Octagonal Shape Reduces Airplane Hangar Costs

While a square hangar would have been simpler to design, an octagonal building substantially reduced life cycle costs

By Charles Sacre, P.E.

The program for a new hangar for the New York Air National Guard (NYANG) near Niagara Falls included meeting a tight budget and minimizing the building's size. Specifically, requirements included:

• Designing an efficient maintenance hangar to fully shelter KC-135 aircraft (including the possible use of lightweight fabric doors)

• Maintaining minimum required clearances around and above the aircraft

• Minimizing surface and total hangar volume for energy savings and reduced construction costs

• Fully adhering to military codes and standards

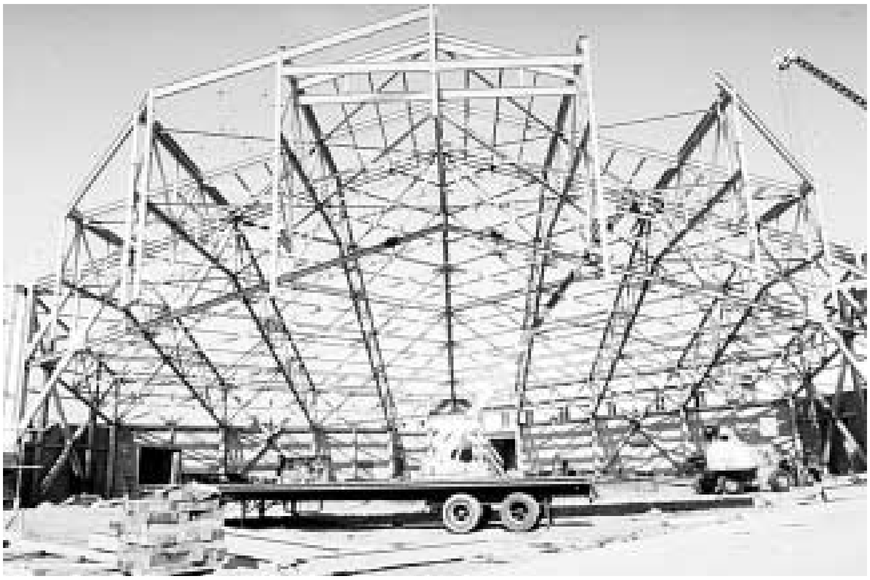
From the onset of the project, it was obvious that a lightweight material, such as structural steel, had the desirable strength characteristics to support the roof structure—including the main loads due to snow and mechanical equipment. Schematic alternatives using concrete roof deck and prestressed girders were too heavy and costly; other alternatives using timber did not have sufficient strength to span and carry the loads. Furthermore, both concrete and timber did not have the resilience of steel for this type of structure nor the inherent simplicity in connecting different steel members by welding or bolting. The roofing material selected was a lightweight sandwich panel weighing less than 4 psf. The panels, which span between roof purlins, include insulation and are capable of supporting the 35 psf basic snow load recommended by code for this area . The structure itself consists of a combination ASTM A36 wide flange members and ASTM A500 Gr. B steel tubes (yield strength of 46 ksi). The columns and walls are supported on concrete footings, with an allowable pressure of 2 tsf, bearing directly on soils.

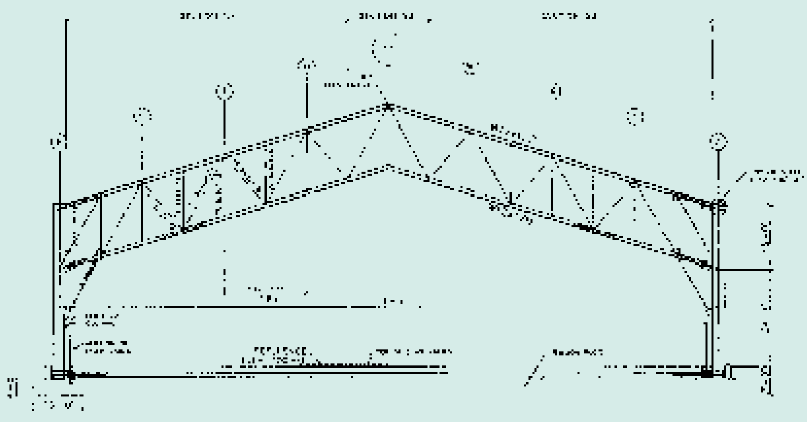
Design Development

The simplest and most typical shape to contain the entire KC-135 aircraft is a square box whose roof area is 168x168 ft. at a constant height of 65 ft. above ground level. The structural system could also be simple: trusses or frames spanning over the aircraft in a direction parallel to the wings supported by steel columns. The steel columns could be stabilized by bracings or moment connections in two directions. The structure of the door could be installed between the first and second trusses.

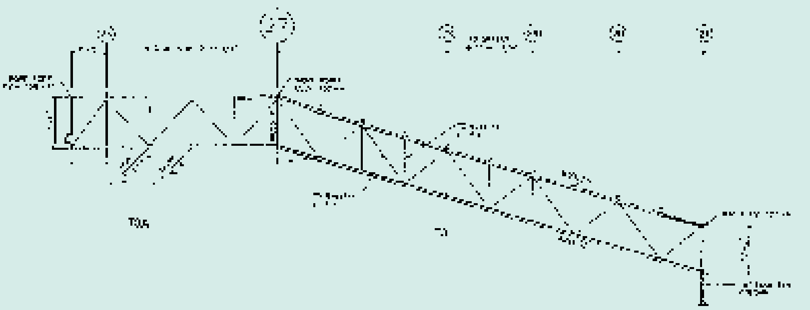
Unfortunately, while that simple design would have met most of the NYANG requirements, it failed to minimize surface area and total volume of the hangar for future energy saving and for economy of construction.

SEA Consulting Engineers designers researched a variety of alternate shapes to reach this goal before settling on a modified octagon. This shape also allowed the height of the roof over the aircraft to be reduced. A light, fabric roll-up door was recommended in lieu of traditional sliding hangar doors. Top of steel elevation varied from 65 ft. maximum above floor level at the main door center over the tail to a minimum of 28 ft. at the nose of the aircraft. This scheme fulfilled all the design requirements and was approved by the NYANG for further design development. This scheme has 30% less surface area and 55% less volume than a more traditional square hangar. Substantial savings in construction cost and energy are a natural consequence of this reduced volume.





Truss T1



Truss T3, T3A

However, the resulting structure still presented many challenges to be resolved:

• Part of the roof area above the door had to overhang from the remaining roof. How can a 6,000 square-foot cantilever area be supported by the remaining 13,600 square-foot roof area ?

• How can the 17.5-ton door including its motors be supported at the tip of the roof cantilever and how can its framing fit the shape of the door opening to resist the horizontal wind pressure?

The overhang had to be counterbalanced by the remaining part of the roof. A simplified structural model of a beam supported at one end and continuous at the other with a cantilever was found to be a representative picture of the structural system that could be used for the roof. Based on this model, the roof was subdivided into areas perpendicular to the main entrance, spaced every 20-ft.-1½-in. Beams supported each area. A column supported each beam at one end and a main girder supported the other end of the beam and the overhang.

Preliminary analysis revealed that deflections would be excessive (more than 14 in.) at the tip of the cantilever supporting the main door. This would have created problems to the structural system of the door. In addition, the diaphragm action of the roof which was essential to the distribution of horizontal forces of wind to the bracings was not adequate. Therefore, the beams and the main girder were replaced by trusses. In the final configuration, seven 12-foot high trusses (T2 through T5) supported by 18-in.-diameter steel columns at one end, and by a main 16-ft. high truss (T1) at the other end, were designed to carry part of the roof structure and thus serve as the counterweight to the cantilever overhang. In a similar way, corresponding 12-foot high trusses (T2A through T5A) were designed to support the overhanging part of the roof including the door structure and be supported by the main truss T1. This framing resulted in a controlled deflection and a stiffer diaphragm roof action.

After having defined the main components of the structure, two alternate framing systems for the main door of the hangar were considered. The first one literally hung the door structure from the superstructure. This solution would have required retractable vertical trusses to control vertical and horizontal deflections and to allow for the entrance of the aircraft in the hangar. Within the parameters of the project, it was found to be neither feasible nor economical. In the second alternative, which was selected, the different sections of the door are taken separately from each other. Each section, supported by the trusses T2A-T5A, is framed horizontally between vertical steel mullions that allow the different components to slide vertically. When each section of the door is open, the mullions lift vertically to clear the entrance to the aircraft. Two mobile mullions serve the high section of the door for the aircraft tail, four others (two are fixed at the end) serve the remaining low section for the aircraft wings. In the vertical position, the vertical mullions act like a vertical beam with a support at truss level and another at ground level. A recess in the concrete floor prevents horizontal movements due to wind, but allows the mobile mullions to deflect with the structure vertically, for a maximum $3\frac{1}{2}$ inches under full live loads.

The main truss, T1, is made continuous with one built-up column at each end similar to a frame. Four tension rods tie the bottom of the columns to absorb the horizontal shear due to full surcharge of dead and live loads on the roof structure. The tie rods with a yield strength of 60 ksi per ASTM A615 are post-tensioned with a 10-ton force. Trusses T2-T2A, T4-T4A and T5-T5A are similar to T3-T3A but with variable lengths and the exception of truss T2 end support .

Four vertical bracings are distributed along the perimeter of the building. Bracings BR-1 and BR-2 are perpendicular to each other and make a 45-degree angle with the centerline of the main door at Line V. Bracings BR-3 and BR-4 are on each side parallel to the same centerline. The horizontal bracings in the roof structure tie the top and bottom chords of the trusses and constitute a space diaphragm that transmits the horizontal forces to the different peripheral bracings.

The roof purlins over the body of the aircraft are placed along the contour lines. They are supported at the nodes of the trusses to eliminate local bending in the top chord and achieve a more economical truss. The purlins are rotated at an angle of 23.45 degrees with the vertical direction to have one planar surface for the roof panels. Due to the torsion induced and the impossibility of placing sag rods to minimize torsional stresses, tubular steel sections $12x8x\frac{3}{16}$ are used. The geometry of the roof structure (explained later in this article) allows an easy placement of the purlins over the top chord of the truss. However, the purlins in the roof area over the aircraft are placed parallel to the centerline of the main door. The angle of rotation with the vertical is 17.01 degree. Though small, torsional stresses cannot be considered to be negligible. In this particular case, tubular steel sections were not necessary because the symmetry of this part of the roof allows the placement of $\frac{5}{8}$-inch diameter sag rods to tie the W12x14 roof purlins.

Construction

The construction of the maintenance hangar was an integral part of the design development. During design, a simple idea was adopted to simplify the geometry of the structure and the construction phasing. It consists in specifying an equal slope $3\frac{11}{16}$ to 12 in two perpendicular directions. One is along line V or truss T2, the other is along line 27 or truss T1. Truss T2A is level with the high point elevation of truss T2. Consequently, trusses T3 thru T5 have the same slope as truss T2, and trusses T2A thru T5A are level with the high point elevation of the corresponding trusses T3 thru T5. Thus, the structure was divided into four easily constructible quadrants.

After the erection of the double-section columns each weighing 12 tons, and the circular columns, truss T1 is erected first because it carries approximately 75% of the roof area. It was brought to the site in three parts (two 70-feet 6-inches long and one 20-feet center piece) that were assembled in the fabrication shop. The completion of truss T1 assembly was done in the field. The erection of this 36.5-ton truss was done with two heavy-duty cranes.

Trusses T2 thru T5 were also fabricated and assembled in the shop. Truss T2 however, required a field-splice due to its length. These trusses were between 60 and 120 feet long and weighed between 4.10 and 8.20 tons. The erection of these trusses required lighter cranes than those used for truss T1. After these trusses were in place, bolted connections were used to link their corresponding top and bottom chords by W6x12 and L3-$\frac{1}{2}$x3-$\frac{1}{2}$x$\frac{5}{16}$ to achieve diaphragm action.

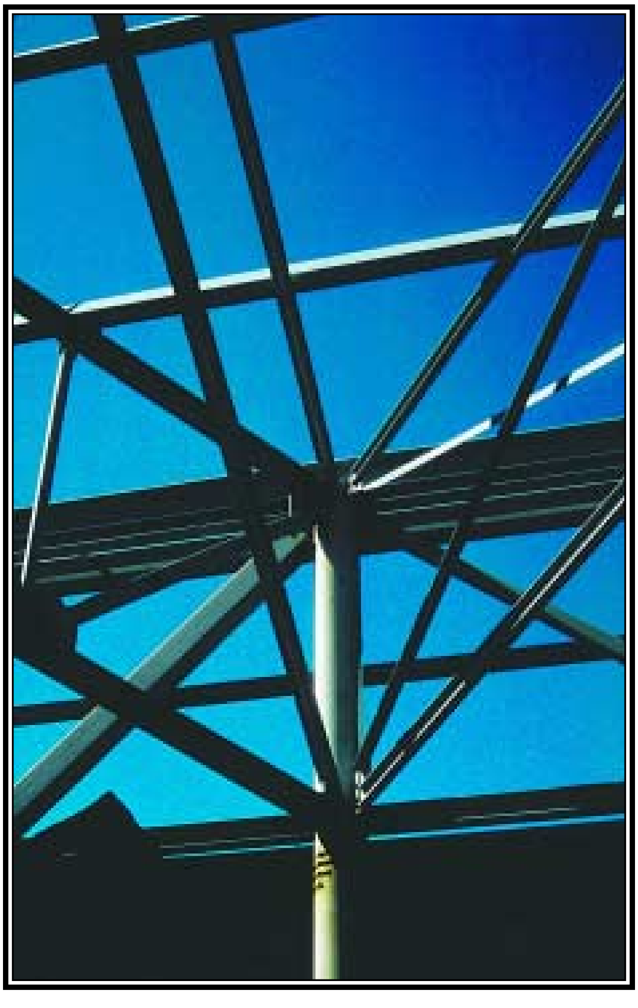
The tubular steel purlins were placed on top of the trusses, at a 45-degree angle and work on the roofing panel proceeded.

Trusses T2A thru T5A were being fabricated while the remaining part of the roof was erected. Though their erection could have immediately followed the erection of trusses T2 thru T5, the contractor chose to install them at a later date to ease the pressure on the fabrication shop until approval of the door framing shop drawings by SEA. This was feasible since trusses T2A-T5A cantilever out from trusses T2-T5. Continuity at negative moments of the cantilever can be provided by detailing the connection at this particular location. After completing coordination with the door manufacturer, the fabrication of trusses T2A-T5A proceeded. Their erection followed in a similar way to trusses T2 thru T5. Attachment of the different components of the structure supporting the door was completed without problem.

Connections

The geometry of the structure required the framing of complex connections at different angles and elevations in space. The location of major connections was planned during the design phase with the bolting or welding requirements clearly indicated. Other connections were left to the contractor to coordinate with his construction means and methods. SEA reviewed and checked all the details proposed by the contractor as part of the shop drawing process.

To connect the different members of the trusses, shop and field-welding were used extensively. At the connecting points of trusses T2-T2A thru T5-T5A, complete penetration groove welds were used extensively to create continuity between the



Pictured are connections at a circular column.

upper and lower chords. Small variations less than ⅛-inch were easily accommodated by groove welding techniques. The seat provided on top of truss T1 for each truss was similar to the seat of a standard steel joist. A plate welded to the top flange of truss T1 upper chord is detailed to accommodate the intersecting slopes in two directions and to allow the temporary placement of the different trusses until continuity by groove welding is established.

The circular columns, infilled with concrete, were easily adaptable to the configuration of the different gusset plates. Machine groove welding was used successfully with no signs of local distortion at the flanges of the built-up columns made of 2-W36x232. Ultra-sonic testing on all groove welds was performed by an AWS certified testing agency.

The tubular steel purlins had their webs welded at the seat location over the trusses. The angular rotation of these purlins is the result of the two slopes in two perpendicular directions. This was feasible because the bottom flange coincided with the upper surface of the trusses.

Bolting was confined to simpler connections such as the structural members tying the different trusses together to make the diaphragm action or the structure supporting the main door of the hangar.

The trusses were modeled with the STAAD-III structural software package. Load combinations including snow drifts and winds applied in different directions allowed a better understanding of the worst loading condition on the different members. Vertical deflections and lateral displacements were analyzed and limited by varying and increasing the stiffness of the structure.

The complex structure was successfully built and completed in October, 1995 within the parameters set by the New York Air National Guard. Steel has proven to be a flexible material for space structures with complex geometry. Substantial short-term and long-term savings have been achieved by molding the structure to its function. The new fabric hanging door fits the needs of the client by allowing great flexibility in the use of space and energy efficiency. Creative problem solving and sound engineering coupled with sophisticated computer analysis led to an economical and functional building solution. Teamwork between client, engineer, architect, and contractor was the key in meeting the objectives of the New York Air National Guard.

Charles Sacre, P.E., is the Chief Structural Engineer at SEA Consultants, Inc. of Cambridge MA. Previously, he has worked on projects such as Boston's Central Artery/Tunnel Project and the Terminal E Renovation at Logan Airport. He is currently managing bridge projects for the Massachusetts Highway Department and is the Lead Structural Engineer on the renovation and retrofitting of historic Union Station in Worcester, MA.