CASE STUDY

FBO Facility
Seletar Airport, Singapore

Client: Jet Aviation (Asia Pacific) Pte Ltd
Facility: Hangar 2, Business Jet and BBJ capable MRO and FBO
Size: Hangar floor area of 5,000m^2 ; Annex Building (offices, workshops) 4,000m^2
External Works (aprons, carparking, landscaping) 18,500m^2
Status: Completed May 2014

About Jet Aviation

Jet Aviation (Asia Pacific) Pte Ltd ("JA"), a wholly owned subsidiary of General Dynamics, was founded in 1967. The company has grown into a world leader in maintenance, repair and overhaul (MRO) services, completions and refurbishment, engineering, and fixed base operations (FBO), which it provides to a wide range of business aviation customers.

A major focus for Jet Aviation is the increasing number of private jet owners, a customer group that is growing rapidly in South East Asia. To serve these customers better, the company decided to expand its facility at Singapore's Seletar Airport by adding a new and state-of-the-art hangar facility.

The Project

In November 2012, Aircraft Support Industries ("ASI") received a Letter of Award from JA appointing ASI as the Main Contractor to design and construct - on a full turnkey basis – JA's new MRO/FBO hangar and associated ancillary buildings and external areas, at their base operations at Seletar Airport, Singapore.

The award came after the culmination of extensive cost and design planning between JA and ASI, with several different design configuration options being developed and tabled by ASI that ultimately resulted in a facility that met both the future business plans for JA and the challenging site and existing infrastructure conditions.

The new facility features an additional (2nd) hangar spanning 100m clear and 50m deep, being capable of accommodating up to 5 Gulfstream G650 aircraft or multiple numbers of various different business jet types. Additionally, the hangar will have capacity for a Boeing Business Jet (BBJ), providing JA with the exclusive capability to service the private BBJ market at Seletar airport.

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The hangar structural design utilised ASI's proprietary and unique stressed arch technology which is unrivalled in providing the most cost-effective steel structure for large clear-spans.

The facility features vertical lift doors, allowing flexible, fast and well-sealed protection from the weather whilst providing the ability to fully open the entire hangar span. Inside, the hangar has overhead crane capability, along with unique large industrial ceiling fans to provide a more comfortable working environment for JA employees.

At the rear of the new hangar was built a 2-storey annex block comprising a total of approximately 4,000m2 of specialty maintenance workshops, stores, office administration, canteen and dedicated customer areas fitted out with high-end lounges, restrooms and sleeping quarters.

The facility is NFPA409-compliant, meeting this internationally recognised standard for fire protection of hangars, which is in line with both ASI and JA's philosophy of maintaining high standards in all respects.

Unique to the new facility is its clever integration with JA's existing hangar – a simple pitched-frame steel building some 50 years old and used by JA for their core maintenance operations. Clever architectural detailing was employed to blend the new arched hangar with the existing pitched hangar to give the impression of one continuous facility that had been planned that way from the beginning – an important aspect for JA and their overall branding.

By combining the two hangars, and providing the seamless workflow integration with the new workshops and offices, JA is able to generate a significant increase to their overall operational capacity, which allows them to meet current demand and also put them in good stead for future expansion for many years to come.

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SUPPORT FROM THE GROUND UP

The Stressed Arch Building System
GENERAL OVERVIEW

1. Introduction

Aircraft Support Industries (ASI), part of the ASI Global group of companies, is a highly specialised engineering and construction firm operating predominantly in the aviation sector, designing and constructing aircraft maintenance facilities and large clear span steel structures worldwide. ASI have designed and built large span facilities in regions including Australasia, South East Asia, Asia, Middle East, Africa and North America.

Researched and developed since the mid-1980's, the Stressed Arch Building System is a patented method for constructing large clear span buildings utilising the combined benefits of the *steel truss*, the *arch*, and *high strength steel stressing tendons*. The construction of a Stressed Arch building involves a unique erection process in which the steel trussed frames are assembled close to ground level in a "flat" position. Using the stressing tendons, the building is "stress-erected" into the final arch shaped configuration typical of the Stressed Arch building. The erection process results in a unique set of structurally favourable conditions imposed on certain members of the Stressed Arch frames, and the building's overall load carrying characteristics.

The resulting purpose designed clear span buildings are suitable for aircraft hangars, bulk storage, warehouses, sports and recreation facilities and, in fact, anywhere there is a requirement for cost effective column free covered space. ASI's website provides further information and numerous examples of buildings completed, which number upwards of 100 buildings worldwide.

2. The Stressed Arch Building System

2.1. Configuration

In the most fundamental configuration, a typical Stressed Arch building comprises a series of structural steel "stressed-arch" frames spanning in one direction and inter-connected via struts, bracing, purlins and girts, over which profiled metal sheeting is installed, as shown in Fig.1. Variations on this configuration are possible but will not be discussed in this paper.

The Stressed Arch building is constructed close to ground level (the assembled position) and then stress-erected into the final shape (the erected configuration) via prestressing strands located in the bottom chord of each frame. The construction procedure is detailed in Section 2.3.

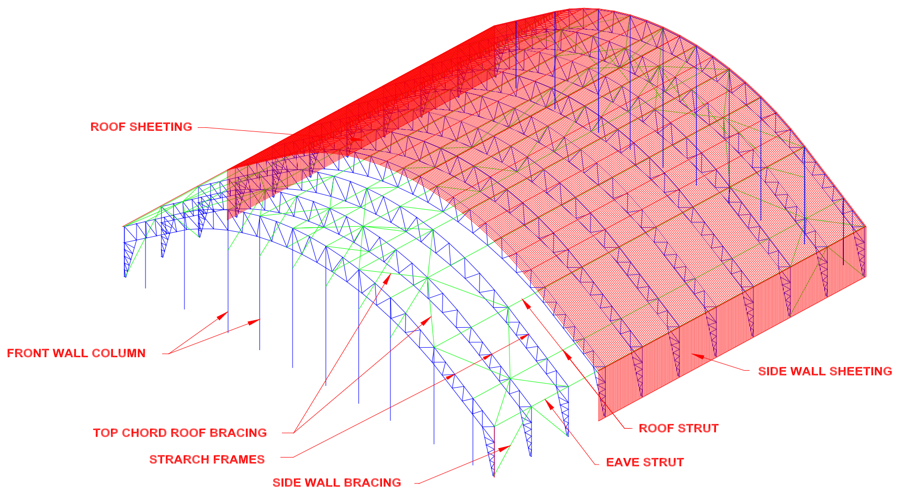

Fig. 1
Typical Stressed Arch
Building Configuration

2.2. Typical Stressed Arch Frame Details

A typical Stressed Arch frame is shown in Fig.2 in the assembled position, together with the usual fabrication details. Note in particular the following:

- The Stressed Arch frame consists of a flexible section, which changes geometry during stress-erection, and a fixed or rigid section, which is only rotated and translated during stress-erection.
- The top chord is a square hollow section member. The behaviour and design of the top chord member is discussed in greater detail in Section 3.1.
- The bottom chord comprises twin hollow section members. These contain the prestressing strands which are used to both stress-erect the structure and apply a level of conditioning prestress to each frame in the final erected shape.
- Between each node (web) connection in the flexible section of the truss the bottom chord contains a sliding joint comprising a gap in the chord, and an inner sleeve guide. The size of the gaps determine the final shape of the erected frame.
- The web members, in the flexible section of the truss utilise a welded flattened end. This connection type has been found to be fabrication efficient and cost effective and allows for a slight relative rotation between chord member and webs during stress-erection.

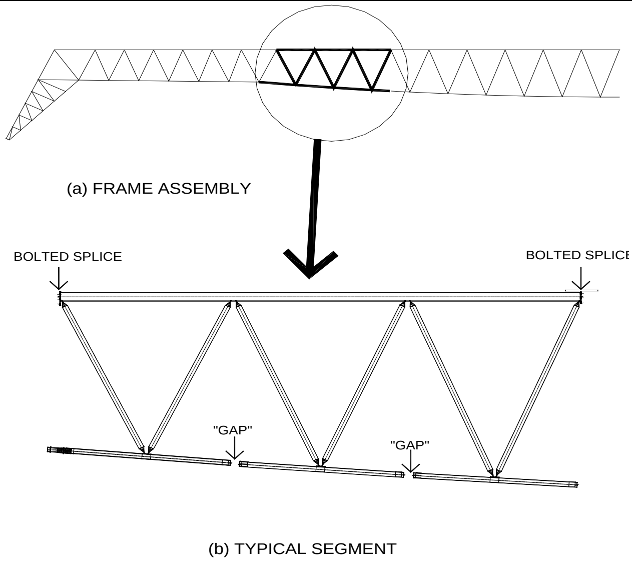

Fig. 2 Typical Stressed Arch Frame Details

2.3. Construction Procedure

Each Stressed Arch frame is assembled from sections prefabricated (usually) off-site and bolted together whilst supported on scaffold towers, as shown in Figs.3(a)(b). Frames are typically assembled from pinned end to sliding end and consecutively from one end of the building to the other. Once the first few frames have been assembled, the roof purlins can be installed, following closely behind the frame erection crew.

As a consequence of the modularity of the Stressed Arch roofing system and the fact that this assembly work, including lights, sprinklers and crane beams (which may also be fitted at this stage) proceeds at low level with reduced lifts and cranage requirements, very real gains in construction efficiency and safety are possible, leading to considerable reduction in the overall construction period.

Once the assembled structure is finalised, prestressing strands are threaded through the bottom chord tubes. On one side, usually the sliding side, the strands are locked off using conventional barrel and wedge assemblies. On the opposite side of the frame multi-strand prestressing jacks are used to apply tension to the strands. The resulting compression at the strand anchorages and bottom chord forces where the strand changes direction lift the frame off the construction supports and upwards in a controlled fashion to the final erected shape. The sequence is shown in Figs.3(d)(e)(f). Several full strokes of the prestressing jacks are required over the duration of the stress-erection, which usually takes from two to eight hours depending on the size of building and jack arrangement.

Once the frames are in the erected position, the columns are bolted to the foundations and a conditioning prestress is applied. The conditioning prestress is the calculated level of prestress necessary to give sufficient pre-compression in the bottom chord members to ensure that the gaps do not open under tension resulting from superimposed load on the frame. The analogy to prestressed concrete is evident. The bottom chord of the Stressed Arch frames is then grouted to fill the void between the strands and tube and provide corrosion protection to the strand. If the Stressed Arch building is required to be demountable, then the grouting can be omitted with greased and sheathed strands used instead.

After stress-erection of the building, the side walls, end walls, cladding, and internal fit-out can proceed as for a conventional building.

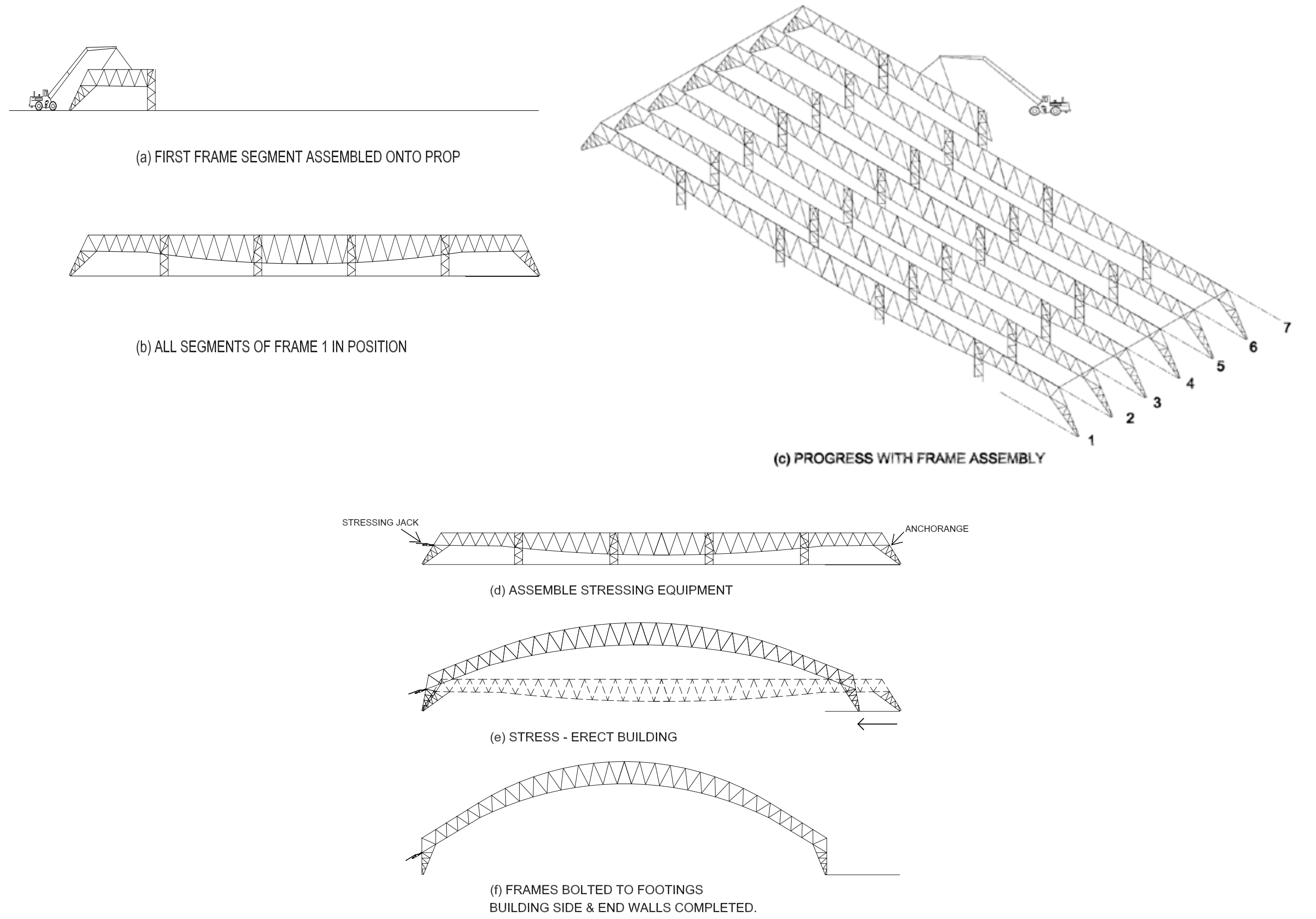

Fig. 3 Stressed Arch Assembly/Erection Procedure

3. STRUCTURAL ANALYSIS CONSIDERATIONS

3.1. Unique Frame Members

The unique stress-erection procedure of the Stressed Arch frames result in an in-situ curvature of the top chord member and, to a lesser extent, the bottom chord member within the flexible section of each frame. Depending on the final shape of the building and the size of the top chord member, the top chord may be stressed into the inelastic range of material behaviour.

In this respect, the design requirements of the top chord members are unique, being based on the behaviour of a truss member with a defined level of inelastic (yielded) material and a degree of out-of-straightness resulting from the erection curvature. The out-of-straightness and bending strain induced by the erection curvature of the top chord in the flexible section of the truss are outside the scope of the initial conditions assumed by the simple beam-column strength interaction equations defined in specifications and standards. Conventional design methods, particularly those based on working stress design code formulations, could not be applied in a rational manner to the design of the top chord members to account for the reduction in strength produced by the erection curvature.

Using the rigorous finite element nonlinear analysis developed at the University of Sydney, a parametric study was undertaken to quantify the effect of erection curvature, member slenderness and material properties on the ultimate strength of the Stressed Arch frame top chord. The resulting data were presented as a set of column curves consistent with the multiple column curve concept favoured by the Structural Stability Research Council.

ASI has undertaken an extensive range of experimental testing and theoretical research in order to investigate the overall behaviour of Stressed Arch frames and, in particular, quantify the top chord member strength. The majority of research was undertaken at the University of Sydney, Australia, and the University of Melbourne, Australia. Independent verification of much of the research has also been undertaken in Japan, Canada and the United States.

The bottom chord, usually comprising twin circular hollow section members enclosing (usually) grouted prestressing strands, behaves as a composite section under forces induced by superimposed loading. Design checks are carried out for the individual components, that is, tube compression, grout compression and strand tension, as well as gap opening and member strength for the combined section.

3.2. Remaining Frame Members

Apart from the top chord members in the flexible section and the composite bottom chord members in the flexible and fixed sections, the Stressed Arch frame members behave and are designed in the conventional manner to the normal design rules of the relevant code or specification.

3.3. Know-how

The design of the Stressed Arch frame members is only a small part of the overall know-how required to successfully design and construct a building of this nature. ASI has developed this knowledge over many decades in the industry. Fitment design and detailing, design for stress-erection and construction methodology form an inter-related mesh of considerations, all critical to the successful completion of a project.

4. CASE STUDY - HANGAR IN SINGAPORE

4.1. Description

A Stressed Arch hangar with building geometry to suit aircraft up to Boeing B747-400 size was constructed in Singapore in 1992 for the client, Singapore Aerospace Engineering (SAE). The Stressed Arch solution to the client brief is shown in plan and elevation in Fig.4. The building consists of a series of 75m span Stressed Arch frames typically at 8.0m centres with a 4.2m roof/front wall overhang for an overall building length of 60.5m. The rear wall has columns extending from ground and supported horizontally at the top by the Stressed Arch roof system. The front wall columns are suspended at the top from a truss system cantilevered out from the Stressed Arch frames and supported at the lower end by diagonal struts back into the roof structure. The cladding membrane consists of cold-formed purlins/girts supporting single skin profiled steel cladding. The building has two 10T SWL overhead cranes supported from the roof.

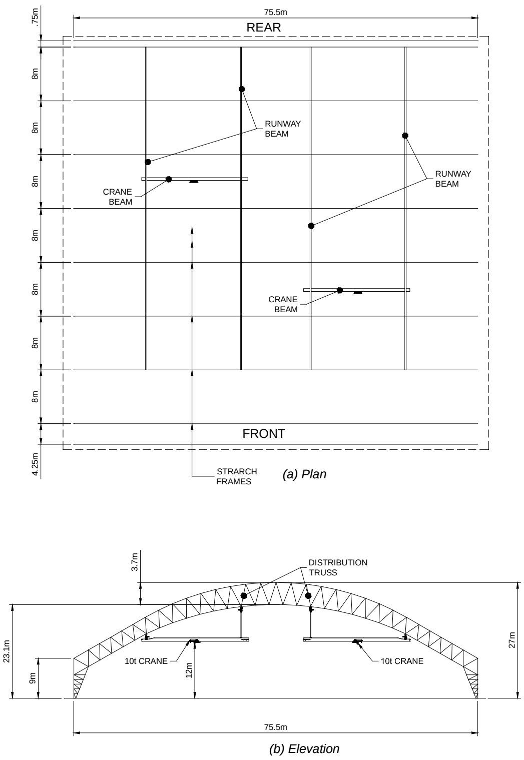

Fig. 4 Layout of SAE Hangar

4.2. Stress-Erection

The building was stressed utilising 4 of the 6 number ϕ15.2mm 7-wire low relaxation strands in each frame. The strand has an ultimate load capacity of 250kN. Prestressing jacks used were single strand jacks.

4.3. In-Service Performance

The completed facility is shown in Fig.5.

A requirement of the contract was the proof loading of the two roof supported 10T cranes and the monitoring of the resultant building performance. Fig. 6 shows both cranes located under a single frame and loaded with certified waterbag weights to 25% overload (12.5T each crane). The resulting live load vertical deflection of the Stressed Arch frame at centre span was only 11.0mm, giving a deflection/span ratio of 1/6800. This compares to a predicted value of 16.0mm. The difference is attributable in part to the stiffening effect of the roof membrane and the concrete encasement of the Stressed Arch frame columns for fire protection. Both effects were not modelled in the analysis.

Fig. 5 Completed SAE Hangar

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4.4. Comparison With Conventional Construction

Table 1 compares design frame weight, total structural steel weight and central vertical deflection for the Stressed Arch solution and a "conventional" hangar design. The conventional hangar has functionally the same plan area and loading condition as the Stressed Arch solution, including 2 x 10T suspended gantry cranes with longitudinal distribution trusses above the inner crane rails. Instead of arch trusses the conventional design has the more traditional horizontal trusses at a uniform height.

Fig. 6 Proof Testing of Cranes in SAE Hangar

Table 1 Comparison of Building Weights and Stiffness

	Stressed Arch	Conventional	% Increase for Conventional
Main frame weight (t) (each frame)	13.1	16.7	+ 27 %
Ancillary steelwork weight (t)	16.2	38.0	+ 135 %
Total structural steelwork weight (kg/m^2) □	29 kg/m^2	41 kg/m^2	+ 41 %
Deflection (mm) *	Design : 16.0 Actual : 11.0	Design : 23.0	

□ Based on plan area of 75m x 55.5m
* Centre span vertical deflection under 2 x 10T crane loading near centre span.

The weights shown are for the main frames and ancillary steelwork (roof bracing, wall bracing) but exclude the weight of the crane beams and the front and rear wall steelwork. In the design of the conventional hangar, section types and grades similar to that for the Stressed Arch frame were adopted, in order that material costs and fabrication details for the two designs could be considered similar.

The figures illustrate the structural efficiency of the arched frame. The considerable saving in ancillary steelwork weight was possible through a combination of stressed skin roof membrane design and the physically smaller outer envelope of the Stressed Arch building. The latter point will also markedly increase the end wall cost (not shown) for the conventional building, which has upwards of 30% greater end wall area.

The preceding comparison clearly illustrates the advantages of the Stressed Arch solution for the given project, combining the inherent stiffness of the arch shape, the bending capacity of the truss and the construction advantages of stress-erection. Significantly, savings in building weight are also coupled with a substantial stiffness in the structure, an important factor when strict deflection requirements for roof supported equipment must be maintained.

A second Stressed Arch hangar was subsequently completed in Singapore for Singapore Aviation Services Company. This structure is similar in general arrangement to the previous hangar, with a span of 74.8m, apex height of 28.0m and a main hangar length of 60m. In this case, roof supported cranage comprised two outer 15T SWL cranes and a central 5T SWL crane. Under the application of 18.75T (25% overload) to a single crane at the centre of the crane span (approx ¼ point span of building), the measured vertical deflection of the building was an impressive 5mm (deflection/span ratio = 1/15000) against a predicted analytical result of 7.2mm.

5. CASE STUDY – COAL COVER IN IRIAN JAYA, INDONESIA

5.1. Description

In 1998 ASI constructed a coal cover facility for the client, PT Freeport Indonesia Company, located in Irian Jaya, Indonesia. The coal storage facility serviced the requirements of the coal fired power station, an integral part of the very large copper/gold mining operation set up by the client. The completed building is shown in Fig. 7 and the concept in Fig. 8. The structure is 120m clear span and 150m long with an apex height of 32m and a side wall height of 12.5m. Stressed Arch frames are located at 10.0m spacing down the length of the building. The roof membrane comprises light gauge steel purlins supporting profiled steel sheeting.

5.2. Construction

The site was an operating coal stockpile prior to the planned construction of the coal cover. Coal supply to the adjacent power station could not be interrupted and therefore the planned construction procedure had to work in conjunction with the existing coal intake and discharge procedures.

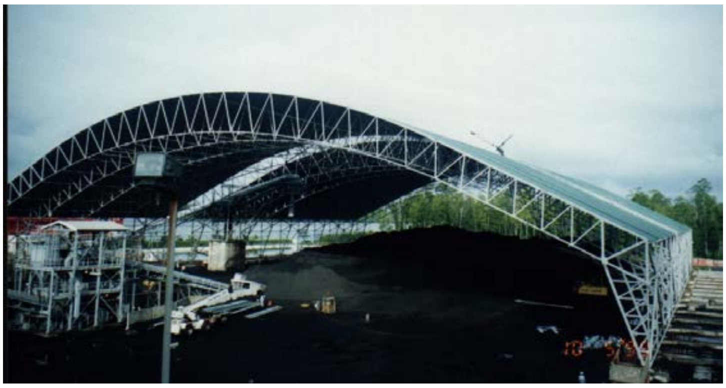


Fig. 7 Freeport Coal Cover

Many different permutations of construction procedure were reviewed in conjunction with the client. The final solution entailed in chronological order:

1. Client to move existing coal pile to the northern end (closest to the intake hopper and power station) of the site and confine operations to this end for the period of construction of the first half of the roof.
2. ASI to assemble and stress-erect the first half of the roof at the southern end of the site.
3. Client to move coal pile to the southern end of the site under the now complete half-roof structure. Client to confine operations to this end as much as practical.
4. ASI to assemble and stress-erect the northern half of the roof structure. This operation required very close coordination with the client, as the intake hopper for material to the power station was located underneath the assembled roof structure. A clear access route was maintained throughout the construction works for large bulldozers to move coal from the pile to the intake chute. Coal retrieval operations continued on a 24 hour basis, even while stress-erection was underway.
5. ASI to make good the bay of purlins/cladding between the two erected halves of the roof.

The construction of this facility was one of the more challenging logistical exercises undertaken, given the very real downside of power outage to the complete facility if coal supply to the power station could not be maintained.

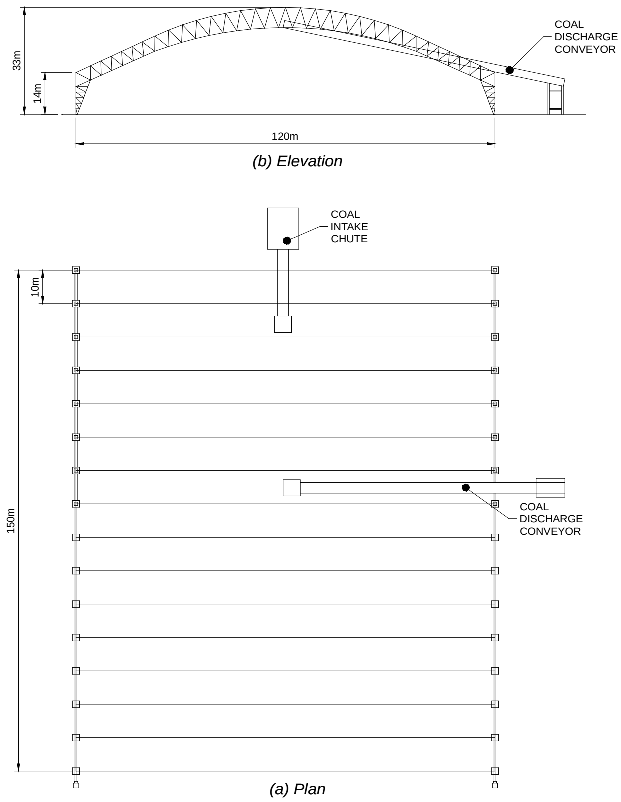


Fig. 8 Freeport Coal Cover Layout

5.3. In-Service Performance

The client was extremely happy with the functional performance, both during construction and in-service. Problems with coal pile instability and wash-away during heavy rain have been eliminated. The ambient moisture content of the coal has also reduced, leading to more efficient firing in the power station.

5.4. Comparison With Conventional Construction

As part of the pre-contract review and due diligence, the client examined a number of competing structural systems in the international market. It is understood that in the final assessment, none of the reviewed systems were able to compete with the Stressed Arch solution, either on a weight/m^2 or cost/m^2 basis. The final as-built structure had a total structural steel content (columns/rafters/struts/bracing) equating to 28 kg/m^2 based on plan area. This is for a structure of 120m clear span by 150m long.

6. CASE STUDY – HAINAN AIRLINES HANGAR, HAIKOU, HAINAN PROVINCE, CHINA

6.1. Description

In early 2002, ASI completed construction of a hangar for Hainan Airlines, located at Haikou, Hainan Island, China. The facility is a 2 bay heavy maintenance hangar intended to service A340 and B737 aircraft. The completed building is shown in Fig. 9(a)(b) and the concept in Fig. 10.

Fig. 9(a) Hainan Airlines Hangar Opening Ceremony

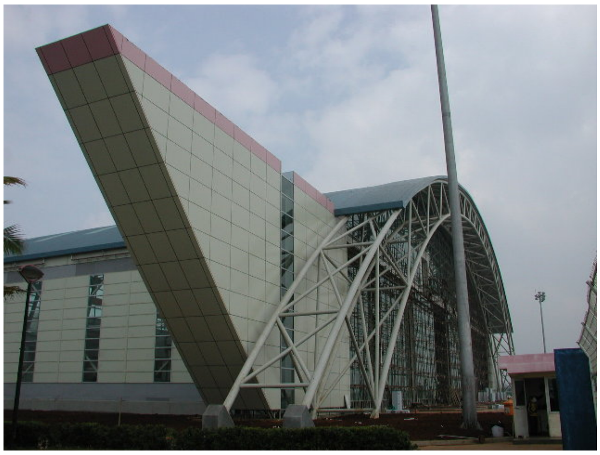


Fig 9(b) Hainan Hangar Architectural Detail

The structure is 100m clear span and 49m long with an apex height of 29m and a side wall height of 15m. Stressed Arch frames are located at 8.2m spacing down the length of the building. The roof membrane comprises light gauge steel purlins supporting profiled steel sheeting. Crane coverage is provided by 10T and 5T cranes fully supported from the roof of the structure.

The structure is an outstanding example of architectural flair applied to an arch shaped building. Full glazing of the front and rear walls and hangar doors lead to a light airy feel internal to the hangar. The structural intent of the arch shape is given outward expression by exposed trussed box arches at the back and front of the hangar. Hangar door pockets have been shaped to make a statement.

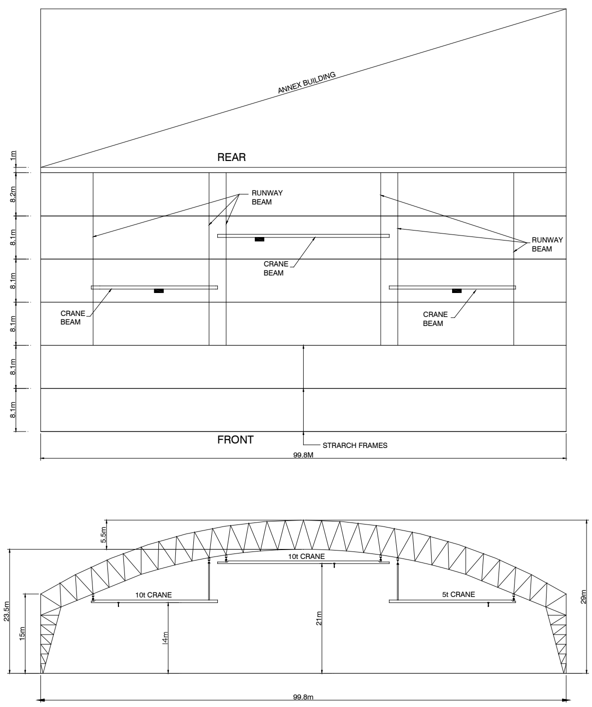


Fig. 13 Hainan Airlines Hangar, Hainan Island, China

6.2. Design & Construction

The structural design for the main hangar component was undertaken in Hong Kong by a Stressed Arch licensed and trained consulting engineering firm. Many different permutations of construction procedure were reviewed in conjunction with the client. The final solution entailed the majority of structural steel components being fabricated in Malaysia and shipped to site for assembly of bolted components into frame segments, final paint coat and assembly into the completed building. Site construction work, painting and stress-erection of the completed hangar was undertaken by local contractors under the project management of ASI.

6.3. In-Service Performance

The client is happy with the functional performance, both during construction and in-service. The inherent strength and stiffness of the Stressed Arch structure has allowed a glazing system to be incorporated into a large span construction in a straightforward manner.

7. CONCLUSION

The Stressed Arch building system, a method of constructing a clear span building structure at low level prior to stress-erecting into the final arched configuration, has been presented in the context of a mature technology with applications to a number of different building solutions. Comparisons have been made with more conventional structural configurations and it has been shown that the inherent structural efficiency of the arched truss, combined with the speed of construction and safety of the stress-erection procedure, results in an effective solution to specific client requirements.

8. ASI CONTACT DETAILS

Email: enquiries@asiglobal.net

Website: www.asiglobal.net

For more information or a confidential discussion of your requirements, please contact us.

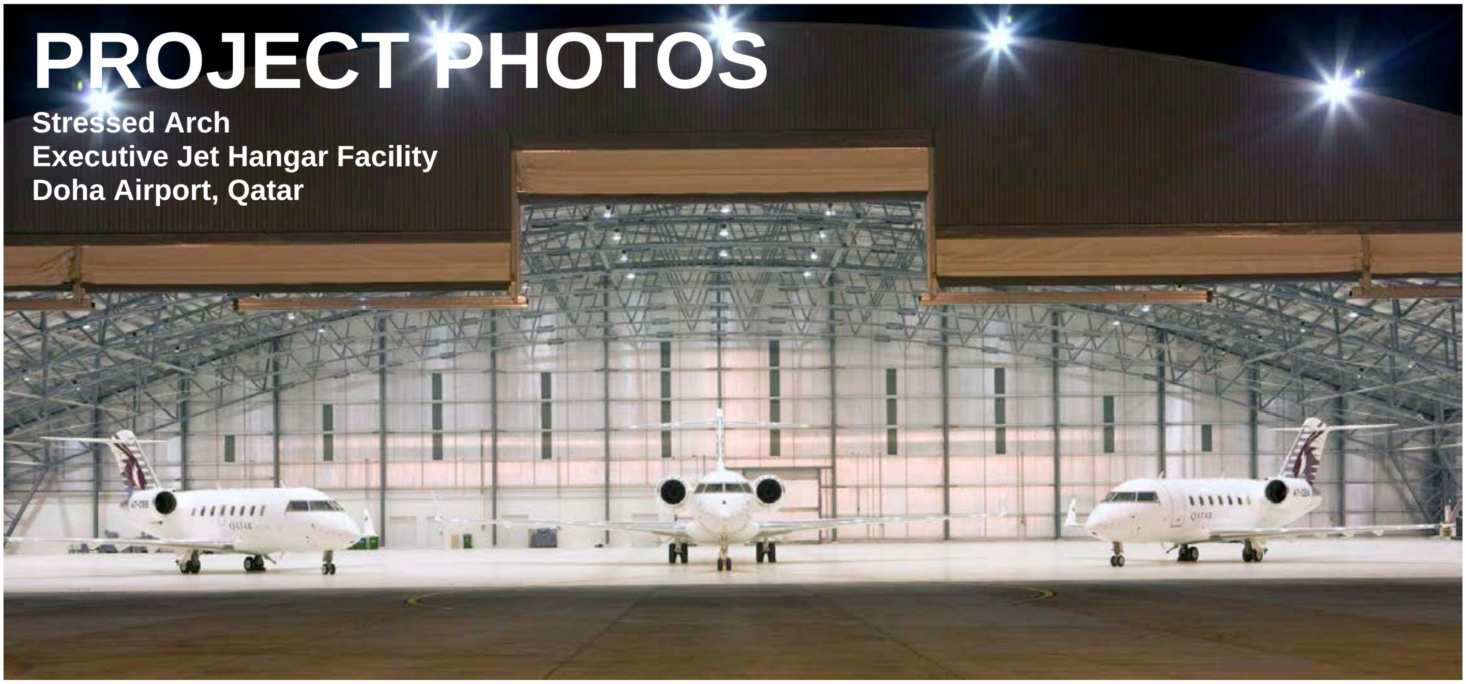
ASI ENGINEERING, AUSTRALIA
Suite 201, Level 2, 39 East Esplanade
Manly, Sydney, NSW 2095
Australia
P. 61 2 9976 0188
F. 61 2 9976 0199

ASI SOUTH-EAST ASIA
67 Beach Road
#02-01 Bulkhaul House
Singapore 189688
P. 65 6337 3160
F. 65 6337 3325

ASI MIDDLE EAST
DWC Business Center
Dubai Aviation City - Logistics City
United Arab Emirates
P. 971 4806 3418
F. 971 4816 0010
M. 971 56 102 5001

PROJECT PHOTOS

Stressed Arch
Executive Jet Hangar Facility
Doha Airport, Qatar



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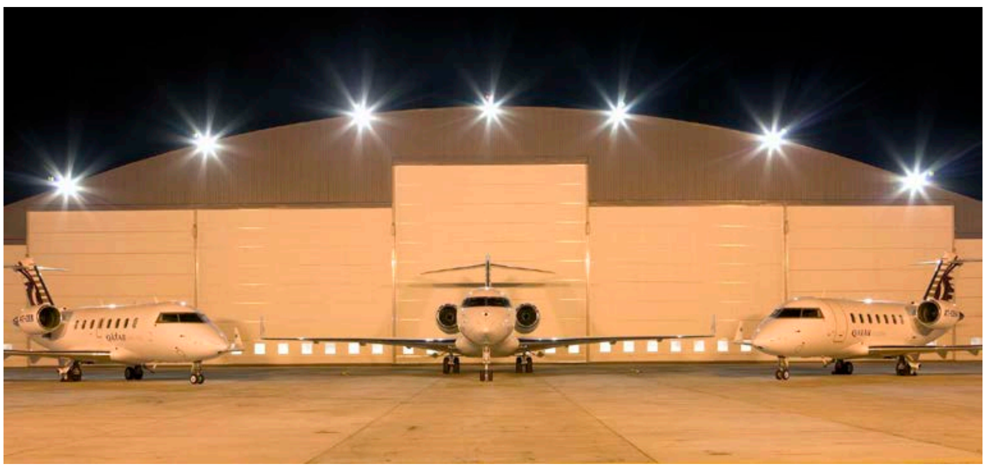

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