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Case studies in steel and composite design

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Abstract. This paper outlines the current steel design climate and describes some recent and unusual designs using structural steel or composite steel and concrete which have been carried out in Hong Kong and the East Asia region. Composite structural systems for very tall buildings are outlined. A case study of concept designs for one of these is presented. Two further case studies are presented: a refurbishment project where the use of steel and innovative strengthening techniques allowed an additional five stories to be built on an existing reinforced concrete frame and a monumental sculpture.

Key words: tall buildings; buttressed core; mega columns; refurbishment; composite design; load transfer; monumental sculptures.

1. Introduction

1.1. Design climate in Hong Kong

Relative costs, and the ability of local contractors to build reinforced concrete structures rapidly has led to concrete being the most economic solution for typical buildings in Hong Kong and thus the majority of recent buildings here are of reinforced concrete.

If we consider the "triangle of balance" between the competing requirements of cost, construction quality and time, it is usual that clients consider time and cost the more important. An understanding of the long-term benefits of quality and of life cycle costs is either poor or not considered, because the product will be sold and maintenance becomes someone else's problem. Whilst this may benefit the original owner / developer, it is usually not in the best interests of society or the environment.

Clients and Architects often prefer concrete structures as they are able to make late design changes. They are unable to do this with steel because of long lead times for fabrication.

Steel is usually used for long span roofs, stadia, industrial low rise buildings, and steel composite construction is increasingly being used for very tall buildings.

Basement columns for "top down" construction are often made from heavy steel plates, and steel is used widely for shoring up excavations and for site hoardings.

Structural steel sections and plates are imported from overseas and either fabricated in Hong Kong or in the Pearl River Delta region. Some special steelwork is fabricated further afield.

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Hong Kong steelwork practice has previously led to poorly executed site flame cutting and welding of steel, and inadequate site painting. It appears that the construction team try to transfer the flexibility of concrete construction to steelwork, and that the contractual and supervisory climate unfortunately may accept this poor workmanship.

1.2. The need for change

The difference in speed of construction between steel and concrete will reduce with better and more integrated use of design and drafting software between the design team and the fabricator, better use of standardized connections, and use of numerically controlled machine tools for fabrication.

Use of steel provides a better environment with more prefabrication off-site, less noise and less use of wet trades on site. It also leads to lighter structures and reduced foundation costs. The benefits of life cycle cost evaluation are becoming more widely recognised.

More disciplined architecture with firmer adherence to "design freeze" dates, use of modular construction with factory-type quality and speed, will improve design efficiency. Better design, construction methods and quality control are required.

Modern design codes should encourage all the above, provide clear and simple clauses for normal structures and also contain guidance for more complex structures and design issues.

2. Concept designs for very high rise buildings

Tall buildings are common in Hong Kong and East Asia, and particular systems and combinations of materials are evolving. A widely used structural system for very high rise buildings is demonstrated by No. 2 International Finance Centre, see Fig. 1, and the Cheung Kong Centre. It comprises a concrete

Fig. 1 No. 2 International Finance Centre, HK

Fig. 2 A office building at Sheung Wan, HK

Fig. 3 Commerzbank, Frankfurt

Fig. 4 Swiss Reinsurance Building, London

core with a limited number of very large perimeter mega columns of composite steel and concrete sections. These columns interact with one to four levels of outrigger girders placed as regularly as possible at various levels of the building to provide lateral stability and to increase its stiffness and strength. The core carries all the shear force and a proportion of the bending caused by lateral loads. Typical floors are of concrete cast on permanent steel formwork acting compositely with steel beams.

The most efficient structural system for very high rise buildings is the large space frame, or external mega truss as used by a slender office building at Sheung Wan, Hong Kong, see Fig. 2, and the Bank of China. This is because the system maximises bending stiffness of the whole building acting as a cantilever beam.

The Hong Kong and Shanghai Bank and the Commerzbank Headquarters in Frankfurt, see Fig. 3, use giant portal frame systems or mega frames.

An efficient alternative to the mega column system is a perimeter tube structure. The Central Plaza in Hong Kong is a good example of such a system in reinforced concrete. A more recent and unusual example is the Swiss Reinsurance Building in London, UK, which has an external steel diagrid tube, see Fig. 4.

2.1. Twelve mega column outrigger scheme

Fig. 5 shows a scheme for an outrigger stabilised structure using 12 rather than the more usual 8 perimeter columns. This scheme means that the sizes of individual outrigger girders and column sections are reduced, making transportation and crane handling weight more manageable, and spans for perimeter girders can also be reduced. Also the plate thickness and the weld sizes for very tall buildings, over say 400 m, can become almost unmanageably large, thus reduction is of benefit.

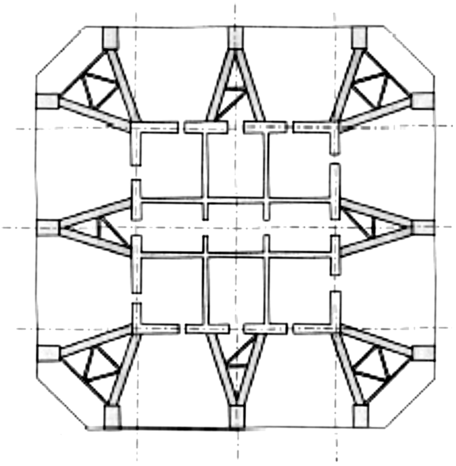

Fig. 5 Floor plan

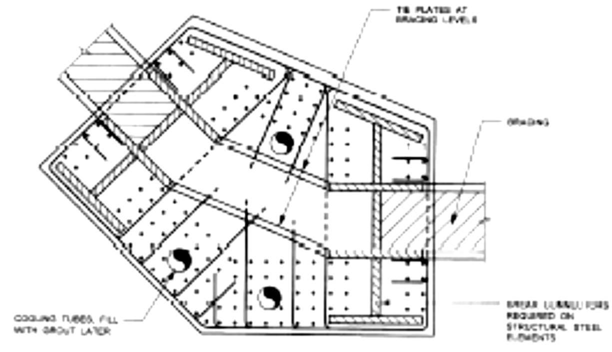

Fig. 6 Megacolumn detail

2.2. Large composite columns

Very large composite columns are key components for various types of high-rise structures such as outrigger or space truss systems.

Relatively thin external steel tubes filled with concrete provide a design solution which does not require formwork. However, splicing of internal reinforcement can be difficult and care has to be taken to ensure full compaction of connection. If the external steel casing is not fire protected, then at present its strength contribution is neglected in fire limit state design. However for large sizes a fire engineering approach may demonstrate that the thermal mass of the steel and the concrete can provide fire resistance for a specific period.

An alternative design solution is to encase large steel sections made from heavy plates with concrete. Typically around 12 to 14% of structural steel and 3 to 4% of reinforcement is a practical upper limit, see Fig. 6. For robustness, it is important that all the steel elements are well connected. Concrete grades of 60 to 100 N/mm^2 and steel yield stresses of 350 to 460 N/mm^2 are used. The buckling stability of very large columns in a tall building needs special analysis and design as relatively thin typical concrete floors often cannot provide sufficient lateral restraint to those columns. Guidance on design of such columns is highly desirable.

2.3. Active outrigger concept

Fig. 7 shows a concept for an outrigger girder with a movable reaction arm powered by computer controlled hydraulic jacks. This system reacts to and reduces building top sway and allows design of less stiff passive structure.

2.4. Composite external moment frame with buttressed core scheme

Fig. 8 shows a concept for a perimeter moment frame and buttressed core. The frame is designed as composite steel and concrete, and the concrete operation follows off the critical path after the steel

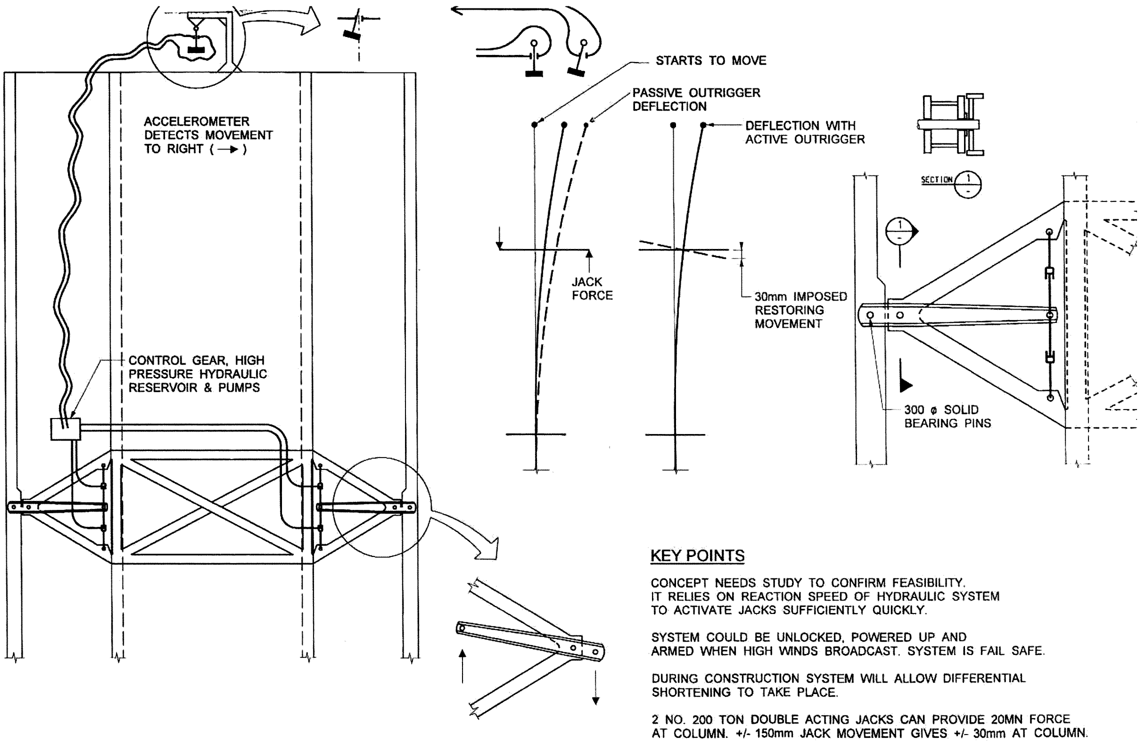

Fig. 7 Active outrigger

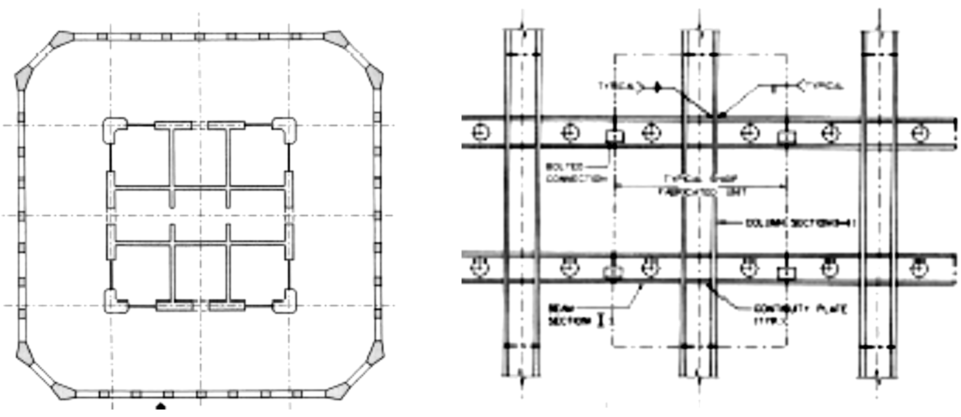

Fig. 8 Frame and buttressed core

beam / column "trees" have been erected. A particular feature of this design is the use of large corner columns which increases overall bending efficiency of the tube, linked by relatively smaller "shear" perimeter panels.

The composite core uses a similar concept. The corner buttresses are large and they are joined via quite large openings to the rest of the core. This allows major service ducts to exit from air handling units. Such a core can also work effectively in an outrigger scheme.

2.5. Structural optimisation

A recent development in the design of structural systems for tall buildings is the use of automated optimisation software, either as stand-alone programs or as part of a structural analysis program suite. The software can be used to seek optimal designs according to pre-set parameters by varying the stiffnesses of selected elements. These design goals can be specified as minimum weight, minimum cost or minimum overall cost including the expected income from increases in lettable floor area.

3. Addition of new floors to an existing structure

In February 1987, the Hong Kong Jockey Club decided to implement a project for the renovation of the grandstands at the Happy Valley Racecourse. One of the major planning constraints was that major demolition and refurbishment work could only be carried out during the annual off-racing season between June and September. Therefore a total of four working phases were planned and carried out over a period of two years.

The main objective of the project brief was to provide upgraded facilities in the public stands which would accommodate the full attendance capacity at all race meetings. The principal requirements were to ensure that the crowd capacities could be handled whilst eliminating the principal source of discomfort due to overcrowding, to improve facilities and to provide more race viewing areas. Additional floors and a new roof structure for the public stands were to be built on the existing foundations and structural frames of the building.

3.1. Addition of new floors to blocks P1 and P2

A particular architectural requirement was to produce an elegant and uniform roof line with partial cover over the existing racecourse stands.

The part of the project described here involved the complete stripping back to a bare reinforced concrete frame and addition of new plantroom floors as well as suspended rear stairs to public blocks P1 and P2. New structural systems had to respect the constraints of these existing buildings, as well as to provide an integrated framework for the architecture and the extensive building services requirements.

The existing structure comprises block P1, about 70 m long, and block P2, about 40 m long, separated by an expansion joint. The original building was about 14 m wide increasing to 27 m at the lower terraced stories, and 30 m high and of conventional reinforced concrete construction founded on 1.8 m deep pile caps and groups of friction piles each of 700 kN capacity.

3.2. Design constraints

The planning and programme requirements imposed some difficult constraints on the form of the structural solution as deep structural beams ran across the public stands from front to back, preventing major services distribution running along the buildings. The height of the building was increased by three stories, or about 40%, and the width by about 30%. This increased wind forces acting at right angles to the stand by about 50%, whilst wind forces parallel to the stand increased by 70%. The additional floors increased vertical loads by about 50%. Because it was necessary to provide cantilevered external rear stairs, some two-thirds of this increased load is carried by the columns on the rear elevation. All of these new loads had to be transferred down from the top of the existing structure.

The existing structure is somewhat ‘brittle’ in structural terms. Demolition and removal of finishes revealed a considerable extent of poor quality concrete, which required repair. It was not possible to place new foundations outside the building line and new foundations within the building had to be installed in a low headroom.

3.3. New structural systems

The key points in determining a structural solution to these problems were considered to be that new foundations would be required to carry all the new loads and prevent damage to the existing structure. Therefore the additional structure had to be lightweight. In principle, all new loads, both caused by wind and by the additional floors, should be carried by a new strengthening structure to a new foundation. Thus the existing structure, which had performed adequately to date, would actually be subjected to less load because of the removal of the original roof.

The principal elements of the new structural system are illustrated in Fig. 9 which consist of:

(a) New concrete floors acting compositely with steel beams to minimize floor weight, and spanning onto steel frames and roof trusses to minimize weight and allow fast erection.

(b) Lightweight steel hanging stairs which cantilever over the rear elevation and generate additional space in the building, see Fig. 10.

(c) A reinforced concrete strengthening frame sandwiching the existing columns and beams to carry the new horizontal and vertical loads to foundations.

(d) A system of transfer beams at ground level to transfer the new loads from the columns to the only possible new pile locations between existing piles and pile caps.

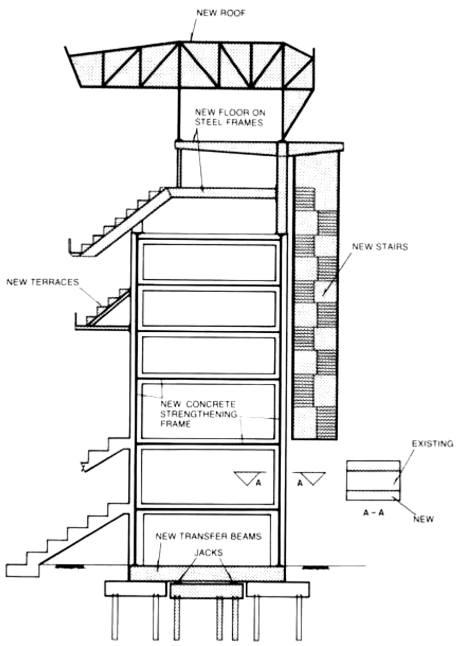

Fig. 9 Section

Fig. 10 Hanging stairs

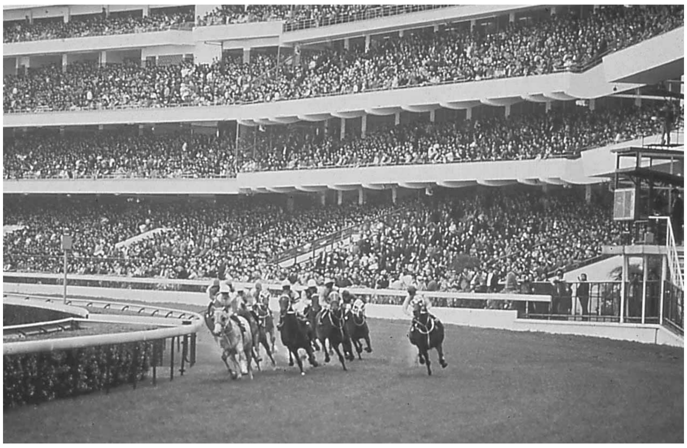

Fig. 11 Race day

(e) 500 mm diameter bored friction piles bored in temporary casings to minimize disturbance to the existing piles and to provide a ‘stiff’ pile with low settlement characteristics. These pile were installed with specially modified rigs to fit within the limited headroom of 4.5 m and a system of jacks to ensure that the new loads were transferred to the new foundations in order to minimize any possible differential settlement.

(f) Lateral stability for the new structure was provided as follows: The roof cantilevers resist lateral loads via a sloping prop-tie element at the rear of the truss from L8 to the roof, whilst longitudinal loads are resisted by braced bays in the front and the rear plant room walls. The new level 6 to level 8 structure resists lateral loads by “portal frame” action, and longitudinal loads by bracing in bays between rear elevation columns remote from the rear stairs. Finally, the strengthening structure between to ground and level 6 acts together with the existing frame to resist lateral loads and to transfer forces to ground level. Fig. 11 shows the finished project during a race meeting.

4. The Balanghay monumental sculpture

The creation of a large sculpture often requires significant structural input. As each artwork is unique, the engineer must respect the Sculptor’s vision and somehow visualise a structural system within an organic form. Solutions must often be derived from first principles and a proper understanding of structures and materials is required. Material strengths may not be codified and testing of materials and even the whole structure is often necessary.

It is necessary to develop an ability to explain structural principles simply to the Sculptor whilst respecting artistic requirements. Thus good engineering judgment is vital, and experience of other technologies is often helpful.

The Philippino Artist and Sculptor, Leo Gerardo C Leonardo, won a competition to build a monumental sculpture, the Balanghay, at Fort Bonifacio in Manila. His artistic vision as illustrated in a maquette, is shown in Figs. 12 and 13:

The sculptural concept and design must be based on the Filipino experience and tradition. It deals with images uniquely Filipino, but also has a universal appeal. It encapsulates and takes inspiration

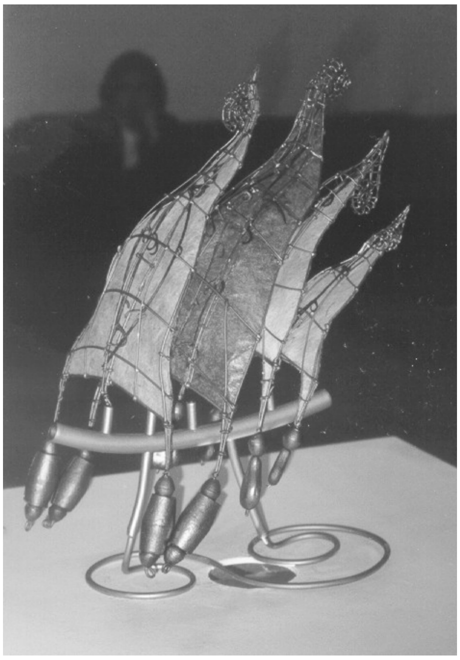

Fig. 12 Balanghay maquette

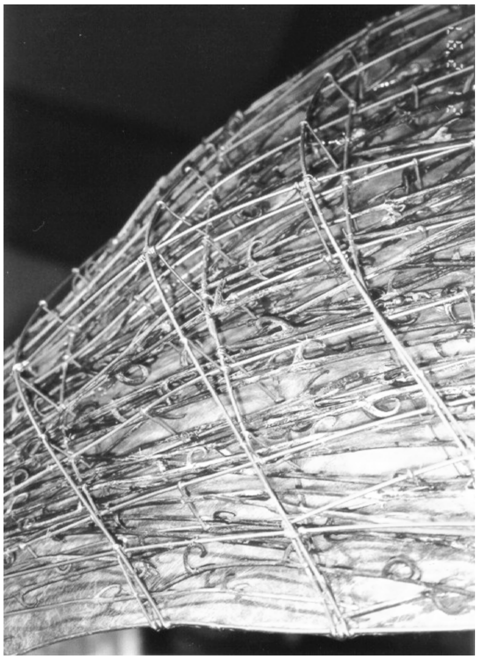

Fig. 13 Wing maquette

from many Philippine images such as the "balanghay" (vessel), Manunggul jar, Mindanao vinta, "sabong" (cockfight), sarimanok. It should facilitate interaction and engage the viewers in new experiences relevant to their aspirations and adhering to the goals and values of the Fort Bonifacio Corporate Credo.

To translate this piece to its actual size, it had to be constructed with the highest standards of craftsmanship and durable materials in order to withstand the demands of a kinetic as well as an outdoor sculpture.

4.1. Loads

The environmental loads used for the engineering design of the sculpture were a wind load of 2.5 kN/m^2 on plan area to allow for wind flow above and below wing sails, and seismic loads calculated assuming Uniform Building Code (US) Zone 4 and a short period structure i.e., 40% of the self weight of the sculpture. Vertical loads arise from self weight only.

4.1.1. Components of structural system

The sculpture consists of four triangular shaped wing sails joined to a hull by pivots at the centre of the base of each triangle. The wings are about 6 m high by 3.5 m wide.

The lower corners of the triangles are extended below the pivot and end in paddle weights, thus the wing remains upright on its pivot because the centre of gravity of each wing - paddle assembly is below the pivot.

The wing support pivots are mounted about 600 mm above the hull structure which is about 8 m long and gently curved up at each end.

The hull is supported by two pedestals which will carry the weight of the sculpture through water in

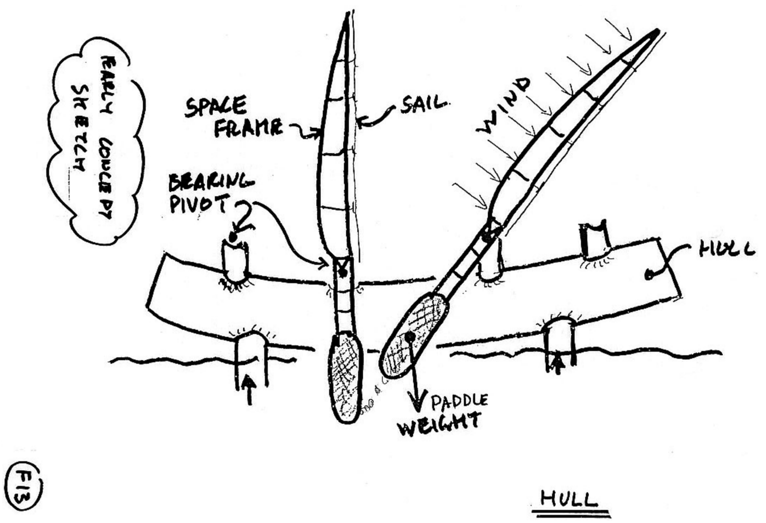

Fig. 14 Structural diagram

an ornamental pond to the ground. It was originally proposed to make the hull as a space frame clad with stainless steel panels. Finally a reinforced concrete option was used.

Wind or seismic forces on the winds will cause them to move from the vertical by rotating about the pivot. This movement is resisted by the self righting moment of the paddle weights. A system of links and stops prevent the four wings from moving too far or colliding with each other. Fig. 14 shows a concept sketch for the structure of the sculpture.

4.1.2. Wing sail frames

The wing sail frames are to be fabricated stainless steel space frames. Areas of higher load will use diagonal bracings and other areas, near the top of the wing, will resist loads by Vierendeel action. The space frame grid is around 600 by 600 mm with a thickness varying from about 400 mm downwards.

The wing plate collects the wind loads (which govern) and transfers them to the central trussed “spine” and edge members. The spine cantilevers from the pivot/spigot/spring and the sides in effect cantilever from the paddles as the wing moves from the vertical. The lowest horizontal pair of tubes form a “torsion box” truss at the bottom of the wing. The fixing of the spine truss to the ball pivot and spigot is critical as this is the most highly stressed part of the wing.

4.2. Main hinge pivot

Various options were studied for this: a cast steel sphere moving in a bronze or “Lubrite” cup bearing, or a gimbal bearing fabricated from stainless steel, or a lorry universal joint. This option was used, see Fig. 15.

4.3. Wing material and fabrication

The wing frame was fabricated from grade S316 stainless steel tubes. The basic ultimate design strength of grade 316 stainless steel may be taken as the 0.2% proof stress using a material factor of 1.0 i.e., approximately 205 N/mm^2, and a load factor of 1.5 is adopted. Tube sizes ranging from 42 mm

Fig. 15 Bearing detail

Fig. 16 Trial wing

diameter by 3.6 mm thick to 73 mm diameter by 7 mm thick were used for the structure of the wings.

It was envisaged that fabrication would be carried out by the Sculptor and his assistants thus design weld sizes were up-rated to allow for fabrication by semi-skilled workers. Changes in tube size were neatly effected across the joints.

4.4. Prototype full size wing

The bearing and movement requirements are not standard, nor it is easy to predict with confidence how the structure behaves. Therefore, a full size wing prototype was fabricated following the making of the above prototype models. This allowed discussion and modification of tube arrangements suit both artistic and structural requirements. It also allowed speeds of movement to be assessed and tuned by adjusting weights and springs. This prototype is shown in Fig. 16. The completed sculpture is shown in Fig. 17.

5. Conclusions

Currently, structural steel in Hong Kong is mainly used for long span structures, such as the Airport Terminal Roof or the new Convention Centre, and, acting compositely with concrete, it has been used for very tall buildings such as the Bank of China, and No. 2 International Finance Centre. It is expected that the use of steel will continue to increase in the region.

This paper has described some conceptual design options for high rise-buildings where composite steel and concrete provides the most appropriate structural solution. A large refurbishment project is also reported, it is made possible by use of steelwork which was fabricated off-site. Finally it has shown how steel can be used as an art form!

Fig. 17 Balanghay sculpture

Worldwide there are increasingly conflicting requirements of building faster and more economically yet with better quality and safety. Finding sufficient time for proper design in the conventional way is becoming a major problem. Design codes are becoming more complex, partly in response to better knowledge.

Well designed and properly fabricated steel structures can benefit the environment and permit faster and cleaner on-site construction by carrying out more manufacture in high quality factories and by use of modular design.

The building construction team, Clients, Architects, Engineers and Contractors, will all need to become more efficient in their process, collaborate more closely and work as an integrated team, rather than a struggle between opposing parties. Computers will help, but should be seen as servants to, not masters of, the process.

Modern design codes should improve design efficiency, provide clear and simple clauses for normal structures and also contain guidance for more complex structures and design issues. The benefits of life cycle cost evaluation should become more widely recognised.

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