SKYDOME ROOF ASSEMBLY DESIGN

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The Toronto Skydome is the first major sports stadium constructed with a fully retractable roof. Made up of four separate part-domes and parabolic arches, the roof covers eight acres. The panels are conventional rigid, stiff structures of hollow tubular steel members and steel deck supporting the roof assembly. It includes: acoustic insulation, vapor retarder, mechanically secured thermal insulation and a reinforced polyvinyl chloride membrane secured by lineal fixation elements, placed over the top of the assembly.

The building was designed to resist extreme loads, exceeding current Canada Building Code Standards. The roof was evaluated to resist hurricane force winds. Design uplift forces were the equivalent of the 300 year return period for the city of Toronto. The ability of both the membrane and its fixation to resist extensive dynamic wind was studied using full scale simulation.

With almost half a million fasteners securing the assembly, thermal bridging effects were a great concern. Extreme conditions were tested and building operating guidelines established accordingly.

This paper reviews assembly design and reports results of wind and thermal tests.

KEYWORDS

Dynamic wind design, mechanically fastened assembly, pull-out testing, Toronto Skydome.

INTRODUCTION

The Toronto Skydome (Figure 1) is a fully enclosed 60,000 seat stadium covered by an eight acre roof. The roof is strong enough to sustain a major impact such as a crash by a small aircraft from the adjacent air field in one area without collapsing the structure, it will withstand constant hurricane force winds, and support the cumulative load equivalent of five years of snowfall.[1] The roof rises to 92m above the playing field. Of the roof's 6808 metric tons, 5557 metric tons are retractable, leaving 91 percent of the seats and the entire field fully exposed when open (Figure 2).

The design concept[2] is based on the telescoping and nesting of shell elements about a circular stadium base. It consists of part domes and curved shells moving along a combination of circular and straight tracks. Panel 1 moves along a circular track to stack on the stationary Panel 4. Panels 2 and 3 move along linear tracks to stack above 4 and 1 (Figures 3 and 4). Thin roof sections without horizontal ties are supported on tubular steel framed, parabolic, discreetly arched, bogie mounted, secondary framed panels.

ROOF ASSEMBLY

The roof sections (Figure 5) consist of:

■ Acoustic steel deck—D200 (200mm) profile in 22 gauge, 20 gauge and 28 gauge steel, and D150 (150mm) profile in 18 gauge steel, with 3mm diameter perforations, staggered 10mm o.c. in the vertical members.

■ Underside acoustic insulation—38mm of 28.8 kg/m³ fibrous glass insulation with a nylon scrim reinforced microlith glass fabric facer. It is adhered to the underside of the deck and secured with metal bands.

■ Topside acoustical insulation—75mm of 17.6 kg/m³ fibrous glass insulation.

■ Vapor retarder—10 mil, low density polyethylene, with all joints sealed with butyl tape.

■ Thermal insulation—Trilaminate (foil/kraft/foil) faced polyisocyanurate insulation, 44.5mm thick, stabilized thermal resistance of 2.09 R.S.I. The 1220mm by 2440mm insulation panels are secured with six #11 fasteners and 75mm stress plates.

■ Membrane—1.2mm woven polyester reinforced white PVC membrane. The membrane is secured by 14 gauge steel, U-shaped, roll-formed lineal fixation bars placed above the sheet and sealed with coverstrips. Fasteners are #11 carbon steel screws with buttress threads and a corrosion resistant coating substantially exceeding the requirements of Factory Mutual specification #4470.

Every seventh fixation bar is replaced by a water diverter (Figure 6). These diverters insure rainfall run-off is evenly distributed around the entire stadium base. The bar and cover strip assembly was chosen for many reasons including:

• proven performance worldwide.

• aesthetic qualities.

• superior wind uplift resistance.

The lineal fixation system assures balanced wind loads along the bar and distributes stresses evenly to the fasteners.[3] This paper will primarily address the wind resistance of the roofing waterproofing assembly. This area was vitally important to the design process, as the design competition called for an assembly that could resist a uniform wind loading of 3.6 KN/m² (75 lbs/ft²). This pressure is equivalent to the 300 year return period wind for the city of Toronto. According to the National Building Code Supplement, at this pressure localized winds of approximately 268km/hr (167 mph) may be experienced.

STATIC DESIGN LOAD

The membrane fixation was evaluated according to a Limit States Design as outlined in the National Building Code Canada, 1985[4]:

$$\phi \; R \; \blacktriangleright \; \alpha Q \qquad\qquad (1)$$

where ϕ = resistance factor[5]

= 0.67

R = resistance[5]

= 0.85 • R_t

where R_t = x_3 • n

x_3 = the average of the three lowest pull-out values tested[5] [KN]

n = number of fasteners per fixation point

α = load factor[4]

= 1.5

Q = wind uplift at a fixation point [KN/point]

= $\dfrac{db \; X \; P}{N}$

where db = distance between fixation bars [m]

P = uplift pressure [KN/m²]

N = number of fixation points per meter.

To provide maximum load distribution, all fixation bars were run perpendicular to the steel deck. To minimize bending moments on the fasteners, they were only secured to the top flanges of the deck. Therefore, fixation point spacing is equal to the flute spacing, 200mm for D200 profile, 150mm for D150 profile. This allowed 5 and 6.6 fixation points (N) per meter, respectively. A maximum bar spacing of 1.8m (db) was evaluated to accommodate the membrane's ability to resist the wind loads and to allow sufficient fasteners. Despite the irregular layout of the four different deck types, a single bar spacing was specified over most of the roof surface to insure a uniform appearance and to simplify the application.

As highlighted earlier, the uniform design wind load specified was 3.6 KN/m². This included a positive internal pressure allowance of 0.3 KN/m². It was felt that with the polyethylene vapor retarder and the mechanically secured insulation, the effect of the internal pressure on the membrane underside would be negligible. Therefore, the actual assembly was designed to a 3.3 KN/m² uplift force.

The determination of the allowable fastener load was crucial to the long term performance of the assembly. During routine pull-out testing from deck samples, it was found that results were consistently below those quoted in the manufacturer's literature.[6] In following up this matter with the supplier, a number of important issues became evident:

• Literature values were the mean of 25 tests, minus the high and low values.

• Pull out tests were carried out with screws fastened into calibrated steel plate.

• The steel had a Rockwell hardness (B scale) in the 71-72 range.

The suppliers's results may not accurately reflect field conditions. The deck for this project was specified according to Canadian Sheet Steel Building Institute Standard 101M-84, Grade B. This is a typical quality of deck, and it has a hardness in the 61-63 Rb range. It was decided that new data should be generated using deck samples taken from the site. A full cross-section of flute was used instead of the simple plate configuration normally employed.[7] Data from the supplier's literature and the test program are outlined in Table 1. Also shown are mean results of the three lowest values, as called for in CAN3-S136-M84. Subsequently, over 200 pull-out tests were performed in the field on the panels.[8] These results are also shown in Table 1. Both sets of test data show both laboratory and in-situ results below literature values at the lowest gauges! The differences between the in-situ and laboratory results have not been fully analyzed. The difference in test methodologies is certainly a factor. Laboratory testing was done on a Tinius Olsen Tensile Tester at a crosshead speed of 5mm/min. In the field, a manual apparatus was used. The design was based entirely on the generally more conservative laboratory results.

Using all the above detailed information, it was found that the only way to meet the requirements of the Limit States Design for the D200 profiles was to use two fasteners per flute. It was assumed that the two fasteners per fixation would provide double the pull-out resistance of a single fastener. This was confirmed by the in-situ testing.[8] Double fixing yielded results ranging from a minimum of 1.97 times the single pullout for the #11 fastener to greater than two times, with the overall average greater than 2.

The results of the Limit States Design are summarized in Table 2.

As can been seen from the table, the requirements were met for all deck configurations using double fixation in the D200 profiles and single fixation in the D150.

DYNAMIC LOADING ON THE MEMBRANE

The Limit States Design reflects a static, peak load analysis and addresses only the membrane attachment. The effect of cyclic, dynamic loading on the membrane was also addressed during the design stage.

Extensive wind tunnel testing was performed on various scaled models of the building. Of particular interest were tests conducted on a 1:500 scale model, with the roof in a closed position, and all surrounding buildings within a 600m radius modelled.[9] Wind loads were obtained by combining the results of the tunnel tests with a statistical analysis of wind readings from three Toronto area airports. On the basis of these tests, it was recommended that evaluation of the dynamic behavior of the assembly be based on the 100 year return wind. The measured pressures are shown in Figure 7. Once again, these results include an internal pressure allowance of 0.3 KPa, which for our analysis was deducted from the overall load in determining the force acting upon the membrane.

Under loading, the loose membrane between the fixation bars may billow, as illustrated in Figure 8. Providing the tensile stress within the membrane does not exceed the sheet's elastic limit, the membrane will always return to its original position when the load dissipates. It will not permanently deform or stretch.

The membrane's elastic limit was estimated to be between 2 and 3.5 percent strain, by taking the first deviation from linearity of the material's stress strain curve (Figure 9). Samples were then stressed to predefined strain levels y%, between 2 and 3.5 percent, using new samples for each strain level. The samples were stressed cyclically between 0 and y% strain. The elastic limit of the membrane is taken as the

strain level for which there is no decrease in stress over numerous, typically 200, cycles. For the 1.2mm polyester reinforced membrane used on the Skydome, in the cross-direction this value was 3 percent strain and 4.1 KN/m stress.

Within its elastic range, the tensile stress on the membrane is defined as[10]

$$\sigma = \frac{\sigma_e}{\epsilon_e} \cdot \frac{8 \, f^2}{3db^2} \tag{1}$$

Where σ = membrane stress

σ_e = membrane stress at its elastic limit

= 4.1 KN/m

ϵ_e = membrane strain at its elastic limit

= 3 percent

f = height of billow [m]

As a function of pressure (p), it can be defined as

$$\sigma = \frac{p.db^2}{8 \, f} \text{ or } f = \frac{p.db^2}{8 \, \sigma} \tag{2}$$

Inserting (2) into (1) gives the following relationship.

$$\sigma = \frac{\sigma_e}{\epsilon_e} \cdot \frac{8}{3} \cdot \frac{1}{db^2} \times \left(\frac{p.db^2}{8}\right)^2 \tag{3}$$

At the membrane's elastic limit, $\sigma = \sigma_e = 4.1$ KN/m.

$$\sigma = 1.79 \sqrt[3]{p^2 \cdot db^2} \tag{4}$$

For a 1.8m bar spacing, it was determined that the maximum uplift pressure the membrane could resist without deformation, (Pmax) is 1.9 KN/m². As can been seen in Figure 7, even discounting for the 0.3 KPa internal pressure, there are a number of areas along the leading edges of panels 2 and 3 where the 100 year wind exceeds this value. In these areas, an intermediate bar was specified, dropping the bar spacing to less than 0.9m on-center. This insures the membrane stays within its elastic limit and will not deform permanently under the 100 year loading.

"Overlaying" the 100 year wind pressures over the deck sheet layout, fastener safety factors were evaluated for each area.

$$S = \frac{F}{L} \tag{4}$$

where S = safety factor

F = pull-out strength per fixation point [KN/point]

= n • x$_s$

L = Design load per point [KN/point]

= $\frac{db \cdot Pm}{N}$

Where Pm = Pt − Pi [KN/m²]

Pt = total pressure (Figure 7)

Pi = internal pressure allowance 0.3 KN/m²

Table 3 shows the minimum fastener safety factors evaluated for the 100 year return wind for each deck configuration for panel 3. The results are typical of all four panels. The very high safety factors are a direct result of the extremely demanding requirements of the Limit States Analysis,

which was based on the uniform 300 year return wind load (3.6 KN/m²). An attempt was made to keep bar and fastener spacings uniform which resulted in the wide range of safety factors.

DYNAMIC TESTING

The designed assembly was then put to the test.[12] Kramer and Gerhardt have developed a full scale, wind loading fatigue test.[11] Complete roof sections are placed on a 6m x 1.5m x 0.75m test rig. The entire assembly is then covered by an airtight, air containment vessel. By means of a fan connected to the vessel, suction is exerted on the assembly. The magnitude and duration of the load is controlled by a microcomputer via a pneumatically activated governor valve. Traditional wind uplift test methodologies test only the resistance to a peak load, statically. This assembly allows the complete spectrum of wind load amplitude to be tested dynamically. Of particular importance are the low amplitude, high frequency loads, which effectively vibrate the roof assembly. According to Kramer and Gerhardt, this action leads to fastener back-out and ultimately failure in some mechanically fastened assemblies.[11]

It was decided to model the worse case scenario.[12] A test panel was constructed per Figure 5, without the acoustic insulations, using 22 gauge deck. The peak load was taken as the maximum 100 year load identified on the stadium, 3.0 KN/m², found along the south-edge of Panel 2. For the test, the internal pressure allowance was not subtracted (i.e., it was assumed the entire load would reach the membrane). The Skydome consultants working the Kramer and Gerhardt evaluated the wind profile shown in Table 4. Each cycle was preceded by one hour of high frequency, low intensity (100 N/m²) load fluctuations according to Table 5. The complete series of loadings listed, including the high frequency phase, represents the equivalent of 100 years of wind loading that could be exerted on the Skydome roof, and was considered a cycle. In an attempt to identify any possible weaknesses in the system, the same sample was subjected to five complete cycles. Therefore, the sample was subjected to five times 100 years of simulated wind loading. Although some membrane flutter was observed during testing, there was no damage to either the membrane or fixation elements. The result fully supports the design calculations, and the roof was constructed as designed.

THERMAL BRIDGING EFFECTS

Just under half a million fasteners perforate the steel deck, securing the insulation, fixation bars and diverters. The 1 percent winter design temperature for the City of Toronto is −20°C. It was estimated that with a large event taking place in the building, while the outside ambient air was at −20°C, the underside of the roof, with the seating air supply fans functioning would be 30°C and a relative humidity of 30 percent, (dew point T = 10.5°C). There was an obvious concern that with such a large thermal gradient across the roof assembly, the fasteners would be thermal bridges and there would be condensation at the fastener tips. The potential for condensation at fasteners in similar systems has been documented.[3] However, the presence of both acoustic insulations in the assembly rendered previous studies useless. It was expected that the underside insulation would shield the fastener tips from the building warmth,

keeping them cooler. Despite the thermal breaks in the diverter detail, their effect on fastener condensation was also a concern.

A series of thermal tests were conducted to study these issues.[13] Two, 1.9m by 1.9m panels were prepared, one roof section with a rain diverter, the other with a fixation bar. Thermocouples were installed at pertinent locations within the samples. 150mm of rigid insulation were used to insulate the perimeter of the sample. A dry ice cooled chamber was placed over the sample until steady state conditions were achieved. The chamber was then removed, and the panel allowed to warm up to room temperature. The procedure was carried out on both panels. The data generated by the thermocouples was used to evaluate a temperature index:

$$\text{Temperature Index} = \frac{T_{screw} - T_{membrane}}{T_{inside} - T_{membrane}}$$

$T_{membrane}$ was taken as the ambient outdoor temperature.

Based on the temperature data, indices were calculated and are shown in Table 6. For the design interior and exterior conditions, estimated temperatures for the various fasteners at the deck level were evaluated (Table 7). It appears the insulation and fixation bar fasteners will be much cooler than anticipated from 'non-acoustically-insulated' experience. The insulation has an appreciable impact. As can be seen at the worse case design conditions, the diverter screws could potentially be subjected to condensation. The large metal surfaces of the diverters are acting as fins, cooling the fasteners attached to them remarkably, relative to the insulation and fixation bar fasteners. This is particularly striking since, unlike the latter two, the diverter fasteners do not span the entire thermal gradient.

Loss of heat to a clear night sky could decrease the membrane temperature by as much as 10°C below the air temperature, further increasing the potential for condensation.

The architect and the owner decided that in light of the low likelihood of these conditions occurring simultaneously, they would not modify the assembly. Instead they have proposed an active control strategy. The ventilation system would be operated to maintain interior temperatures above the critical values. This was done successfully during the first full winter of operation.

CONCLUSION

The roof has gone through one complete winter cycle and has performed as expected. To date, interior conditions have been controlled such that the critical conditions for fastener condensation have not been encountered.

The fastener pull-out value issue has not been fully explored and merits further research.

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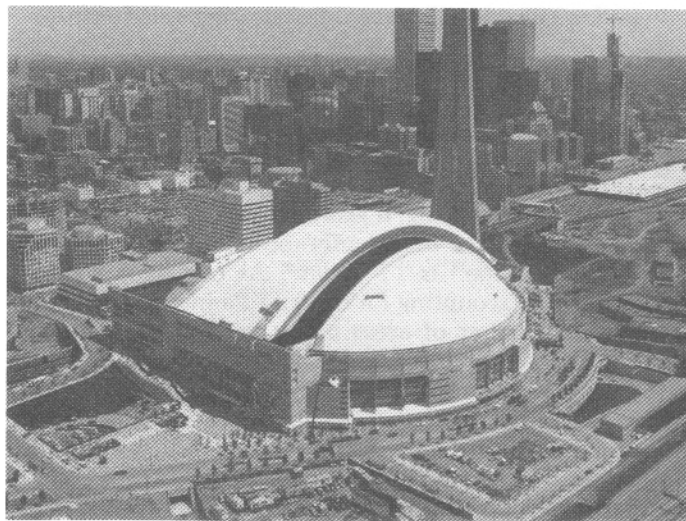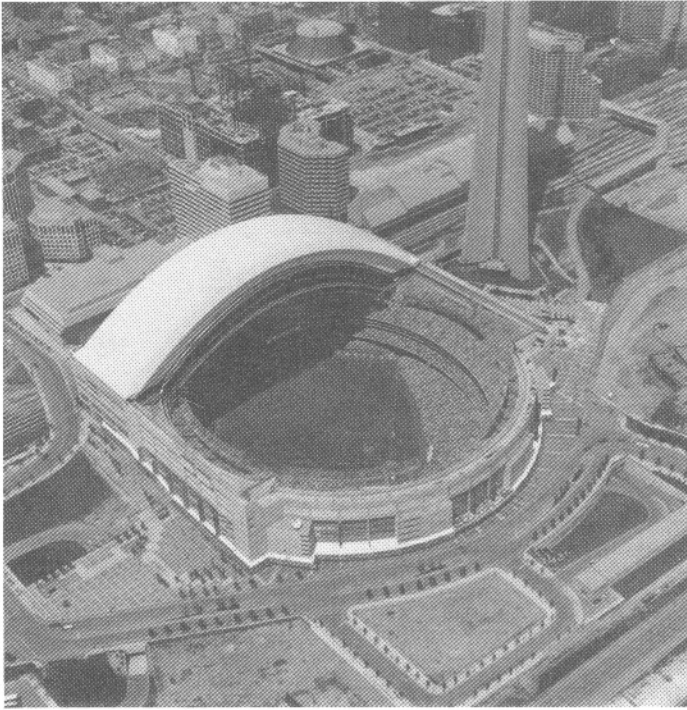
Figure 1   Toronto Skydome, roof in closed position.

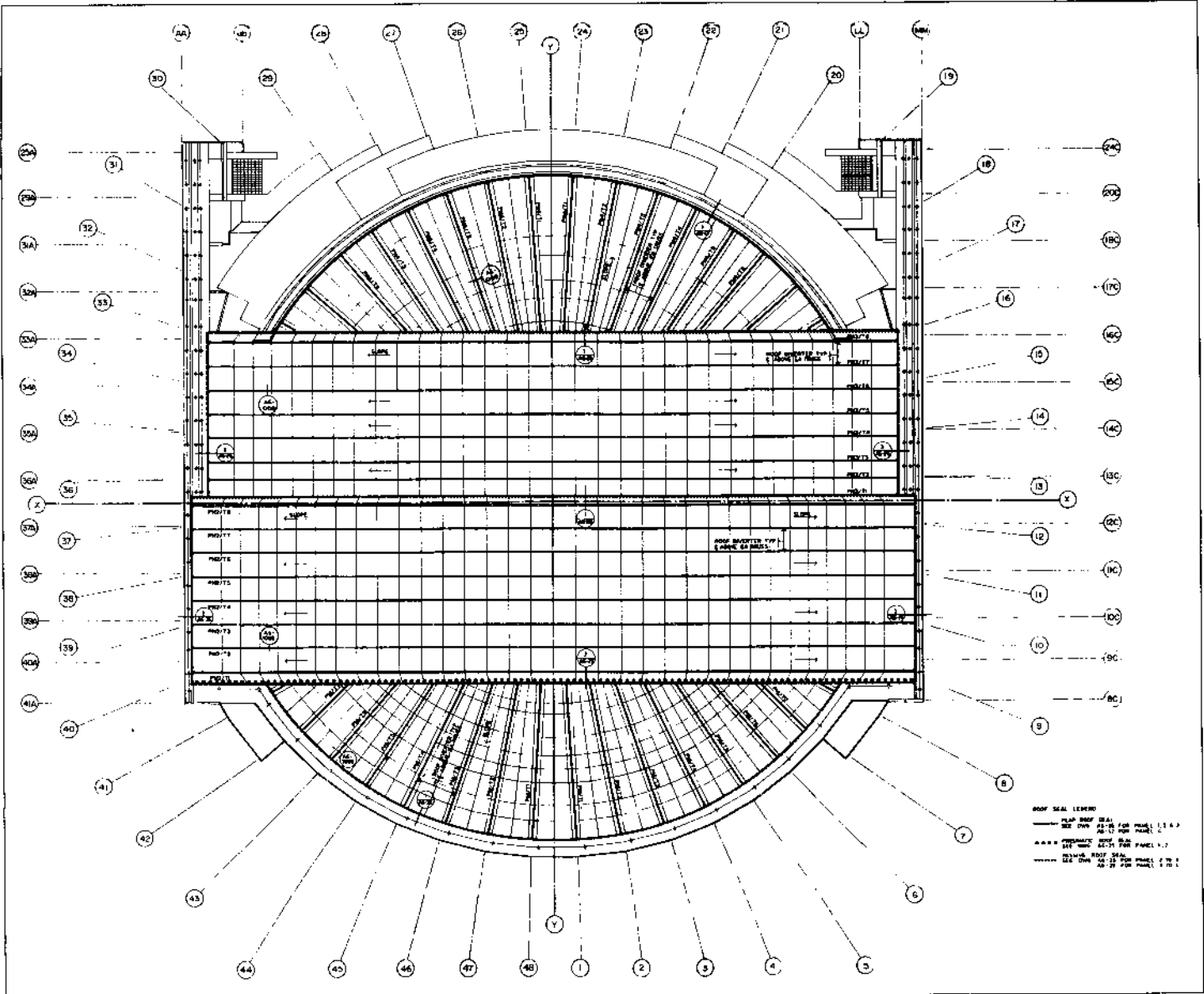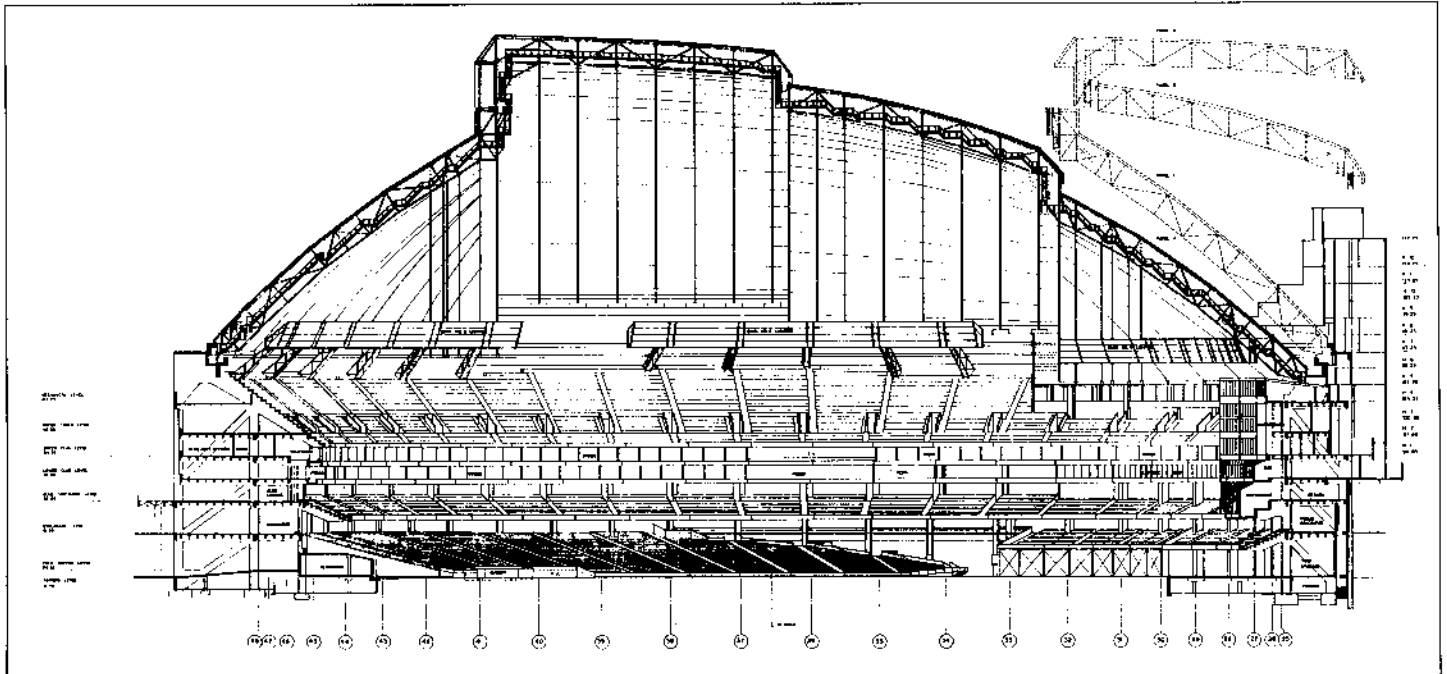*Figure 2*   *Toronto Skydome, roof in open position.*

Figure 3 Roof plan.
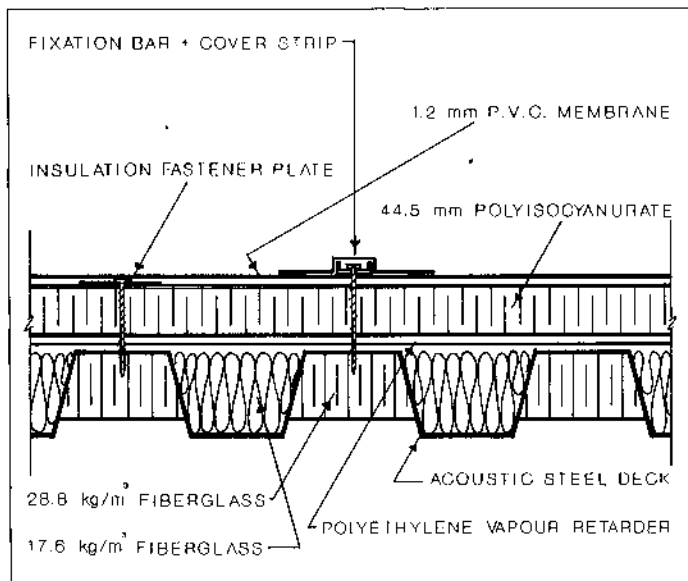
Figure 4 Elevation.

FIXATION BAR + COVER STRIP

1.2 mm P.V.C. MEMBRANE

INSULATION FASTENER PLATE

44.5 mm POLYISOCYANURATE

ACOUSTIC STEEL DECK

28.8 kg/m³ FIBERGLASS

17.6 kg/m³ FIBERGLASS

POLYETHYLENE VAPOUR RETARDER

Figure 5 Skydome cross-section.

18 ga DIVERTOR

FULLY ADHERED P.V.C.

44.5 mm POLYISOCYANURATE

18 ga DIVERTOR BASE

POLYISOCYANURATE

17.6 kg/m³ FIBERGLASS
TOP FLUTE OF DECK

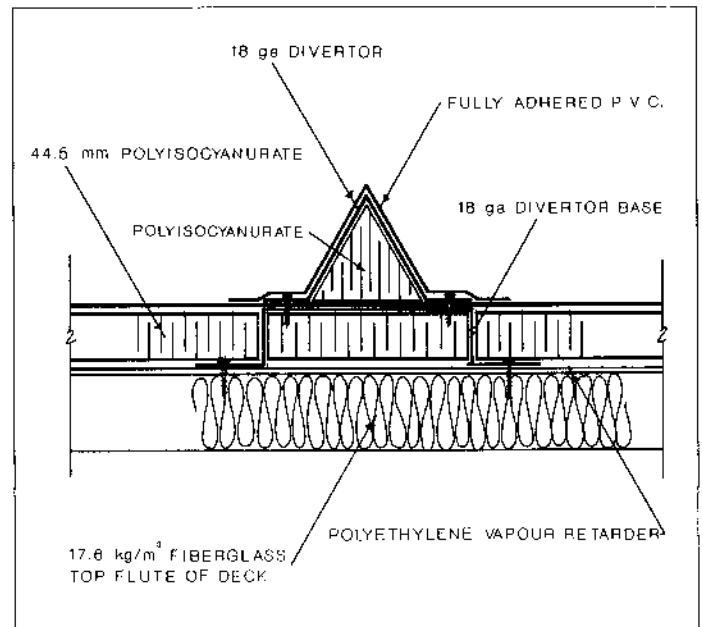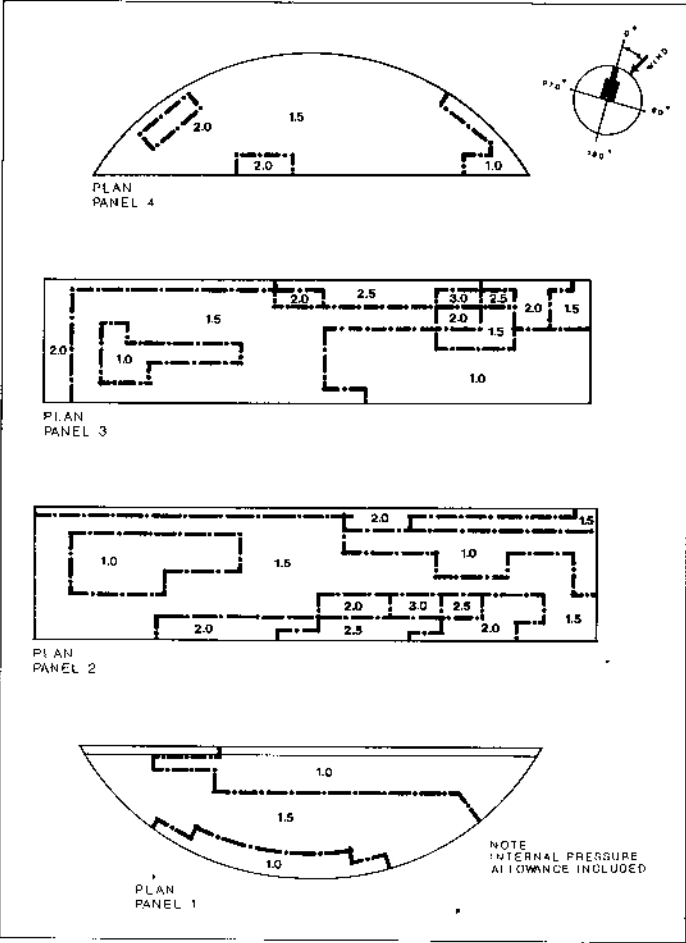POLYETHYLENE VAPOUR RETARDER

Figure 6 Water diverter.

Figure 7   100 Year Return Wind Loads
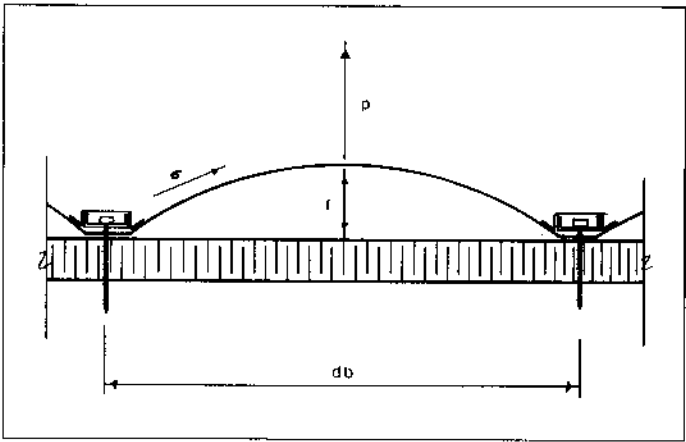
Figure 8   Membrane under load.
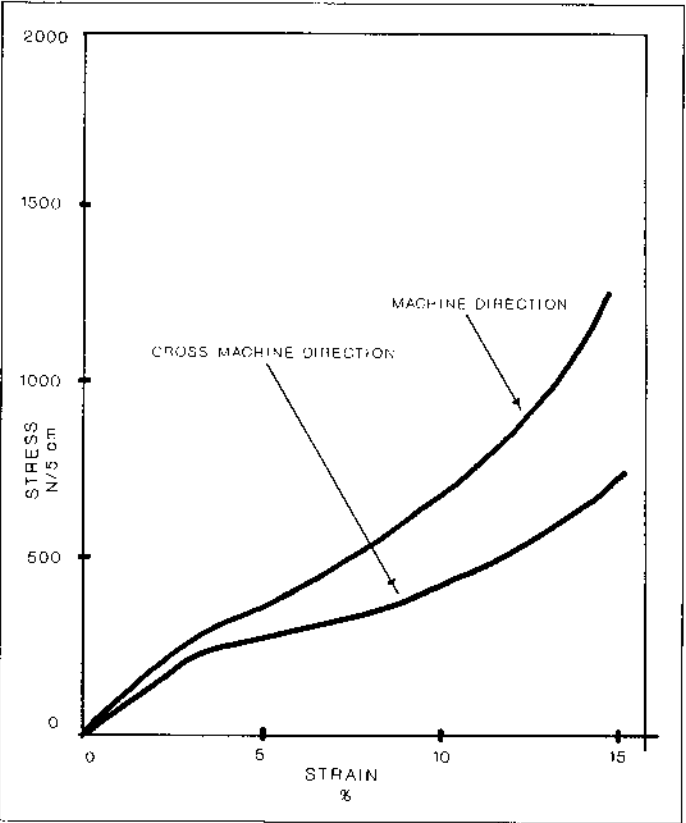
Figure 9   Membrane stress-strain curve.

	22ga.		20ga.		18ga.	
	x	xs (*)	x	xs (*)	x	xs (*)
Manufacturer's Literature	1.9	N/A	2.2	N/A	3.0	N/A
Laboratory Testing	1.8	1.5	2.1	2.1	3.0	2.5
In-Situ Testing	1.8	1.7	2.1	1.9	3.0	2.9
(*) Average of the three lowest sample values as per CAN3 S136- M84 (9.3.3.3)						

Table 1   Fastener pull-out values (KN).

Deck (ga)	N Fixation points/m	n Fasteners per point	xs KN	R KN/point	ϕ R KN/point	Q KN/point	α Q KN/point
22	5	2	1.5	2.55	1.7	1.15	1.7
20	5	2	2.1	3.57	2.4	1.15	1.7
18	5	2	2.5	4.25	2.8	1.15	1.7
18	6.6	1	2.5	2.12	1.4	0.87	1.3

Table 2   Limit States Design results.

Deck	Nominal Bar Spacing (mm)	Safety Factor
22ga, D200	1,800	5.0
18ga, D200	900	6.3
	1,800	8.4
18ga, D150	900	10.6
	1,800	5.5

Table 3   Panel 3 fastener safety factors.

Fastener Type/Location	Temperature (Degree Celsius)
Diverter	2
Insulation	18
Fixation Bar	21

Table 7   Estimated fastener temperatures at design conditions.

Magnitude of load (KN/m²)	% of maximum load	Number of loadings	Duration of load seconds
3.3	100	1	5.0
3.0	90	13	4.0
2.3	70	480	3.2
1.6	50	14000	2.9

Table 4   One-hundred year recurrence wind profile.

Cycle	Frequency Hz
1	15
2	20
3	25
4	15
5	25

Table 5   High frequency loadings.

Fastener Type/Location	Temperature Index
Deflector	0.44
Insulation	0.82
Fixation Bar	0.76

Table 6   Temperature index for various fastener types.