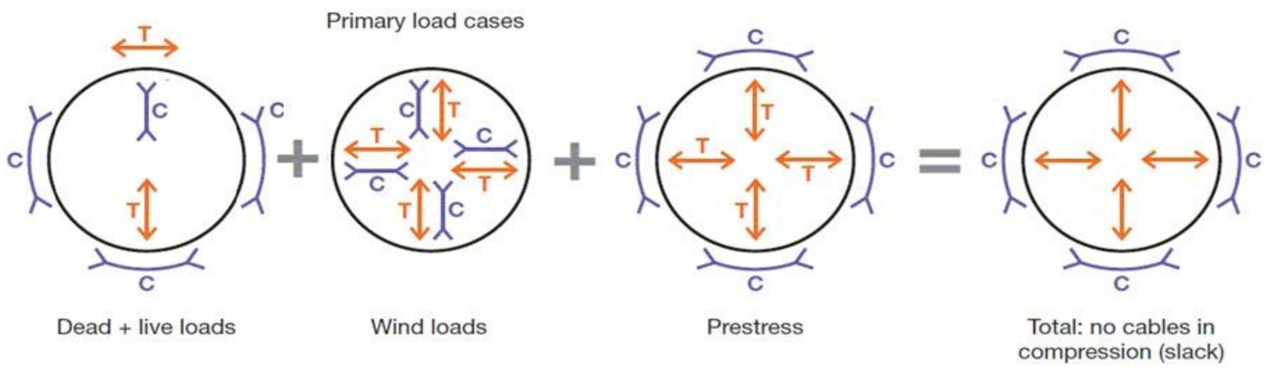

Figure 4 : Spoke Cable Components of Force.

The 2-D ladder truss helps reduce the wind load on the Flyer rim. This is important as, even though the wind load is only about a 10th of the weight, it generates approximately the same prestress requirement because the cable angles are unfavourable for resisting lateral load. To minimise the prestress required against wind, the width of the Flyer hub was maximised and cables were selectively crossed to the opposite side of the rim to increase their efficiency.

About half the weight of the rim, and a significant portion of the wind load, comes from the non-structural items such as the capsules, bus-bars, and drive rails. As these items fell within Mitsubishi's specialist design role, the Arup team impressed upon the various component designers the need to make these items as light and as streamlined as possible.

The final requirement is to minimise the weight of the rim primary structure. The rim needs to resist buckling under the compression (induced primarily by the spoke prestress) and to span between the lateral and radial restraints provided by the cables.

The team used purpose-written software to study rim buckling. The problem mode tends to be lateral/torsional buckling, with a critical load factor depending on the product of the lateral bending and torsional stiffness's of the rim. In designs like the London Eye, the rim provides both the large lateral and torsional stiffness, and hence needs to be in the form of a substantial 3-D truss.

An important aspect of the Singapore Flyer design, however, is that it maximises the contribution the spoke cables make to the stability of the rim. The lateral stiffness provided by the cables is limited, because practical and aesthetic limits on hub width mean the cable angles will always be unfavourable. However the radial stiffness of the cables is large, and attaching them to the sides of the rim provides considerable torsional stiffness. The rim then just needs to be laterally stiff, making the 2-D ladder truss an appropriate form.

With the lateral/torsional buckling performance provided by the spokes and ladder truss, the spanning requirement determines the bending capacity of the rim in the plane of the wheel. Rim bending moments are minimised in normal operation by aligning the cables with the capsule supports. The CHS (circular hollow section) 864 x 25.4mm chord size allows for an accident condition in which a cable is assumed to break. This also allows for cable replacement if required.

As the prestress determines the rim compression, and the rim compression is the dominant loading on the rim, a cycle of cause-and-effect is set up. If the rim design can be made more efficient and the dead load of the rim reduced, then the required prestress in the spokes decreases. This decrease in spoke prestress results in a reduced compression in the rim. This allows the rim to be made lighter, starting the cycle over again (Fig 5).

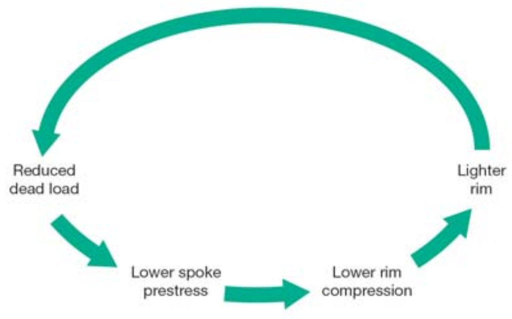

Figure 5 : Virtuous Dead Load cycle

As well as spending effort to reduce the weight of the rim, the design also looked at the breakdown of the traditional code load factors in more detail. A reduced dead load factor was justified on the basis that the variance in dead load that could be expected in the structure was low when compared to that of a typical building. Here, the weights of the capsules and other applied dead loads were known much more accurately than typical building dead loads. As a result, dead load factors more akin to those used in bridge design were adopted for the design of the rim structure.

Dynamics

Passenger comfort is a key design consideration for GOWs. Comfort in terms of vibration depends particularly on the wind response of modes involving movement out of the plane of the wheel. The team studied how the properties of these modes were affected by changes in lateral restraint at the bottom of the wheel, and changes in the stiffness of the support structure cable stays. The optimum level of damping to be added was also examined.

The studies showed that comfort benefits could be gained by increasing the size of the support structure cable stays over that required for strength, so as to enhance their stiffness. They also concluded that damping should be introduced at the base of the wheel, so this was incorporated into the passenger deck structures along with the drive train mechanisms (Fig 6a-c).

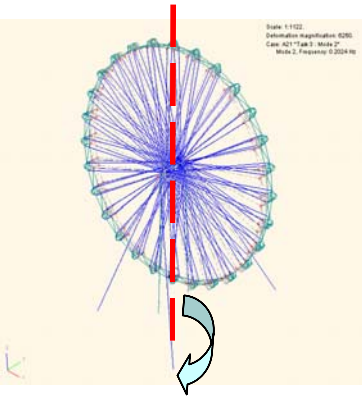

Figure 6a: First translational mode (support mode), In plan rotation (0.2Hz)

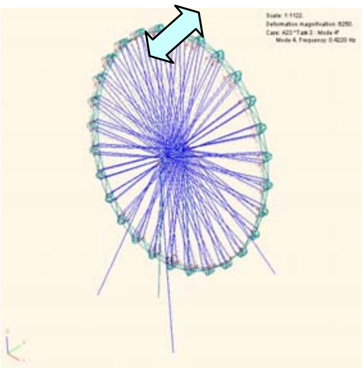

Figure 6b: Second Translational mode (Rim mode), lateral displacement at top of rim (0.42Hz).

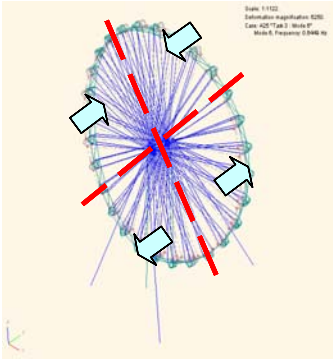

Figure 6c: Fourth translational mode, 4 lobe displacement (0.65Hz).

Singapore Wind & Design Speeds

Singapore experiences unique wind conditions: "Sumatra" squalls blow in from the Straits, and in this mixed wind climate monsoons and thunderstorms are also commonplace. While in general wind speeds are low, the peak gusts in Singapore, resulting from thunderstorms, can arise very quickly and with limited warning. It is therefore difficult to reliably manage evacuations of the wheel in advance of strong winds as can be done on the London Eye. Fortunately such storms normally consist of only a few strong wind gusts.

The variation of wind speed with height in convective events (such as thunderstorms) is known to be quite different from the standard code profiles, and often the strongest winds occur below 100m height. Unfortunately there are currently no procedures that can be considered reliable for modelling this kind of behaviour, so in accordance with current design practice a standard wind model was assumed to fit the predicted 50-year gust speed at 10m height. This model is likely to overestimate the wind gust speeds as the top of the wheel but may underestimate the dynamic response factor - a rational compromise, given the unknowns! An allowance for the provision of dampers on the rim was made in the design should they have proven to be required under actual wind conditions.

During normal operation, a wind speed limit of 13m/s average at 10m height was used, together with gust and dynamic response calculations based on the ESDU (Engineering Sciences Data Unit) wind model, which is compatible with British Standard code design. Given the unpredictable nature of squall/thunderstorm conditions in Singapore, however, a design acceleration limit (comparable to that experienced on the MRT trains) was imposed under the full design wind condition. Damping was also provided to ensure movement dies out quickly and any passenger alarm quickly alleviated.

Wind Tunnel Testing

In view of the importance of the wind loads in helping to determine minimum prestress limits, a segment of the rim and a capsule was tested in MHI's Nagasaki wind tunnel facilities to verify the assumptions made on wind drag. Only a segment of the wheel was tested in this large and high-speed tunnel, since the model needs to be at a scale where Reynolds' number effects can be managed. Measurements were taken for a variety of wind approach angles and rim inclinations to enable accurate application of the results in the design model.
There was some doubt about the extra drag that would result from the cylindrical shape of the Flyer capsules, compared to the better aerodynamic shape of those on the London Eye. It was also necessary to model accurately the service bus-bars and drive plates, etc, which significantly increase wind drag compared to the bare tubes of the rim structure itself.

Due to programme constraints, the foundations were designed using more conservative assumptions on overall drag, prior to the wind tunnel results being available. The more refined wind tunnel test results were incorporated into the superstructure design.

Aeroelastic Stability

Questions were also raised about the risk of large amplitude vibrations due to effects such as "galloping", "vortex shedding" and "flutter". The porous nature of the rim and the low sustained wind speeds in Singapore both pointed away from problems with response of the whole wheel. Local vibrations of long slender tubular elements and cables were also considered. The main elements of the rim were found to be stable, but the possible need for cable dampers was kept on the risk register.

The main strut columns were found to fall within the range of potential vortex shedding. Tuned mass dampers were installed at mid-height in each of the columns after site measurements of the natural inherent structural damping were found to be below the values required to mitigate response.

Some vibration in the cable spokes was also observed on site during construction and ascertained to be due to wind/rain-induced responses. Rivulets of water running down the spokes alter the geometric form and result in a dynamic response. Stockbridge dampers tuned to the third and forth natural frequencies of the cables (those frequencies at which resonance was observed), were provided subsequent to operations commencing.

Erection Method

Many options for the erection of the Flyer were studied both with the client and the contractor in order to satisfy a number of constraints:

- Available space on site
- Limitations imposed by support structure
- Programme
- Achieving final dimensional and prestress force tolerances
- Level of acceptable risk

The horizontal lifting method used on the London Eye was not favoured for the Singapore Flyer primarily due to the space constraints on site, but also due to geometric clashes with the terminal building proposed for the base during lifting.

Instead a vertical erection method was used. This involved erecting the support structure strut columns in segments using bolted splices, and then lifting the hub and spindle together (weighing 180t), from strand jacks off of a temporary gantry.

The Wheel itself was then erected in a “pie slice” fashion. Rim segments were delivered to site and laid level on a temporary stage. Cables were then installed in a slack condition. Temporary struts were provided between the hub and the rim enabling segments of the rim to be stable in their own right (See Figure 7).

Upon completion, each segment would be rotated to clear the way for the installation of the next and so on. Additional temporary strengthening was provided to the rim in the form of a lightweight chord to form a bowstring truss maximising the size of the segments able to be built.

Once the full perimeter of the rim was in place the cables were stressed in two stages, and the capsules installed.

Figure 7 : View looking North West during erection

Comparisons with London Eye (Millennium Wheel)

The London Eye was an architecturally-led project formulated to mark the turning of the Millennium for the city of London. The Singapore Flyer was a commercially-led development supported by the Singapore government, to inject investment into the country’s tourism economy. In both instances, the importance of creating a world-class attraction of exceptional quality and appearance was recognised as essential to success.

Arup developed the design of the London Eye to tender stage. At the time, the design was for a 150m diameter wheel with 36 capsules. The design was taken forward by others at a slightly reduced size, leading to the 135m, 32-capsule Eye that exists today.

The design of the London Eye was strongly influenced by architectural requirements. From the outset, the architects envisaged it being supported from one side only, and that the rim would be a triangular truss. There was a strong preference for limiting the number of spokes and for them to connect to the central inner chord of the truss.

While the advantages of a wide hub were recognised, the Eye hub width was limited by the distance that even a very thick walled spindle could be made to cantilever. The idea of connecting cables to the edge of the rim to increase its torsional stiffness was accepted, but they were limited to eight pairs, the minimum number that would effectively inhibit the four-lobed buckling mode.

The design of the Singapore Flyer was engineer-led. It was felt appropriate to support the spindle on both sides, which made it easier to achieve good support stiffness, as well as allowing a much wider spindle to be used and consequently improving the angle and efficiency of the spoke cables. This increased efficiency, together with a spoke arrangement developed to resist both lateral and radial forces and provide torsional restraint to the rim, meant that the Flyer rim structure could be reduced to a bare minimum.

The two differing erection methods were both effective. The horizontal lifting approach employed on the Eye made use of the Thames as additional construction site area, and was well suited to the one-sided support framing. The vertical method adopted on the Flyer was ideally suited to the two-sided support arrangement. It also minimised the plan area required on site for erection, allowing the surrounding retail construction to proceed unhindered.

Concluding Remarks

The design of the Singapore Flyer was an engineering led process that recognised the importance of a number of geometric effects on the efficiency of the structure. Differing site constraints to those of its predecessor the London Eye, as well as alignment with the development driver of reducing cost resulted in a more efficient structure being developed. The two dimensional truss form of the Singapore Flyer is both taller and lighter than the London Eye, and brings a new lightweight elegance to GOW design.

SEI Data Block	
Owner/Tenant: Singapore Flyer Pte Ltd	
Architect: Kisho Kurokawa Associates / DP Architects	
Structural Design: Arup	
Foundation/Building Contractors: Takenaka Corporation	
GOW Superstructure Contractors: Mitsubishi Heavy Industries Pte Ltd	
Project Management/Cost Consultant: Rider Levett Bucknall	
Steel (t):	1,950t
Total Cost (USD million):	175
Service Date:	February 2008