

## BC PLACE STADIUM

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# ROOF DEFLATION INCIDENT INVESTIGATION ENGINEER'S REPORT

12 October 2007

For: BC Pavilion Corporation  
777 Pacific Blvd.  
Vancouver, BC V6B 4Y8

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## INTRODUCTION

This report summarizes Geiger Engineers' investigation of the BC Place Stadium Roof deflation incident of 5 January 2007. This report focuses on the technical aspects of this event. Operational aspects of the event are addressed in reports prepared by the BC Place OH&S committee and the Investigation sub-committee. These reports taken together address the complete scope of the roof deflation incident investigation.

## INFORMATION SOURCES

This report is based on the information gained during visits to the site on Saturday 6 January and Friday 12 January by the author, Kris P. Hamilton P.E. and Quinn Hanks, PE, also with Geiger Engineers; during multiple phone and personal conversations since with BC Place staff and management. Other resources include:

1. Documents prepared by the BC Place Incident Investigation Team:
  - a. Analysis of the Rapid Increase in Building Pressure on Jan 05, 2007
  - b. Sequence of Events leading to the Controlled Deflation of the Roof Jan 5, 2007
2. Reports by two different agencies regarding tests on samples of roof fabric.
3. The remaining portion of the original project files and design calculations developed by Geiger-Berger Associates PC, and held in storage by Geiger Engineers.
4. Interviews with BC Place operating and other staff, in person and by telephone.

5. Interior operating pressure charts for the stadium, recorded by control room instruments.
6. Other charts and control room computer records.
7. Various news media and private party films and accounts.
8. Weather Data from Vancouver International Airport and other sources.
9. The BC Place Investigation and Joint OH&S Committees and their in-depth investigation of which this report is a part.

## BACKGROUND

BC Place Stadium opened in the summer of 1983 as the first domed stadium in Canada. It features a low-profile cable-restrained air-supported fabric roof. It was at the time of its construction and remains the world's largest air-supported roof.

The design and construction of the BC Place stadium were executed on a “fast-track” basis; construction of the foundations and the lower parts of the structure began before the design of the roof and the upper parts of the structure were completed. As is typical for the fast-track process, the roof contract was bid before the completion of design documents. A partial sequence of events is as follows:

Design Team Selection:	April 1980
Roof Design Development completed:	January 1981
Roof design Revised for cost-reductions	March 1981
Roof Construction Contract Award:	12 March 1981
Foundation Construction begins:	17 March 1981
Roof Inflation:	14 November 1982
Stadium Opening	19 June 1983

The final basic value of the installed roof assembly including cables, fabric, ring-beam cover, and all connectors, but not including the ring beam, ring beam support columns, or duties, was \$8,881,553 CAN.

Key design and construction team members were:

Architects and structural engineers:	Phillips-Barrett Architects & Engineers (now Univar, Ltd)
Roof Specialty Engineers:	Geiger-Berger Associates, P.C.
Roof Specialty Contractor:	Owens-Corning Fiberglas Ltd.

The fabric roof contracting division of OCF was merged a few years after the construction of BC Place with Birdair Inc. which did business as OC Birdair and later Birdair Inc.

A detailed discussion of the design and performance of the air-supported roof of BC Place Stadium is presented in Appendix D.

## OBSERVATIONS ON SITE

Geiger Engineers was informed of the roof deflation at about 3:00 PM on the afternoon of the 5<sup>th</sup> of January; at that time, we learned only that the west triangle panel had failed during a mild snow event and that there was a complete deflation. At the request of BC Place management

Geiger Engineers came to the stadium the morning of the 6<sup>th</sup> to begin an investigation on the engineering aspects of the deflation. We arrived at the site at about 10:00 AM, and left at about 4:00 PM that same day. The following is a summary of our observations from that first site visit:

1. The roof was fully deflated, and hung in the inverted, pre-inflation position. The lowest point of the roof was 6 to 7.5 meters above the floor; clearance between the deflated roof and the stands was greater. The speaker cluster, however, was resting on the floor.
2. The west triangle panel was substantially destroyed in the deflation incident and by the windstorms of the evening of the 5<sup>th</sup>. Appendix E figure E1 shows the locations of the tears and other observed damage to the triangle panel where the initial roof deflation hole developed. See Appendix A, Figures A1-2, A2-1, A2-2 for photos of the condition of the triangle panel on 6 January.
3. We made a detailed visual examination of each torn edge, and an intermittent sampling of the fabric surfaces, including both the main panel segment remaining partially attached to the roof structure and a smaller piece of fabric that was torn away from the main panel during deflation and later recovered from the parking lot (we will refer to this piece as “Fragment A”). We observed the manner of tearing and whether the glass fiber appeared sound or deteriorated. See photos in Appendix A, Figures A3 through A6.
4. We identified several areas of fabric near the edge of the panel that were possibly weakened, and one area near the center of the panel edge attached to the ring beam that was clearly deteriorated. This locally deteriorated area was torn in two directions; see Figure E1. This appears to be the point of initiation of the tear. There was also a large tear in the main panel parallel to the ring beam edge, perhaps 20 meters from the ring beam. This tear was not connected to any other part of the tear at the ring beam, and had not been reported to be part of the original failure scenario. It is likely that this tear occurred subsequent to the deflation from prolonged buffeting of the triangle in the windstorm of the 5<sup>th</sup> prior to our arrival the morning of the 6<sup>th</sup>. See Figure A1-2, note \*2 and Figure E1.
5. Joint covers of PTFE/glass fabric had been recently installed by heat-welding, over the fabric-to-cable connections and the fabric and neoprene connection at the ring beam. These covers were not part of the original design or construction. The welds showed inconsistent quality, varying from only slightly adhered, so that the weld could be easily separated by hand, to overheated fabric, where a “burned” appearance was visible, despite a subsequent year of weathering and bleaching of the fabric.
6. The main fabric clamps along the ring beam remained intact. However, many of the clamps holding the liner to the ring beam were torn off, as well as a number of the clamps along the cables. The clamp failure was typically a consequence of the bolts and washers pulling through the aluminum extrusions, indications of fabric membrane pulling at extreme angles to the clamp face.
7. The liner fabric pieces that remained attached to the cables were larger than the corresponding main roof fabric pieces.
8. The glass-fiber reinforced plastic cover over the ring beam and the attached neoprene connecting sheet were not damaged.
9. At the west triangle panel there was minimal snow accumulation observed in the ring beam.
10. Most, but not all, of the roof diamond panels retained some snow and/or water; a few of the rectangle panels contained similar ponds.
11. Four additional tears were noted in the diamond panels; I was told that these occurred

during the windstorm on the evening of the 5<sup>th</sup>, which carried on into the morning of the 6<sup>th</sup>. See Figure A1-1.

12. We also examined in detail the fragment of the west triangle panel that had been recovered from the parking lot. Areas of suspected fiber damage were noted along the edge of the fragment that had been clamped to the cable bounding one edge of the panel.

## SCENARIO OF FAILURE

The scenario proposed for the roof’s deflation is based on our on-site observations, examination of the torn fabric, conversations with BC Place staff, review of records, subsequent material test results, evidence from the investigation conducted by the BC Place Investigation Committee, as well as our understanding of the design, behavior, and performance of the of BC Place roof system. This scenario is discussed in detail in appendix B.

## WEATHER

Total precipitation on 5 January from early morning to noon was 17.6mm (172 Pa) in the form of snow and rain. The temperatures were just below freezing. Winds were light and steady from ENE. Appendix C presents the weather records for the relevant period prior to the roof deflation, and discusses the weather’s influence on the cause of the deflation.

## ROOF CABLE INSPECTION

During inspections of the roof on the 7<sup>th</sup> and 8<sup>th</sup>, apparent cracks in the speltered zinc of the cable end connectors at grid locations 2 and 53 was reported. (The cables are terminated in cast-steel end fittings by a plug of zinc. Speltering is the process whereby the molten zinc is poured into the conical “basket” of the socket in which the cable’s wires have been unwound). Subsequent close examination showed that these anomalies were superficial, and were part of the original fabrication of the connectors, and were not indicative of any damage. No further examination was performed.

## FABRIC TESTING

Results of tests on the west triangle panel fabric and a detailed discussion are presented in Appendix E. Undamaged fabric in the vicinity of the tear along the edge of the panel shows strip tensile strengths in the fill direction close to the material manufacturer’s originally published strengths for new fabric; tests in the warp direction could not be made. Significant degradation, 30 to 40%, is indicated at discrete points at the field welded seam where the fabric joint covers had recently been installed. Some loss of strength is also found at the factory made roped edges and cuffs.

The fabric tensile strength tests in the center of the panel are slightly equivocal; the test results are about 15% higher than the material manufacturer’s originally published values for new fabric. These tests indicate strength that would be normal for new fabric, but is surprisingly high for material that has been in service for over 24 years. This may simply indicate that the original strength was far higher than advertised.

## FINDINGS AND OBSERVATIONS

1. Failure Scenario:
  - a. The fabric failure that resulted in the roof being deflated was caused by the impact of a mass of water and slush and the wave it created in the fabric of the west triangle panel crashing into the ring beam. This began with the accumulation of snow in the center diamond panel region of the roof. This led to the accumulation of load in the valleys between the diamond panels and ultimately to complete inversion and ponding of at least a few diamond panels over the speaker cluster.
  - b. It is not clear, however, where or when this began. The internal pressure at the time that the problems were first observed inside the stadium was nominally 260 Pa, which had been maintained throughout the morning; absent snow or other applied loads this would result in a net upward pressure in the diamond panel region of 145 Pa and nominally 115 Pa over the speaker cluster. Beginning in the early morning the total accumulated precipitation by 12:00 noon was 17.6 mm, or 172 Pa. Most of the precipitation that fell on the center diamond panel region of the dome remained on the roof. See Appendix B for further discussion.
  - c. Photographs of the roof at 12:24 PM show that the center area of the roof was essentially flat, although tilted to the west because of the weight of the speaker cluster. The reported “bowl” or depression in the roof is not evident.
  - d. The same photographs do not show many inverted panels, even where the roof ventilators add weight to the center of the diamond panels. However, at least one diamond panel over the speaker cluster appears to be inverted. These inverted panel(s) had “ponded”. See Appendix D.
  - e. Nine minutes later at 12:33 PM, witnesses report that the speaker cluster was on “on the field”, the implication being that by this time the west end of the dome had descended at least 15m, which was the cluster’s trim height. From outside the western portion of the diamond panel region would have appeared concave or depressed, accounting for the reported “bowl”.
  - f. Whatever the prior extent of ponded panels, the depression of the roof at this time resulted in consolidation of the mass on the roof as it flowed to the depressed area over the cluster. In all likelihood a number of diamond panels west of center were inverted and filled with water and slush.
  - g. In response to the reports of the roof descending, internal pressure was increased and the roof ascended. However, this ultimately caused the accumulated mass of snow, slush, and water, which had been concentrated when the roof descended to spill out of the inverted panels and “slide” down the roof to the west. The resulting “cascade” created a traveling dimple-like wave in west triangle panel as the mass accelerated to the perimeter. Ultimately this mass and the wave it created in the fabric surface crashed into the hard edge of the ring beam, causing the fabric to tear. The tear propagated resulting in the failure of the triangle panel.
  - h. The fabric of the west triangle panel failed where it was weakest. However, the peak dynamic stress caused by the impact of the moving mass/wave may have been sufficient to fail new undamaged fabric. We have made approximate calculations with different sets of assumptions in an attempt to prepare upper and lower bounds for the stress on the triangle panel at the impact the mass/wave with the ring beam. The calculated upper bound stress is 140.0 N/mm (800 pli), and the lower bound is 35.0

N/mm (200pli). The upper bound stress is high enough that failure of undamaged fabric is at least somewhat likely, but failure of damaged fabric is certain.

## 2. Weather Conditions

- a. See Appendix C for weather summaries and additional comments.
- b. Total precipitation was 17.6mm (172 Pa). For a short period between 11:00 AM and noon, the precipitation rate was approximately 5 mm per hour (48 Pa/hr).
- c. Winds at the time of the failure were less than 20 kph and likely around 15 kph. Importantly, this light wind had been steady from the ENE since the advent of precipitation early in the morning.
- d. Weather conditions in the period leading up to the deflation were well below the design capacity of the structure under proper operations. Conditions were also well below what had previously been experienced by the structure, without damage.

## 3. Fabric and Fabric Condition

- a. See Appendix E for test results and for a detailed discussion of fabric strength.
- b. Failure occurred at the weakest portion of the fabric affected by the dynamic load of the cascading mass/wave. The strength of the material at the point of tear initiation had been compromised due to exposure of the fabric’s glass fibers. The tear initiation point contains fibers that are short and discolored, indicating long-term exposure the fibers to the weather. Such exposure was likely due by a scratch in or abrasion to the surface of the fabric, which removed a band of the protective PTFE coating. Outside of the initiation zone the fabric fibers are long and white, and the fabric has delaminated, indicating that the fabric had not been exposed to weather damage.
- c. Tests demonstrate that at least in some discrete points fabric adjacent to the tear was significantly degraded, with a reduction of strength of about 40% below nominal strength near the failure, or 30% below specified minimum strength. See Appendix E for a detailed discussion of sources of loss of strength.
- d. While it did not contribute to the fabric failure, tests also show that the fabric from the west triangular panel has lost some strength were it is clamped to the cables. The loss of strength appears to be developing at several locations adjacent to and within the clamps:
  - i. At the front edge of the clamps.
  - ii. Around the bolt holes in the fabric at the edge of the clamps.
  - iii. In the fabric within the clamp
  - iv. At the seam where the fabric cable covers were field attached to the main fabric panel.

## 4. Operations

- a. The stadium operations staff did not follow proper procedure, in that they did not promptly react to the snow accumulations by using any of several actions available to them. These would have included one or more of:
  - i. Increasing the ambient temperature of the stadium.

- ii. Increasing the internal pressure of the stadium.
- iii. Using the full snow melting system, circulating heated air directly between the outer and inner layers of fabric.
- iv. Using the ventilation system to circulate ambient interior air temperature at the stadium between the outer and inner layers of fabric.
- v. After ponds had formed and the roof had sagged, by increasing pressure only as required to maintain roof at a constant elevation until ponds could be cleared. However, it must be noted that this is quite difficult to accomplish as the situation is dynamic and changing; and quite possibly not achievable given the reaction time of the roof controls, particularly the pressure relief dampers. Ideally, the situation where ponds form and the roof has developed a significant depression should be avoided.

Any of these by themselves would have been sufficient to avoid the west triangle panel failure, if begun early enough. It is not within the scope of this investigation to identify the party or parties responsible for any given decision or lack thereof.

- b. The operators did not have sufficient visual or instrumental information available to them to permit an accurate judgment as to the roof condition, so that the initial change in shape was not detected.
- c. The building pressure should have been increased sooner, so that the rain and snow could not have collected to the extent that it did. Only 50mm of wet snow and 6mm of rain fell on the roof. If the pressure had been increased by 100 Pa to 360 Pa in response to the accumulating snow on the roof around 8:00 or 9:00, the situation could have been avoided. Because the load accumulated slowly over the early morning hours, the normal operation pressure of 250 Pa was overcome in the flat region of the roof and there was no means for the operators to discern the problem.
- d. Sometime just after 12:00 noon at least the western portion of the diamond panel region of the roof reached neutral “buoyancy”, where the internal pressure was equal to the total load in the region. This portion of the roof had become very soft, so that small changes in load resulted in large movements.
- e. By 12:31 PM the western diamond area of the roof over the cluster descended by at least 15 m, creating a depression in the roof surface. Diamond panels in this area over the speaker cluster were inverted with water, slush and snow. The roof descent and deformation caused the water and slush retained in the flat center diamond region of the roof to drain toward the depressed west end supporting the speaker cluster. The eastern central area of the roof that was thus relieved of some of its load then rose higher, increasing the flow and supplying more mass to the inverted diamond panels in the vicinity of the speaker cluster. In this manner mass was consolidated in the western diamond panels.
- f. The rapid increase in pressure in the stadium raised the roof. As the roof ascended and approached a more normal profile, water and slush retained in the west diamond region of the roof over the speaker cluster began to drain rapidly to the west. As the roof area was thus relieved of some of its load, it rose higher, increasing the spill out of the inverted panels. The resulting cascade effect was essentially unstoppable once begun. Any increase in internal pressure at that point would have caused the cascade to occur more rapidly.
- g. Nor is the cause of the failure over-pressurization of the roof. The internal pressure

records indicate this to be so. Our conclusions in this report vary from the preliminary report because of revised information on the calibration of the pressure gages. The only way in which the cascade could be stopped, once started, would be to very rapidly reduce pressure in the stadium. However, it is unlikely that the control systems would have reacted quickly enough to operator input to stop the cascade.

- h. The response of the roof to the operator’s instructions was not adequately monitored, nor was there any means to do so, so that the cascading effect of the water and slush was not observed by the operators.
- i. The control room staff obtained a weather report at 4:40 AM. During the course of the morning, there were several updates to the weather report (at 5:42 AM, 6:45 AM, and 11:00 AM) that indicated more snow than was predicted at 4:40. The record indicates that the 5:42 report was given to the control room staff at about 6:45, however, the staff was not aware of the 6:45 or 11:00 reports. This led to underestimating the level of response and vigilance required later in the morning.

## CAUSES OF FAILURE

As with any such failure, there are a number of incidences of inter-related events that contributed to the failure of the west triangle panel; these vary from primary causes to significant but indirect causes. In order of importance, starting from the most important, these include the following:

1. The control room operators were unable to observe the developing situation with the roof, and thus did not know until too late that action was required. However, the operators did not make full use of the tools available to them.
2. Workers on the stadium floor observed some oddities in the roof position 2 1/2 hours before the failure, but did not understand that it needed to be brought to the attention of supervisors. Had the control room operators adequate visual information about the roof, this input would not have been needed.
3. The control room staff was not trained in the detailed behavior of the roof with ponded water, and were thus unable to determine the best response to an emergency situation. This may be considered to be the ultimate cause, but as with all of the other issues identified above, it does not operate in isolation from the other issues.
4. The control room computer and dial packs were inadequate for the emergency response that was ultimately demanded of them. However, had the necessary actions been taken earlier, such a response would not have been required.
5. The mechanical room controls, motorized dampers, fans, and other roof support equipment were not capable of the rapid response needed. Again, had the response been started earlier, this would not have been an issue.
6. The fabric of the west triangle panel had been damaged by moisture, beginning at sometime in the past and worsening until the present. The degree of damage, however, would not have led to failure without the impact of the moving mass and fabric dimple-wave.
7. Although there was snow and wind to contend with, both were relatively mild, and proper operation would have avoided any problems.

## RECOMMENDATIONS – SYSTEMS AND EQUIPMENT

The following recommendations for improvements to the roof, the roof instrumentation and operating equipment, and the roof operations are based on the experiences of other facilities, and on the studies made of this facility and the roof deflation event.

1. The penultimate cause of the failure was the inability of the operators both to see the actual condition of the roof before taking action, and to see the response of the roof to that action as it occurred. The current situation of determining status from inferred data must be replaced with direct information. The direct information should include:
  - a. A direct reading of the roof elevation. This may be accomplished with any of several instruments that will gage the height of the roof above the floor. Systems available include:
    - i. water gauge
    - ii. laser target sighting
    - iii. radio wavelength distance measurement.

The first of these is the simplest, in that is not sensitive to orientation or floor occupancy, and it is direct. The other two require electronic tracking systems to remain on target. These systems may easily be used to monitor more than one point on the roof; however, we believe that a single measurement at the center of the roof will suffice.
  - b. An improved view of both the interior and the exterior of the roof. On the exterior, it will be necessary to mount cameras in a position that will show the condition at the highest points of the roof; i.e. at least one camera mounted on one of the high-rise buildings in the vicinity.
  - c. On the interior, there should be multiple cameras aimed at the underside of the roof, with a sufficient field of view to gain a full time view of the entire roof without needing to reposition the cameras. The effect should be such as to approximate the view that would be obtained by moving the control area to the press boxes.
  - d. Alternately, consideration may be given to separating the facility’s security functions from the roof and mechanical systems operation, and relocating the system control room to a location with a direct view of the roof, preferably at one of the upper levels.
  - e. Control equipment should be updated to prevent simultaneous engagement of multiple control programs. The system should permit manual control or automatic control with an override, but the use of the override should switch the system from automatic.
  - f. The control system will need to give the control room operators flexibility to govern the roof pressure and temperature manually.
  - g. Consider subscribing to a private weather service to help keep the staff better informed on weather events.
2. The operating staff should receive additional training in the behaviour of air-supported roofs structure under various loads and conditions. This training should include the following:
  - a. Visual instruction on the action of the roof structure in the event of ponding, the creation of ponds, stability and movement of the roof under various load conditions.
  - b. Instruction on the behaviour of the roof in response to various commands to the control system.
  - c. Regular refresher courses should be given.
  - d. Other facilities should be contacted regarding reactivation of the former stadium

operators group for trading information and experiences.

- e. Instruction on the potential damage that an impact of moving masses may cause to the fabric at the face of the ring beam.

### 3. Roof fabric material testing and inspection.

It is reasonable to assume that there are other areas of damaged fabric material in the roof. Moreover, deflation/inflation cycles are known to result in minor cuts and tears that require repair. While it is unlikely that a deflation will occur from the exact same sequence of events in the future, there is no question but that if there is such damage in other areas, the loss of strength will continue, and the likelihood of another failure for some cause in the weakened fabric will increase.

Consequently a program of inspection and testing of the roof fabric is recommended:

- a. The outer fabric at all cable clamp lines should be inspected for tearing or other damage, as pinching and tearing of the fabric adjacent to the clamp lines is common in deflation/inflation cycles.
- b. The fabric-to-cable clamping system should be visually inspected over the entire roof. Damage to the clamps is common in deflation/inflation cycles.
- c. Some inspection of fabric in the clamps should be made on a statistical basis to determine whether there is any noticeable long-term deterioration. This will require removing the added fabric covers, loosening a section of clamps and neoprene, and making a visual inspection of the fabric. This inspection should occur as soon as the weather permits having portions of the roof loosened for a day at a time. This may be done on a statistical basis, depending on the rate of defects found. A minimum rate of a randomly selected 10 to 15% of the clamp lines should be inspected; this number would increase as a function of the number and size of any defects found.
- d. Fabric connections at the ring beam should be unclamped and examined at a greater frequency, say 25 to 30%.
- e. Some representative samples of the roof fabric should taken and tested to ascertain the general state of the material and to determine how it has weathered.

## FABRIC REPLACEMENT

The inspection and testing program may indicate that the roof fabric is approaching the end of its service life. Clearly at some point the roof fabric will have deteriorated sufficiently to warrant replacement of the material. Such degradation is not expected to be uniform, requiring attention to any specific areas that show signs of degradation. Planning for replacement is appropriate so that the impact on the facility can be anticipated. Should the recommended testing and inspection program indicate that the material is in good condition, annual inspections are recommended to allow for anticipation of when replacement will be appropriate.

## SUMMARY

Failure Scenario: The scenario that lead to the failure and subsequent deflation can be summarized as a three step process:

1. The center area of the roof was slowly loaded over the morning from snow, and later rain, that was retained on the roof.

2. The roof flattened under the retained load and descended some 15m causing the retained load to concentrate over the speaker cluster, west of center in the diamond panel region of the roof.
3. The internal pressure was increased raising the roof to its design profile where it spilled the concentrated load down the west end of the roof. The resulting cascading mass and the wave it created in the fabric failed the west triangle panel when it collided with the ring beam.

This scenario would have best been prevented by:

1. Increasing the internal pressure to prevent the roof flattening and its subsequent descent.
2. Early in the morning, utilization the ventilation system to circulate warm “room” air between the liner and outer fabric or activation of roof snow-melt system, thereby precluding accumulation of retained load on the roof.
3. Once the roof had descended and there were ponded diamond panels, maintaining roof elevation where the ponds could be cleared slowly by draining them into the stadium, prior to raising the roof to its design profile.

#### **APPENDICES**

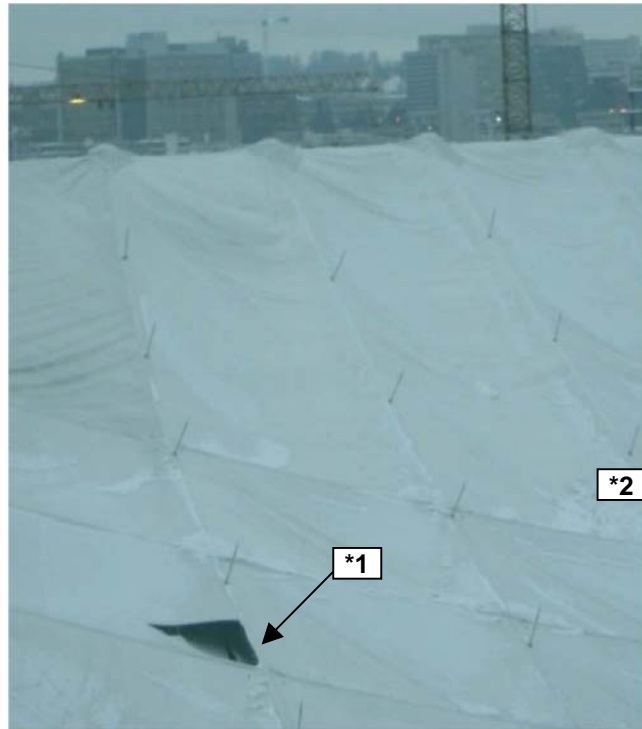
**Appendix A: “Photos of Roof Damage“**

**Appendix B: “Failure Scenario”**

**Appendix C: “Weather”**

**Appendix D: “Structural Design and Performance of Long-Span Low Profile Air Supported Roofs”**

**Appendix E: “Fabric Tests & Results“**



**Figure A1-1:** Looking across deflated roof, Jan 5, 2007

- \*1 – Secondary tear caused by motions of roof due to windstorm the night after the deflation.
- \*2 – Note the accumulated snow along bottom edge of each panel where it hits cable.



**Figure A1-2:** Damaged Triangle Panel, Jan 6, 2007.

- \*1 – Fabric delaminated along existing factory seam.
- \*2 – Panel partially separated here due to violent motions of panel during deflation and the high winds

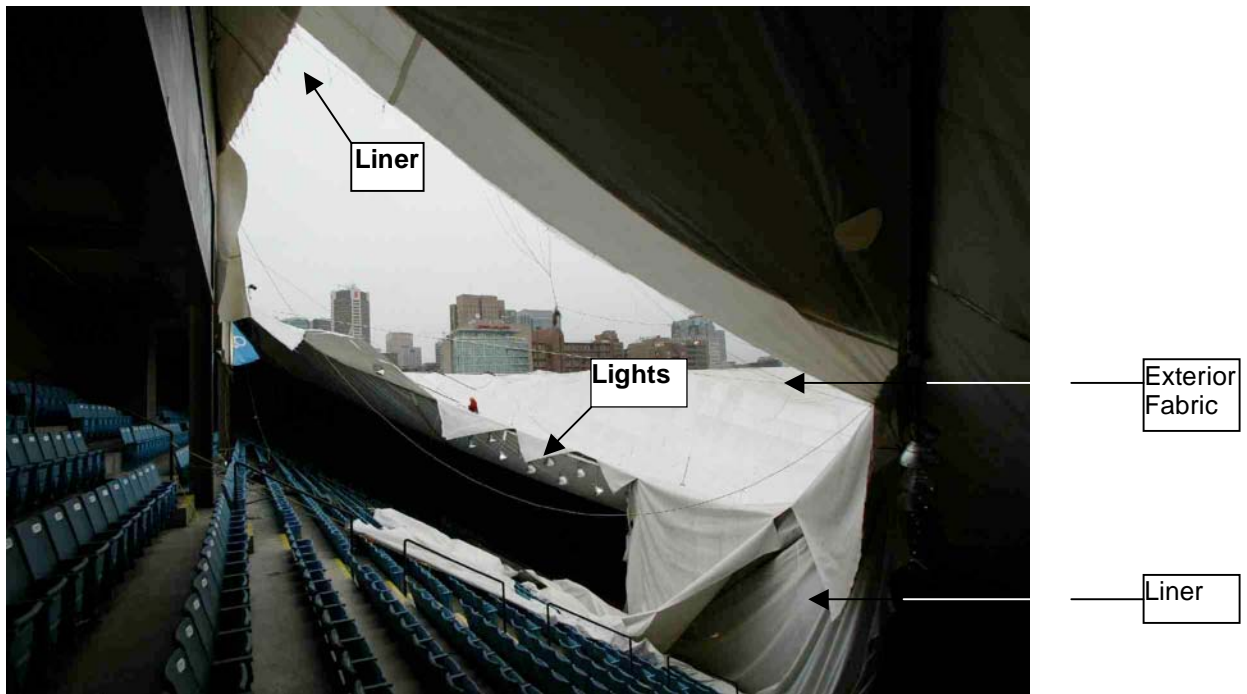


Figure A2-1: Damaged Panel View from Inside Looking West.

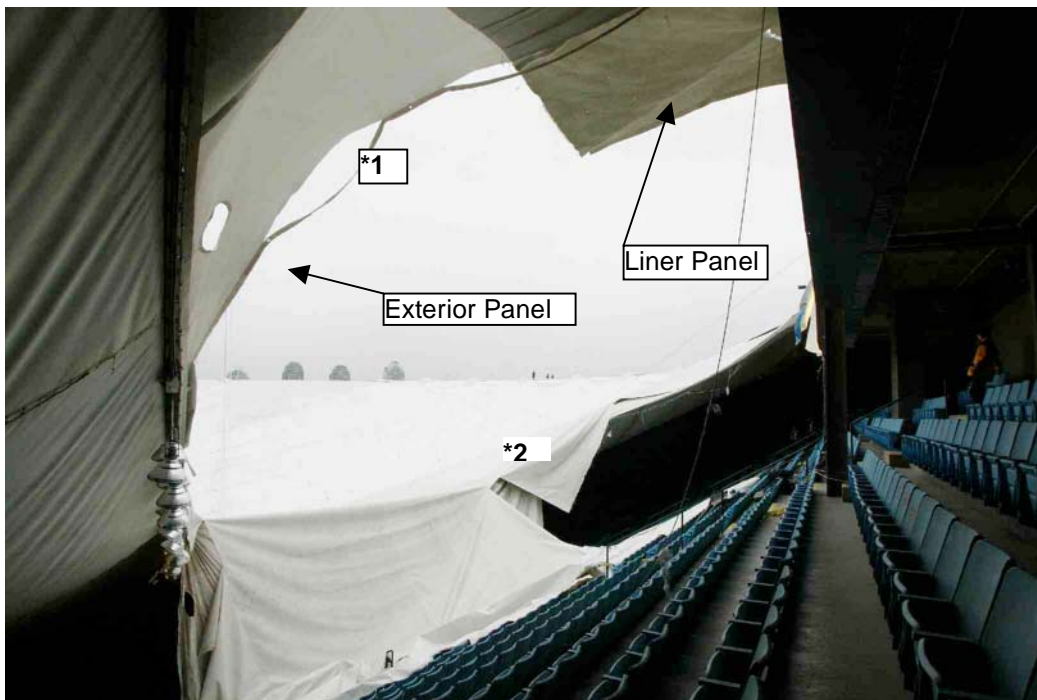


Figure A2-2: Damaged Panel View from Inside Looking East

\*1 – Segment of double fabric at longitudinal seam.

\*2 – Transverse tear across the fabric, away from seam because of double thickness and positive adhesion by heat sealing, the seam itself represents a stiffer and stronger load path. Under the shaking undergone by the panel it is reasonable to have such a separation.

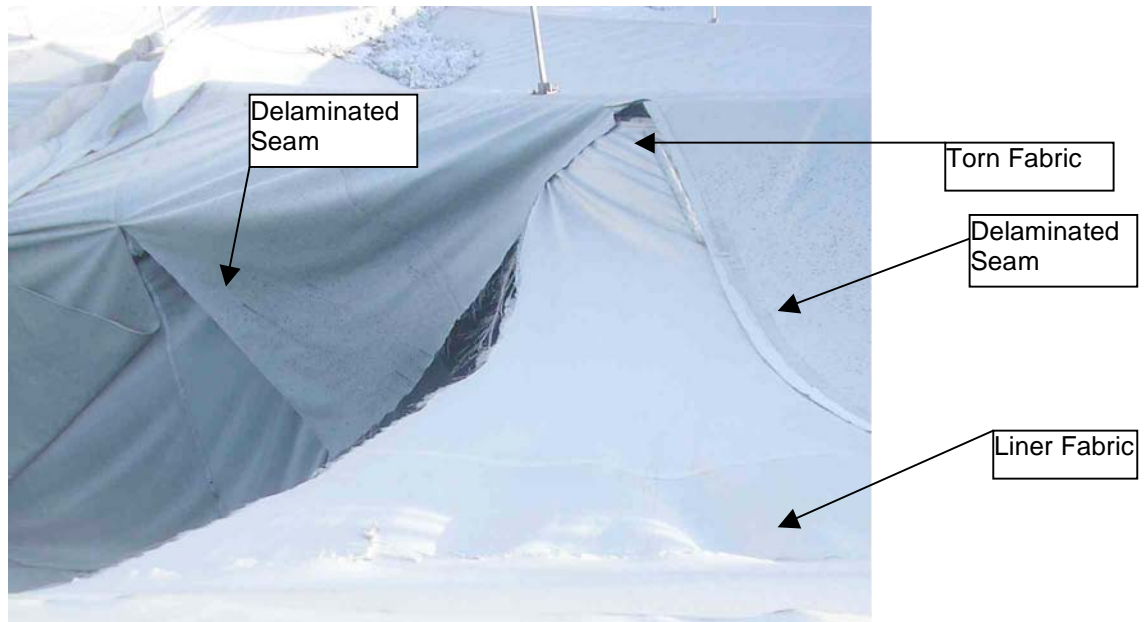
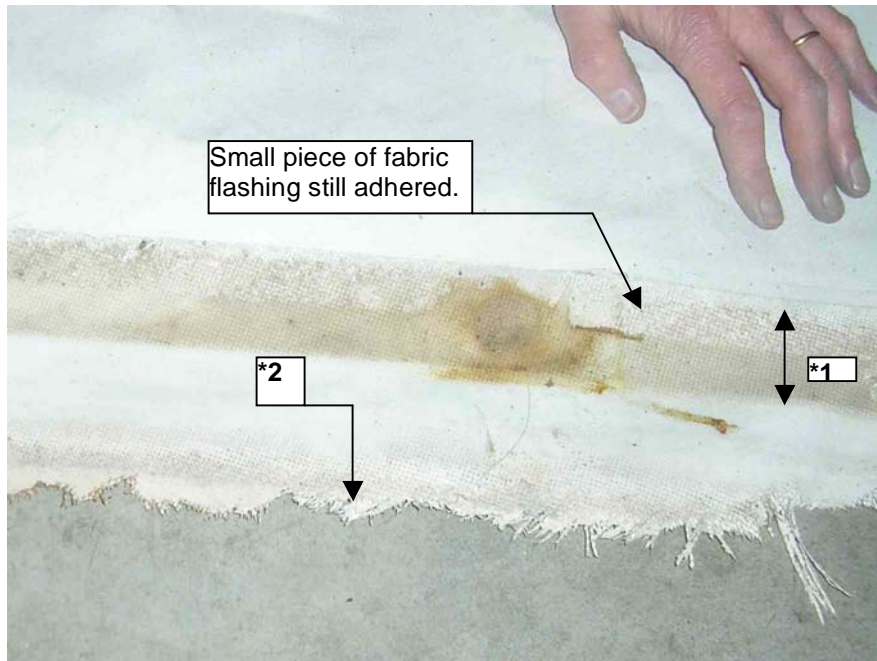


Figure A3-1



Figure A3-2

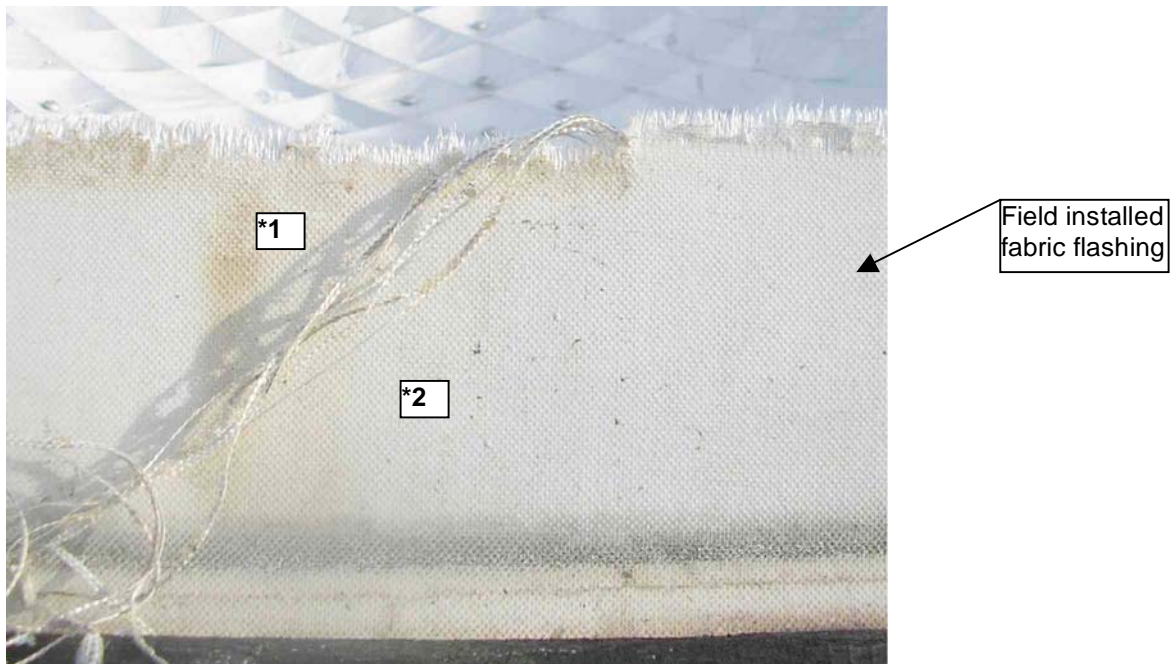
- \*1 – Torn fabric near ring beam. The long and clean fibers are characteristic of tears due to tension failure on undamaged fabric.
- \*2 – This tear has begun to progress up the center of a heat welded seam, which due to doubled fabric, is an unusual circumstance. The shorter, cleaner fibers visible in the tear are commonly associated with propagation due to tearing.



**Figure A4-1**

\*1 – Discolored area at attachment of flashing fabric to main fabric. Usually a darker color at a seam indicates higher temperatures used in making the seam.

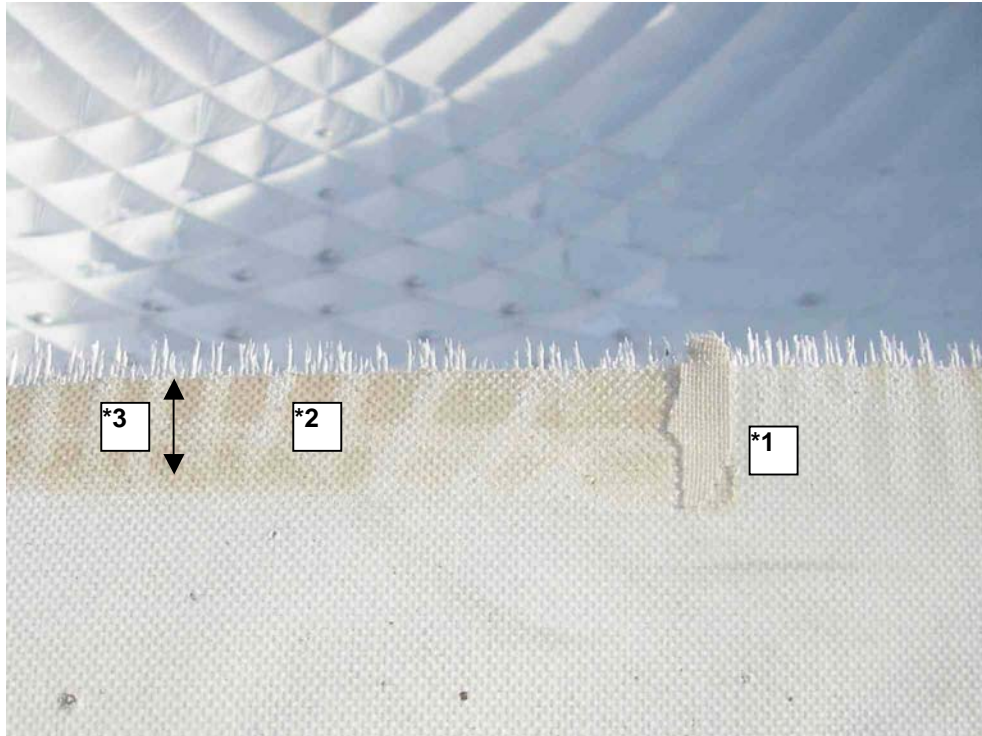
\*2 – Light discoloration is at the upper edge of the heat seal at the roped edge. Random edge indicates irregular degrees of heat seal adhesion.



**Figure A4-2**

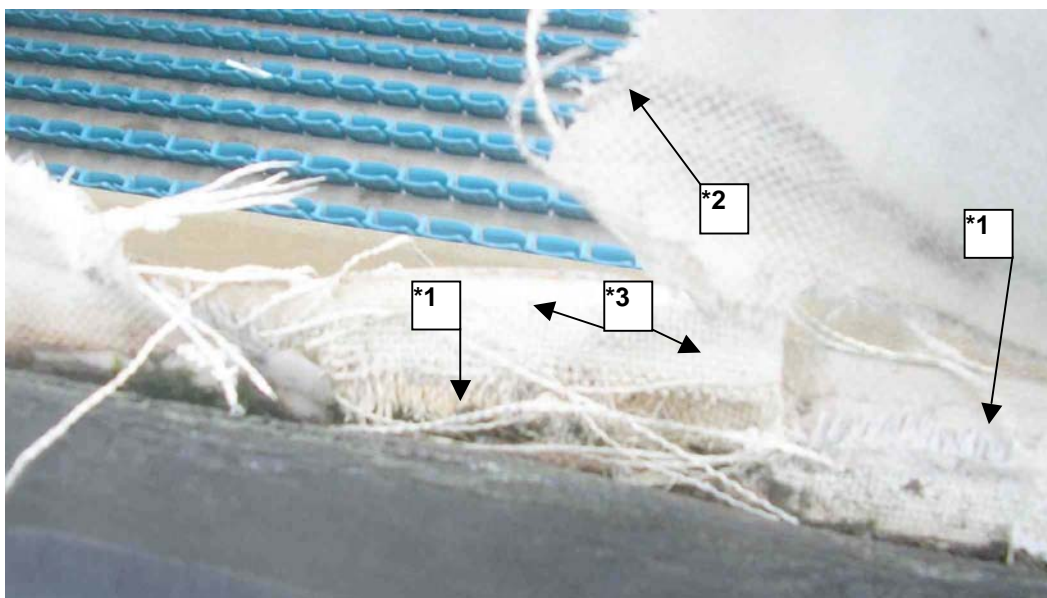
\*1 – Heat seal location from field installed fabric flashing. The short and clean fibers indicate tearing along the edge of seam.

\*2 – Long, loose yarns in these are indicative of tearing failure fill direction.



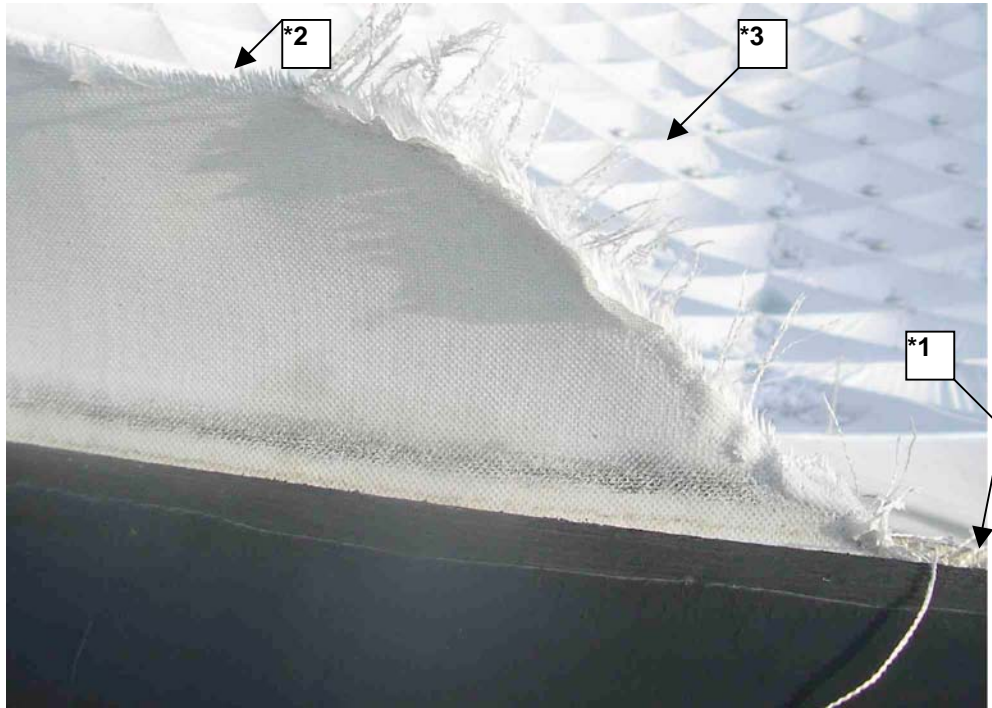
**Figure A5-1**

- \*1 – Small segment of the flashing fabric still attached. This lines up with a seam in the fabric flashing.
- \*2 – Short clean fibers indicate a tearing failure.
- \*3 – Field heat seal at flashing fabric.



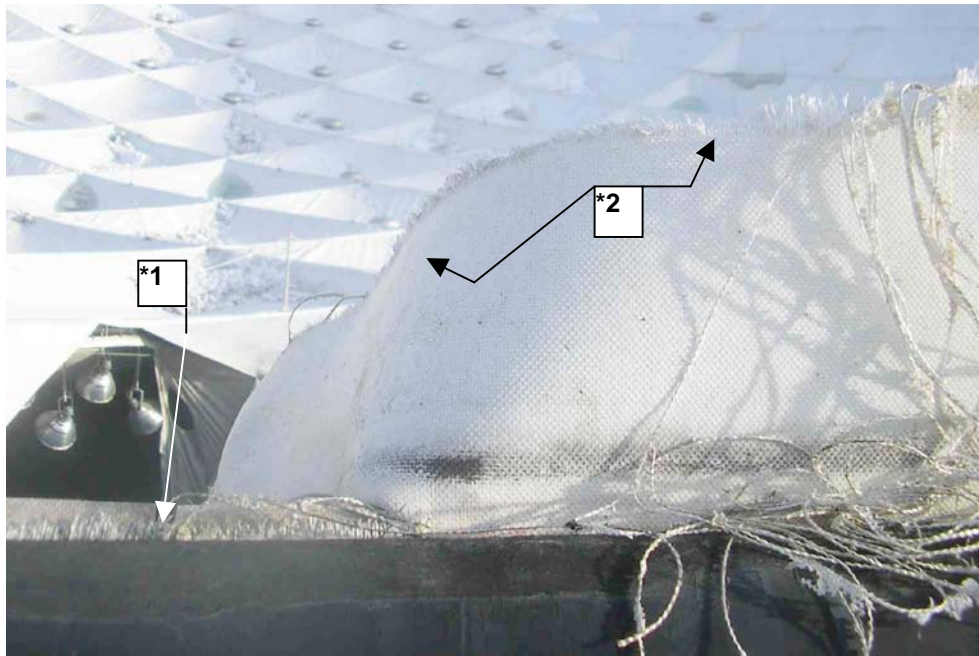
**Figure A5-2: Along ring beam**

- \*1 – Small segment of the flashing fabric still attached. This lines up with a seam in the fabric flashing.
- \*2 – Short clean fibers indicate a tearing failure.
- \*3 – Liner fabric



**Figure A6-1:** Roof at ring beam edge at postulated tear initiation location

- \*1 – Note short discolored fibers at edge of ring beam clamp.
- \*2 – Short discolored yarns at break, near edge of field weld at fabric flashing.
- \*3 – Longer fill yarns.



**Figure A6-2:** Roof at ring beam edge at postulated tear initiation location

- \*1 – Note short discolored fibers at edge of ring beam clamp.
- \*2 – Short discolored yarns at break, near edge of field weld at fabric flashing.

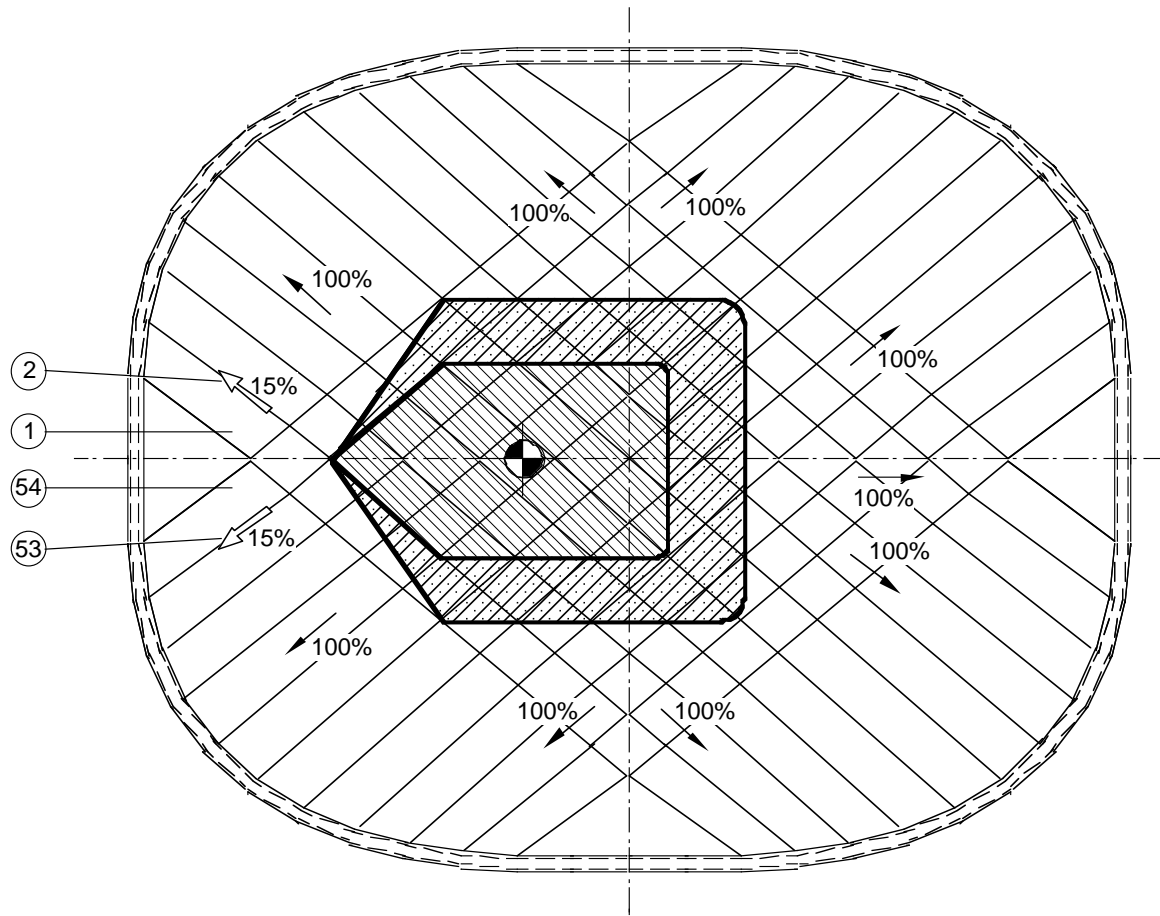
**APPENDIX B**  
**FAILURE SCENARIO**

The actual and complete scenario of 5 January 2007 that led to and resulted in the failure of the roof's west triangle panel and the subsequent roof deflation must be reconstructed forensically. Consequently, it can only be "proposed" as consistent with records, evidence, witnesses' observations and understanding of the air-supported roof system. The scenario proposed for the roof's deflation is based on our on-site observations, examination of the torn fabric, conversations with BC Place staff, review of records, subsequent material test results, evidence from the investigation conducted by the BC Place Investigation Committee, as well as our understanding of the design, behavior, and performance of the BC Place roof system. It deals with physical effects only, and does not address issues of management and decision-making, except as noted. We have omitted some details that are well covered in the other appendices or in other documents.

1. A light snow began to fall in the early morning of 5 January, with measurable amounts beginning at about 4:00 AM. The rate of snowfall and precipitation was irregular and intermittent, averaging about 11 Pa per hour until 10 AM, then increasing to 34 Pa per hour until 12 noon, then tapering off. The cumulative total was about 172 Pa.
2. Operating pressure was quite constant at 260 Pa during this time. Four of 16 fans were operating, 2 adjustable speed fans and 2 constant speed fans in conjunction with the relief dampers in operation for ventilation. This is more fans in operation than is normal because of temporary operating requirements for ventilation of vehicle exhaust during turf set-up.
3. The roof supported speaker cluster rigged from the roof was at a trim height of 15 m off the field for exhibit show mode. The cluster is rigged on the longitudinal centerline to the west of center of the dome. See Figure B1.
4. From the beginning of the snowfall, snow accumulated on the cable lines, which form valleys between the diamond panels in the central region of the dome. The valley accumulations resulted from a combination of drifting and sliding. The light wind contributed to drifting.
5. Blockages developed in the valleys between fabric panels in the central diamond-panel area, impeding the drainage of water. The melt water from any snow melt that occurred could not flow out and water began to accumulate in the valleys. (See Appendix D for more detail).
6. When sufficient load had accumulated on the diamond panels and in the valleys, the diamond-panel area began to flatten out due to the accumulated weight. This flat profile further impeded drainage.
7. Rain fell and accumulated in the valleys adding to the mass on the central region of the roof. See Figure B1.
8. As water, slush and snow continued to accumulate in the valleys between the diamond panels the profile of the dome in the central area continued to flatten tipping slightly to the west, where the weight of the speaker cluster contributed to the load. See Figure B-2.1, an illustration of the likely condition about 12:00 noon.
9. By around 12:00 noon the western portion of the diamond-panel approached "neutral buoyancy" as the accumulated weight plus the weight of the dome reached the internal pressure. This portion of the roof became very soft, so that relatively large vertical displacements would result from small changes in applied load.






10. The dead load of cables, cable clamp hardware, exterior and liner fabric, and lights in the diamond panel area is 115 Pa over most of the area. Over the part of this area supporting the main speaker cluster, the dead load is greater at 144 Pa, leaving a balance of 116 Pa for snow and water accumulation. This is nominally 2/3rds of the total precipitation. See Figure B1 for a diagram of the roof and the assumed drainage pattern.
11. Up to this point, about 12:00 noon it is unclear whether any of the roof panels had actually inverted and filled with water. If so there was little relief from the panel "pop-out" drains. The possible ineffectiveness of the drains could be due to several causes: the drains were not positioned at the bottom of the depression but along its sides and even above the water line, or the drains were prevented from automatically opening because the inverted roof panel had pressed down upon the lower liner panels and stopped the drain mechanism.
12. During this time, there was no adjustment to the internal temperature or pressure. Records show a steady operating pressure between 249 Pa to 268 Pa until about 12:35 PM on January 5<sup>th</sup>. Sometime after noon the asymmetric profile of the roof structure resulted in a depression in the roof profile at the speaker location. This resulted in more water and slush flowing into the area, which in turn increased the depression in the roof.
13. Photos of the roof at 12:24 PM indicate an inverted diamond panel above the speaker cluster but without a discernable depression in the roof profile. See Figure B-2.2.
14. Nine minutes later at 12:31 PM, staff working on the floor pointed out to the control room staff that the main speaker cluster was on the field, about 15m lower than its trim elevation. Four or more diamond panels in the roof depression were inverted and filling. See Figure B-2.3. At this point any water retained in the central area of the roof had flowed to the depression over the speaker cluster, in effect concentrating a large mass at this location.
15. At 12:33 PM the roof operations staff then began to increase the pressure and applied steam, turning on the snowmelt system. Because of procedure discrepancies and shortcomings in the control system response, more fans were turned on than was ideal under the circumstances.
16. Pressure remained constant for 5 or so minutes, while the roof began to rise until it achieved its full height after which the pressure rapidly increases to 520 Pa at 12:42 PM.
17. As the roof was raised during the period from 12:33 to 12:42 PM, the perimeter rose first. This is because of the greater area density of the diamond-panel region, the retained load in the valleys, the extra weight of the speaker cluster, and flooded diamond panels. So the triangle and rectangle panel areas began to rise first, and then the western end began to rise. Pressure remained nearly constant as the roof rose. It was just greater than the mass of the roof and applied load, which while redistributed was still what it had been at 260 Pa.
18. As the roof approached its inflated profile, the pressure increased as the fans were now working to increase tension in the roof. The pressure peaked at 520 Pa at 12:42 PM upon which the controls began to reduce pressure. See Figure B-2.4. Normal operating pressure was achieved by 12:46 PM at 277 Pa.
19. The increased internal pressure raised the roof and removed the depression where the rain and snow had ponded. Films show that the roof height was nearly fully restored. See Figures B-2.4 and B-2.5.

20. About this time, staff inside the building reported hearing a noise like “elephants walking across the roof”. The large mass of snow, slush, water and ice that had been consolidated over the speaker cluster spilled out as the roof reached its full height and began to cascade down to the west onto successive panels. We surmise that the sound of “elephants” was the individual diamond panels snapping back into position as the weight of water suddenly was removed. Similar sounds were heard during the re-inflation, when the re-inflation of the panels could be observed and correlated with the sounds.
21. The mass of snow, ice, slush and water cascaded down the roof to the west. It created a dimple-like wave in the fabric as it moved. The mass and dimple-wave in the fabric accelerated down the west triangle panel and crashed into the inflexible ring beam. Within a few seconds of hearing the “elephants walking” at 12:46 PM, light was seen at the bottom of the triangle panel, and simultaneously, the clock at the scoreboard on the west end shattered. Large quantities of water poured into the upper deck seating from the bottom of the panel.
22. The fabric of the west triangle panel failed as a consequence of the impact of the sliding mass and the wave it created in the fabric with the ring beam. This may well have been a sufficient impact to fail new fabric; however, the fabric strength in the vicinity of the impact was degraded and failure occurred at the location of the weakened material.
23. At 12:48 PM the decision was made to make a controlled deflation of the roof. Fans were turned off and the roof deflated to its inverted position by 12:51 PM. See Figure B-2.6.

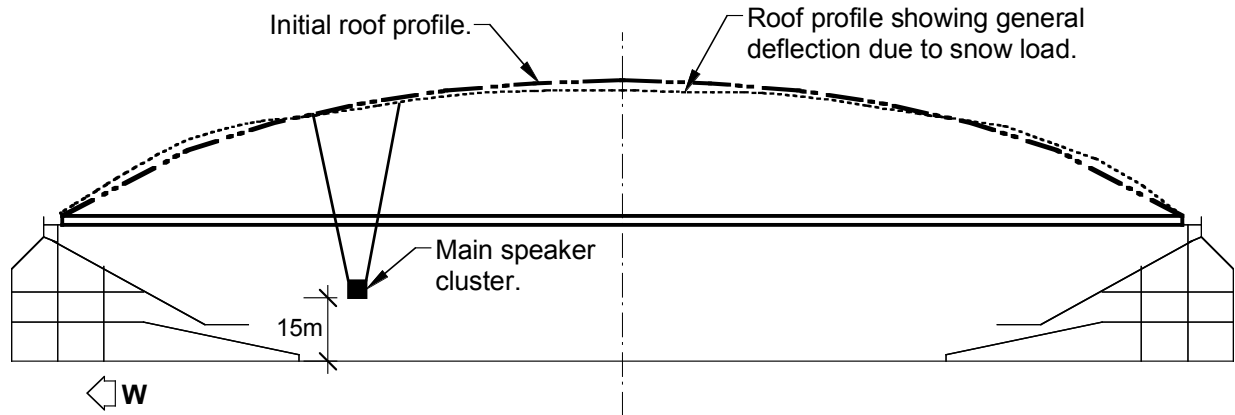


The above plan shows the assumed drainage and collection of melt-water and rain on the roof. The manner in which load consolidated on the western center region of the roof through the morning of 5 January 2007 is illustrated. The approximate drainage away from the depressed portion of roof versus the retained load that that would become part of cascade towards triangle panel is shown.

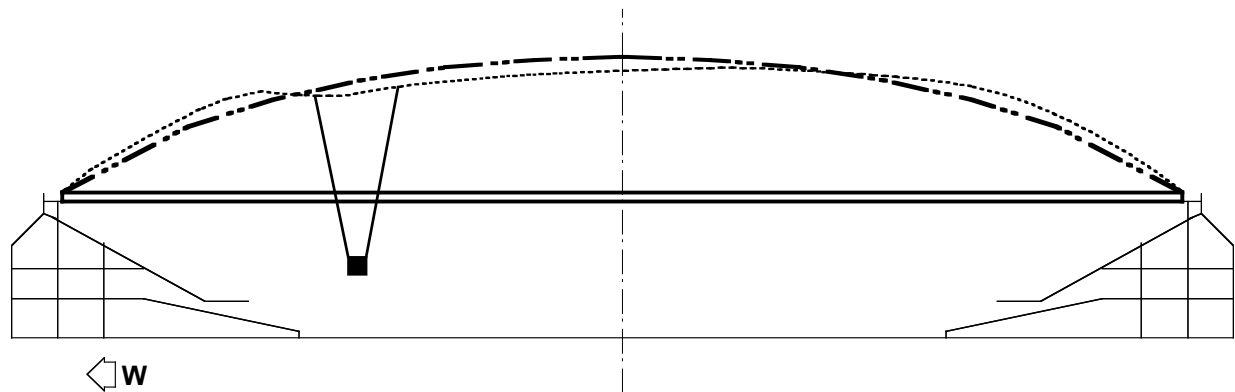
Key:

- 
 100% Area where all water / snow on roof flows away from central area of roof during period of snowfall and rain.
- 
 Until about 11:00 AM, water in this area flows away from center. Subsequently, water flows towards area above speaker cluster.
- 
 Until about 9:00 AM, water in this area flows away from center. Subsequently, water flows into depression.
- 
 15% Illustrates portion of water in cascade assumed to go down valleys, instead of down center of triangle panel.
- 
 Speaker cluster.

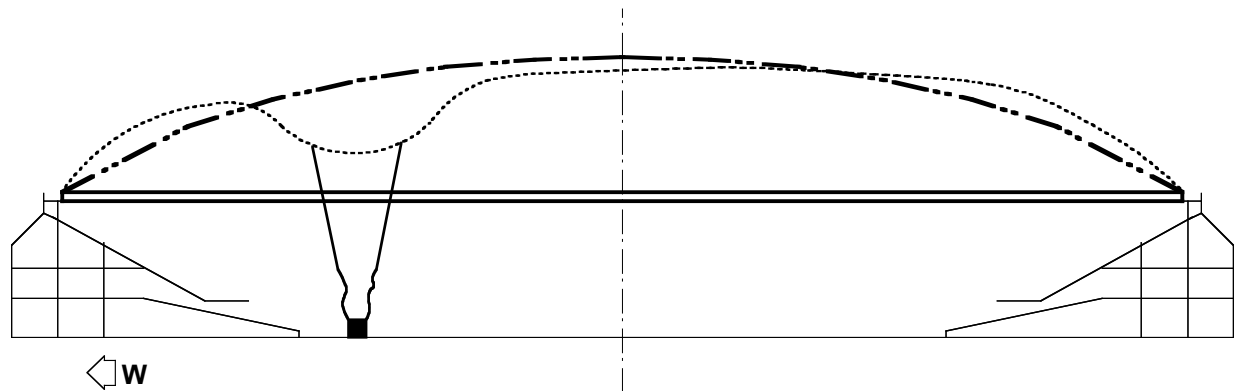
**Figure B1: Assumed Load Accumulation on Roof and Contribution to Failure**



**Fig. B-2.1 Longitudinal Section -- Approximately 12:00 NOON**

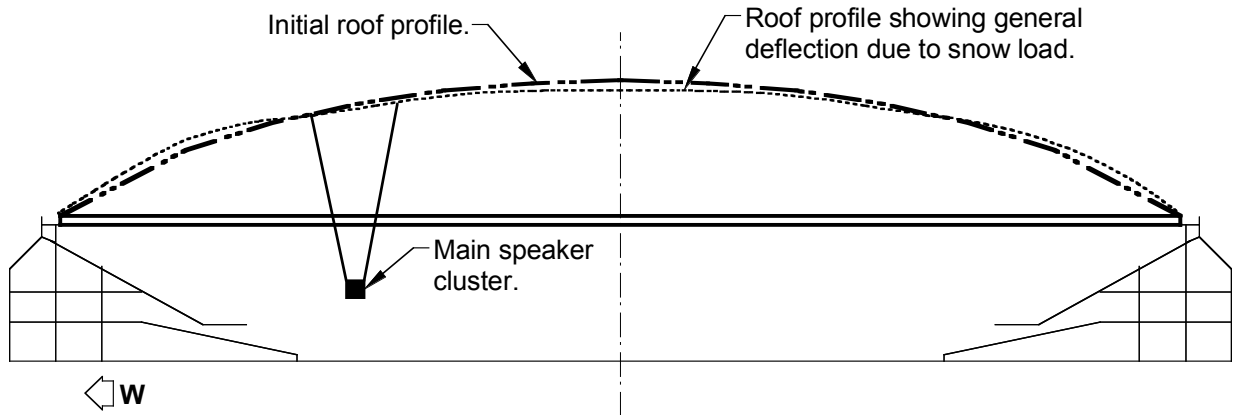


**Fig. B-2.2 Longitudinal Section -- Approximately 12:24 PM**

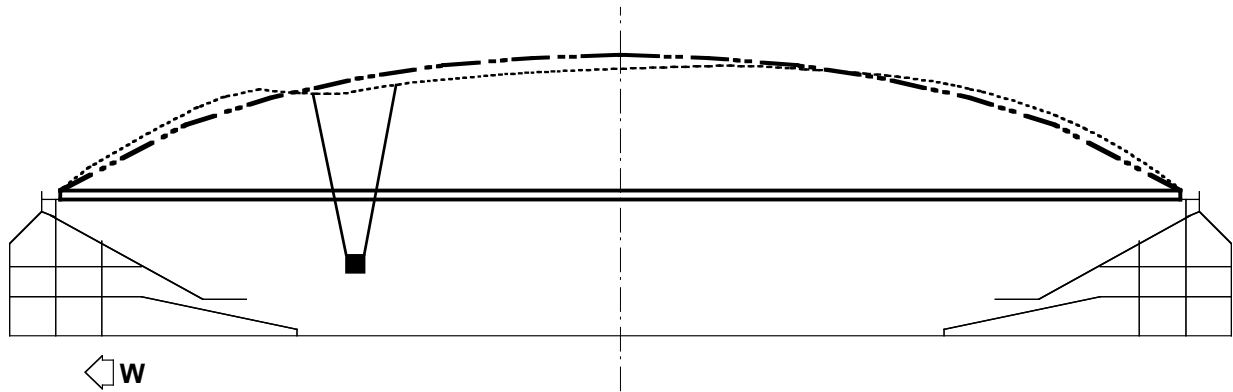


**Fig. B-2.3 Longitudinal Section -- Approximately 12:31 PM**

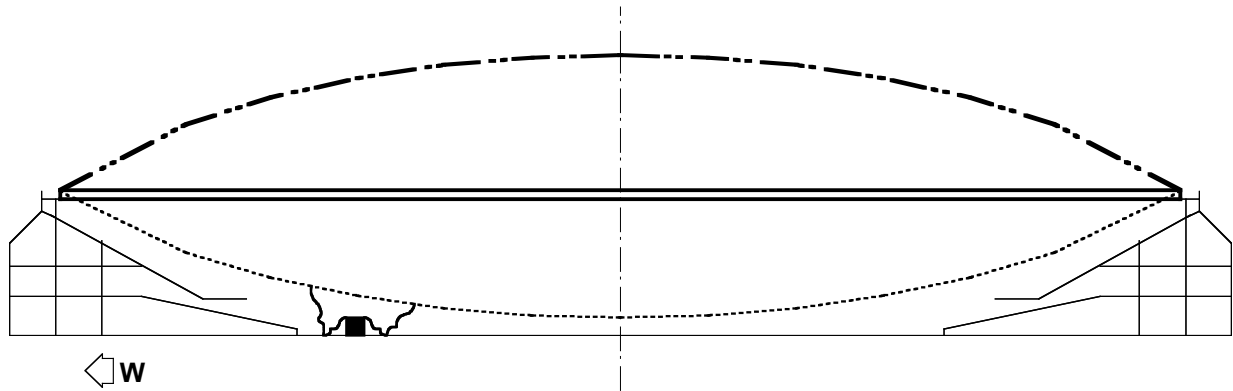
**Figure B2: Inferred Sequence of Roof Motions During Failure**



**Fig. B-2.4 Longitudinal Section -- Approximately 12:42 PM**



**Fig. B-2.5 Longitudinal Section -- Approximately 12:46 PM**



**Fig. B-2.6 Longitudinal Section -- Approximately 12:51 PM**

**Figure B2: Inferred Sequence of Roof Motions During Failure**

**APPENDIX C**

**WEATHER**

There are several different sources of weather information available for the morning hours of January 5, 2007. The sources are not completely consistent, because they are from different locations around downtown or the harbor. As Vancouver has several microclimates, it is necessary to examine different sources and extrapolate to the Stadium location.

Reports from Environment Canada and the GVRD are summarized in the following tables. (N.B. The tables are in different formats, as supplied by the agencies.)

Source:	GVRD - Kitsilano												
Location:	Kitsilano												
Period Cov'd:	5 Jan 01:00 to 5 Jan 13:00												
Time	0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100	1200	1300
Wind (kph)	8	12	11	10	11	10	13	13	13	13	14	14	13
Direction (deg)	80	80	77	74	73	71	67	68	70	68	73	69	70
Precipitation -Water Equiv (mm)	0.0	0.0	0.0	0.6	0.8	0.0	2.0	1.8	1.8	2.2	3.6	4.8	1.6
Temp (C)	2.3	1.9	1.9	1.1	0.7	0.7	0.8	1.1	0.9	1	1.2	1.3	1.7

Source:	Environment Canada				
Location:	Vancouver Airport				
Periods Covered:	4 Jan 18:00 to 5 Jan 13:00				
Date/Time (GMT)	Weather	Temp (deg C)	Wind Dir.	Wind Speed (kph)	Gusts (kph)
Jan 04 2100	A few clouds	5	W	56	67
Jan 04 2200	Clear	5	W	43	59
Jan 04 2300	Clear	5	NW	50	63
Jan 05 0000	Clear	4	NW	50	59
Jan 05 0100	Clear	4	NW	44	56
Jan 05 0200	A few clouds	4	NW	43	
Jan 05 0300	Clear	4	W	33	46
Jan 05 0400	Clear	3	NW	30	41
Jan 05 0500	Clear	3	W	24	
Jan 05 0600	Clear	3	W	28	
Jan 05 0700	A few clouds	2	W	28	
Jan 05 0800	A few clouds	3	W	22	
Jan 05 0900	A few clouds	4	W	9	
Jan 05 1000	Cloudy	2	E	7	
Jan 05 1100	Overcast	2	E	15	
Jan 05 1200	Rain	2	E	20	
Jan 05 1300	Mixed Rain Snow	1	E	22	

## Precipitation

In addition to these tables, there is a great deal of anecdotal evidence about the snow and rain load on the roof, some of it contradictory. The first contact to the author about the failure was a phone call from a reporter at about 3:00 PM on 5 January; the reporter said that 25 to 50mm of snow had fallen. The following morning, various staff members gave estimates ranging from 25mm to 76mm of snowfall. Nothing was said at that time about rain falling on the snow. However the precipitation records indicate that the total water equivalents were much greater than the reported snow, the precipitation must have included rain.

Based on the data summarized in the tables above as being more objective than the anecdotal evidence, and accepting the Kitsilano station report as being the most applicable to the situation at BC Place, I suggest the following approximate scenario of precipitation accumulation at BC Place:

Time	Accumulated Precipitation	Cumulative weight
12:00 AM – 4:00 AM	Dry	0.0 Pa
4:00 AM – 6:00 AM	1.4 mm (water equivalent) of wet snow	14 Pa
7:00 AM – 11:00 AM	11.4 mm (water equivalent) of wet snow and rain	<u>110 Pa</u>
	Subtotal as of 11:00 AM	124 Pa
11:00 AM – 12:00 PM	4.8 mm (water equivalent) of rain	<u>48 Pa</u>
	Total as of 12:00 PM	172 Pa

As the conditions at Kitsilano were likely different than at roof elevation at BC Place, these numbers are only indicative of what occurred at the stadium roof. It is clear that there was sufficient precipitation to cause distress to the roof at constant operating pressure so long as the precipitation did not immediately drain or was blown away.

It is unlikely that much of the precipitation drained away indicating that it was cold enough at the roof surface so that the snow remained frozen. Possibly there was freezing rain as well. There are reports of ice frozen to the roof fabric at the time of the triangle panel failure and video of the deflation shows ice being thrown from the flapping fabric of the failed triangle. So the roof fabric surface was cold enough to preclude much melt.

Between 7:00 AM and 9:00 AM, the snowfall rate was sufficient to cause blockage of valleys to occur, permitting ponding of any subsequent snow melt or rain on the flatter valleys at the top of the roof.

## Temperature

Temperatures at the Kitsilano station hovered around the 1 C mark from 04:00 to 12:00, and the Airport station measured from 3 C at 04:00 AM to 1 C at 13:00. The trend from the Airport to Kitsilano is to lower temperatures, and the "official" measurements are taken at 10m above ground compared to an average roof height of 47.5 m. Both indicate that the stadium roof was likely to have been a bit colder than either recorded report, confirming that the measured -1 to -2 C at the roof is consistent with the other reports.

The condition with -2 C exterior temperature with wind, combined with an interior temperature of 10 C and no air-flow, would permit freezing temperatures at the roof, so that snow would accumulate.

## Wind

Although wind has been spoken of as a direct factor in the deflation, the records do not support this. The winds at BC Place were likely higher than at Kitsilano, but less than those at the Vancouver Airport.

At the Airport, starting at 4:00 AM, when snow began, the wind speed was 30 kph, gusting to 41 kph, and at the time of the failure were nominally 20 kph. At Kitsilano, the winds were less; about 10 kph at 4:00 AM, and were remarkably steady from the ENE increasing slightly to 14 kph at 12:00 PM. (Gusts are not recorded at the Kitsilano location.) Although there is a slight channeling effect in False Creek, the winds at the time of failure could not have exceeded 20 kph and most likely was nominally 15 kph.

These wind velocities in either case are not sufficient by themselves to cause a significant stress in the fabric. However, even these light winds would have been sufficient to cause some motion of the center region of the roof, as the net pressure in the region, internal pressure less self-weight, snow and water, approached zero. In this state the roof is very soft structurally, so small changes in applied load can result large amplitude movement.

As a secondary factor, however, the velocities are such that some snow drifting could and probably did occur, concentrating snow in the valleys between the roof panels. Wind tunnel tests with snowfall simulation have been performed for one large air-supported roof. These tests indicated that for dry snow, the wind speeds causing the largest drifts are between 9 and 16 kph; for moderately wet snow the range is from 13 to 19 kph. Snow with a specific gravity greater than 0.2 is unlikely to drift. The wind speeds in the morning right in these ranges.

It is worth noting that the wind direction was steady from the ENE, which would tend to blow any drifting snow to the western portion of the roof.

The size of a "snowdrift" is limited by the amount of snow available to it. In the case of the diamond panel area of a large air-supported roof, that amount is roughly determined as the amount of snow falling over the 12,800mm width of the adjacent upwind panel. The maximum amount of snow that could have accumulated into the valley, allowing for some loss by initial melting and assuming a specific gravity of 0.2, was about 0.37 m<sup>3</sup> per meter of length along the valley being filled. Distributed across the width of the valley, the drift at the center would be about 150mm, which is sufficient to restrict drainage.

A similar result is obtained if one assumes that wind speeds do not support drifting, and instead that the snow as it is deposited on the warmer than freezing surface of the Teflon coated fabric slides into the valleys. More of the total weight would then be in the form of liquid water which would promptly run off, but on the other hand there would be more of a tendency for the slush to move down the valley and accumulate at a single location, most likely where the cables cross. This could actually result in a larger blockage than drifting.

Most likely as a result of both drifting and sliding, snow accumulated in the valleys between the diamond panels. This consolidation of snow and ice reduced the rate of any subsequent melting as well as hindered drainage.

The process of initiation of a pond is described in Appendix D, and the probable distribution of precipitation and cumulative drainage from 4:00 AM to 12:00 PM is shown in Figure B1. If drifts or other means of obstruction form, then drainage of melted snow and rain can be blocked, as mentioned above, and initiate formation of a pond.

## **APPENDIX D**

### **STRUCTURAL DESIGN AND PERFORMANCE OF LONG-SPAN LOW PROFILE AIR-SUPPORTED ROOFS**

The basic technology of air-supported roofs is straightforward, the roof is continuously supported by the air in the building. In order to accomplish this the roof structure is made as light as possible by using strong, airtight fabric supported by a net of steel cables. The interior of the building is pressurized using fans so that it exceeds the weight per unit area of the roof. The basic equipment required is not unlike that in high-rise buildings; the number of fans is governed by the needs for ventilation during events, not by the requirements of the roof itself.

The roof is constructed in the deflated position,, in the case of BC Place Stadium free hanging in the facility. Air pressure inside the facility is increased by adjusting relief dampers and fan speed, until the pressure exceeds the weight of the fabric and cables and begins to lift the roof. The air pressure will then remain essentially constant until the roof is mostly inflated, then begin to increase further as it tensions the roof giving it stiffness. This stiffness is necessary to prevent excessive motions of the roof under wind or snow. Operating pressure is nominally double the weight per unit area of the dense region of the roof.

The original design criteria for the BC Place air-supported roof included the following:

1. Under normal operating conditions, it should be possible to use pressure balanced doors rather than revolving doors for mass exiting.
2. The roof should be able to resist the same wind and earthquake loads as a conventional roof. Wind loads were structurally much more significant than the earthquake loads. The wind loads were established as a nominal 104 k/hr wind. Time-averaged and adjusted for roof elevation, the nominal wind speed is equivalent to a speed of 134 k/hr over the entire roof. Wind tunnel tests were performed on a scale model of the building and roof to determine the distribution of pressure across the roof at different wind speeds and directions.
3. The roof should also be able to resist the code-required rain and snow loads by a combination of strength provided by internal pressure and by use of snow removal methods. The basic roof snow loads for Vancouver at the time the BC Place was built were 1,150 Pa (24 psf) adjusted for height and shape of the roof. It was decided that the inflated roof should be designed to carry 620 Pa of snow by internal pressure (requiring a total internal pressure of 750 Pa), and the balance dealt with by snow melting. When deflated, the roof should carry 1,150 Pa of snow and/or water.
4. The geometry should be such that when deflated, the roof should hang at least 6 meters clear of the seats and field.

### **DESIGN AND CONSTRUCTION OF THE ROOF**

Individual panels are constructed by first preparing a pattern so that the fabric, when cut, assembled and loaded, will be of the correct shape; the fabric has very little stretch. After cutting, the individual strips are heat-welded together at the factory into full panels. Each edge of a panel has a "roped edge", where the fabric is wrapped around a 12 mm or 16 mm diameter synthetic rope and welded back onto itself. The panels are then folded or rolled and transported to the site, where they are installed, with the roped edge fitting into a continuous clamp, which is padded and sealed with neoprene strips or with additional fabric. The fabric load is anchored by the roped edge of the panel bearing on the clamp bars.

The supporting cablenet system consists of eleven cables each direction, running parallel to the diagonals of a rectangle super-scribed around the stadium (similar to Figure B1.a). The cables are spaced uniformly across the roof, to a point where the last cable of the group still crosses

the center axis of the stadium. The fabric panels between the cables are diamond shaped along the top of the roof, and rectangular or triangular around the roof's edges.

### **Consideration of Roof Geometry and Structural Design**

For a low-profile air-supported roof, a two way cablenet is used with cable ends anchored to a "funicular" compression ring, that is, a ring beam formed in plan as a closed curve which for a given distribution of loads carries those loads without bending moments or shear forces in the ring. The ring shape shown in Figure B1-a approximates a "super-ellipse", which is the general

case of an ellipse, with the formula  $(x/a)^n + (y/b)^n = c^n$ , where "n" is any number from 0 to  $\infty$ .

The cables are laid out parallel to the diagonals of a rectangle superscribed over the ring, permitting a nearly uniform roof weight across the roof.

The sparsest possible cable grid - with cables of equal spacing and carrying equal horizontal components of cable tension - results in a roof with the minimum number of cable intersections, the minimum attachments of fabric to cables, the minimum number of cable anchorages, and the lowest cable weight. All of these would lead to the lowest roof cost. This set of assumptions leads to the plan configuration shown schematically in Figure D1-1.

Clamps at cable intersections are designed to prevent cable slippage at cable intersections. Although a cablenet may be laid out so that no sliding force will occur between the intersecting cables when they are loaded with uniform loads, the high variations in loads from snow and wind will create large sliding forces.

Once the plan configuration is established, the roof rise must be set. Design issues include:

1. Minimizing the cable tension by keeping the rise as high as possible. A tall rise also provides the height clearance required for playing baseball games under the roof.
2. Keeping the roof rise low enough that it will hang clear of the floor by an adequate clearance when deflated; this same criterion will also mean that in the event of a deflation, there will be adequate clearance above the floor and the seating to avoid injury.
3. Keeping the rise to a level that will keep wind forces reasonably low. (Figure D1-2 shows the typical distribution of pressure on the roof – including both outward wind suction or localized inward pressure.)
4. The maximum cable tension and thus the required cable size.

The rise is usually set a maximum of approximately 1/10th of the span, giving the minimum cable force for a given load and the steepest roof for drainage, and a minimum of 1/20th of the span, minimizing the effect of wind loading. Requirements for internal clearance (such as for baseball) may require a slightly higher rise. BC Place has a rise-to-span ratio of about 1:8 with respect to the longest diagonal cable span.

### **Design Loads for BC Place Stadium Roof**

The BC Place roof was designed for loads that are similar to those used for the design of conventional building structures, with a few key differences:

- Snow Loads: 1,150 Pa (24 psf) with roof in the deflated condition.  
622 Pa (13 psf) with roof in the inflated condition, with the use of snow removal to take care of any snow load above that amount.
- Wind Speed: 105 kph at 10m above ground. (Equivalent to 135 kph at ring beam)

Seismic: 13% of g (gravity).

Wind tunnel tests were performed on a scale model of the building and roof to determine the distribution of pressure across the roof at different wind speeds and directions. A typical profile of wind pressures is shown as Figure D1-2.

There were two governing load conditions that were used for the design and sizing of major structural elements:

Load Case 1: Full Dead Load (roof + lights + speakers) + 1,150 Pa in deflated position

Load Case 2: Partial Dead Load (roof only) + wind + maximum internal pressure

Load Case 2 considers only partial dead load to evaluate the condition of wind suction lifting simultaneously with the maximum applied internal pressure.

### Dead Loads

The typical roof dead-loads (self-weight and collateral loads) are as follow:

	Diamond Panels Pa	Rectangular and Triangular Panels, Pa
Outer fabric	13.4	13.4
Liner	4.3	4.3
Cables	57.5	28.7
Clamp Bars	25.9	12.9
Lights & Typical Speakers	11.5	11.5
Total	=112.6	=70.8

### Loads

The self-weight of the fabric and cables is intentionally quite small, the proper evaluation of superimposed loads is of particular importance. Stresses due to wind and snow govern. The wind pressures and distributions were determined for BC Place Stadium from tests may be performed in a boundary layer tunnel.

Figure D1-2 shows how the wind pressures vary over the surface of the roof. The arrows show the direction of the wind force on the roof; note that in most conditions, the wind tends to lift the roof up. Thus, the force on the roof due to wind tends to add to the forces on the roof due to internal pressure, and the roof therefore must be designed for a condition of maximum wind uplift pressure plus the maximum possible internal pressure.

Snow loads require special consideration. While an inflated air-supported roof can resist wind pressures, snow can readily exceed internal pressure deflating the roof. The amount of the uniform snow load that can be supported by an air-supported structure is equal to the interior air pressure, minus the dead load of the roof, lights, etc. An internal pressure of 290 Pa might support a maximum of 200 Pa of snow, which is about 250 mm of dry snow or 64 mm of very wet snow. If the pressure is increased to 575 Pa, nearly the maximum, then the roof could support about 485 Pa, which is about 150 mm of heavy wet snow. Either of these situations is well under the design snow load for Vancouver and less than typical design snow loads for Canada and much of the USA. For this reason, air-supported structures typically are designed with snow-melting systems. In steeper parts of structures, snow will slide off. It may, however, accumulate locally due to sliding into valleys or due to wind effects. When this occurs, the fabric may dimple locally, which will then have the effect of distributing the load to other parts of the loaded panel. If the entire panel is loaded in excess of the internal pressure, it will invert.

Figure D3 illustrates how a fabric panel can carry a local load concentration that greatly exceeds the internal pressure, if its area is sufficiently small. If concentrated loads from snow drifting or puddled water become too large and too heavy, they then can change the shape of the fabric locally, dimpling the surface and facilitating load consolidation further increasing the load. The true size of a drift or pond may be disguised by the fact that it is hidden in the dimple of the fabric (the "iceberg" effect). For this reason, careful observation of the roof surface and removal of drifts and ponds is important; observation should be from both a distant perspective and first-hand and close up.

Whether concentrated or blanketing a large region of the roof the total mass of applied snow, ice and water cannot exceed the internal pressure less the dead load of the roof in the region without effecting the overall roof profile. As in the case of individual panels, the overall roof can become dimpled. However, this is more serious as the scale of the deformation and the total mass involved is large.

In either case, the effect of retained loads in weather conditions such as those that occurred on 5 January are not sufficient to affect the cables themselves, which carry tensile loads of up to about 1,800 kN. Specifically, water ponds on a single diamond roof panel have little effect on the curvature of the cables.

### **Roof Stability**

The structural behavior of air-supported structures is radically different from all other structural systems. Conventional structures, achieve stability by a combination of gravity and rigidity of the members and, in the case of arches and shells, curvature. Design is based on weight, strength and stiffness of materials in bending and shear, and compressive strength, whereas for membrane structures design is based on curvature and tensile strength alone.

The components of a membrane structure have essentially no rigidity compared to their span, and so no capacity to carry load in bending or in shear. Stability and strength must be generated by curvature and tension only. This is the dominant feature of all membrane structures including air-supported membranes.

Because of the absence of self-rigidity, air-supported membrane structures can be subject to large deformations under superimposed load. In an air-supported structure with synclastic curvature (curvature in the same direction in both axes of the membrane), cable deformations tend to increase their capacity to carry load. The analysis of these structures requires methods that take into account the deformation of the structure, generally called "geometrically nonlinear" analysis. The large deflections possible also create situations where loads such as water ponds can be carried in a state of "unstable equilibrium".

In general, air-supported roofs are very stable. With all components operating in tension, there is no tendency to buckle or to collapse in the typical sense.

An exception to this rule occurs when the roof retains sufficient snow, ice and/or water so that the total load in a large region exceeds the internal pressure. A likely scenario which can produce such an effect is when a heavy, uniform snow falls on a roof with little or no wind. In this instance, when the weight of the snow plus the roof dead load in the diamond panels equals the internal air pressure, then the tension in the cables reduces to zero in the center area, and the entire roof may oscillate in a very long-period motion. The roof becomes very soft such that small changes in load result in large movements. Moreover, the center area no longer drain and can readily become inverted.

### **Instability in Inflated Structures with Concentrated Loads**

Inflated fabric roofs supporting weather induced small ponds of water form an energy balance system. We know that water runs to the lowest point possible, and when it reaches that point, it stops. The water's weight load is resisted by the supports (the roof's cables & fabric) and, if

moved or disturbed by a small outside force, will return to its starting position. The system is then in stable equilibrium.

A pond near to the summit of the roof may be in "equilibrium" (i.e., motionless), but it may also be unstable because a disturbance such as adding a bit more water may cause the entire pond to suddenly start moving down the side of the panel. Thus, that pond is in "unstable equilibrium".

At the point of stable equilibrium, the system energy "E" will be minimum. The total system energy "E" includes of the height related, potential energy "V" and the material stiffness related, strain energy "U". Anthropomorphically speaking, the load tries to get to the lowest position it can (minimum "V"), or the structure tries to get to the point of minimum strain (minimum "U"), so that the sum "E" is a minimum.

The approach in solving static stability problems is to take an applied load and move it around in the computer model until we find minimum "E" values. Once that is accomplished we've found a point of stable equilibrium. In practice, of course, the points of stable or unstable equilibrium can be located simply by observing pond location.

Figure D3 shows snow mass buildup and then motion of the mass from the valley between panels to mid-panel in an air supported roof. A small pond develops when the snow loads change the fabric geometry by locally overcoming and reversing the upward curvature created by the internal air pressure. If more water is added, the pond gets bigger, which changes the total energy function.

Note that in all the time this is occurring, the structure is still capable of carrying the total load; it is the position of the load that is in question.

Once concentrated loads form on the roof they can shift and spill into adjacent panels, further consolidating the mass. As they migrate toward the perimeter they will reach a point where the roof slope is sufficient so the mass will accelerate to the perimeter. This moving mass and the dimple-like wave it creates in the surface can damage the fabric membrane when it impacts a stiff boundary like the ring beam.

A major lesson learned from past roof deflation incidents, primarily at the Metrodome in Minneapolis, is that in order to prevent such cascades and the potential danger they pose, an essential part of the operator's task is to keep the geometry of the roof as stable as is possible, until clearing operations and emptying of inverted panels is completed. This will require continual observation and monitoring of roof height and profile.

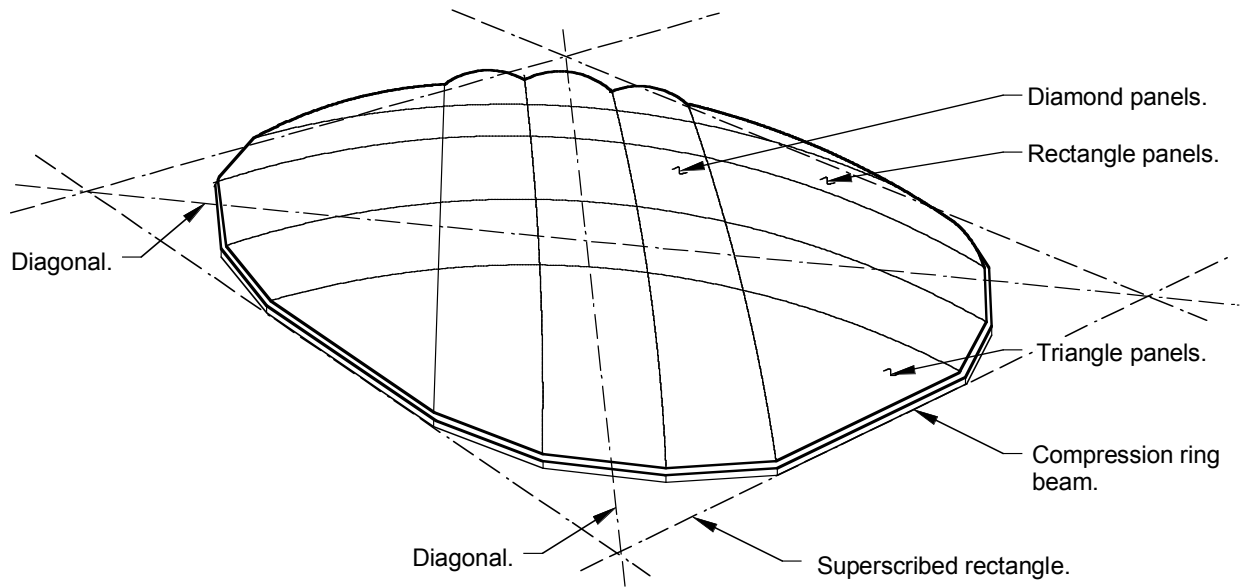


Figure D1-1: Simplified Diagram of a Low Profile Air-Supported Roof

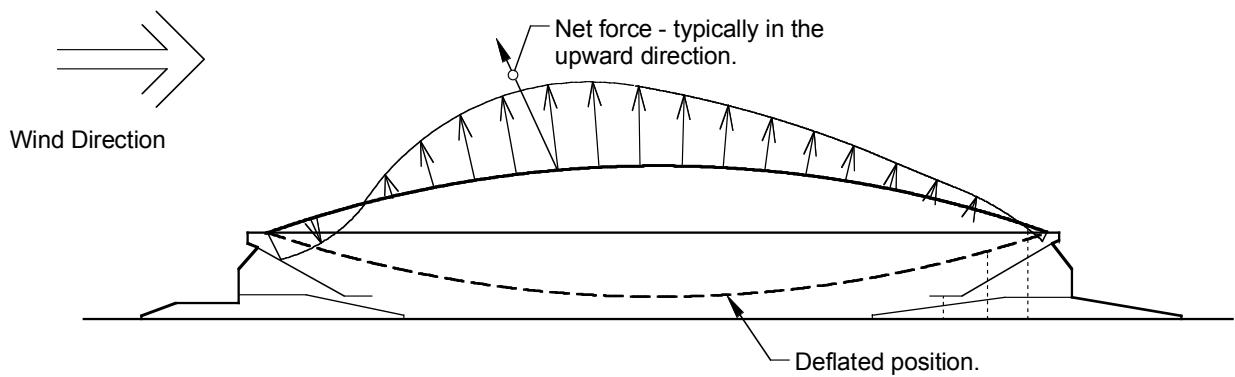


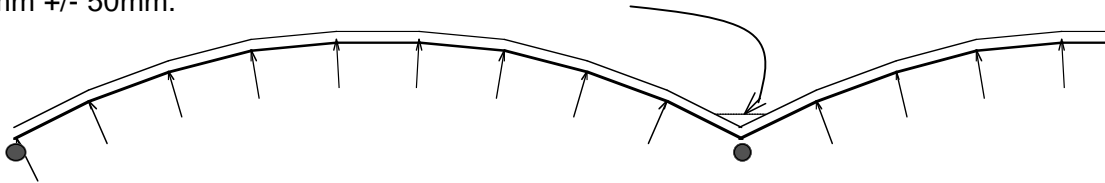
Figure D1-2: Wind Forces on a Low Profile Air-Supported Roof

Figures D1: Basic Roof Configuration

**FIRST STAGE:** Accumulated snow and rain drain to valley (valley is assumed to be blocked by snow and slush.)

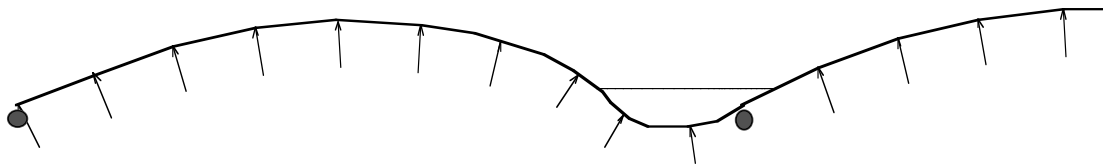
A mixture of snow, water and ice collects in the valleys between panels; for calculation purposes assume that the valley is blocked with snow & slush at the next intersecting valley, preventing drainage. The water depth accumulating into a valley from the panels each side is = 200mm +/- 50mm.

If one additional diamond panel valley drains into the same valley, the resulting depth will be 300mm +/- 50mm.



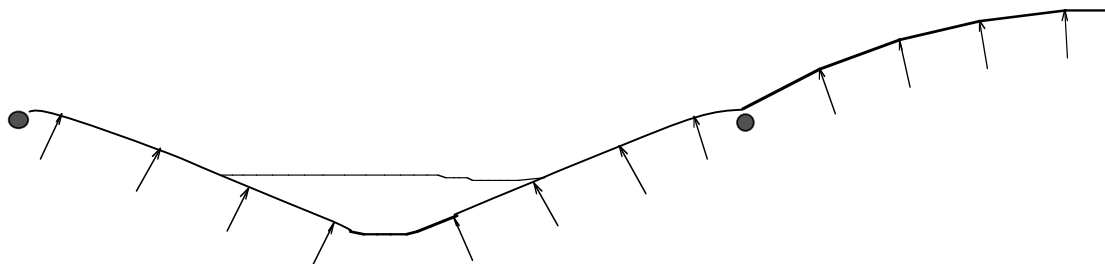
**SECOND STAGE:** Snow and rain continue to accumulate; pond starts to form.

For a typical fabric tension of 2 N/mm at 250 Pa interior pressure, and a uniform load equivalent to 50 mm of wet snow, a water depth of about 300mm +/- is necessary to initiate and maintain a pond.



**THIRD STAGE:** Full pond develops.

Fabric still pulls up but total weight nearly exceeds the internal pressure. The total pressure over the area of a diamond panel is approximately 40 kN, which is equal to 4 cubic meters of water. This would be a pond about 2.7 m in diameter and 700mm deep.



**NOTES:**

1. The above scenario is one of several possible for the formation and propagation of the ponds.
2. The parameters are based on the best available estimate of snow depth and density.
3. Approximate applied uniform load at the time of failure was approximately 50 mm of wet snow with a specific gravity = 0.15 (ref. CSA #2542) + 6 mm of rain held within snow = 135 Pa.

**Figure D3: Pond Formation at Diamond Panel**

## **APPENDIX E**

### **FABRIC TESTS AND RESULTS**

#### **FABRIC MATERIAL**

The fabric membrane used for the BC Place roof and for most large fabric structures built at that time or since is a woven fiberglass cloth with a Teflon® coating, usually described simply as "PTFE/glass". There are four main constituents to the fabric:

- A woven textile of glass fiber yarns in a simple warp-fill-warp weave.
- A silane (silicon compound) coating on each fiber to protect the fibers from direct contact with moisture.
- A PTFE fluorocarbon coating of the fiberglass cloth.
- An outer coating of FEP fluorocarbon.

The glass fiber cloth provides the tensile and tear strength of the fabric; the PTFE coating is the weathering layer and the primary protector of the glass fiber against damage by abrasion, moisture, UV radiation, pollution, and heat. The FEP coating has a lower melting point than the PTFE product, to facilitate heat welding of the fabric at seams.

One weakness of glass fiber is that it can be attacked by moisture, and the silane coating is intended to combat this problem. The fluorocarbon coatings have a very slight porosity, permitting water moisture by way of water vapor to penetrate. The silane coating provides the glass fibers of the yarn with protection against the moisture; however, if the silane coating is damaged then the glass fiber will eventually be subject to damage and loss of strength.

#### **FABRIC SPECIFICATION**

The fabric for the BC Place roof was manufactured by the Owens Corning Fiberglas Corporation (OCF). Two different weights of fabric were used. The majority of the roof panels are of medium-weight StructoFab 375. However, because of the greater span of the end triangle panels and hence greater strength demand, the heavier and stronger StructoFab 450 was used at those locations. It is believed that the particular StructoFab 450 material used for this project was part of a material over-run for a previous project by Owens-Corning. OCF ceased producing StructoFab fabric a few years after the BC Place roof was completed.

A few of the manufacturer's published material specifications for these two products and the liner are shown in Table E1 below. The properties listed are selected to provide a means of comparison to the properties tested by Baker Engineering, and represent only a small portion of properties identified in a complete specification for structural fabric.

**Table E1 Manufacturer's Published Material Properties**

	StructoFab 450	StructoFab 375	StructoFab 120
Where Used	End Triangle Panels	Balance of Roof	Liner
Coated Fabric Wt	41 oz/sq.yd <b>1.39 kg/m<sup>2</sup></b>	29 oz/sq.yd <b>0.98 kg/ m<sup>2</sup></b>	12 oz/sq.yd <b>0.41 kg/ m<sup>2</sup></b>
Thickness	38 mils <b>0.97 mm</b>	32 mils <b>0.81 mm</b>	12 mils <b>0.31 mm</b>
Dry Strip Tensile Strength			
Dry, Warp	800 #/in <b>140 N/mm</b>	520 #/in <b>91.1 N/mm</b>	320 #/in <b>56.0 N/mm</b>
Dry, Fill	700 #/in <b>122.6 N/mm</b>	430 #/in <b>75.3 N/mm</b>	230 #/in <b>40.3 N/mm</b>
Strip Tensile Strength Across Transverse Seam (Lap Strength)			
Warp	400 #/in <b>70.0 N/mm</b>	260 #/in <b>45.5 N/mm</b>	---
Fill	350 #/in <b>61.3 N/mm</b>	215 #/in <b>37.7 N/mm</b>	---
Trapezoidal Tear Strength			
Warp	60 # <b>267 N</b>	35 # <b>156 N</b>	20 # <b>89 N</b>
Fill	80 # <b>356 N</b>	38 # <b>169 N</b>	18 # <b>80 N</b>

**TEARS IN FABRIC**

Although the measured tensile strength is a standard indicator of the overall strength of the fabric, the key indicator of resistance to failure is the tear strength, as measured by the Trapezoidal Tear test. Whether damage is initiated by a puncture or cut, or by a tension failure at a broader region of high tensile stress, tearing action will be responsible for the growth of the defect to the point of becoming a failure.

In general, coated fabrics with less membrane shear stiffness such as the vinyl-coated polyester membrane materials have better tear characteristics than the PTFE/glass fabrics. This is at least in part due to the ability of fibers transverse to the direction of propagation of a tear to “bunch up” within the softer coating, rather than resisting the tearing forces singularly.

PTFE/glass fabrics characteristically have low tear strength in relation to the their tensile strength. The BC Place roof materials are typical in this regard. To put this into perspective using the originally published values for the warp tensile strength and tear strength for the triangle panels' material, a 4 mm initial cut mid-strip in the warp will result in a tear failure before tensile failure in a fabric sample.

**OBSERVED FABRIC DAMAGE**

Figure E1 is a map of the observed condition of the failed triangle panel, prepared from direct observation on the morning of Saturday January 6 and from photographs taken at the same time.

In making this examination, one area of the tear close to the edge of the ring beam was observed to have fibers at the tear that were a dirty grey-brown color, and were very short and

uniformly torn, with a "soft" appearance. This tear pattern is usually indicative of water damage of the glass yarn, either through a scratch, abrasion or other breach of the PTFE coating. Exposure of the glass fibers to water, such as would be caused by a scratch through the fiber coating across the yarn, is one of the few potential causes of damage to glass fiber.

Other damage noticed at that time included tears at the edges of the clamps that attach the fabric to the cables, and tears and/or separations of the fabric at seams. Close inspection of a section of the panel that had been completely torn away from the rest of the destroyed panel suggested that there were other types of damage to the fabric, possibly due to aging, but likely a consequence of the buffeting the material was subject to following the initial tear.

### AGING OF PTFE/GLASS FABRICS

It is known that Teflon® coated fiberglass fabrics have some loss of strength with time and exposure. Tests of fabric taken from in-service locations at more southerly and drier climates have shown a loss of between 18% and 30% over a period of 20 years; actual results depend on sunlight, physical damage, and abrasion, among other factors.

The damage to the glass fibers is directly or indirectly the result of moisture contact with the fibers. Moisture gains access to the fibers by three routes, either through the surface of the fluorocarbon coating, through cracks in the coating, or along cut edges:

1. PTFE and FEP coatings are very slightly porous. Although they have a high surface tension that makes them "water-proof", they are water vapor permeable. Normally, the glass silane coating prevents any damage to the glass fibers. However, the silane can be damaged by excess heat, such as at field welds, where equipment and weather conditions limit the degree of control. Where the fibers' silane coating is damaged, moisture will proceed to damage the fiber.

This effect can also occur at factory welds, but better control at the plant would usually prevent overheating during heat-sealing.

The penetration of water through the coatings is enhanced by addition of certain surfactants, which are sometimes used in manufacturing processes as a non-staining non-toxic lubricant. It was discovered in the late 1990's that one source of such surfactants is the Dacron rope that is commonly used in the roped edges. Although the exteriors of the yarns themselves are cleaned of the surfactants, the individual fibers are not. As the project ages, the surfactants will assist any moisture or vapor that may gain access to or condense within the cuff containing the rope, in penetrating to the fiber and through the silane. The ensuing damage to the fabric can cause the roped edge itself to become a failure point.

For more recent projects, the industry has been changing to using plastic rods or hard neoprene rope within the cuffs, instead of Dacron rope. Neither of these use surfactants.

Damage to the field-welded areas can be seen in Figures E-4 and E-5.

2. The fluorocarbon coatings are rigid when compared to the base yarn. If the coating is cracked, then again moisture can gain access to the surface of the fibers, in relatively large quantities. Such cracks are typically formed where the fabric has to make a sharp bend, which can happen during shipment or around the fabric clamp connections.

Because of the known sensitivity to cracking, the fabricator will make a detailed folding plan to minimize opportunity for sharp corners, and then will pad those areas where creasing cannot be avoided. Workers are trained to identify potential creases and prevent them with padding or by changing procedure.

A second source of cracks can be at the exposed edge of the hardware connecting the fabric to cables or to exterior supports. If there is repeated flexure at the roped edge,

then a crack can form, somewhat like metal fatigue. To alleviate this problem, the hardware is typically shaped with at least a ¼" radius at the edge.

An "artificial" crack will happen where a sharp implement, such as a tool carried by a worker, or equipment dragged across the roof, damages the fluorocarbon coating.

3. Where the glass fiber is exposed at a cut edge of the fabric, water can wick along the yarn and gain access to the fiber. This action is accelerated by the presence of surfactants such as in the roped edge. There, the bolt holes where the roped edge is clamped into a connection are the primary weak spot. Other points of access are the cut edges at seams, and at the edges around details and cuffs. The cut edges on the exterior surface are covered with a thin tape of FEP, which is then heat-welded into and over the seam. Interior cut edges may or may not be so treated, and details and cuffs rarely are.

There was a good deal of discussion with the contractor on this topic during construction; the records are not clear, but it appears that a compromise position was reached. Bolt holes do not appear to have been protected. Damage to the cuffs and bolt holes may be seen in Figures E-4 and E-5.

4. Fabric which has been damaged by a scratch in the PTFE coating will darken as moisture accumulates at the surface of the glass fibers. Ordinarily this darkening would be seen during careful inspection of the roof.
5. Where a tear occurs in fabric which has not been degraded by moisture, there are several distinguishing characteristics. The glass yarn will be clean white in appearance and the yarns will break at random distances away from the nominal location of the tear. The Teflon coating will tend to delaminate on either side of the tear, because the yarns will pull out of their crimped positions in the basic fabric, pushing the coating away from the base fabric.
6. Where damage due to moisture has occurred, there is a markedly different appearance. Fibers at the tear will be discolored, and will break with very little extension on either side of the tear. The coating will not delaminate, because the weakened yarns will break locally rather than pull to the point that delamination is caused.

## **TEST PROGRAM**

Because of the apparent pre-existing damage to the fabric at the location of the tear, and certain other indications of aging on the fabric, a test program was developed to determine:

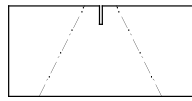
1. If there was any unusual age-caused or other weakness in the existing fabric,
2. If so to what degree, and
3. The influence of the apparent scratch on the failure.

Figure E3 is an enlarged portion of Figure E1, showing where the test samples were removed from the failed triangle panel. Figures E4 and E5 are photographs of the actual test sample locations.

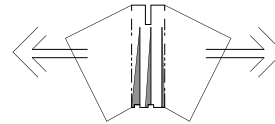
Except as noted below, the fabric tests were performed using the general methodology of ASTM D-4851. Two types of tests were performed:

1. Dry strip tensile strength: The strip tensile strength of fabric is measured by pulling to failure 1" wide x 12" long specimens, five for each test. The reported strength for each test is taken as the average of the five specimens and reported as force per unit width, e.g. pounds per inch.
2. Trapezoidal Tear (ASTM D-5587): The trapezoidal tear strength is tested by pulling to failure a 76.2mm x 152.4mm (3" x 6") piece of fabric cut and clamped so as to place all of the force on one edge, at a notch; see figures following. This mimics the propagation of a

tear in the membrane, and provides both objective and subjective information as to the resistance to tearing of any particular piece or style of fabric. See the following figures:



notched sample coupon



folded and pulled coupon

Strength tests were performed on samples from two different areas of the roof; test results are shown in Tables E2.1 and E2.2. A series of samples from the edges of the separated fabric panel and close to the tears was tested under the direction of Harvey West, P. Eng., a principal with Baker Engineering of Vancouver. Birdair, Inc, the fabric roof contractor who made the repairs and provided the replacement triangle panel, tested an additional set of samples from the main segment piece of the triangle panel.

Because of the very nature of a tear, it was not possible to obtain either the number of samples desired, nor at the locations most desired. Areas requiring interpolation or extrapolation outside of what would ordinarily be considered good practice include:

1. The tear itself, particularly near the supposed point of initiation. Ideally, one would have a measure of tension strength across the tear, but this is clearly not possible. Instead, strip tensile tests were made with the long edge parallel to the tear, ie testing tension strength on the fill rather than the warp yarns, in the hope that we could at least qualitatively demonstrate if there was a loss of strength at the tear. In this instance, only the strips closest to the tear are relevant.
2. Near the cable clamps. As can be seen from Figures E4 and E5, the location and nature of the tear vary along the length of the joint, implying that the inferred damage varies as well. The weakest areas seem to be at or under the cable clamps. However, there is not enough material remaining at those exact locations to make any sort of direct test. Again, we must extrapolate to the damaged areas from the nearest available test locations.
3. Near edge clamps. The room available permitted strip tensile tests only in the fill direction, not in the warp direction, whereas the latter is more directly related to this type of failure.
4. At all tests performed on samples taken from the zones damaged either before the deflation or during the deflation, there are not enough samples to enable a statistically valid analysis. In Table E3, we have given an indication of the range and the expected minimum strengths from a large sampling. However, these are indications only.

## TEST RESULTS

Summaries of the results from the two groups of tests are presented as Tables E2.1 and E2.2. The results from three tests are shown, as being most pertinent to the observed modes of failure in the triangle panel: dry strip tensile strength, trapezoidal tear strength, and seam lap strength. Four or five samples of the roof fabric from various significant areas of the failed roof panel were tested for each. The test locations in the fabric panel are described in Figures E3, E4 and E5.

For each panel test location the results presented in Table E2.1 and Table E2.2 are the average strength value and the lowest value. These same results are then presented as a percentage of the specified strength of the fabric. Table E3 provides a summary the test data analysis,

computing the test averages, standard deviations and the averages less 2 x the standard deviation. Certain general observations may be made from the strip-tensile test results:

1. The control strength in the middle of the panel (Birdair) tested about 120% to 125% higher than the original specified values; nearer the failure areas (Baker) the average values are about 15% higher than specified, but the minimums are 25% lower indicating significant variability.
2. The control strength in the fill direction near the edges of the panel is about the same as in the center of the panel. Control warp-direction tests near the edge of the panels are not available, due to the difficulty of locating acceptable sample locations.
3. The strip tensile strength of the base fabric where material was field-welded to it at the fabric joint cover is significantly reduced to 60% of the control strength in the warp direction, and 70% in the fill direction.
4. Near the ring beam edge (series 4X, 5X and 6X) the test group averages are similar to the values in the Birdair warp-direction tests. However, the individual sample values adjacent to the tear are lower, in particular values for series 6X.

Additionally, a visual examination of the photographs at the edge clamps and cuffs shows a number of discolorations and small random tears.

**TABLE E2.1**

**RESULTS OF TESTS CONDUCTED BY BIRDAIR STRUCTURES**

Note: All samples were taken from an area near the center of the panel, away from damage.

1L-ST	174.9	999	162.9	930.0	140.1	800	125%	116%	
1X-ST	149.7	855	136.6	780.0	122.6	700	122%	111%	
2L-TT	316	71	280	63	267	60	118%	105%	
2X-TT	449	101	409	92	356	80	126%	115%	
3X-ST	160.2	915	154.1	880.0	70.0	400.0	**	**	Across welded joint. (** the test performed is not directly comparable to the above.)
3L-ST	132.0	754	122.6	700.0	61.3	350.0	**	**	

**TABLE E2.2**

SUMMARY OF TEST RESULTS ON FABRIC SAMPLES TAKEN 9 JAN. 2007

LEGEND  
 1st Number = Test Set Number  
 1st Letter = Test Pull Direction L=warp, X=Fill  
 2nd Letter(s) = Test Type ST= Strip Tensile  
 TT=Trapezoidal Tear

(NOTE: See Figure E3 for locations of test sets)

RESULTS OF TESTS CONDUCTED BY BAKER ENGINEERING

MARK	TEST: (AVE) N/mm	TEST: (AVE) PLI	TEST (MIN) N/mm	TEST (MIN) PLI	DESIGN SPEC N/mm	DESIGN SPEC PLI	AVE TEST/ SPEC (%)	MIN TEST/ SPEC (%)	LOCATION
1L-ST	163.4	933	105.9	605	140.1	800	117%	76%	Center area of detached segment
1X-ST	139.0	794	87.7	501	122.6	700	113%	72%	
2L-ST	97.7	558	67.9	388	140.1	800	70%	49%	Along diagonal edge of detached segment
2X-ST	98.4	562	85.5	488	122.6	700	80%	70%	
3X-ST	90.0	514	62.0	354	70.0	400	129%	89%	Across welded joint
4X-ST	179.5	1025	160.8	918	122.6	700	146%	131%	Control: Bottom edge
5X-ST	169.2	966	159.9	913	122.6	700	138%	130%	Outboard edge of tear along bottom edge of ring beam
6X-ST	133.4	762	94.0	537	122.6	700	109%	77%	Outboard edge of tear along bottom edge of ring beam
1L-TT	320	72	307	69	267	60	120%	115%	In field of detached segment
1X-TT	378	85	360	81	334	75	113%	108%	
2L-TT	276	62	258	58	334	75	83%	77%	Along diagonal edge of detached segment
2X-TT	334	75	320	72	311	70	107%	103%	
4L-TT	311	70	285	64	311	70	100%	91%	At joint at flap

**SAMPLE NOTES, TABLE E3**

- 1L 1-5 Control
- 1X 1-5 Control
- 2L 1-5TT Control
- 2x 1-5TT Control
- 2L 1-5 Discoloration

Appendix E: Fabric Tests & Results

12 October 2007

2X 1-5        Discoloration  
 2LTT 1,4,5    Discoloration 2 3 damaged  
 2XTT 1,3,4    Discoloration 1 2 5 damaged  
 3X, 3-L        Nothing abnormal  
 4X             1-3 across heat stain, 4-6 are control  
 4LTT            1-3 are in stain, 4 - 6 are control  
                - notch is parallel to tear  
 5X             1&4 are adjacent to tear  
 6X             1&4 are adjacent to tear

**TABLE E3**

ANALYSIS OF TEST RESULTS ON FABRIC SAMPLES TAKEN 9 JAN. 2007

**Strip Tensile (ASTM D5035)**

Specimen	Load N/m m	Load (pli)	Load N/mm	Trap Tear Specimen	Load N	Load (lbs)	Load N
1L - 1	169.7	969	Ave = 163	1L-1TT	311	70	Ave = 322
1L - 2	105.9	605	Std 34	1L-2TT		78	Std Dev 17
			Dev =		348		=
1L - 3	187.2	1069	Ave - 96				Ave - 288
			2*Std	1L-3TT	311	70	2*Std
			Dev =				Dev =
1L - 4	188.5	1077		1L-4TT	309	69	
1L - 5	165.5	945		1L-5TT	330	74	
1X - 1	140.4	802	Ave = 139	1X-1TT	360	81	Ave = 375
1X - 2	114.2	652	Std 41	1X-2TT			Std Dev 15
			Dev =		393	88	=
1X - 3	87.7	501	Ave - 57	1X-3TT			Ave - 344
			2*Std				2*Std
			Dev =		387	87	Dev =
1X - 4	157.3	898		1X-4TT	372	84	
1X - 5	195.9	1119		1X-5TT	360	81	
2L - 1	106.3	607	Ave = 98	2L-1TT	276	62	Ave = 277
2L - 2	107.0	611	Std 17	2L-2TT		65	Std Dev 13
			Dev =		288		=
2L - 3	106.7	610	Ave - 64	2L-3TT		57	Ave - 250
			2*Std				2*Std
			Dev =		254		Dev =
2L - 4	67.9	388		2L-4TT	283	64	
2L - 5	100.6	575		2L-5TT	283	64	
2X - 1	91.5	523	Ave = 98	2X-1TT	315	71	Ave = 331
2X - 2	101.3	579	Std 10	2X-2TT		72	Std Dev 20
			Dev =		321		=
2X - 3	85.5	488	Ave - 78	2X-3TT		71	Ave - 291
			2*Std				2*Std
			Dev =		316		Dev =
2X - 4	102.8	587		2X-4TT	344	77	
2X - 5	110.8	633		2X-5TT	360	81	

Appendix E: Fabric Tests & Results

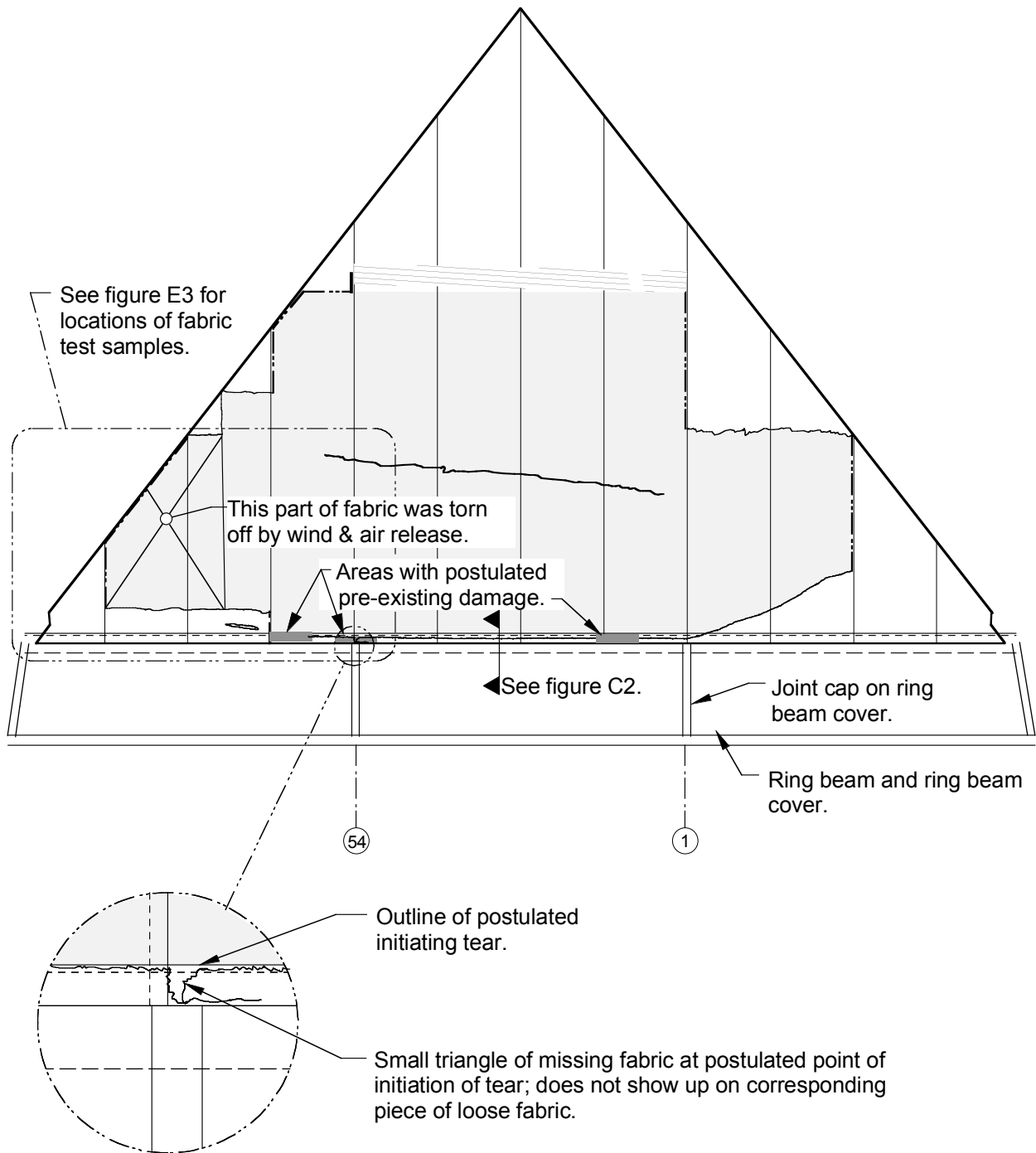
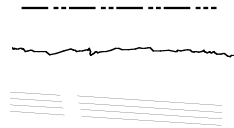
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3X S - 1	<b>62.0</b>	354	Ave =	90	4L-1TT	283	64	Ave =	315
3X S - 2	<b>88.0</b>	502	Std	29	4L-2TT		68	Std Dev	24
			Dev =			303		=	
3X S - 3	<b>120.1</b>	686	Ave -	32	4L-3TT		68	Ave -	267
			2*Std					2*Std	
			Dev =			301		Dev =	
					4L-4TT	343	77		
4X - 1	<b>172.1</b>	983	Ave of	177					
			(4X-						
			1&4X-						
			4)			343			
4X - 2	<b>192.1</b>	1097	Ave =	182	4L-5TT	318	72		
4X - 3	<b>187.7</b>	1072	Std	13					
			Dev =						
4X - 4	<b>182.7</b>	1043	Ave -	156					
			2*StdD						
			ev =						
4X - 5	<b>160.8</b>	918							
4X - 6	<b>195.1</b>	1114							
5X - 1	<b>159.9</b>	913	Ave of	174					
			(4X-						
			1&4X-						
			4)						
5X - 2	<b>163.1</b>	932	Ave =	169					
5X - 3	<b>167.5</b>	956	Std	10					
			Dev =						
5X - 4	<b>188.1</b>	1074	Ave -	149					
			2*StdD						
			ev =						
5X - 5	<b>170.7</b>	975							
5X - 6	<b>165.4</b>	945							
6X - 1	<b>94.0</b>	537	Ave of	115					
			(4X-						
			1&4X-						
			4)						
6X - 2	<b>160.7</b>	918	Ave =	133					
6X - 3	<b>121.8</b>	696	Std	24					
			Dev =						
6X - 4	<b>135.9</b>	776	Ave -	86					
			2*StdD						
			ev =						
6X - 5	<b>153.8</b>	878							
6X - 6	<b>133.8</b>	764							

Seam tear; formed either by tearing at the edge of the seam, or by separation of the two layers of fabric across the full width of the seam.

A tear across or along the fabric, not along a seam.

Fabric remained connected along this line.



**Figure E1: Plan Of Damaged Triangle Panel**

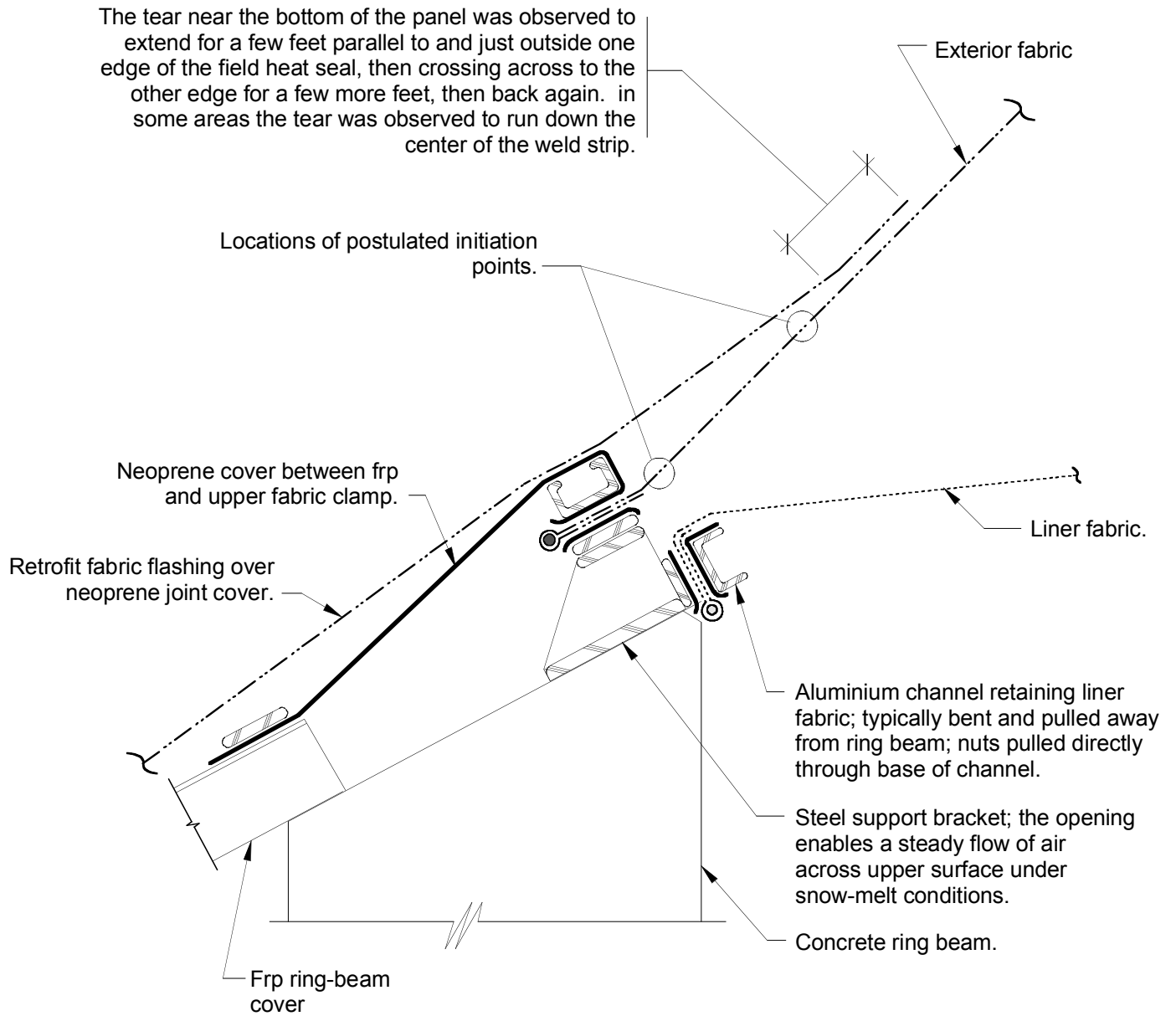


Figure E2: Triangle Panel Attachment at Ring Beam

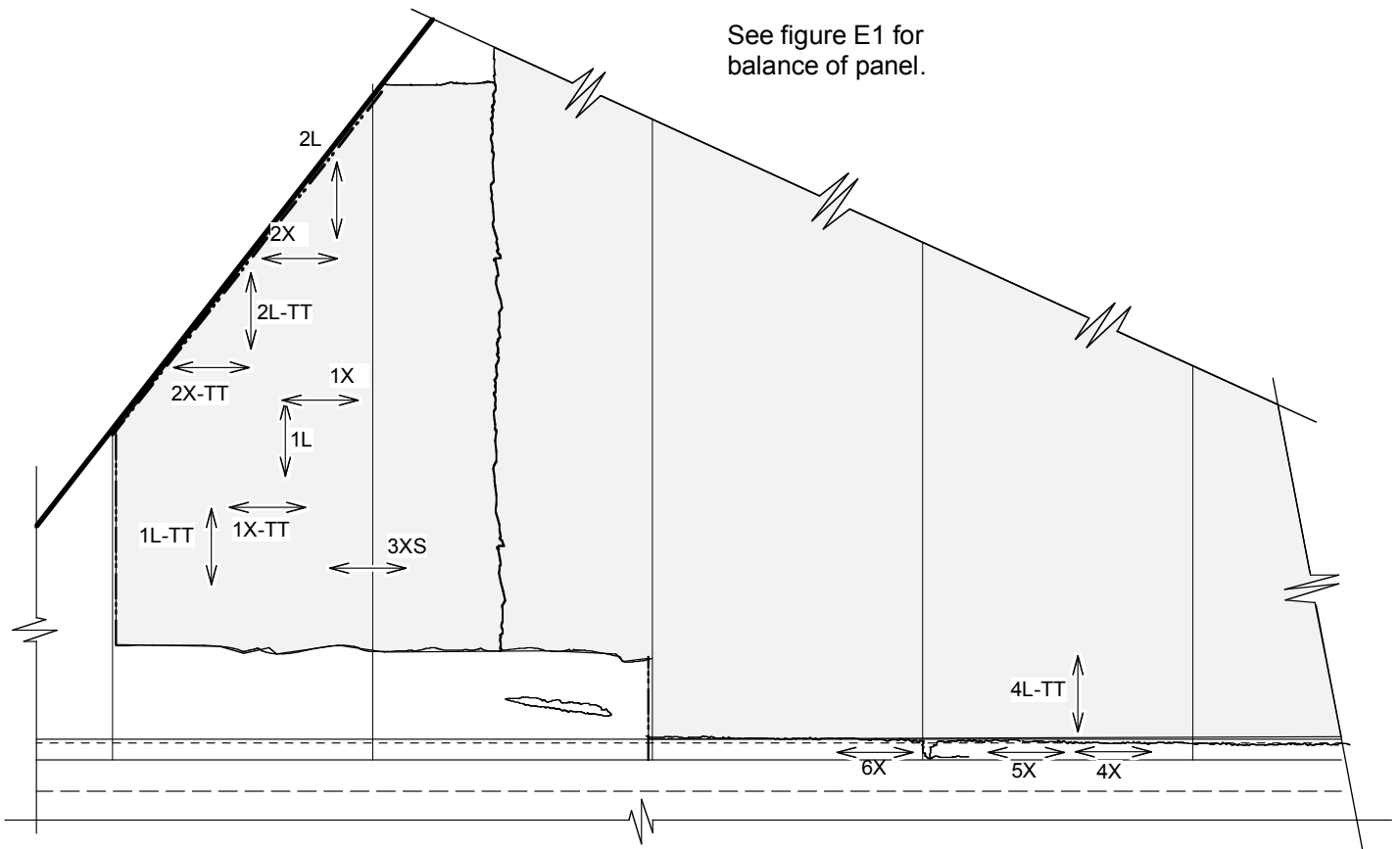


Figure E3: Location Of Fabric Test Samples

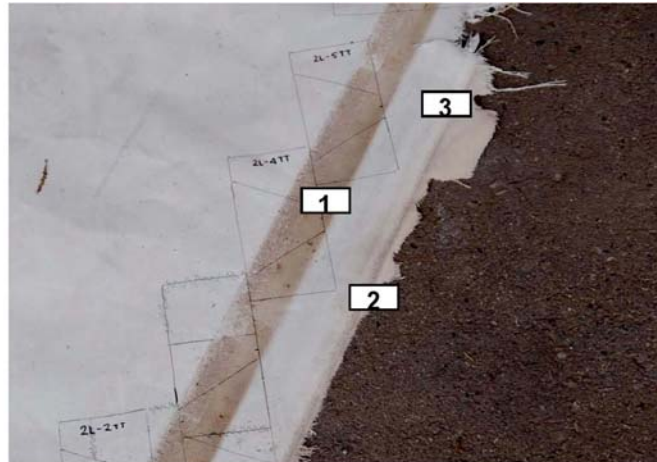


Figure E4-1: Samples 2L-TT

- 1 Darker discolored strip is field heat seal for the post-installed fabric flashing, which has pulled away.
- 2 Lighter discolored area was under edge clamp. Short fibers and irregular tear indicate weakened glass yarn
- 3 Distorted edge of a clamping bolt hole



Figure E4-2: Samples 2X, 2L-TT Triangular notch does not correlate with anything on adjacent fabric segment. This was possibly removed by a souvenir hunter prior to recovery by BC Place staff.

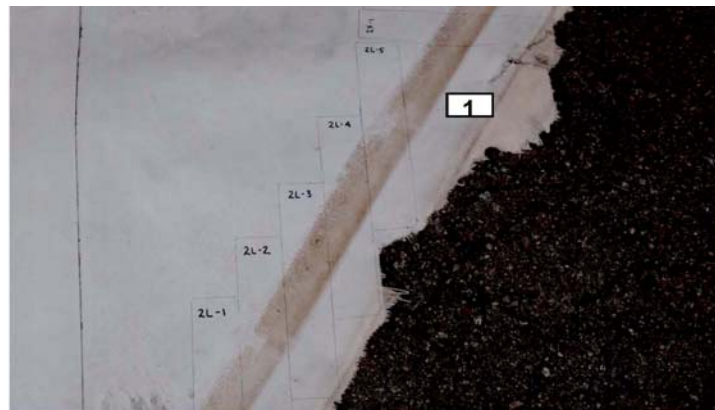


Figure E4-3: Samples 2L, 2X

- 1 Edge of bolt hole at fabric clamp; failure varies from behind clamp at roped edge to front edge of clamp.

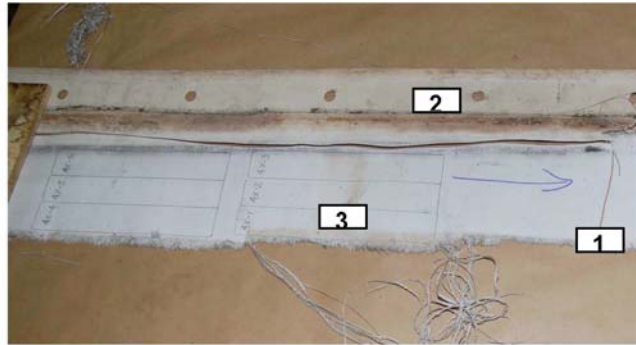


Figure E5-1: Samples 4X

Samples taken between tear at lower edge and ring beam.

- 1 – Shows irregular edge with short, clean yarn. The tear is at the bottom edge of the field weld.
- 2 – Knife cut made in field to remove fabric for sampling; this is not a tear.
- 3 – The edge is discolored at several points, and the corresponding yarns are short.

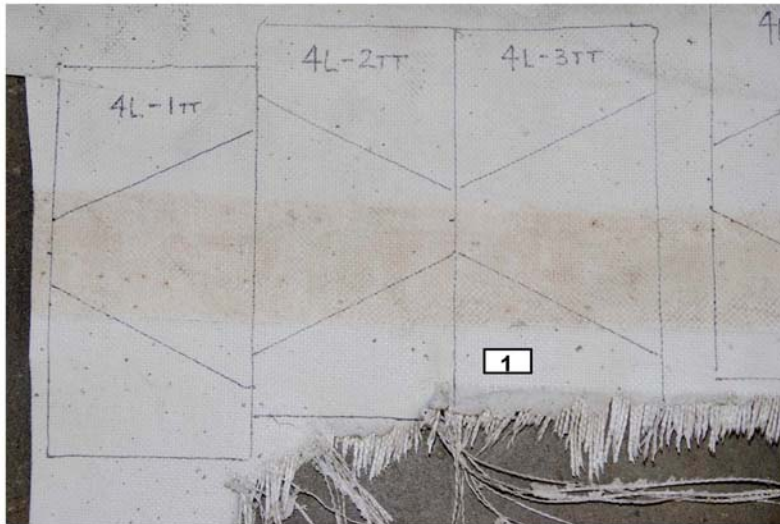


Figure E5-2: 4L-TT

Sample is taken from just above the tear along the ring beam.

- 1 – Note the slight discoloration of yarns at the edge.

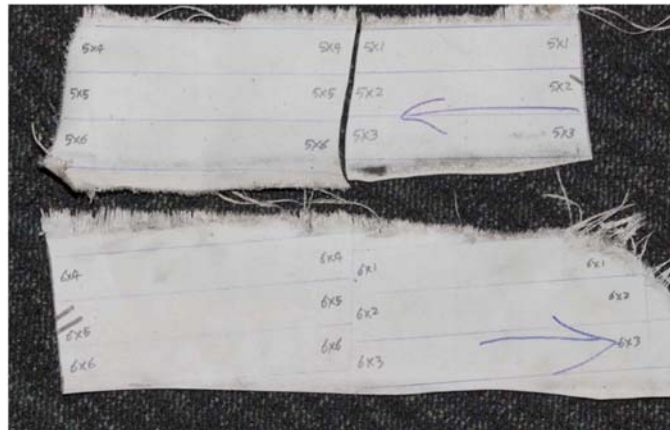


Figure E5-3: Samples 5X, 6X Samples taken from just above the tear.