Minneapolis Metrodome

December 2010 Roof Deflation Assessment

Summary and Recommendations

Prepared for:

Metropolitan Sports Facilities Commission

900 South 5th St.

Minneapolis, MN 55415

Prepared by

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Walter P Moore Project S02.10026.01

February 10, 2011 FINAL REPORT

WALTER P MOORE

February 10, 2011

Mr. Steve Maki
Metropolitan Sports Facilities Commission
900 South 5th Street
Minneapolis, MN 55415

Re: Minneapolis Metrodome
December 2010 Roof Deflation Assessment
Walter P Moore Project No. S02.10026.00

Dear Mr. Maki:

We have completed our assessment of the condition of the roof structure of the Minneapolis Metrodome following the December 12, 2010 roof deflation. The attached report contains our findings and recommendations regarding the extent of restoration required to the roof tensile membrane material. A future report will address detailed recommendations for specific features and engineering requirements implemented in the roof restoration process.

We very much appreciate the opportunity to assist you with this important evaluation process. Please do not hesitate to contact us should you have any questions on our recommendations or require further assistance with any aspect of the restoration process.

Sincerely,

WALTER P. MOORE AND ASSOCIATES, INC.

PROFESSIONAL ENGINEER
I hereby certify that this plan, specification or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws in the State of Minnesota.

Signature ____________

Typed or Printed Name Ruben Martinez

Date 2/10/2011 License # 41753

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EXECUTIVE SUMMARY

Walter P Moore has conducted an independent assessment of the condition of the Metrodome roof structure following the December 12, 2010 deflation event. The Metrodome roof consists of an air-supported tensile membrane structure restrained by a cable net system anchored to a perimeter ring beam. Though we have evaluated the condition of the steel cable and aluminum clamping system as well, the focus of our assessment has been on the condition of the tensile membrane fabric material as the critical element for which there remains uncertainty in safety during the restoration process.

We have concluded that the entire roof membrane must be replaced. Further, were Walter P Moore acting in the role of Engineer of Record for the Metrodome roof restoration, we would not be able to certify that the roof membrane meets industry standard levels of safety without a complete replacement of the roof membrane

Our assessment is based upon our own visual observations, results of fabric sample testing, review of the Birdair detailed visual survey, consideration of further damage in the deflated condition, and various forms of qualitative and quantitative risk analysis we have conducted on the roof. Taken together, our findings suggest an unacceptable level of risk for future deflation events without complete replacement of tensile roof membrane.

When evaluated as individual panels alone, in addition to the four failed diamond panels and one failed triangular panel, our evaluation has identified 26 diamond panels, 22 rectangular panels, and 9 triangular panels as unacceptable. This represents approximately 60 percent of the roof panels. Due to a considerable risk of undetected flaws in the remaining panels caused by prolonged moisture exposure and wind flutter in the deflated condition, we recommend a full replacement of the fabric roof system.

Detailed recommendations for specific features and engineering requirements implemented in the roof restoration will be addressed in a separate future report.

LIMITATIONS

This report has been prepared for the sole purpose of assisting the Metropolitan Sports Facilities Commission in evaluating the structural condition of the roof structure of the Metrodome following the roof deflation that occurred on December 12, 2010. It has been prepared on behalf of and for the exclusive use of the Metropolitan Sports Facilities Commission. The report is based on a limited investigation of the main roof elements including the perimeter ring beam, primary cables and tensile membrane covering the roof. The investigation has concentrated on the condition of the PTFE fiberglass tensile membrane following the December 2010 deflation event. A future report will address our recommendations regarding design and performance of the restored roof condition.

The original design of the Metrodome was performed by Geiger Engineers acting as Engineer of Record for the structural design of the roof. The scope of this report has not included a Peer Review of the original structural design performed by Geiger Engineers. The responsibility for the structural design of the roof structure rests solely with the original Engineer of Record.

Walter P Moore and Associates, Inc has made every effort, in the limited time available for the MSFC to make a decision regarding the future status of the roof structure, to identify areas of structural concern of the roof structure using all information available and presented to us during the investigation period. If there exist any perceived omissions or misstatements in this report regarding the observations made, we ask that they be brought to our attention as soon as possible so that we have the opportunity to fully address them in a timely manner.

This report and the findings herein shall not, in whole or in part, be disseminated or conveyed to any other party or used or relied upon by any other party without prior written consent of Walter P Moore and Associates and the Metropolitan Sports Facilities Commission.

SUMMARY OF FINDINGS

Note: full size images attached in Appendix A.

Figure 1: Roof Model Inflated

Figure 2: Roof Model Deflated Position

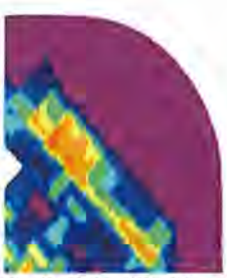

Figure 3: Deflated Position Fabric Stress Results

Our recommendations are based upon evaluation of both the deflated condition as well as consideration of future performance of the re-inflated roof. Detailed evaluation has been conducted in four separate parts, each documented in a separate report. Findings of each evaluation are summarized below.

Part 1 – Deflated Condition Analysis

The purpose of the Part 1 study is to evaluate levels of stress experienced by the fabric while the roof held large amounts of snow following the December 12 deflation. By relating predicted stresses to the normal allowable stresses of the material, areas of overstress can be identified as likely candidates for damage or other detrimental effects of the heavy snow loading. This analysis only considers the effects of the large snow loads held on the roof for roughly two weeks until clearing by melting was completed, and does not address the dynamic effects of the snow shifting during the deflation itself. It is likely that short term dynamic stresses during the deflation event were higher than those found in our static study.

On December 17, a laser scan of the underside of the deflated roof was conducted by Clark Engineering. This scan provided documentation of the deformed condition of the roof for the areas accessible to the scan. Using the original project specification cable geometry, inflation pressure, and prestress values, an independent model of the roof was built in the baseline inflated condition (Figure 1). This model was then loaded to invert it into the deflated position (Figure 2). Loads were then applied to each panel between cable lines until the deformations of the model reasonably matched those observed in the laser scan. The resulting fabric stresses (Figure 3) have been evaluated against normal allowable stresses. Various modeling sensitivity studies were also performed.

Our findings show that a number of the more heavily loaded panels experienced stresses above normal allowable values. However, where overstresses occurred the predicted stresses are generally less than the expected fabric strength excluding safety factors, which explains why these particular panels did not fail following the deflation event. Though


Figure 4: Biaxial Test Setup


Figure 5: Panel 72 Biaxial Test

overstress alone cannot be directly concluded to compromise panels, it is a strong indication of the presence of potential damage. Overstressed panels have been the subject of further detailed physical testing and visual observation as described in Parts 2 and 3 respectively.

Part 2 – Review of Testing

As of the date of this report, fabric test samples from 9 locations in the roof have been removed and tested. Standard strength tests have been conducted at all samples, and biaxial stiffness tests (Figure 4) have been conducted on four of the samples. A benchmark biaxial test was also conducted on similar virgin fabric material. At some sample locations, prior test results from the original roll tests, the 2003 Birdair weathering tests, and the April 2010 Birdair weathering tests were available for comparison. A microscopic evaluation of the fabric material from one of the more heavily loaded panels was also conducted. A detailed description of all tests conducted during this study can be found in the Part 2 report.

While much of the testing generally showed favorable results as compared to the original project specification, other tests indicated that the strength of some areas of fabric may be severely compromised. The circa-1980 material specification for the Sheerfill II material is known to be rather conservative, so to evaluate actual material strength retention the test results have also been compared to the actual original roll test results, the 2003 Birdair weathering tests, and the 2010 Birdair weathering tests. While strength retention was found to be within expectations for base strip tensile strengths, a strength drop-off was observed in flexfold tensile and tear tests. The flexfold tensile test measures strength following creasing, which is highly relevant due to the large number of observed creases imposed by snow and ice chunks, as well as creases caused by wind flutter in the deflated position. The tear tests are also particularly important because most fabric failures initiate as tears.

Of particular interest are several very low tear test results at Panel 72, followed by the failure of a biaxial test (Figure 5) of material from the same sample at a very low load. Such correlated test results are indicative of base yarn material damage, which is likely caused by exposure to moisture.


Figure 6: Typical Tear Damage


Figure 7: Typical Exposed Yarn


Figure 8: Typical Roof Moisture Retention


Figure 9: Creasing Caused by Wind Flutter

If the outer protective PTFE coating is damaged such that water in sufficient quantities is allowed direct access to the underlying glass yarns, a mechanism forms that rapidly breaks down the glass yarn. Given the numerous abrasions caused by sliding snow and ice, combined with the prolonged exposure to captured moisture in the deflated position, yarn moisture damage is a major concern. Such damage is not necessarily easily identified visually, as was the case at the Panel 72 sample which showed no visual signs of damage.

Due to the limited time available to take samples and conduct tests, it is not possible to take a sufficient number of test samples to definitively identify all possible yarn moisture damage. Two subsequent tests that attempted to sample material from conditions similar to Panel 72 did not replicate the ver low test results. Nonetheless, the potential for distributed yarn moisture damage is high and has been validated by one test out of the nine taken, an ominous ratio if extrapolated to the full roof. The full body of test results is generally insufficient taken alone and requires consideration in conjunction with the visual survey discussed in Part 3.

Part 3 – Review of Visual Survey and Risk Assessment

A complete visual survey of the roof condition has been performed by specially trained high rope access fabric inspectors employed by Birdair, Inc. Detailed indexed photographic reports have been provided to Walter P Moore for independent evaluation.

In general, the visual survey indicates that the condition of the fabric material is poor. Numerous cuts, abrasions, scratches, tears (Figure 6), and exposed yarns (Figure 7) were observed. In addition, long-term retained water (Figure 8) in the deflated position was observed on numerous panels. Widespread creasing both from snow sliding as well as subsequent wind flutter (Figure 9) was observed. All observed conditions have been cataloged on a panel by panel basis and are shown in Part 3 of the report.

Birdair, who is the original roof builder, conducted an inspection of the Metrodome roof fabric in April 2010. During this inspection the condition of the fabric was rated by Birdair as "Good-Fair". A limited number of areas in need of minor repairs were observed. Following the deflation visual survey, however, the diamond panels have downgraded to "Fair-Poor" and the rectangular and triangular panels have been downgraded to "Poor".

In order to provide a rational basis for categorizing the observed damage, we have conducted a qualitative risk assessment of the fabric damage on a panel by panel basis. A risk assessment provides a means to relate the likelihood of certain undesirable events, primarily an in-service fabric material failure of various sizes, to the consequence of the event, up to and including full roof deflation. Based on the number of flaws observed in particular panels, a qualitative rating can be established that relates to the likelihood of flaws occurring in the panel. Various failure scenarios and corresponding consequences are then postulated, allowing a qualitative evaluation of risk.

The results of the risk analysis identify 26 diamond panels, 22 rectangular panels, and nine triangular panels that we recommend for replacement, in addition to the four diamond panels and one triangular panel that have already failed. This represents approximately 60 percent of the panels. Because statistically significant testing data is not available, the risk assessment is necessarily qualitative and somewhat subjective based on engineering judgment of acceptable risk levels. A more quantitative analysis approach is discussed in Part 4 below.

Part 4 – Quantitative Reliability Analysis

In order to provide a more quantitative analysis to supplement the qualitative findings of the Part 3 risk assessment, a reliability analysis of the roof panels has been conducted. In this analysis, flaws existing in the roof are treated statistically as a randomly distributed variable scaled to certain reasonable flaw sizes. The probability of a flaw of a critical size occurring spatially at the same location as stress of a level that would lead to failure is simulated using a statistical analysis process known as Monte Carlo

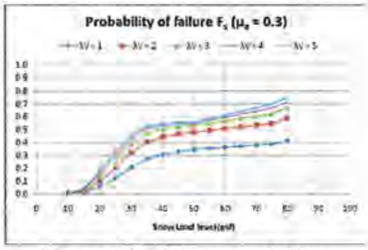

Figure 10: Representative Reliability Analysis Results

simulation. In this simulation, a large number of possible scenarios are evaluated rapidly using a computer program and then the outcome set is analyzed statistically. Several hundred thousand simulation scenarios have been run considering both snow and wind loading scenarios in the inflated condition. A detailed description of the reliability analysis can be found in the Part 4 report.

The results of the reliability analysis (Figure 10 representative) show levels of risk of future deflation in the presence of distributed flaws that exceed normal acceptable levels referenced in the structural building codes and standards. Note that if all currently existing flaws in the roof could be identified and repaired, the risk levels would reduce to normal acceptable levels. However, in our opinion it is not practical to conduct the reviews necessary to ensure confidence that all flaws have been identified in a reasonable timeframe. Instead, the reliability analysis provides a tool for evaluating the potential risks of a future deflation if it is not possible to identify and repair all fabric damage and flaws.

Consideration of Disproportionate Collapse

The industry standard document for general requirements and loading criteria for structures is ASCE 7-05, "Minimum Design Loads for Buildings and Other Structures". Section 1.4 of ASCE 7-05 addresses general structural integrity and is reproduced below:

> **1.4 GENERAL STRUCTURAL INTEGRITY**
>
> Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage. This shall be achieved through an arrangement of the structural elements that provides stability to the entire structural system by transferring loads from any locally damaged region to adjacent regions capable of resisting those loads without collapse. This shall be accomplished by providing sufficient continuity, redundancy, or energy-dissipating capacity (ductility), or a combination thereof, in the members of the structure.

The intent of this provision is to require the designer to consider potential accidental actions beyond the normal prescriptive load requirements and evaluate certain actions that may cause widespread damage disproportionate to the initiating damage. This phenomenon is also referred to as progressive collapse, and can be characterized as rapid spread of local damage to the global extents of the structure before the system can be stabilized by intervention.

Air-supported fabric structures are particularly vulnerable to disproportionate collapse. When local areas of the fabric contain damage caused by debris impact, local overload in snow conditions, or undetected prior damage, in the presence of a critical stress under externally applied loads the extent of damage will rapidly spread by tearing. When the size of the damage reaches a sufficient size the roof as a whole can no longer hold the inflation pressure and will deflate entirely.

In the original design the consideration for disproportionate collapse was to design the cable net and ring beam to be in the inverted position with a design level uniform snow of 25 pounds per square foot. This protects the cables and ring beam from damage in a deflation, and in fact controlled the original design for these elements. However, as can be seen from the current situation, when the roof is inverted the fabric itself is highly exposed to further damage. In addition, there are significant economic implications to the MSFC and its tenants in loss of use of the building until it can be re-inflated.

Given the sensitivity of the global structural system to disproportionate collapse caused by localized damage, the careful consideration of the possibility of undetected localized damage should the existing membrane be re-inflated takes on heightened concern. A single undetected flaw is capable of causing a future deflation. Considering the damage caused by the initial deflation followed by subsequent exposure to the vulnerable deflated position, in our opinion there is a high global risk of the presence of undetected local damage.

RECOMMENDATIONS

Though Walter P Moore is not the responsible Engineer of Record for the Metrodome roof restoration, our recommendations are made considering the obligations of a Professional Engineer in the State of Minnesota to the public safety. Our restoration recommendations are based upon the evaluations described above. They include review of the physical test results of existing fabric, analytical results of fabric stresses using estimated actual snow loading, extensive visual observations of actual fabric panels and a quantitative reliability analysis based on observed flaws. Collectively, this information leads us to believe that a significant portion of the existing fabric panels could have suffered damage that compromises their structural integrity to resist future snow and wind load events.

Extent of Restoration

In addition to the four failed diamond panels and one failed triangular panel, our evaluation has identified 26 diamond panels, 22 rectangular panels, and 9 triangular panels that require replacement based on condition assessment alone. These locations have been identified considering the following:

1. Level of loading in the deflated condition.
2. Presence of exposed yarns in combination with prolonged moisture exposure.
3. Observed creasing, tears, and other damage.
4. Physical testing results.
5. Risk of exposure to in-service loads based on panel location.

In addition to directly observable damage, the panels remain at high risk in the deflated condition because the tensile membrane structure is not tensioned by air pressure. Significant "flutter" of the roof panels has been observed at relatively low wind speeds. Such action presents a strong risk for introducing damage to the fabric material due to repeated working of the yarns over a large displacement range. This risk is particularly high directly adjacent to the aluminum clamping system, which is covered by a weather seal and has not been available for direction visual inspection. In order to eliminate this risk, we recommend that the remaining membrane panels also be replaced.

A summary of our recommended restoration extents is as follows:

1. We recommend a full replacement of the tensile membrane roof system.

2. Extensive damage to the inner acoustic liner has been observed. We recommend a full replacement of the inner liner at rectangular and triangular panels concurrent with the external membrane replacement.

3. We recommend that the inner acoustic liner at the diamond panels be removed to allow direct access of heat introduced by the bowl supply system to reach the underside of the fabric. Supplemental acoustic measures may be necessary.

4. Our review of the condition of the cables and ring beam suggests that no remedial work to these elements is required.

5. Local areas of aluminum clamping will require replacement, and should be evaluated in detail as the existing fabric is removed.

Detailed recommendations for specific features and engineering requirements implemented in the roof restoration will be addressed in a separate future report.

CONCLUSIONS

PTFE coated fiberglass roof fabrics are normally quoted to have a 20 to 30 year life before replacement is required. As many of the early fabric structures reach this life, the industry is finding that the life of a well maintained roof can be extended further. While the Metrodome has been well maintained over the years, it has now been deflated for a fourth time in its life. The associated deformations and stress of these events take a heavy toll on fiberglass fabric materials. In addition, the roof has remained in a prolonged deflation condition during which the roof material has been subjected large levels of direct moisture exposure and wind flutter. Therefore, in the interests of public safety, it is our professional opinion that the only prudent course of action is to undertake a full tensile membrane roof replacement of the Metrodome. Our condition and risk assessments described in this report have supported this conclusion. Incorporation of simple measures into the restoration design can enable substantial reductions in the risk of future deflations, leading to a safe spectator environment at the Metrodome.

APPENDIX A

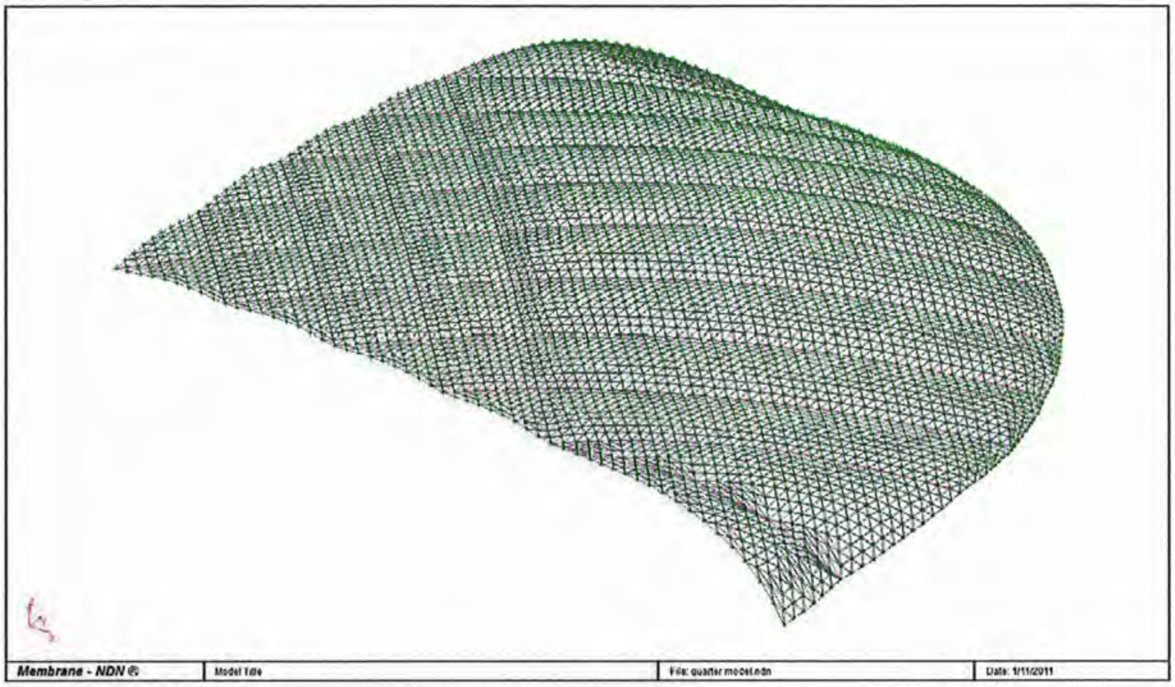

Figure 1: Roof Model Inflated

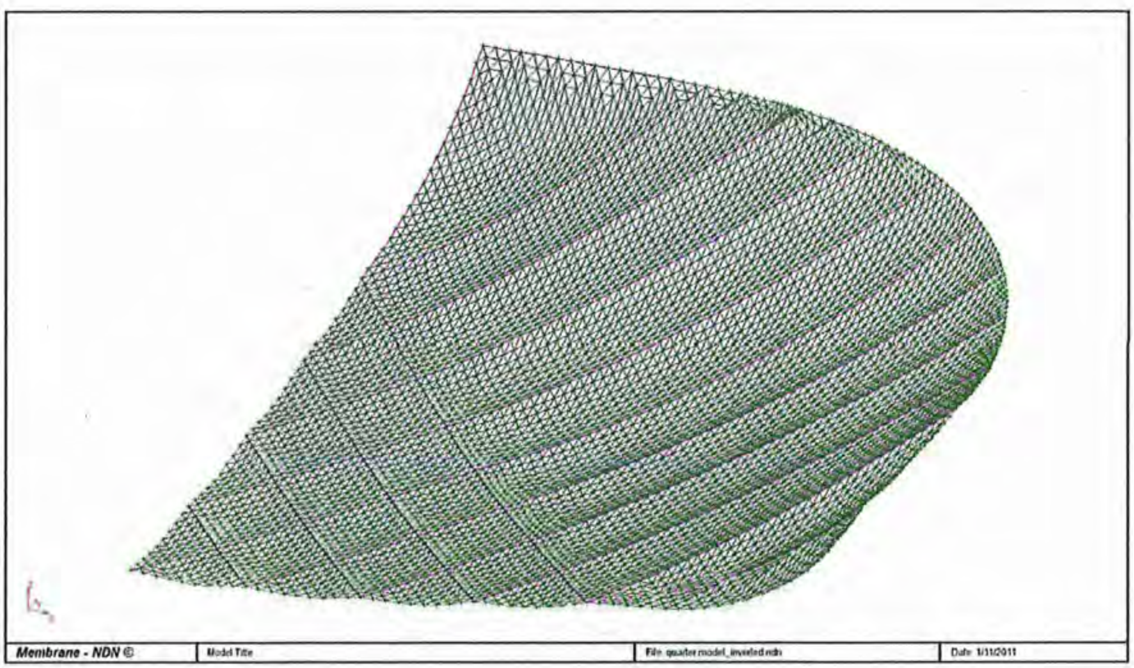

Figure 2: Roof Model Deflated Position

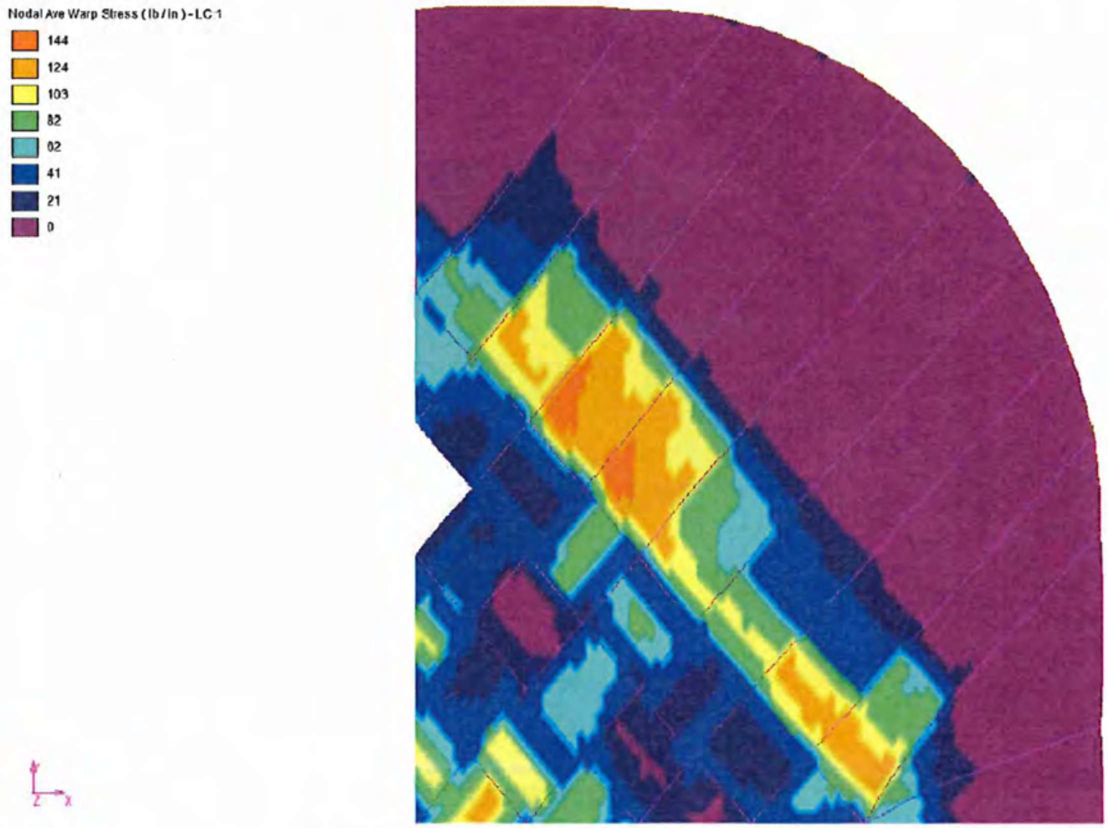

Figure 3: Deflated Position Fabric Stress Results

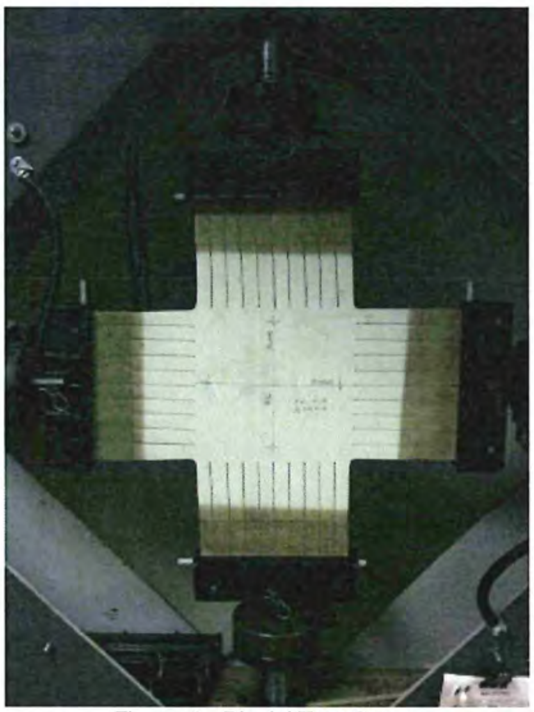

Figure 4: Biaxial Test Setup

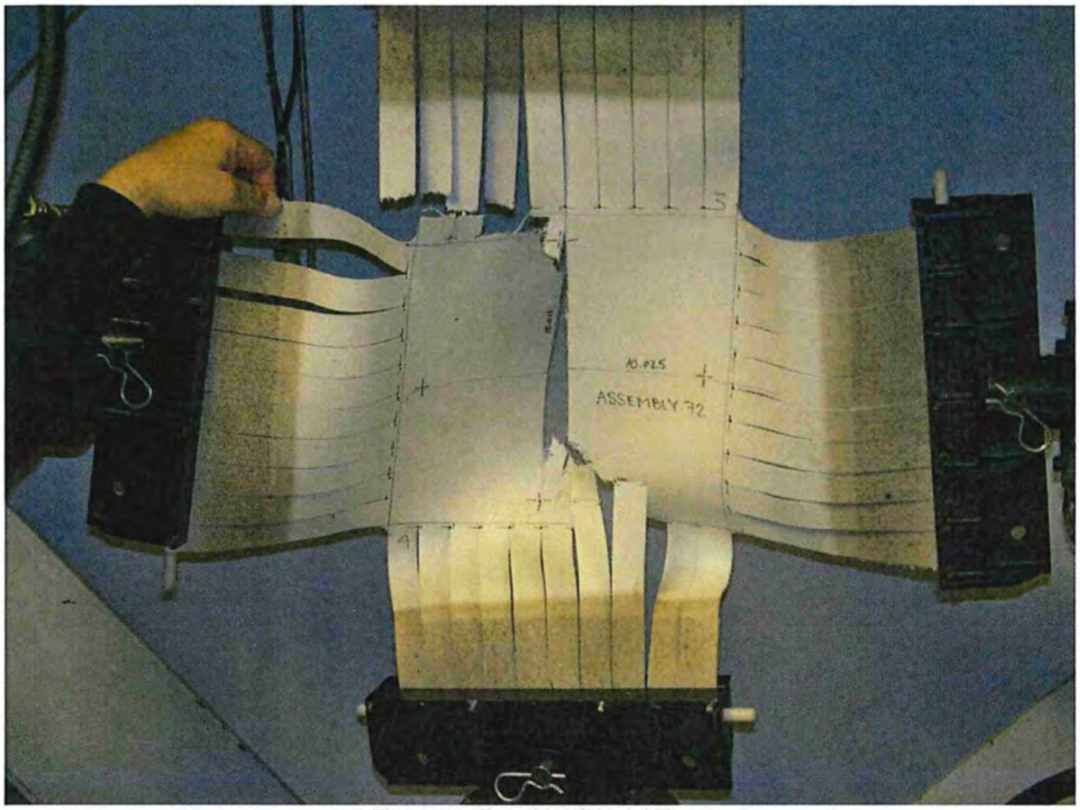

Figure 5: Panel 72 Biaxial Test

Figure 6: Typical Tear Damage

Figure 7: Typical Exposed Yarn

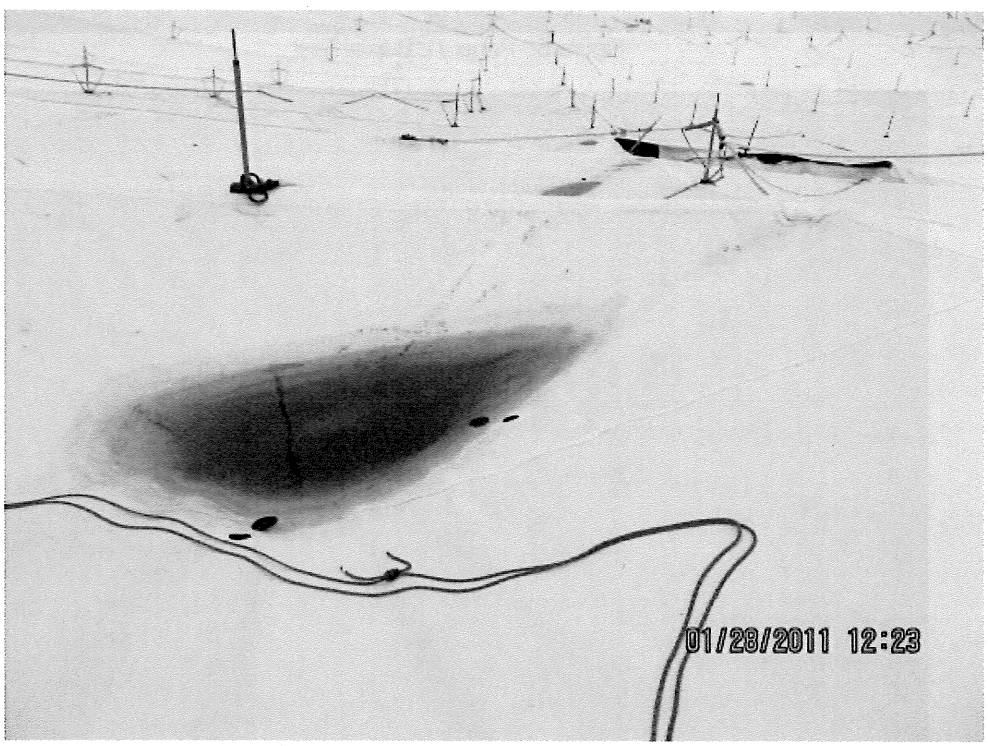

Figure 8: Typical Roof Moisture Retention

Figure 9: Creasing Caused by Wind Flutter

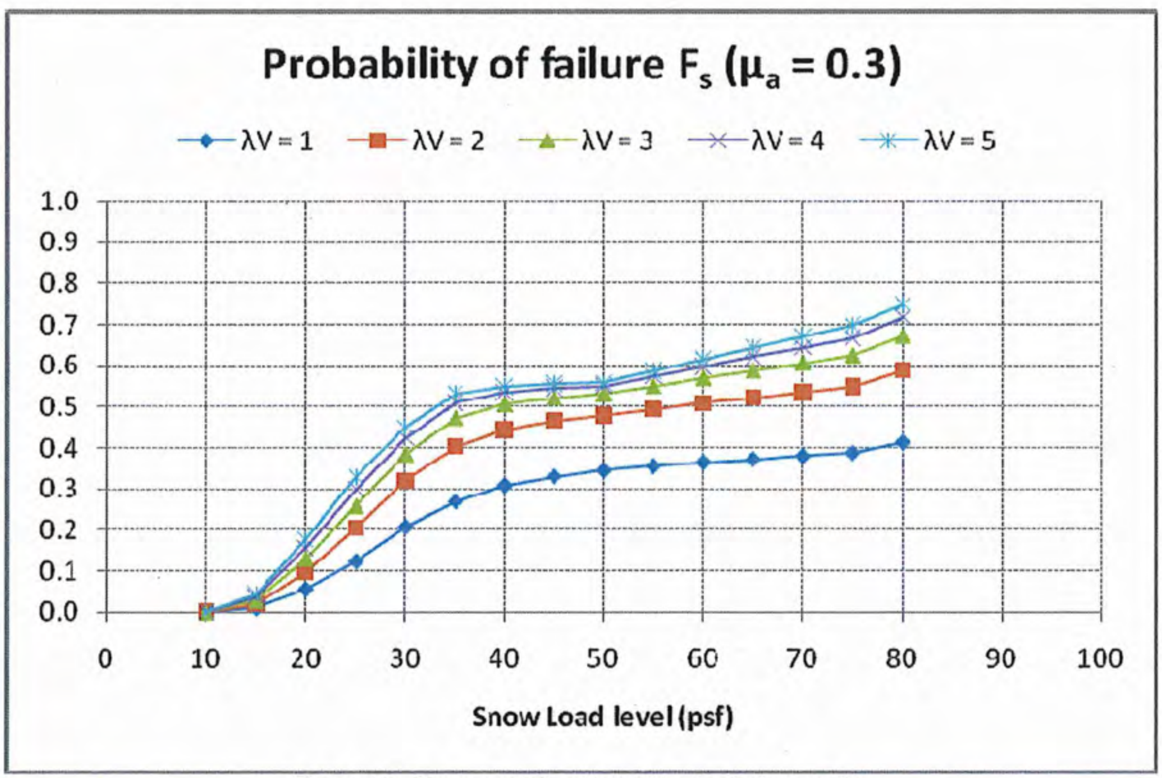

Figure 10: Representative Reliability Analysis Results

Minneapolis Metrodome

December 2010 Roof Deflation Assessment

Part 1

Deflated Condition Analysis

Prepared for:

Metropolitan Sports Facilities Commission

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EXECUTIVE SUMMARY

Walter P Moore has conducted a limited independent assessment of the condition of the Metrodome roof structure following the December 12, 2010 deflation event. This assessment has been performed by Walter P Moore and Associates, Inc. acting as an independent consultant to the Metropolitan Sports Facilities Commission. The purpose of this report is to assist the Metropolitan Sports Facilities Commission in evaluating the condition of the roof structure so that it can make an informed decision about the future use of the Metrodome as it relates to public safety.

Part 1 of our report documents an analytical study of the stresses that the fabric panels were subjected to while heavily loaded by captured snow in the days shortly following the roof deflation. This study allows a quantitative understanding of the condition of the remaining panels by establishing which panels were stressed beyond their normal working limits. This analysis only considers the effects of the large snow loads held on the roof for roughly two weeks until clearing by melting was completed, and does not address the dynamic effects of the snow shifting during the deflation itself.

On December 17, a laser scan of the underside of the deflated roof was conducted by Clark Engineering. This scan provided documentation of the deformed condition of the roof for the areas accessible to the scan. Using the original project specifications from Geiger Engineers, an independent model of the roof was built in the baseline inflated condition. This model was then loaded to invert it into the deflated position. Loads were then applied to each panel between cable lines until the deformations of the model matched those observed in the laser scan. The resulting fabric stresses have been evaluated against normal allowable stresses. Various modeling sensitivity studies were also performed.

Our findings show that a number of the more heavily loaded panels experienced stresses above normal allowable values. However, where overstresses occurred the predicted stresses are generally less than the expected fabric strength excluding safety factors, which explains why these panels did not fail during the deflation event. Overstressed panels have been the subject of further detailed visual observation and physical testing.

INTRODUCTION

Purpose

The purpose of the Part 1 study is to evaluate levels of stress experienced by the fabric while the roof held large amounts of snow following the December 12 deflation. Predicted stress levels in the fabric will be compared to the intended working stress range of the material in the original design in order to identify material that may be have been subjected to extraordinary loading levels and potential associated damage. The results of this study were used to select locations of physical testing as described in Part 2 of our report.

Methodology

The Part 1 study methodology consists of the following steps:

1. Establish the original inflated geometry in a newly built structural analysis model using the NDN program.
2. Using large-displacement analysis, invert the roof to the deflated geometry.
3. Apply snow loading at individual panels to produce a deflection response to match the sag geometry measured through the laser scan by Clark Engineering.
4. Evaluate resulting stresses.

A quarter symmetry model was used to limit the size and analysis time for the models. The model was analyzed for load patterns representing each quadrant.

ANALYTICAL STUDY

Note: full size images attached in Appendix A.

Figure 1 Inflated roof model

Figure 2 Deflated roof model

Quarter Model

Inflated

A quarter model of the stadium roof was prepared in the software program NDN Version 1.54 (authored by Martin Brown) using geometry information from the provided AutoCAD model provided by Geiger Engineers. Only the cable geometry from the Geiger model was used. To achieve better accuracy of stress results, a much finer mesh was created for the fabric panels than given in the original roof geometry documentation. The resulting model was shaped under a internal pressure of 12 psf and cable and fabric prestress as given by the original project specifications to generate a inflated form of the roof (see Figure 1). The resulting geometry was compared to the nodal coordinates provided in the original project specification and found to give good agreement.

Deflated

Analysis was continued by eliminating the internal pressure to generate a deflated shape of the stadium roof as shown in Figure 2.

Membrane properties

Membrane properties assumed for modeling are shown in Table 1 Membrane properties for Sheerfill II. Note that these properties are based on recent testing as modulus testing from circa-1980 was not available.

Table 1 Membrane properties for Sheerfill II

E_W	E_F	ν'_{WF}	ν'_{FW}	G	γ
(pli)	(pli)	(unitless)	(unitless)	(pli)	(psi)
6320	5210	0.589	0.714	353	0.00185

Laser Scan

Figure 4 Panel 22 point coordinates from laser scan

A laser scan of the underside of the Metrodome roof was performed on December 17 by Clark Engineering Corporation. This scan provides a point cloud of survey data at a very fine scale that can be used to establish the deflected geometry of the roof in the deflated position. Due to the time required to take the scan, only one setup location was possible. The setup location chosen provided good vantage points for panels at the East and South sides of the stadium. Panels at the North and West were obscured. Taking laser scans at later days to supplement the December 17 scan was not feasible because of the rapid melting of snow on the roof, which would have led to inconsistent surveys at different dates. Our study has focused on the East and South sides, and the results there have been used to calibrate approximations at the North and West panels based on photographic records. Typical laser scan data is shown in Figures 4 through 7.

Loading criteria

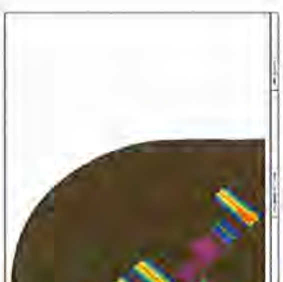

Figure 8 Panels 65-72 load intensity coefficients

A basic load pattern of snow was assumed based on the deformed shape of the panel and the snow observed on the panels. The weight of snow at any one location on the panel varies, generally being highest at the point of maximum observed displacement and lowest near the cable lines. Review of photographs taken simultaneous to the laser scan were also used to guide load selection. Loads on the panels were increased gradually until the deflection of the panels in the models matched that observed in the laser scans. This resulted in about a 70 psf peak snow load at most of the panels. The loading pattern for quadrant with panels 61-72 is given in Figure 8. The loading pattern for quadrant with panels 73-80 is given in Figure 11. The loading pattern for quadrant with panels 81-88 is given in Figure 14. The loading pattern for quadrant with panels 89-96 is given in Figure 17.

It should be noted that the analysis approach taken herein is independent of snow density. By matching the observed displacements, only the total load on the panel is needed. In our opinion estimates of weight using snow volume is subject to a substantial uncertainty.

Figure 3 Fabric panels selected for detailed analysis

Selection of panels

Several panels were selected to calibrate the load levels. The panels selected are shown in Figure 3. Panels selected represent different loading conditions and observed deflections.

- Panel 22 was selected as the diamond panel that visually had the highest amount of snow in a panel that had not been identified for replacement. Laser scan coordinates for this panel are shown in Figure 4.
- Panel 35 was selected as it had a panel missing on one side.
- Panel 46 was selected to represent a number of diamond panels subjected to a triangular loading pattern. Laser scan coordinates for this panel are shown in Figure 5.
- Panel 38 was selected to represent a number of diamond panels with a half panel loading pattern.
- Panel 68 was selected to represent heavily loaded rectangular panels. Laser scan results were most readily available for Panel 68 (Figure 6), but it is representative of conditions at Panels 91 to 96 (laser scan line of sight not available), Panels 83 to 84 (laser scan line of sight not available), and Panels 74 to 78
- Panel 72 was selected as it appeared to be subjected to the most concentrated amounts of snow, ice, and meltwater, and had the highest observed deflections. Laser scan coordinates for this panels are shown in Figure 7.

Summary of analysis results

Analysis results for all panels are listed in Table 5 and are graphically shown in figures as listed below

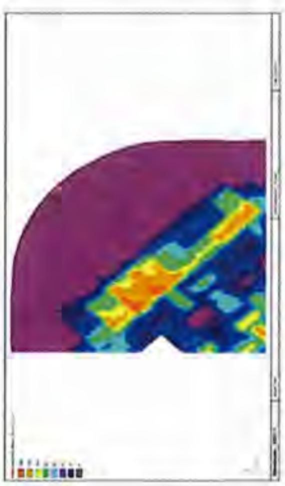

Figure 9 Panels 65-72 warp stresses

- Warp stresses for quadrant with panels 65-72: Figure 9
- Fill stresses for quadrant with panels 65-72: Figure 10
- Warp stresses for quadrant with panels 73-80: Figure 12
- Fill stresses for quadrant with panels 73-80: Figure 13
- Warp stresses for quadrant with panels 81-88: Figure 15

- Fill stresses for quadrant with panels 81-88: Figure 16
- Warp stresses for quadrant with panels 89-96: Figure 18
- Fill stresses for quadrant with panels 89-96: Figure 19

Results from the analysis of selected panels is summarized in Table 2. Allowable stresses for the fabric panels obtained using ASCE 55-10 and the original specified material strengths are listed in Table 3.

Table 2 Analysis Summary Results

Panel No.	Sag from laser scan (ft)	Load intensity (psf)	Sag from analysis (ft)	Max warp stress (pli)	Max fill stress (pli)
22	4.052	70	3.96	90	100
38	2.365	70	3.11	110	110
46	2.999	70	3.07	90	90
68	6.4	70	6.35	140	90
72	6.88	70	6.68	125	120
35	n/a	70	3.45	70	40

Table 3 Sheerfill II allowable stresses

Orientation	Specified stress T_s (pli)	L_l (lifecycle factor)	β (strength reduction factor)	Allowable stress limit
Warp	520	0.75	0.27	105.3
Fill	420	0.75	0.27	85.0

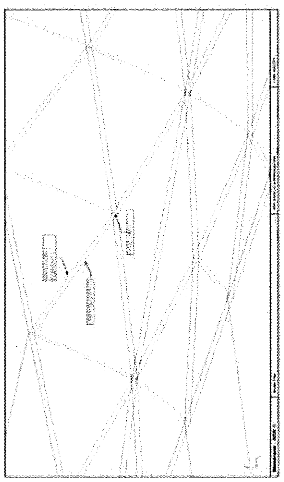

Figure 20 Panel 22 modeled with liner

Sensitivity of analysis results

The effect on the stresses due to variations in the deflections interpreted from the laser scans was studied by varying the load to achieve deflections differing by ±6 inches. The stresses were found to be not very sensitive to these changes in the deflection due to the nonlinear large displacement nature of the behavior.

The effect of interaction between the main fabric and the liner panels was also studied. The liner panel was modeled constrained to the main fabric panel (Figure 20). The liner panel was modeled using properties of Sheerfill V material. Using a process similar to one described above the load was calibrated to achieve a similar deflection in the combined model. To achieve a similar deflection around 105 psf of snow load was applied compared to a 70 psf of load in the model without the liner. The resulting stresses (Figure 21 and Figure 22) were noted to be in the same range as those observed for the model without the fabric liner. Similar studies were performed for the rectangular panels with the same result.

CONCLUSIONS

Our analysis indicates 40 panels were stressed beyond the normal working limits of the fabric material. Of these, 20 panels were overstressed by more than 10% which may be considered a reasonable cutoff for areas of concern. Locations of overstress are summarized in Table 4 below.

Overstress alone does not necessarily mean that the membrane material has been compromised. Fiberglass fabrics generally respond linearly up to a brittle fracture, so damage states at less than the full tensile strengths is unlikely. Regardless, in Part 2 of our report several test protocols have been established to evaluate the effects of high stresses on overloaded membrane material.

The fact that none of the overstress values exceed the factor of safety of the material (roughly 5) compares well with the observation that none of these panels failed during the deflation event. However, the cataloging of overstressed panels provides a guide for review of locations that may have been subjected to greater levels of physical abuse in the form of scratches or tears from snow and ice exposure. In Part 3 of our report the level of stress experienced by the panels is combined with the visual survey to support a qualitative risk assessment.

Table 4 Summary of Locations with Overstress

Panels with Warp Overstress		Panels with Fill Overstress	
Panel	Overstress	Panel	Overstress
67	32.95%	72	37.81%
68	32.95%	37	26.33%
93	32.95%	38	26.33%
72	18.71%	95	26.33%
75	13.96%	96	26.33%
84	13.96%	97	26.33%
92	13.96%	8	14.84%
94	13.96%	10	14.84%
95	13.96%	22	14.84%
73	9.21%	45	14.84%
74	9.21%	76	14.84%
76	9.21%	29	3.36%
10	4.46%	46	3.36%
37	4.46%	67	3.36%
38	4.46%	68	3.36%
66	4.46%	75	3.36%
69	4.46%	83	3.36%
71	4.46%	93	3.36%
83	4.46%	94	3.36%
91	4.46%		
96	4.46%		

APPENDIX A

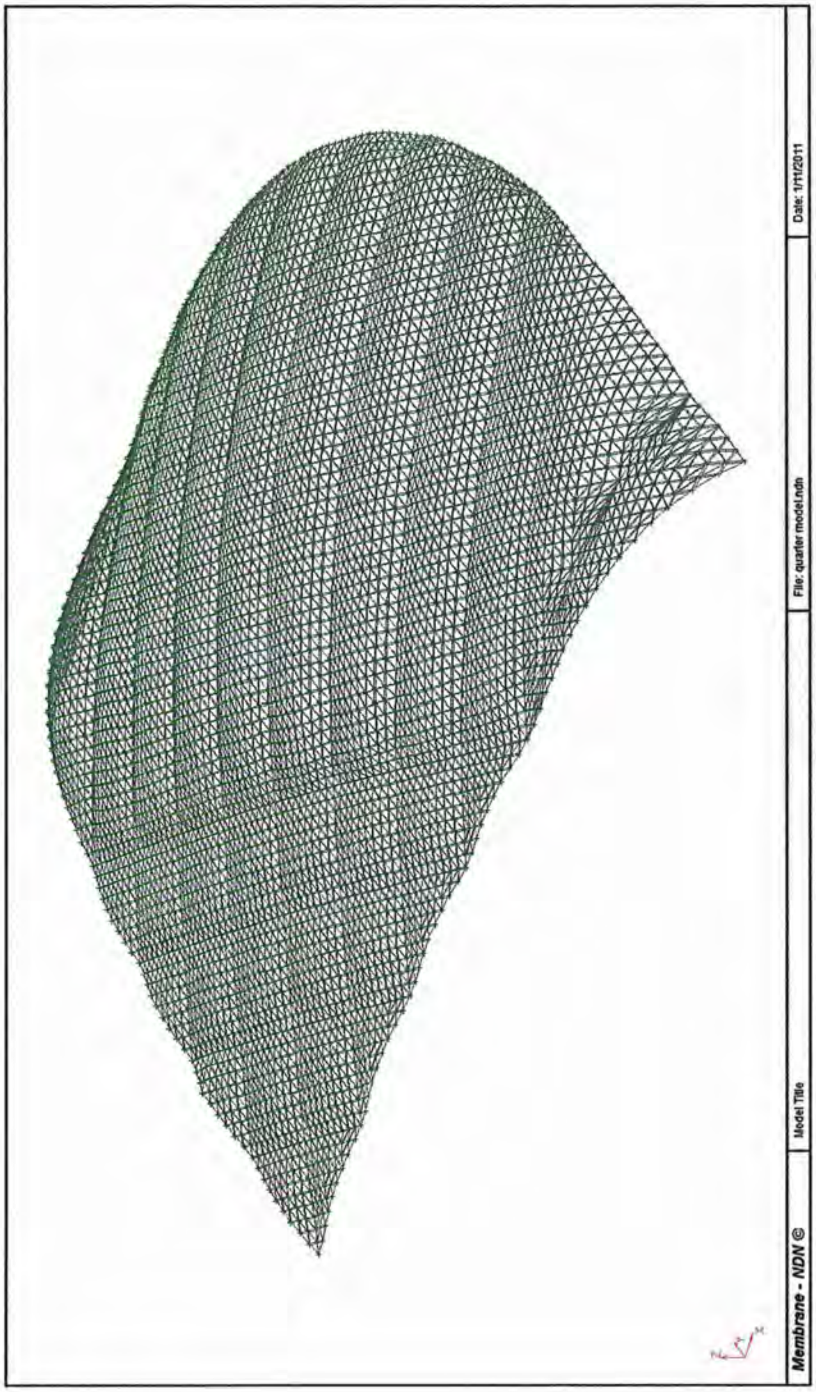

Figure 1 Inflated roof model

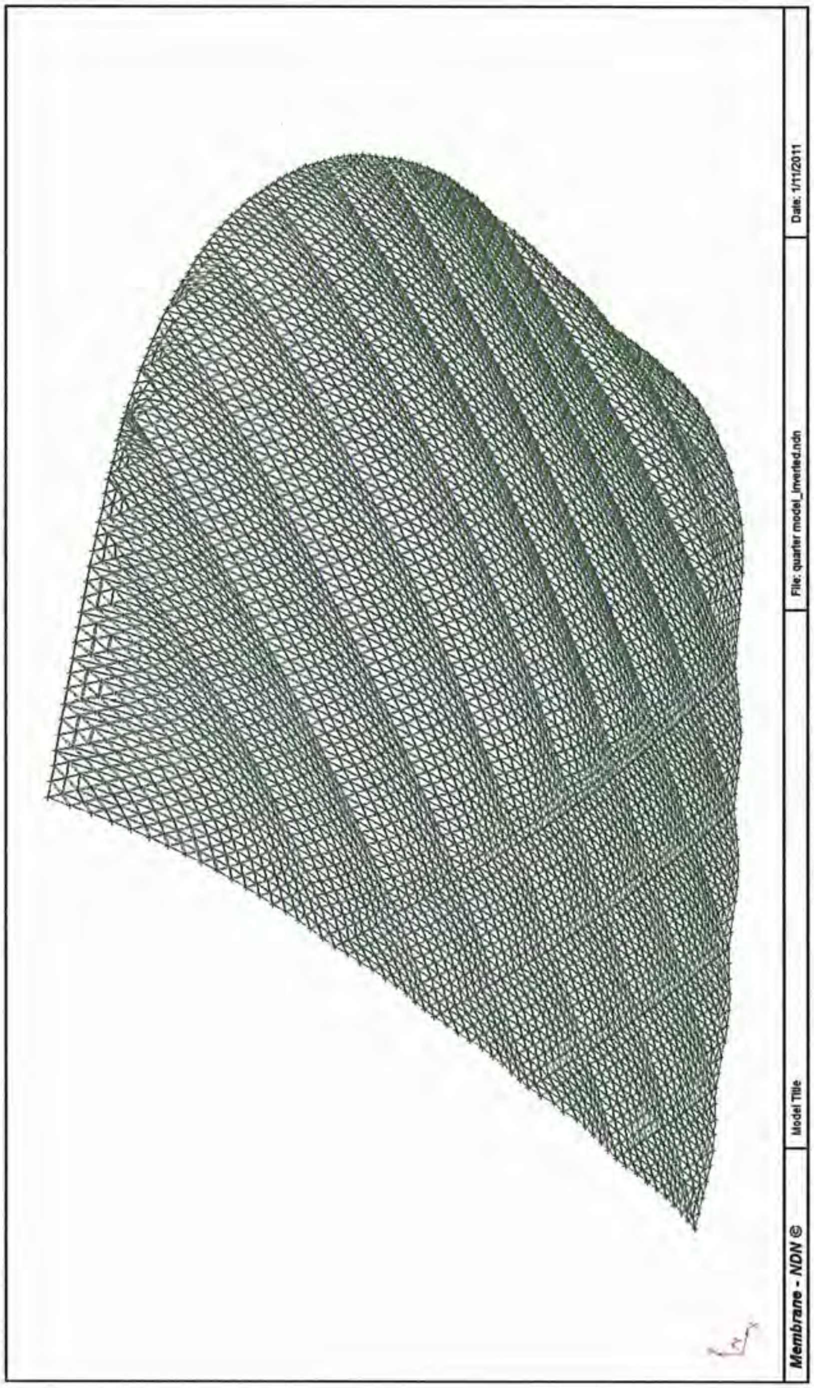

Figure 2 Deflated roof model

Figure 3 Fabric panels selected for detailed analysis

Figure 4 Panel 22 point coordinates from laser scan

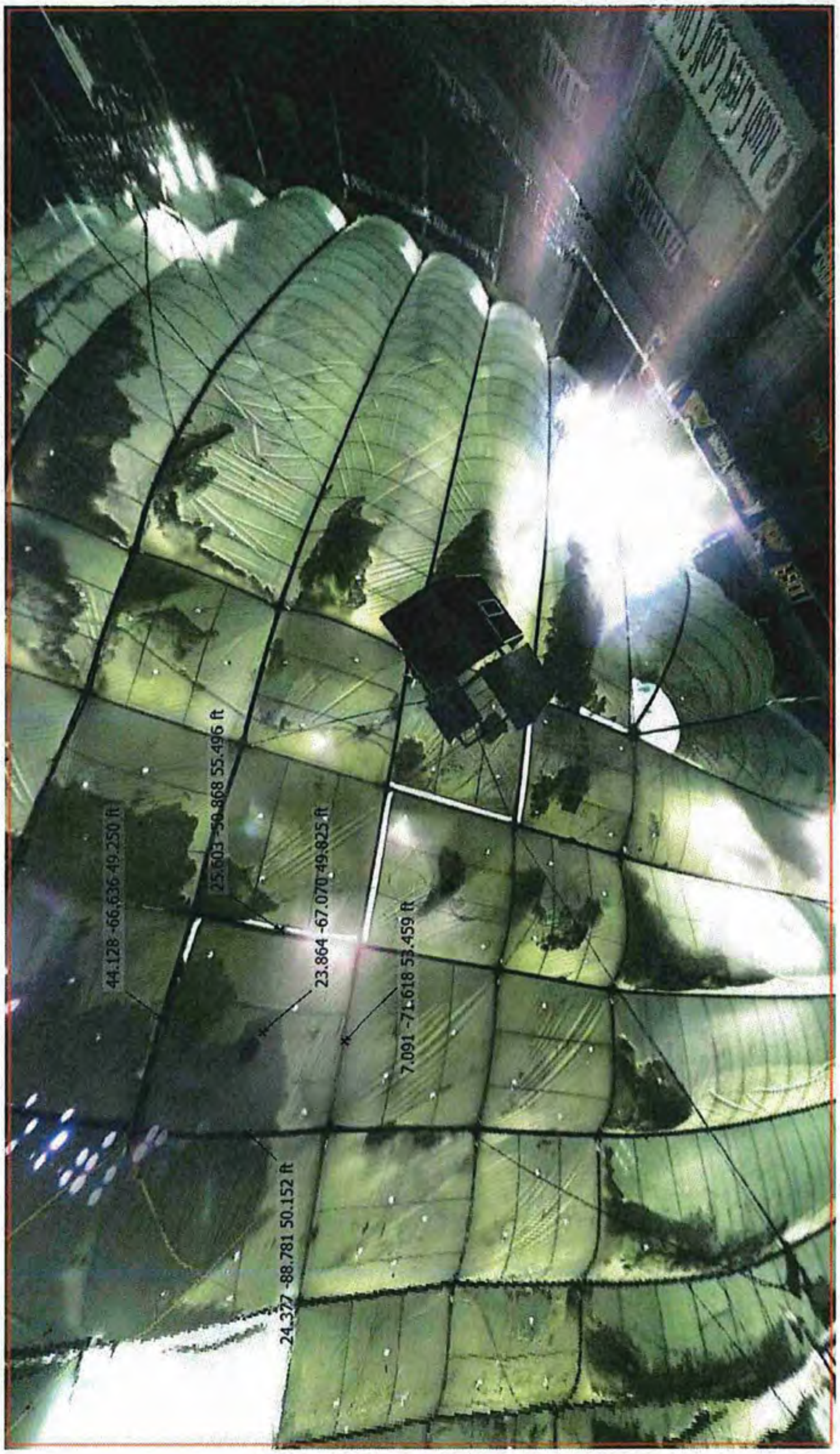

Figure 5 Panel 46 laser scan coordinates

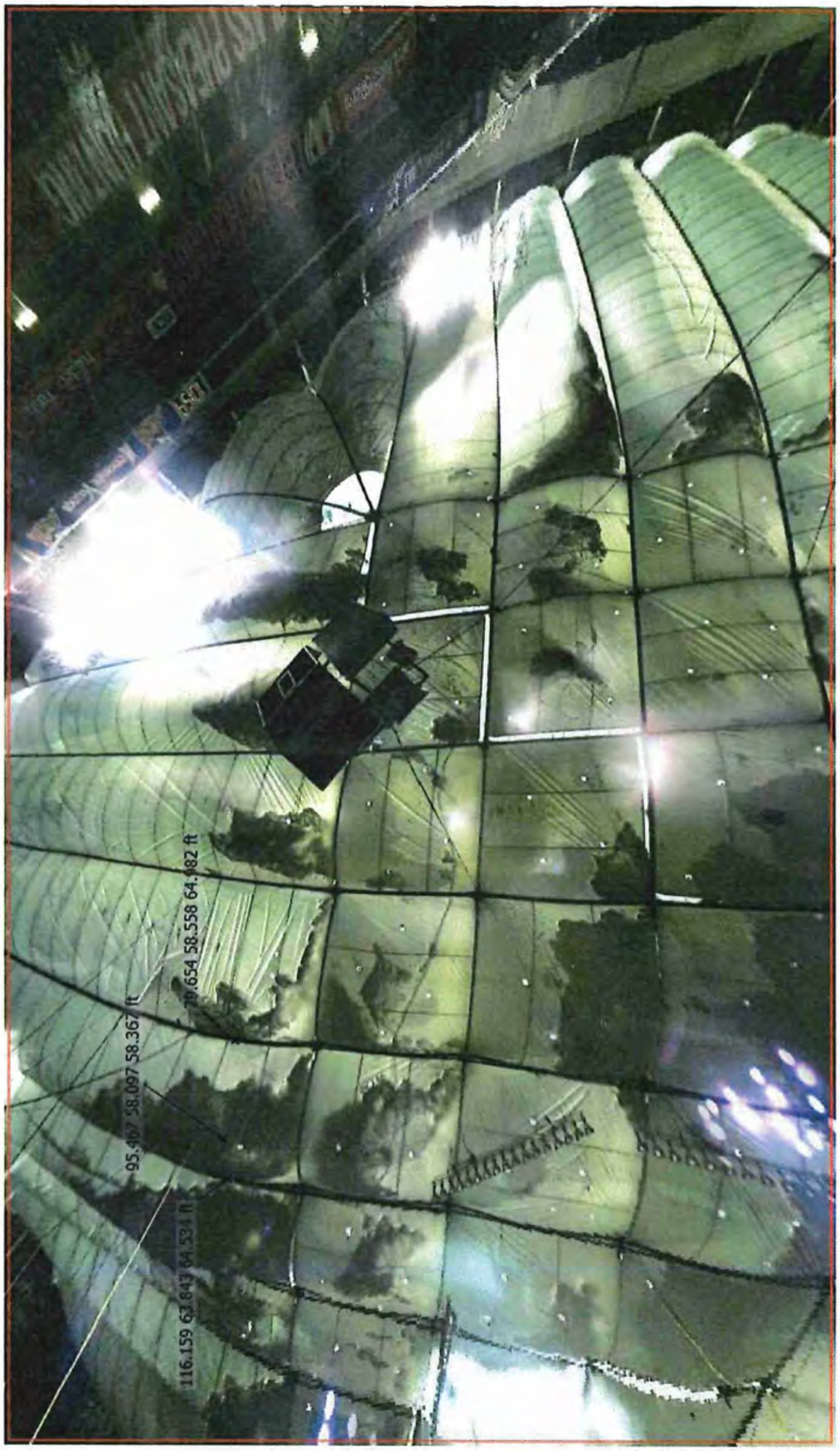

Figure 6 Panel 68 laser scan coordinates

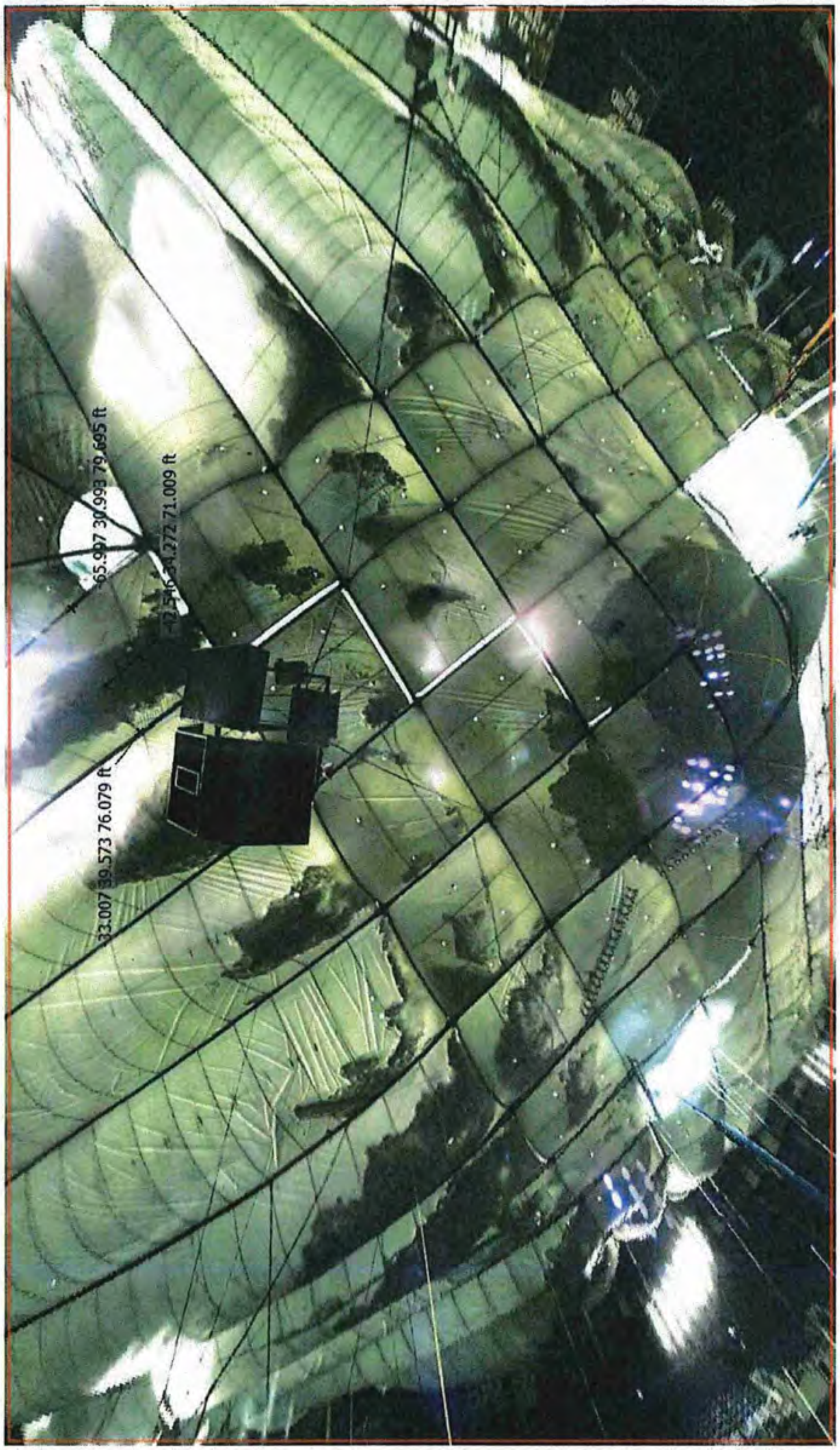

Figure 7 Panel 72 laser scan coordinates

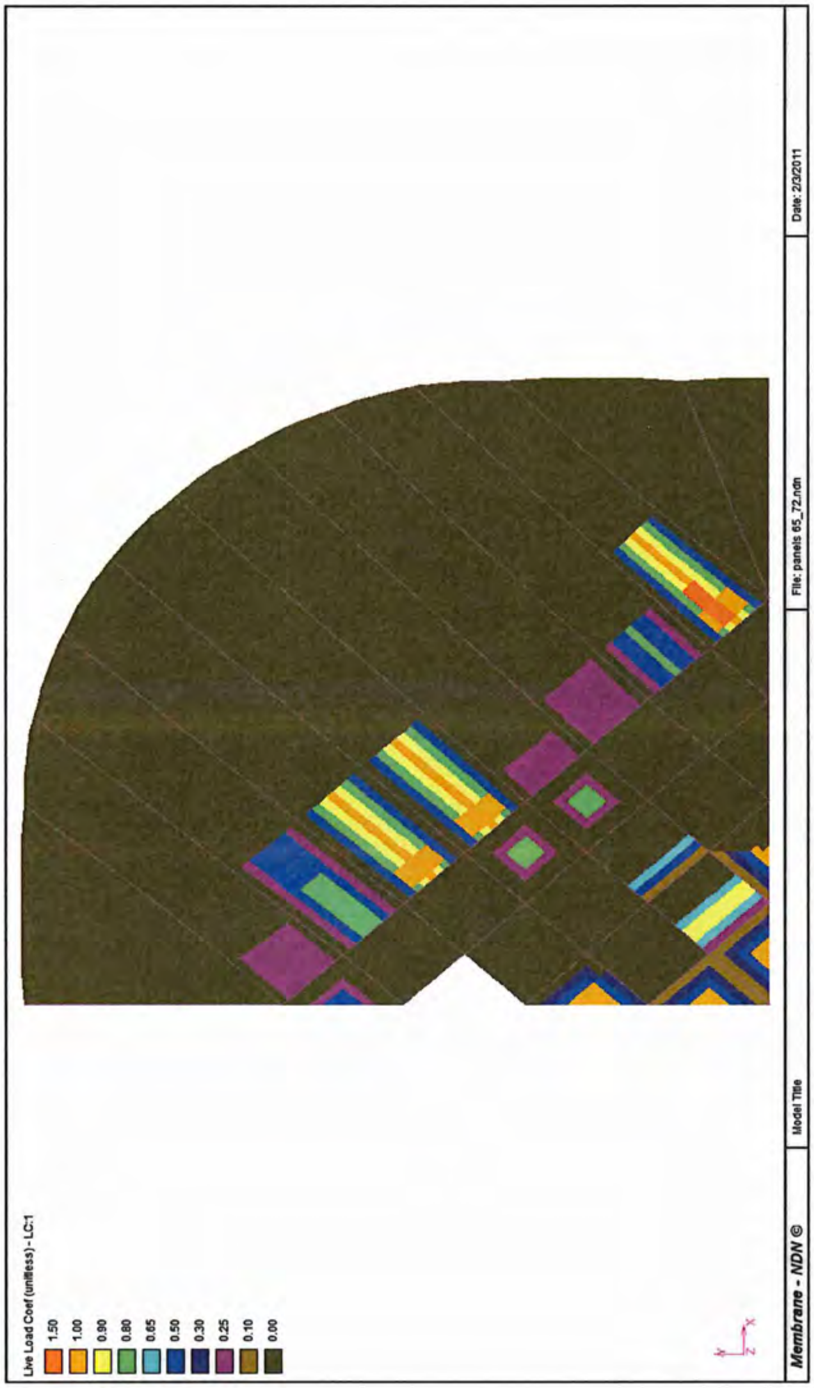

Figure 8 Panels 65-72 load intensity coefficients

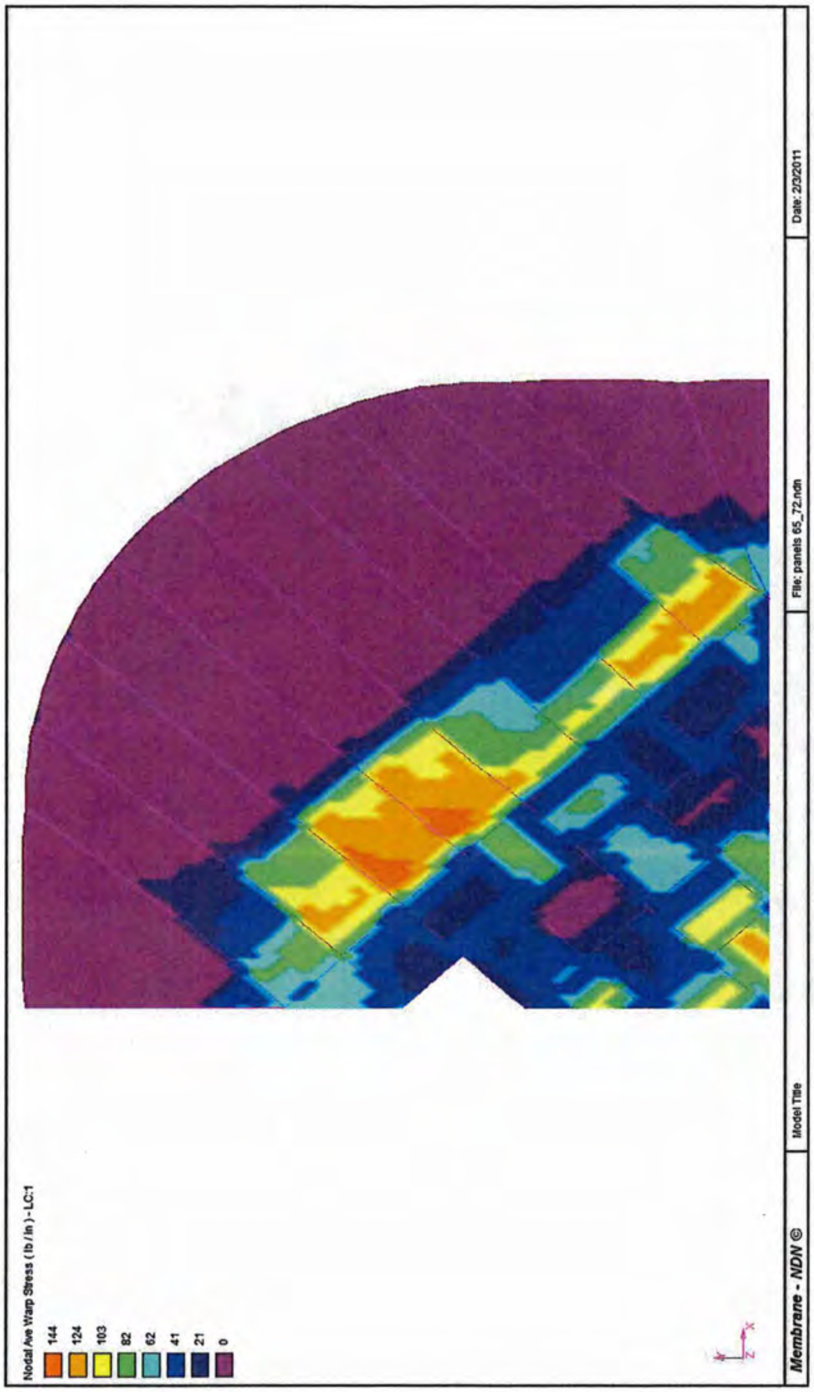

Figure 9 Panels 65-72 warp stresses

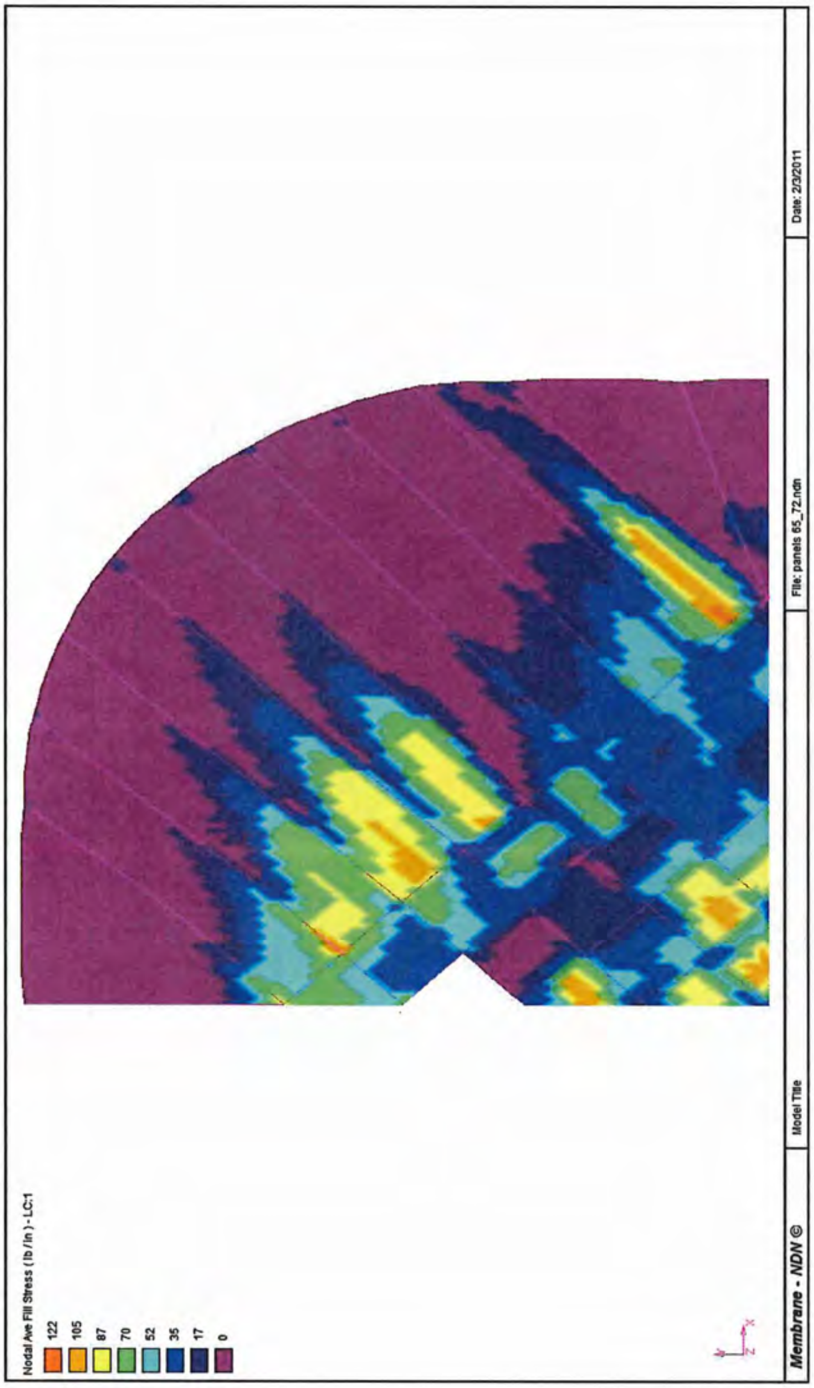

Figure 10 Panels 65-72 fill stresses

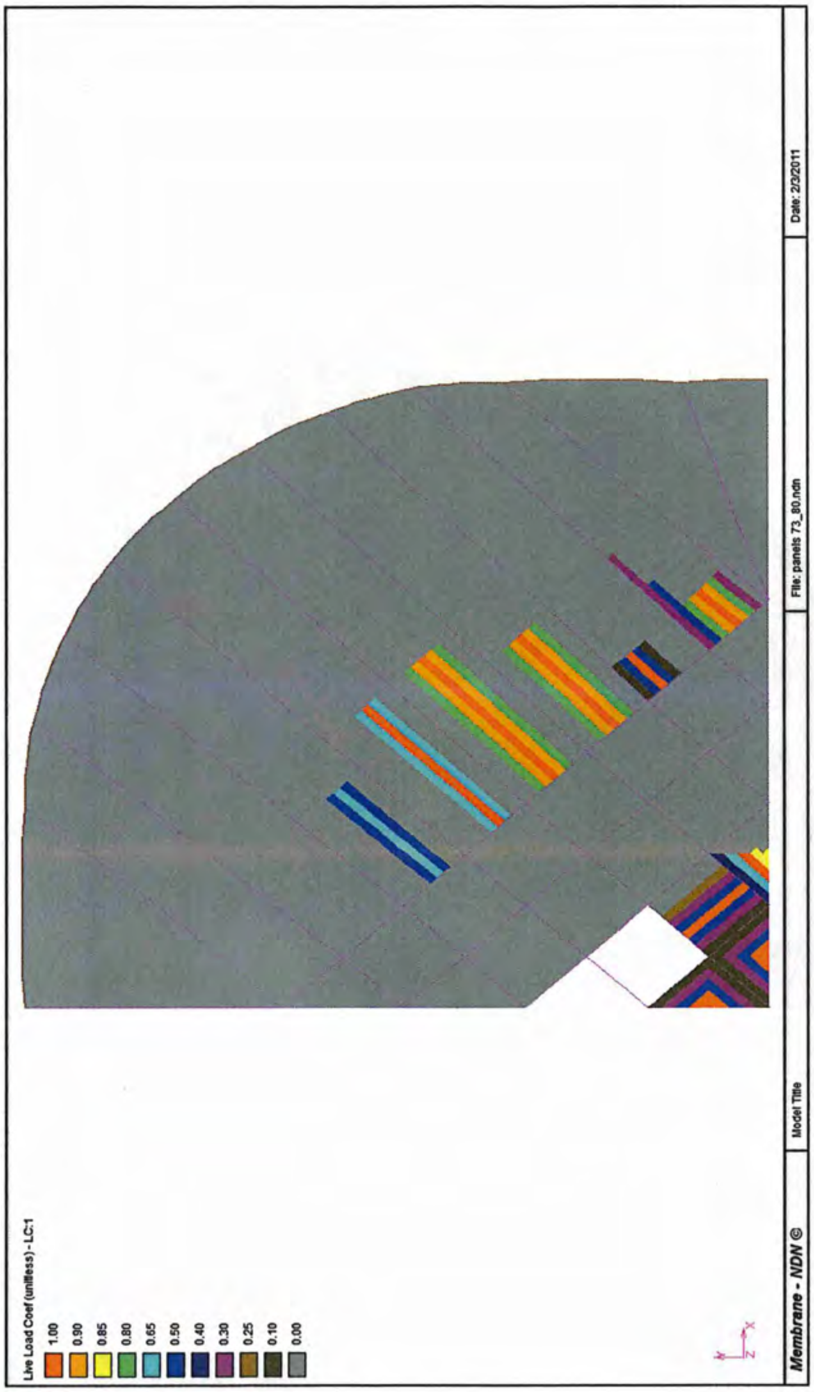

Figure 11 Panels 73-80 load intensity coefficients

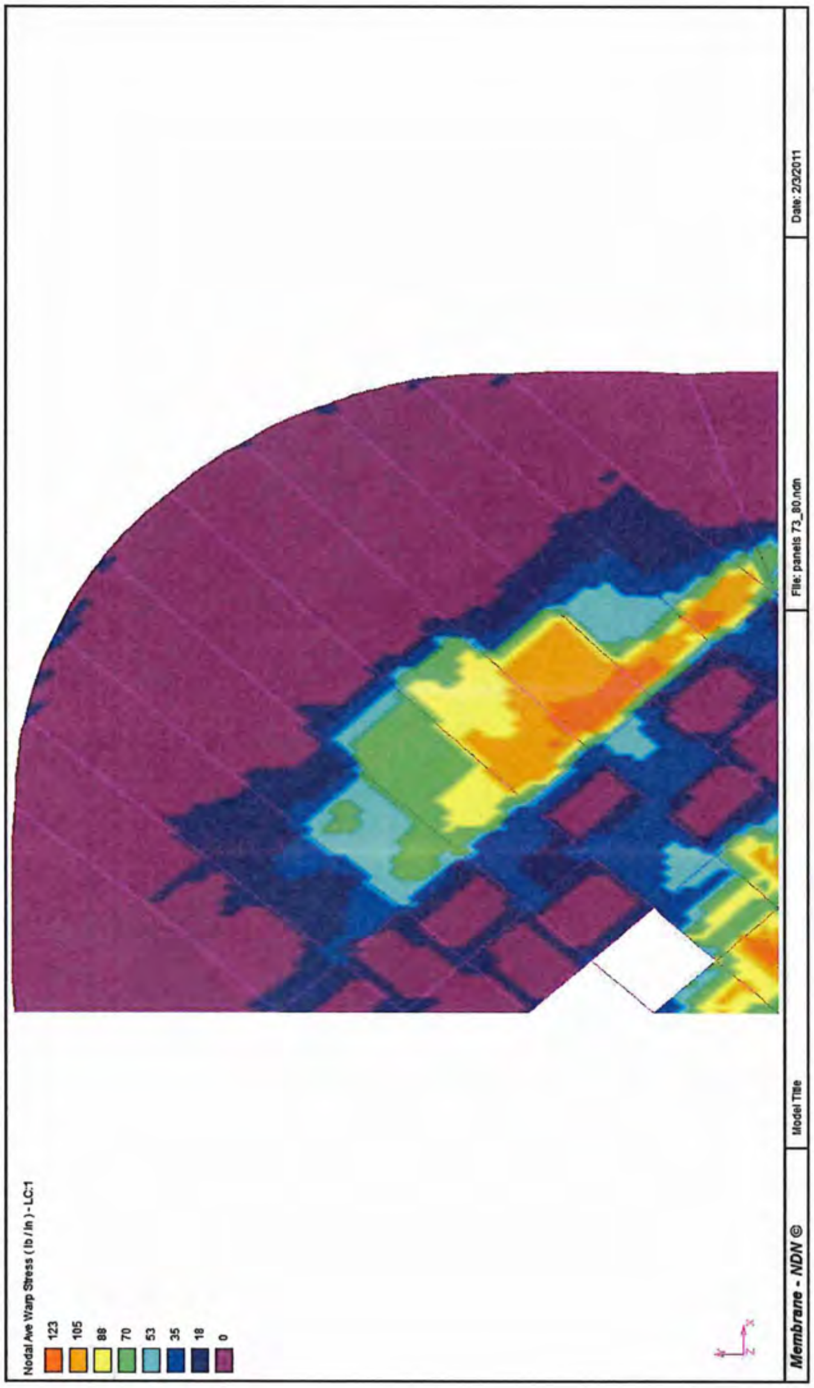

Figure 12 Panels 73-80 warp stresses

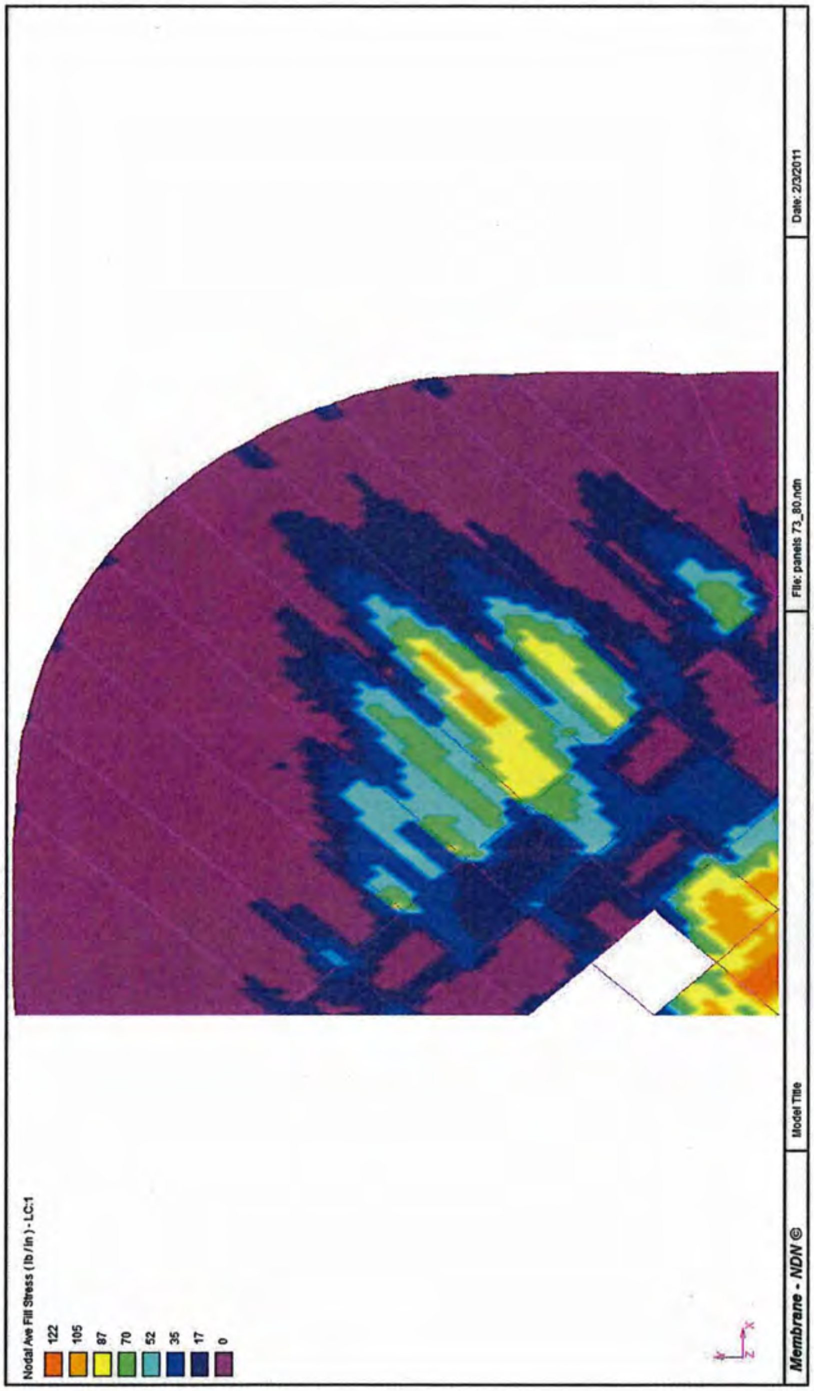

Figure 13 Panels 73-80 fill stresses

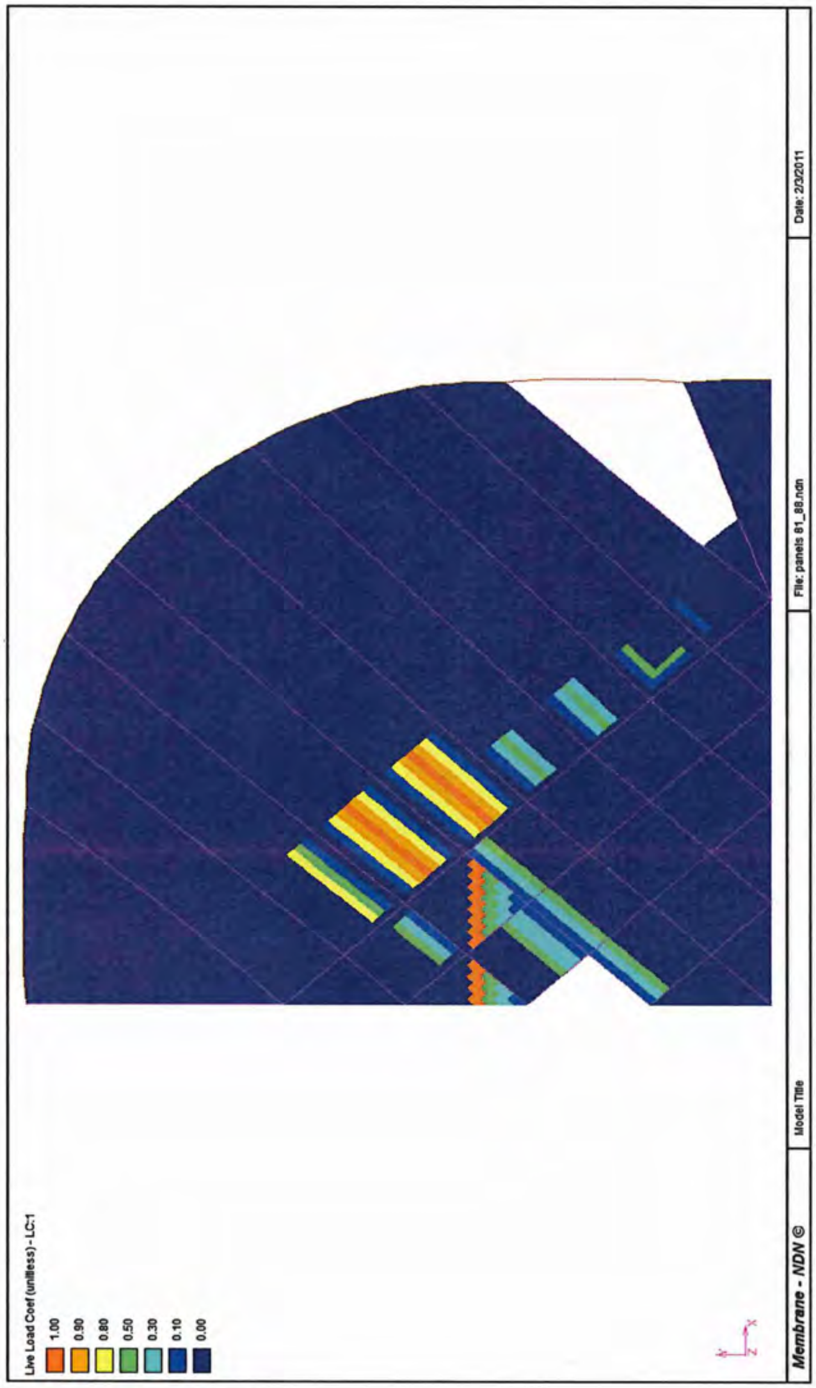

Figure 14 Panels 81-88 load intensity coefficients

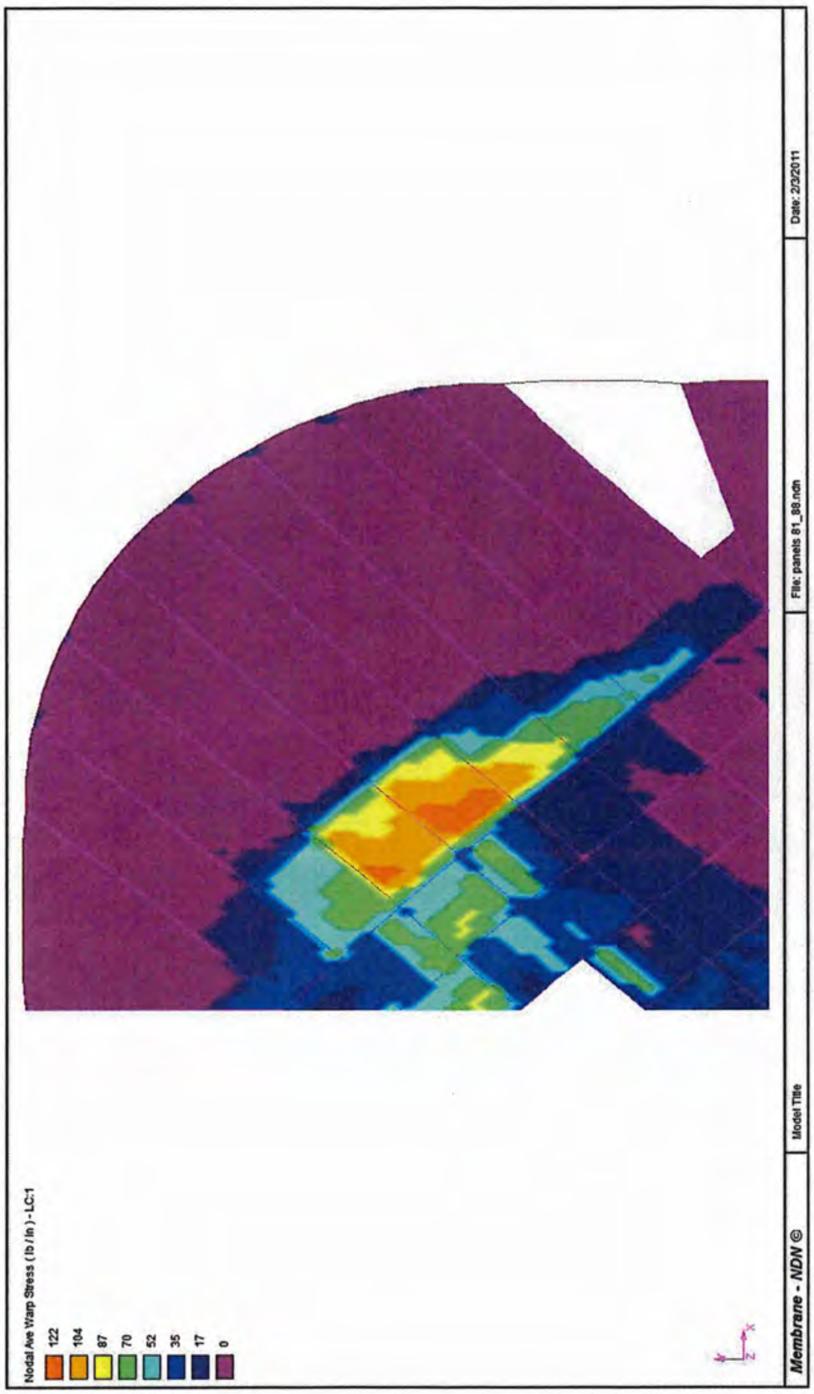

Figure 15 Panels 81-88 warp stresses

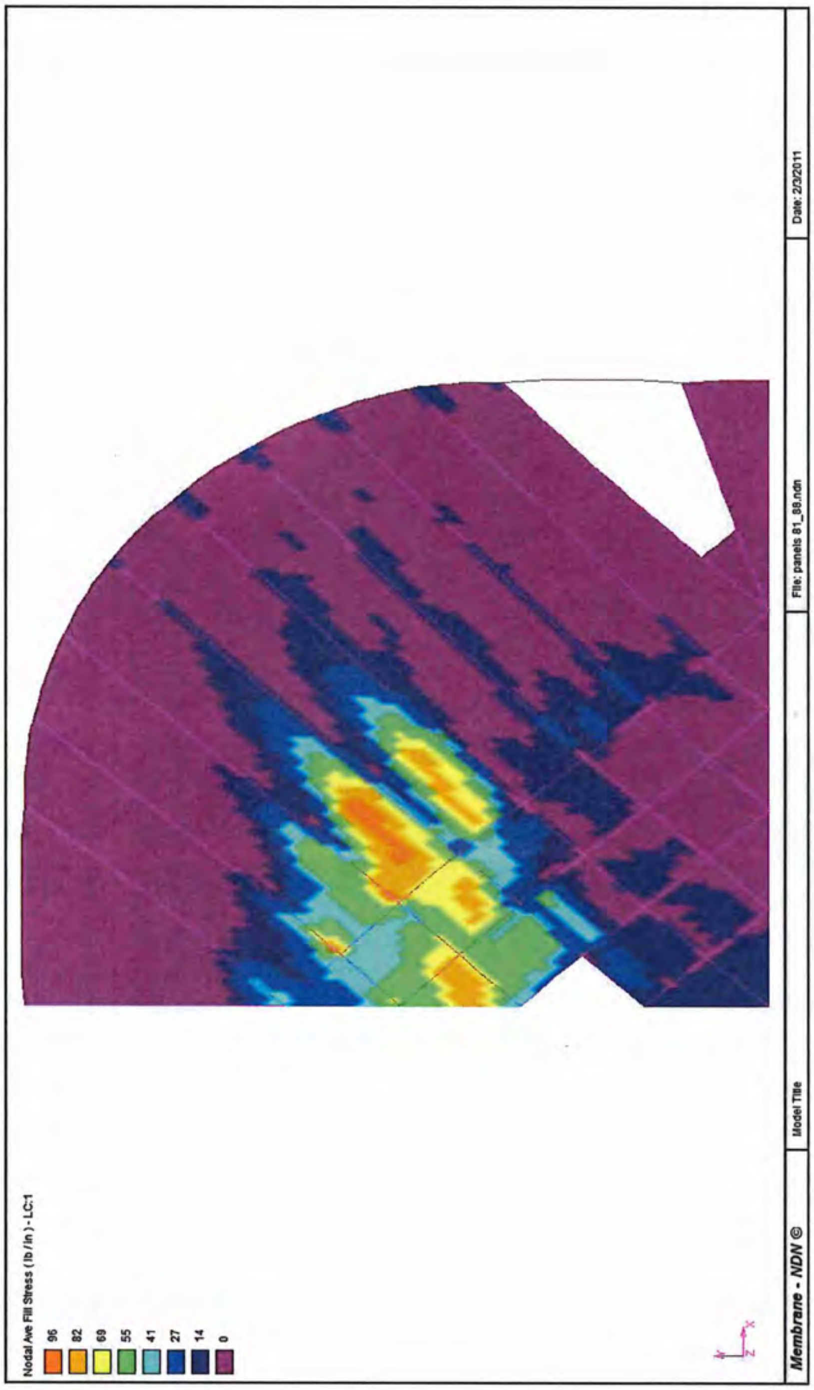

Figure 16 Panels 81-88 fill stresses

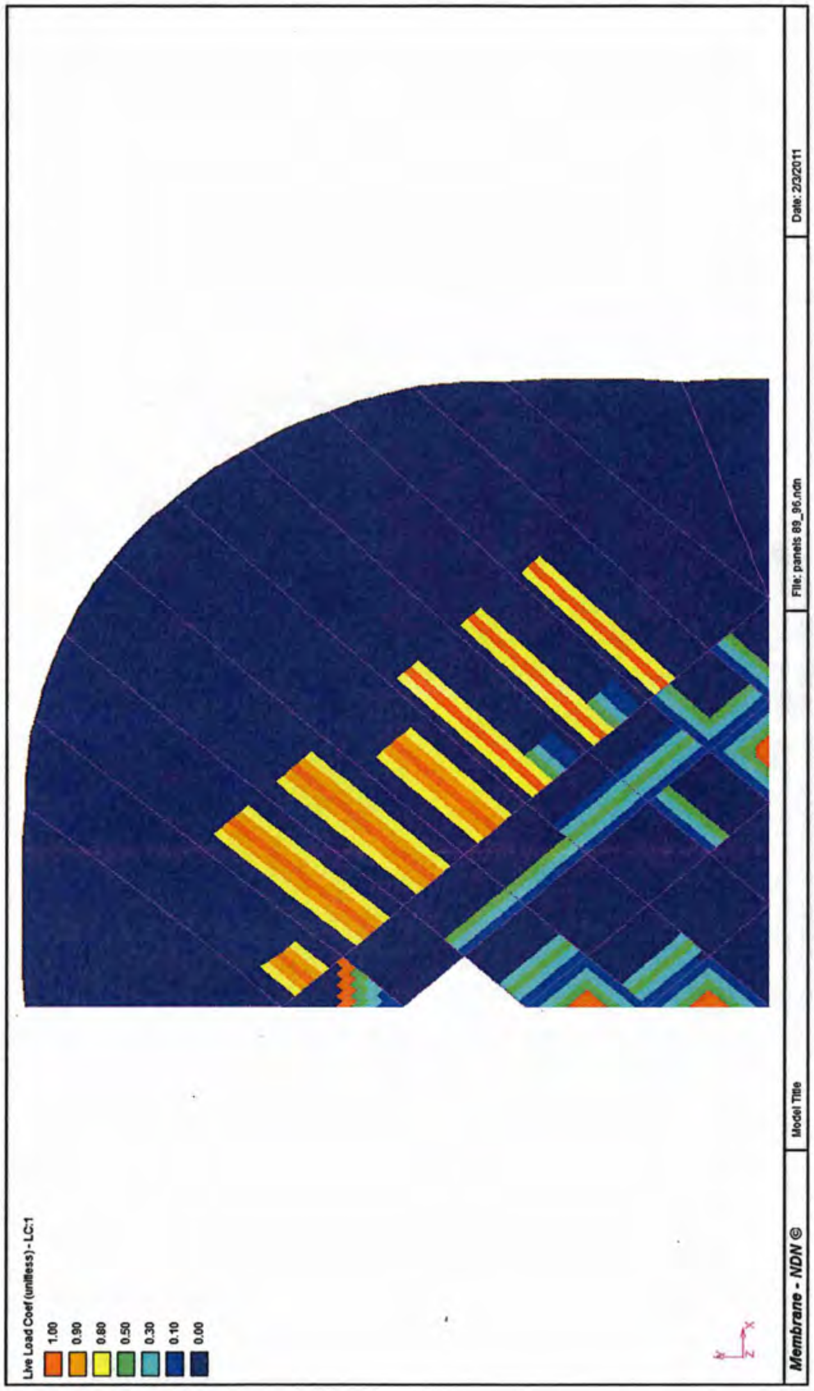

Figure 17 Panels 89-96 load intensity coefficients

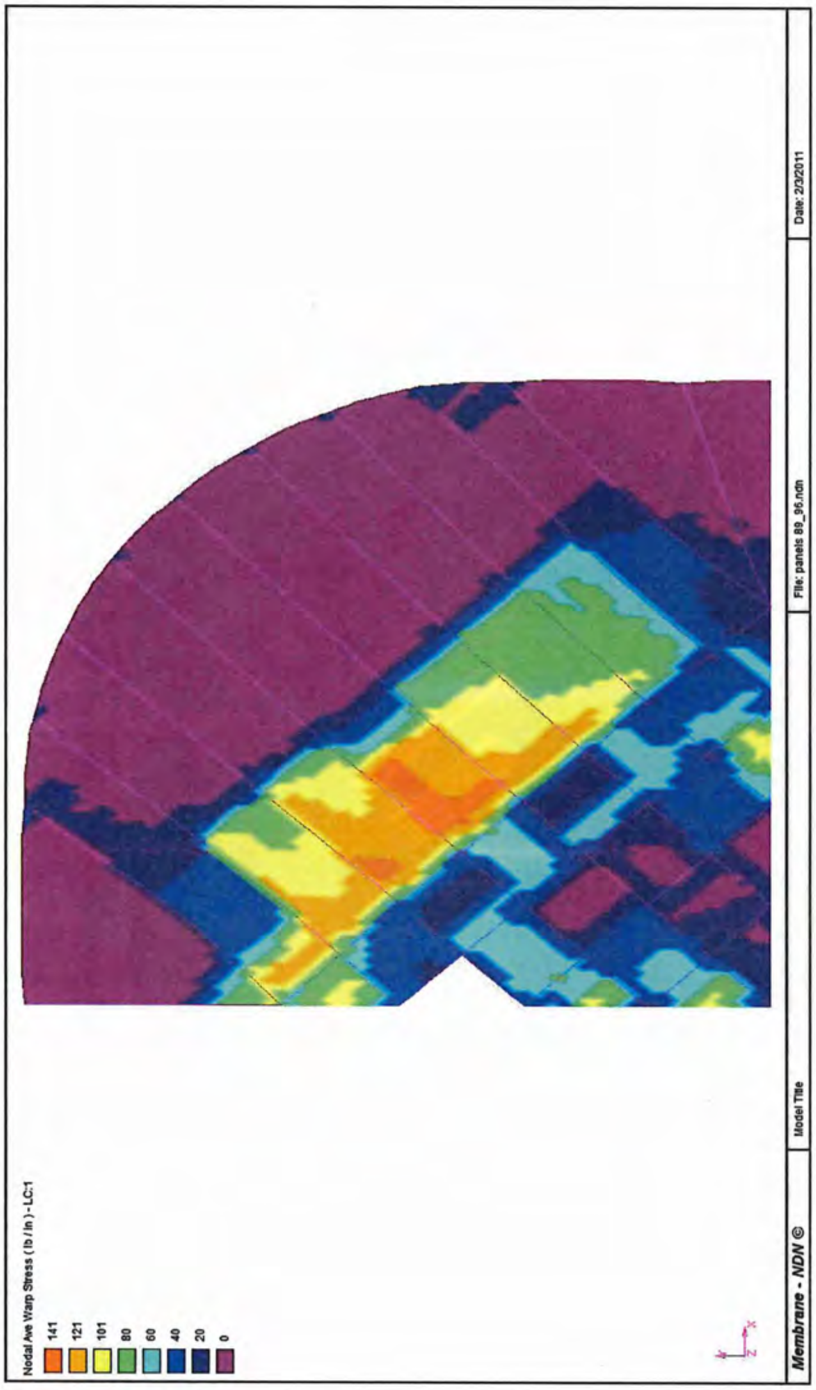

Figure 18 Panels 89-96 warp stresses

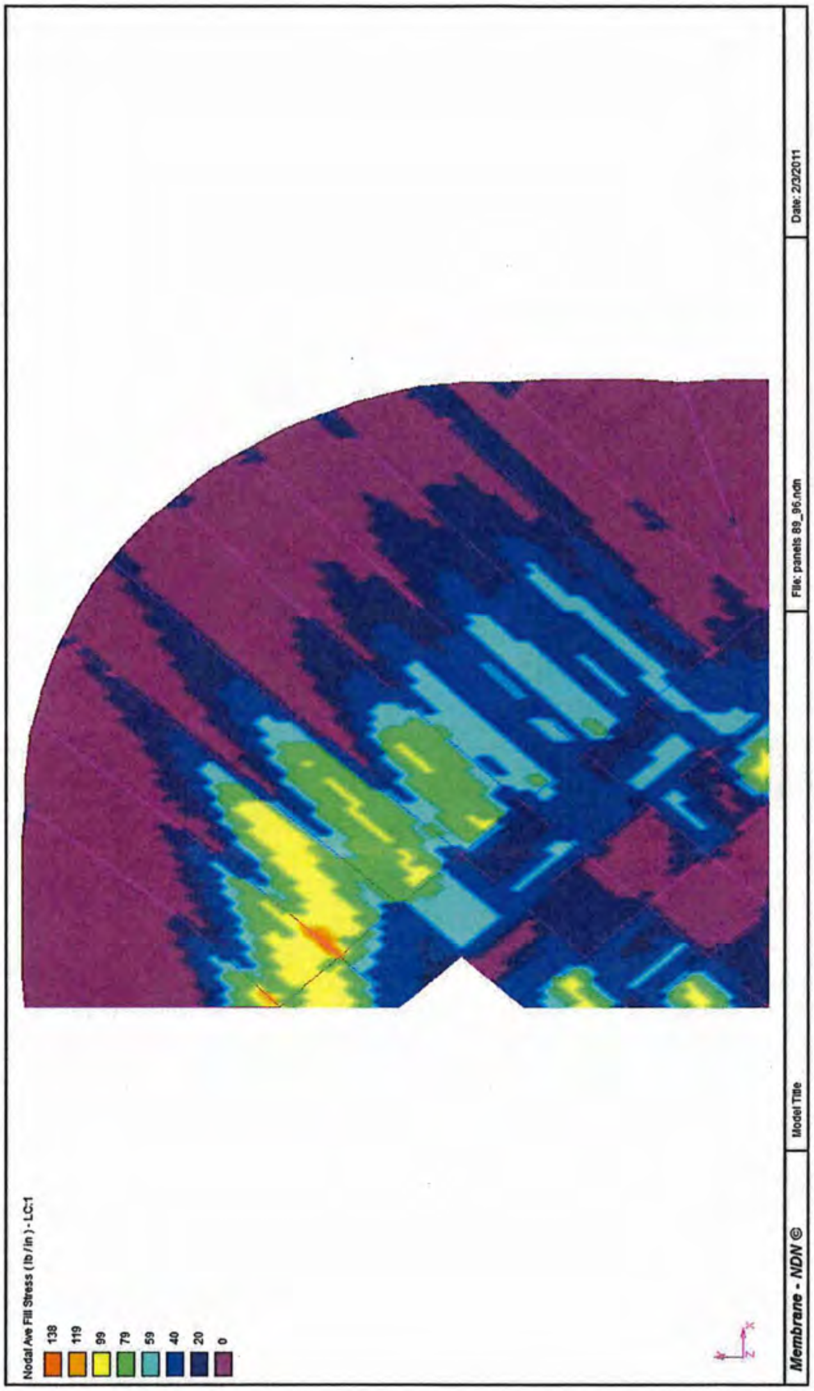

Figure 19 Panels 89-96 fill stresses

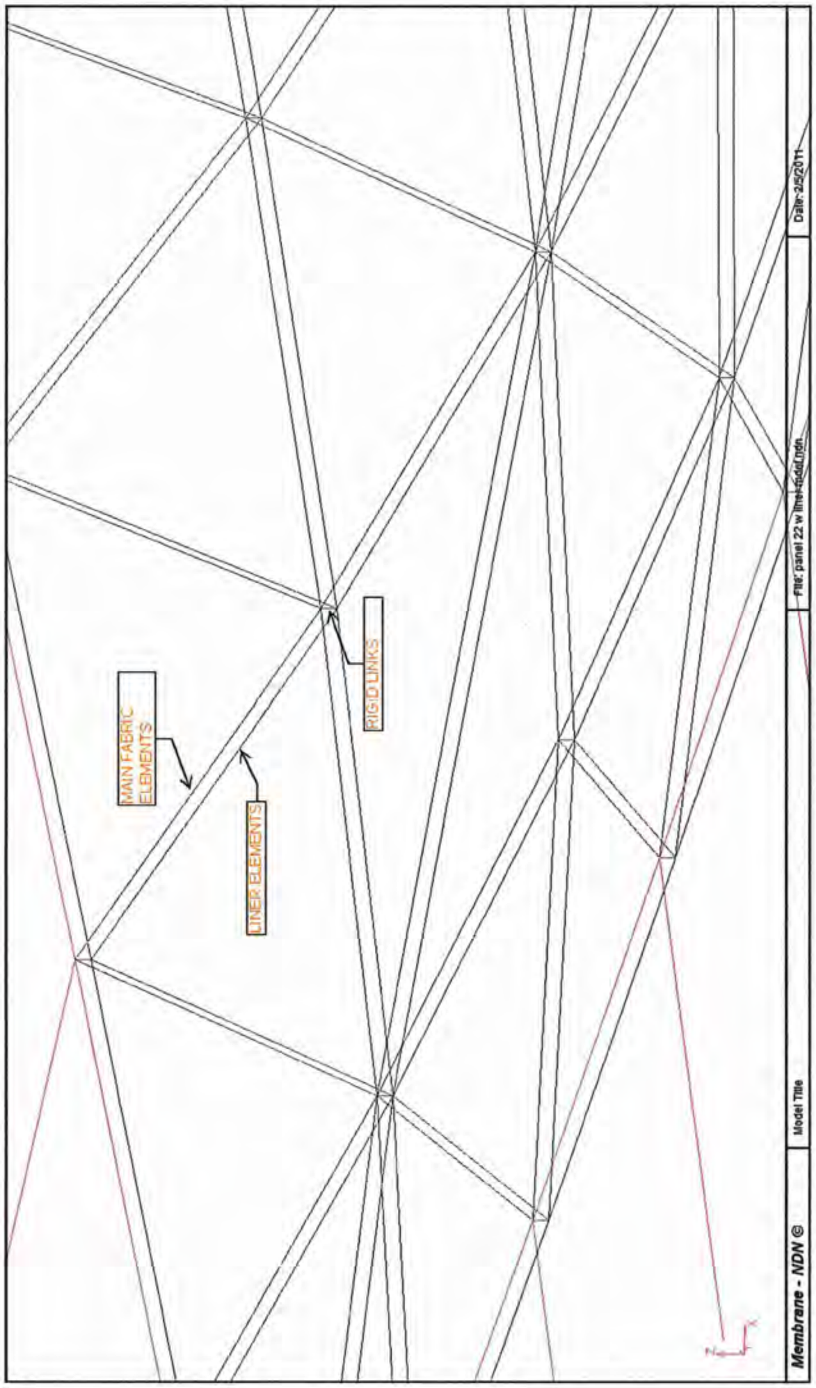

Figure 20 Panel 22 modeled with liner

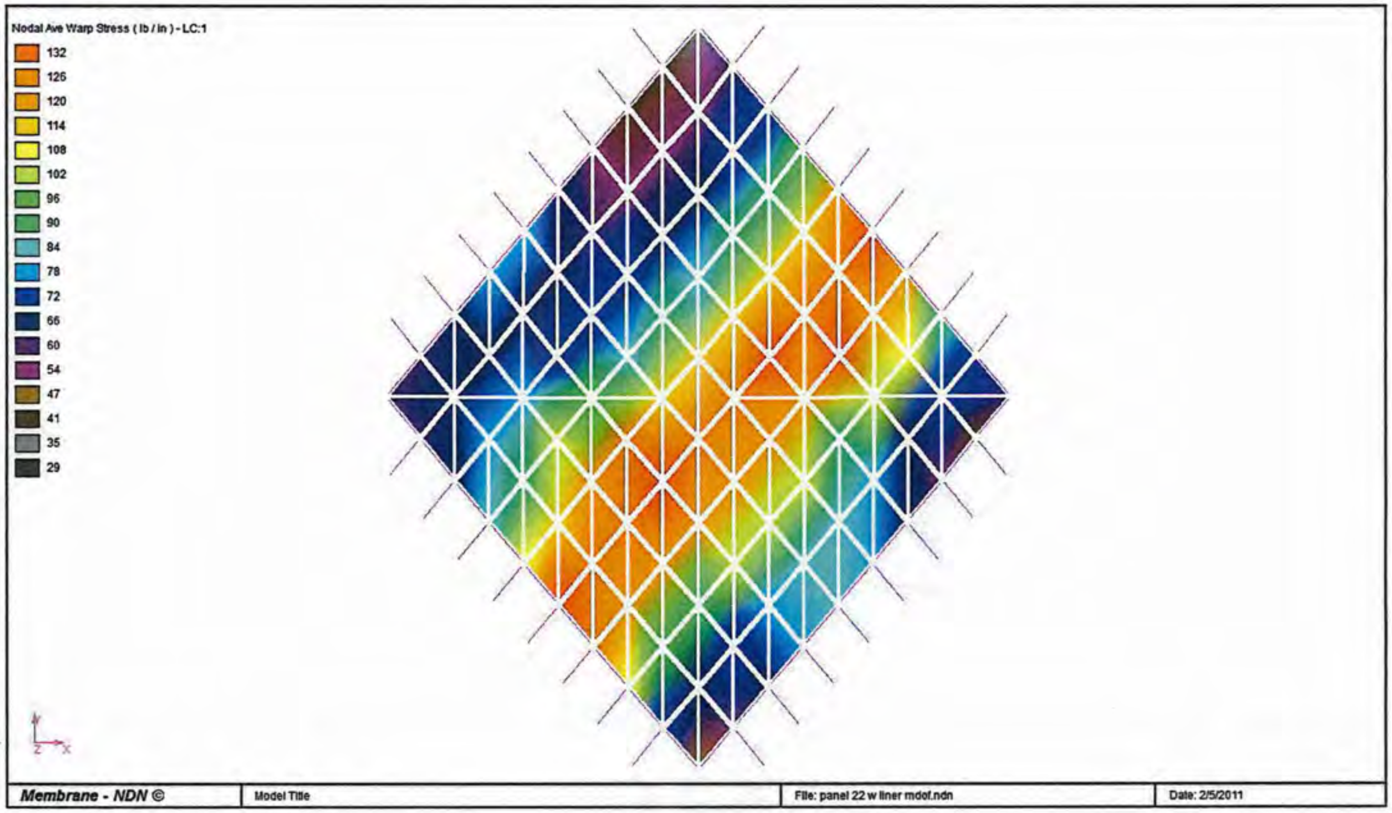

Figure 21 Panel 22 with liner warp stresses

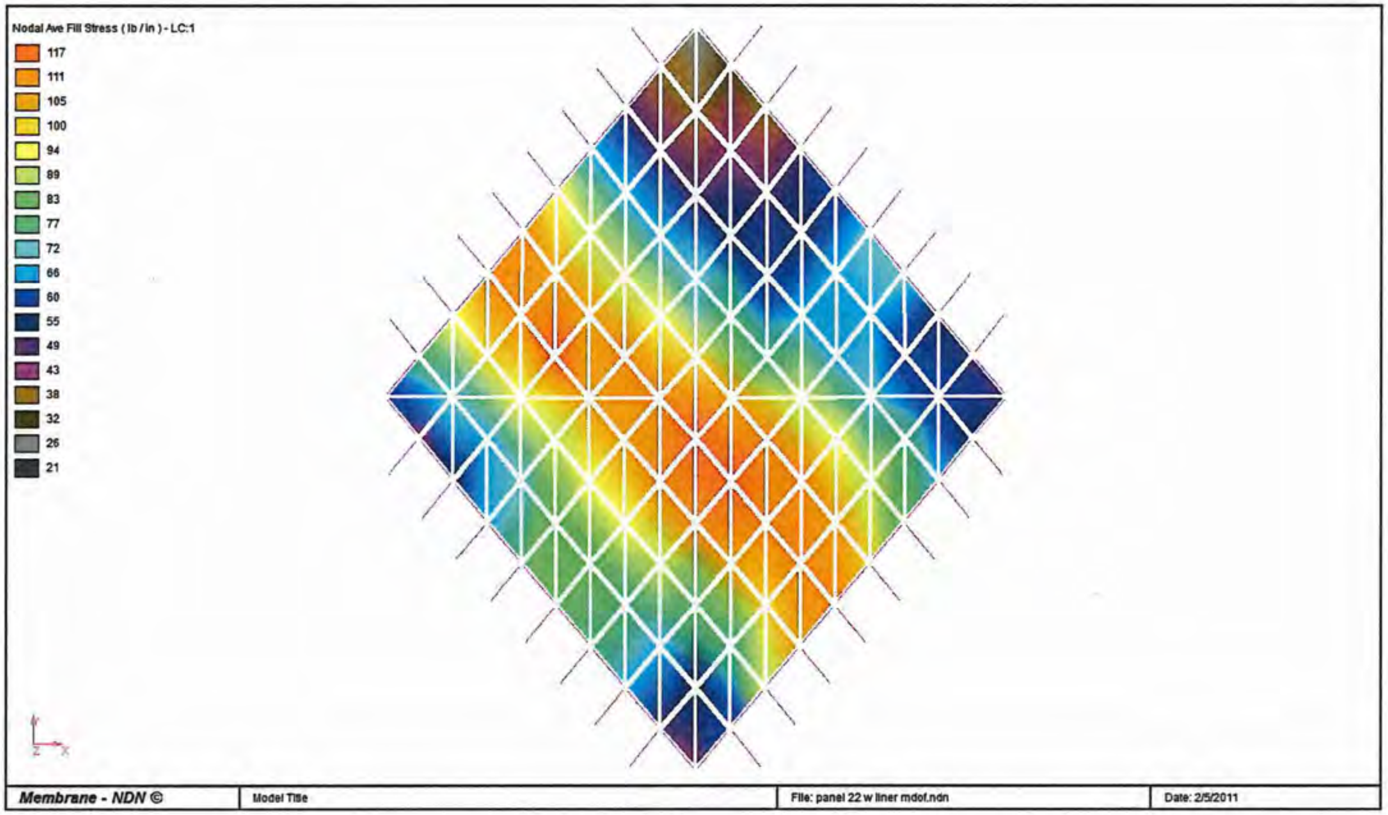

Figure 22 Panel 22 with liner fill stresses

APPENDIX B

Table 5 Panel stress ratios from analysis

Panel #	Panel Type	Status	Maximum deflated stress		Ratio 1980 specification allowable stress	
			Warp	Fill	Warp	Fill
1	Diamond	Intact	55	50	0.52	0.57
2	Diamond	Intact	60	55	0.57	0.63
3	Diamond	Intact	60	65	0.57	0.75
4	Diamond	Intact	75	55	0.71	0.63
5	Diamond	Intact	75	50	0.71	0.57
6	Diamond	Intact	60	75	0.57	0.86
7	Diamond	Intact	50	65	0.47	0.75
8	Diamond	Intact	90	100	0.85	1.15
9	Diamond	Intact	25	25	0.24	0.29
10	Diamond	Intact	110	100	1.04	1.15
11	Diamond	Intact	40	55	0.38	0.63
12	Diamond	Intact	25	20	0.24	0.23
13	Diamond	Intact	25	25	0.24	0.29
14	Diamond	Intact	75	40	0.71	0.46
15	Diamond	Failed	NA	NA	NA	NA
16	Diamond	Intact	45	70	0.43	0.80
17	Diamond	Intact	25	25	0.24	0.29
18	Diamond	Intact	25	25	0.24	0.29
19	Diamond	Intact	25	25	0.24	0.29
20	Diamond	Intact	25	25	0.24	0.29
21	Diamond	Intact	60	60	0.57	0.69
22	Diamond	Intact	90	100	0.85	1.15
23	Diamond	Intact	40	25	0.38	0.29
24	Diamond	Intact	40	65	0.38	0.75
25	Diamond	Intact	25	25	0.24	0.29
26	Diamond	Intact	25	25	0.24	0.29
27	Diamond	Intact	25	25	0.24	0.29
28	Diamond	Intact	35	25	0.33	0.29
29	Diamond	Intact	90	90	0.85	1.03
30	Diamond	Intact	50	50	0.47	0.57
31	Diamond	Intact	25	25	0.24	0.29
32	Diamond	Intact	90	70	0.85	0.80
33	Diamond	Intact	55	50	0.52	0.57
34	Diamond	Intact	50	50	0.47	0.57
35	Diamond	Intact	70	40	0.66	0.46
36	Diamond	Failed	NA	NA	NA	NA
37	Diamond	Intact	110	110	1.04	1.26

Panel #	Panel Type	Status	Maximum deflated stress		Ratio 1980 specification allowable stress	
			Warp	Fill	Warp	Fill
38	Diamond	Intact	110	110	1.04	1.26
39	Diamond	Intact	70	60	0.66	0.69
40	Diamond	Intact	70	70	0.66	0.80
41	Diamond	Intact	80	80	0.76	0.92
42	Diamond	Intact	50	60	0.47	0.69
43	Diamond	Failed	NA	NA	NA	NA
44	Diamond	Failed	NA	NA	NA	NA
45	Diamond	Intact	80	100	0.76	1.15
46	Diamond	Intact	90	90	0.85	1.03
47	Diamond	Intact	50	50	0.47	0.57
48	Diamond	Intact	50	50	0.47	0.57
49	Diamond	Intact	65	60	0.62	0.69
50	Diamond	Intact	80	85	0.76	0.98
51	Diamond	Intact	25	25	0.24	0.29
52	Diamond	Intact	25	25	0.24	0.29
53	Diamond	Intact	50	25	0.47	0.29
54	Diamond	Intact	25	40	0.24	0.46
55	Diamond	Intact	25	25	0.24	0.29
56	Diamond	Intact	50	50	0.47	0.57
57	Diamond	Intact	40	60	0.38	0.69
58	Diamond	Intact	25	25	0.24	0.29
59	Diamond	Intact	25	40	0.24	0.46
60	Diamond	Intact	35	25	0.33	0.29
61	Diamond	Intact	25	65	0.24	0.75
62	Diamond	Intact	50	25	0.47	0.29
63	Diamond	Intact	25	25	0.24	0.29
64	Diamond	Intact	60	50	0.57	0.57
65	Rectangle	Intact	75	65	0.71	0.75
66	Rectangle	Intact	110	80	1.04	0.92
67	Rectangle	Intact	140	90	1.33	1.03
68	Rectangle	Intact	140	90	1.33	1.03
69	Rectangle	Intact	110	10	1.04	0.11
70	Rectangle	Intact	90	40	0.85	0.46
71	Rectangle	Intact	110	65	1.04	0.75
72	Rectangle	Intact	125	120	1.19	1.38
73	Rectangle	Intact	115	65	1.09	0.75
74	Rectangle	Intact	115	50	1.09	0.57
75	Rectangle	Intact	120	90	1.14	1.03
76	Rectangle	Intact	115	100	1.09	1.15

Panel #	Panel Type	Status	Maximum deflated stress		Ratio 1980 specification allowable stress	
			Warp	Fill	Warp	Fill
77	Rectangle	Intact	90	65	0.85	0.75
78	Rectangle	Intact	65	50	0.62	0.57
79	Rectangle	Intact	40	35	0.38	0.40
80	Rectangle	Intact	25	25	0.24	0.29
81	Rectangle	Intact	40	30	0.38	0.34
82	Rectangle	Intact	70	60	0.66	0.69
83	Rectangle	Intact	110	90	1.04	1.03
84	Rectangle	Intact	120	75	1.14	0.86
85	Rectangle	Intact	100	25	0.95	0.29
86	Rectangle	Intact	80	25	0.76	0.29
87	Rectangle	Intact	65	25	0.62	0.29
88	Rectangle	Intact	25	15	0.24	0.17
89	Rectangle	Intact	40	25	0.38	0.29
90	Rectangle	Intact	90	65	0.85	0.75
91	Rectangle	Intact	110	65	1.04	0.75
92	Rectangle	Intact	120	65	1.14	0.75
93	Rectangle	Intact	140	90	1.33	1.03
94	Rectangle	Intact	120	90	1.14	1.03
95	Rectangle	Intact	120	110	1.14	1.26
96	Rectangle	Intact	110	110	1.04	1.26
97	Triangle	Intact	90	110	0.85	1.26
98	Triangle	Intact	60	80	0.57	0.92
99	Triangle	Intact	70	25	0.66	0.29
100	Triangle	Intact	70	25	0.66	0.29
101	Triangle	Intact	70	25	0.66	0.29
102	Triangle	Intact	25	25	0.24	0.29
103	Triangle	Intact	40	40	0.38	0.46
104	Triangle	Failed	NA	NA	NA	NA
105	Triangle	Intact	25	20	0.24	0.23
106	Triangle	Intact	25	20	0.24	0.23

MINNEAPOLIS METRODOME

DECEMBER 2010 ROOF DEFLATION ASSESSMENT

PART 2

REVIEW OF TESTING

Prepared for:

METROPOLITAN SPORTS FACILITIES COMMISSION

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Walter P Moore Project S02.10026.01

February 10, 2011 FINAL REPORT

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EXECUTIVE SUMMARY

Walter P Moore has conducted a limited independent assessment of the condition of the Metrodome roof structure following the December 12, 2010 deflation event. This assessment has been performed by Walter P Moore and Associates, Inc. acting as an independent consultant to the Metropolitan Sports Facilities Commission. The purpose of this report is to assist the Metropolitan Sports Facilities Commission in evaluating the condition of the roof structure so that it can make an informed decision about the future use of the Metrodome as it relates to public safety.

Part 2 of our report addresses our review of the testing conducted by Birdair, Inc. of samples taken from nine locations on the roof. These samples were tested for baseline strength parameters, biaxial modulus testing, and water absorption. In addition, samples from one panel were evaluated microscopically.

Our evaluation indicates that while basic strip tensile strengths are acceptable, there is significant cause for concern in the results of flexfold tensile strength and trapezoidal tear strength. In addition, a biaxial test of Panel 72 produced a dramatic failure at a very low load. In our opinion this test result was caused by weakened yarns from exposure of the yarns to moisture in the deflated condition.

The time required to extract sufficient test samples to ensure that all potential flaws similar to those observed at Panel 72 is not practical. Based on the extents of current testing, there is no way to definitively establish whether such flaws do or do not exist in widespread quantities in the existing membrane material. The consequences of the presence of random distributed flaws in the roof is evaluated further in Part 4 of our report.

TESTING SCOPE

Test samples were extracted from the roof by Birdair from the following locations (see Figure 1):

- Diamond Panel 15. Failed following deflation. Material was readily available on site for rapid initial testing.
- Rectangular Panel 66. Light to moderately loaded during 2010 deflation. Test results exist for comparison from 2010 Birdair weather sample testing.
- Rectangular Panel 72. Heavily loaded during 2010 deflation and subsequent melting.
- Rectangular Panel 93. Heavily loaded during 2010 deflation and subsequent melting. Test results exist for comparison from 2003 Birdair weather sample testing and original 1980 roll.
- Diamond Panel 22. Heavily loaded during 2010 deflation.
- Diamond Panel 21. Lightly loaded during 2010 deflation. Test results exist for comparison from 2003 Birdair weather sample testing and original 1980 roll. Selected as a control sample for membrane material not heavily loaded during 2010 event.
- Triangular Panel 100. Selected based upon visual observation of fabric condition. Test results exist for comparison from 2003 Birdair weather sample testing, 2010 weathering testing, and original 1980 roll.
- Diamond Panel 41. Selected based upon observed snow loading condition and prolonged moisture exposure. Test results exist for comparison to the original 1980 roll.
- Rectangular Panel 71. Selected based upon observed snow loading condition and prolonged moisture exposure. Test results exist for comparison to the original 1980 roll.

Panel samples were typically four feet by four feet. At each location baseline tests as described below were conducted. At Panels 22, 72, 41, and 71 biaxial modulus tests were conducted. A microscopic examination was conducted of material taken from Panel 72. Water absorption tests were conducted on Panels 21, 22, 66, 72, 93, and 100.

Note that other test samples were in progress but not complete at the time of this report.

TEST PROTOCOL

The following protocol was provided for baseline testing:

a. Cutting and preparation of the supplied samples into individual specimens for testing as outlined below.

b. Mass per Unit Area Testing in accordance with ASTM D4851-88 and ASTM D3776. Testing shall be conducted on each of the (64) specimens prepared for the strip tensile testing outlined in item d below.

c. Thickness Testing in accordance with ASTM D4851-88 and ASTM D1777. Testing shall be conducted on each of the (64) specimens prepared for the strip tensile testing outlined in item d below.

d. Strip Tensile Strength Testing in accordance with ASTM D4851-88 and ASTM D1682-64. Create 4 testing specimens for each test below from each sample.

   i. Warp direction – dry (16 tests)
   ii. Fill direction – dry (16 tests)
   iii. Warp direction – wet (16 tests)
   iv. Fill direction – wet (16 tests)

e. Crease Fold Tensile Strength Testing in accordance with ASTM D4851-88 and ASTM D1682-64. Create 4 testing specimens for each test below from each sample.

   i. Warp direction – dry (16 tests)
   ii. Fill direction – dry (16 tests)

f. Trapezoidal Tear Strength in accordance with ASTM D4851-88*. Create 4 testing specimens for each test below from each sample.

   i. Warp direction – dry (16 tests)
   ii. Fill direction – dry (16 tests)

   *Note that ASTM D4851-88 references ASTM D1117 for trapezoidal tear strength, which is only applicable to non-woven fabrics. The original project testing followed FTMS 191A-5136 to determine trapezoidal tear strength. For the purposes of the proposed testing herein, ASTM D5587-96 is an acceptable substitute for FTMS 191A-5136.

Where biaxial modulus tests were conducted, the testing process was generally in accordance with the Membrane Structures Association of Japan "Testing Methods for Elastic Constants of Membrane Materials (MSAJ/M-02-1995). The actual sample size and stress excursion sequence are based upon internal Birdair procedures which encompass all of the requirements of MSAJ/M-02-1995 but provide additional information. Typically stresses are limited to 140 pounds per inch (pli). For some samples "high load" modulus tests were conducted that extended the load to around 275 pli. The biaxial test setup is shown in Figure 2.

TEST RESULTS

Baseline Tests

Baseline test results are shown in Tables 1 through 9 (See Appendix A). Test results have been compared to the original 1980 material specification, the current 2002 material specification, the original 1980 material roll tests (where available), the 2003 Birdair weathering tests (where available), and the 2010 Birdair weathering tests (where available). The most relevant measures of strength loss are the comparisons to the original 1980 roll tests. It should be noted that the original 1980 material specification values were rather conservative, and the current 2002 material specification values are likely more indicative of the actual strength of the original material installed.

Dry and wet strip tensile results generally show good strength retention rates, both compared to original spec and actual prior testing. This finding is consistent with prior weathering testing of PTFE coated fiberglass fabrics for environments similar to Minneapolis (Owens/Corning, 1986).

Test results for flexfold tensile and trapezoidal tear tests generally show higher levels of strength loss. This is evident in all panels where original roll test data was available. Flexfold test loss is as high as 47% and trapezoidal tear loss is as high as 40% in Panel 41. Of particular concern are declines on the order of 20% when compared to 2003 and 2010 weathering data evident in panels 21, 22, 72, and 100. Typically weathering effects reduce strength more rapidly over the first 10 years or so of service life, and then the effect becomes much more gradual thereafter. It is unusual, particularly in trapezoidal tear results, to see sharp drops in strength retention later in the service life. The Metrodome roof material is currently approximately 30 years old.

Panels 72 and 100 each contained trapezoidal tear tests than indicated unusually low results when examined in detail (see Figures 3 through 7, 8, and 9). The ASTM test method averaging technique provides misleading results when averaging the peaks, but the load-extension response at these samples are indicative of undesirable failures. Such results are potentially indicative of underlying glass yarn damage.

The test results for flexfold tensile and trapezoidal tear are concerning because these tests are most closely related to how a fabric structure might actually fail in service. The flexfold tensile test measures the strength of a 1" strip of material after an intentional crease has been introduced. This is highly relevant to the issues at hand due to widespread observed creasing of the Metrodome fabric material from ice and snow sliding as well as wind flutter. The trapezoidal tear test results are indicative of the resistance to spread of local damage initiated either be debris or a pre-existing flaw in the material. Most large-scale fabric failures are closely related to the tear properties of the material, which are generally low for PTFE coated fiberglass fabrics.

Water absorption tests (Table 10) indicate absorption levels higher than allowable by current specification. This may be attributable to breakdowns in the PTFE coating caused by abrasion from snow or ice sliding. Refer to Microscopic Evaluation discussion below for further details.

Biaxial Tests

Biaxial tests were conducted at Panels 22, 41, 71, and 72. In addition, several virgin samples of Sheerfill II-HT were tested biaxially for comparison purposes. Results are shown in Figures 10 through 21.

Biaxial test results provide a means to measure the stiffness, or elastic moduli, of a membrane material. Results depend on the ratio of loading in the orthogonal warp and fill directions. The purpose of conducting biaxial testing on the Metrodome material was to identify if high loading during the deflation event caused detectable changes in the stress-strain properties of the material.

Biaxial test results, with one notable exception, were generally favorable. Tests at Panels 22, 41, and 71 indicated behavior that is within expectations for a membrane material that has been through 30 years of load cycles. Each biaxial test indicated that the membrane material is stiffer than a virgin sample, which is indicative of removal of construction stretch and crimp effects due to repeated loading. Panels 41 and 71 were subsequently loaded to failure (Figure 16 and 17) and results were within expectations for biaxial testing.

Due to lack of existing test results, a baseline test of stiffness effects caused by high loading excursions was performed on virgin Sheerfill II-HT material (Figures 18-20). In the first cycle, the material was put through the standard biaxial test protocol. In the second cycle, the material was loaded up to 275 pli in each direction, well beyond the normal working stress limits of the material. In the third cycle, the material was retested again using the standard biaxial protocol. The first cycle was compared to the third cycle to determine stiffness effects of the high loading excursion. Observed results are consistent with the effects found in testing of Panels 22, 41, and 71, that is, the high loading excursions removed some of the stretch of the material and led to a stiffer membrane. Because the Metrodome roof is air-supported, the ability of the membrane to take on an equilibrium form in the inflated condition is related to the strain of the material. In certain areas, particularly panel corners, stiffer existing membrane could produce higher than anticipated stresses to achieve the inflated roof form. This effect should be evaluated if any of the existing panels are re-inflated for permanent service.

Biaxial testing of Panel 72 produced failure at a very low load level during initiation of the test (Figure 21). The failure appears to have initiated in an area of potentially damaged warp yarns, and spread by tearing across the fill yarn direction. The failed fill yarns were observed to have very little extension out of the PTFE matrix, which is unusual. Further visual observation of the possible area of failure initiation shows discolored warp yarns, which is indicative of moisture damage. It is notable that Panel 72 also demonstrated several low tear test results.

The results of the Panel 72 biaxial test are highly concerning, and represent the possibility of hidden flaws in the material propagating damage upon exposure to in-service stresses. It is hypothesized that the damage in Panel 72 is related to infiltration of moisture to the glass yarns and subsequent damage. Moisture damage of glass yarns is a well documented phenomenon in glass composites (Lee, 1993). To combat this effect, the e-glass yarns used in Sheerfill products are coated with a silicone material during production. The silicone protects the yarn against moisture in the event of a breakdown in the PTFE coating, and also allows the warp and fill glass yarns to move across one another under load without damage. However, if the silicone coated glass yarns are exposed to sufficient moisture, or the glass yarn has been compromised by damage such that the interior of the yarn is exposed, sufficient quantities of moisture will displace the silicone coating and allow direct attack on the glass yarn. Thus, distributed damage of the PTFE coating in combination with large amounts of moisture is an extremely concerning condition for PTFE coated fiberglass materials. This is precisely the environment that the Metrodome roof material has been subjected to since the December 12 deflation. Refer to Part 3 of our report for further details based on the visual survey results.

Microscopic Evaluation

Because of the above concerns, a small piece of the Panel 72 material was observed under an electron microscope at the State University of New York Buffalo. Images are shown in Figures 22 through 28. Of note are the occurrence of a regular pattern of "holes" in the PTFE coating that appear to align with the intersection points of the crossing warp and fill yarns. The microscopic image show these holes to be filled with dirt. It is not apparent from the images the depth of the hole, but if they are assumed to be spherical the depth appears to be above the level of the underlying glass yarns.

Similar observations were made of the fabric at BC Place in Vancouver, British Columbia following the 2007 deflation of that roof (Hightex, 2007). Figure 29 is reproduction of an image from the Hightex report showing ink penetration through the cross section of a similar hole. The ink did not reach the glass yarn. A similar test on material from Panel 41 of the Metrodome is underway at the time of this report.

The observed holes in the PTFE coating samples from the Metrodome are likely related to abrasion caused by ice sliding. As a chunk of ice slides across the surface, the high spots of the membrane surface are found at the crossing of yarns. Impact of the ice on the exposed PTFE likely has lead to "cleaving" of a spherical shape of PTFE out of the surface of the coating. Further evaluation would be required to determine if the potential exists for this phenomenon to produce a depth of cleaving sufficient for exposure of the glass yarns.

CONCLUSIONS

A variety of test have been conducted on samples extracted from the roof of the Metrodome. While some tests showed adequate results, results of flexfold tensile tests, trapezoidal tear tests, the Panel 72 biaxial test, and the microscopic evaluation give rise to concern for the existence of distributed flaws caused by the December 12 roof deflation and subsequent exposure to the elements. The most notable concern is the possibility of moisture infiltration to glass yarns, which cannot necessarily be detected visually.

The number of test samples taken from the roof has been limited by the available schedule to extract the samples in poor weather and dangerous working conditions. Ideally, to make a recommendation based upon testing alone, many more samples would be needed. However, the schedule required to take a statistically meaningful set of samples would extend for months. In addition, each sample is rather large (4 foot by 4 foot), and in itself represents yet another disturbance of the original fabric material that could present a future damage initiation point.

The test results have discovered one location of locally damaged fabric that could potentially lead to large scale damage at Panel 72. In a normal mechanically tensioned fabric structure, this would not be a cause of great global concern to the structure. However, in an air-supported roof the initiation of damage at one localized location can lead to overall deflation of the roof.

In the Metrodome testing program, tests conducted at Panels 41 and 71 were an attempt to replicate conditions similar to those found at Panel 72. These tests did not indicate that the material contained similar flaws. However, given the vast expanse of material on the Metrodome roof, this does not preclude the possibility that similar damage exists. In many ways, finding such damage is like a search for a needle in a haystack. On one hand there can be no guarantee that further "needles" exist if not directly found, but the corollary is that there can also be no guarantee that further "needles" do not exist. This possibility needs to be examined in light of the hazards to the building occupants should the existing roof material be re-inflated. Part 4 of our report attempts to quantify the effects of random distributed damage in the roof.

REFERENCES

Hightex. (2007). *Inspection of the Clamping System on the Fabric Roof on BC Place Stadium.*

Lee, S. M. (1993). *Handbook of Composite Reinforcements.* Palo Alto, California: Wiley-VCH.

Owens/Corning. (1986). *Teflon Coated Fabrics; Structo Fab vs. Sheerfill I Characterization Program; 5 Year Natural Outdoor Weathering - Phase III.*

APPENDIX A

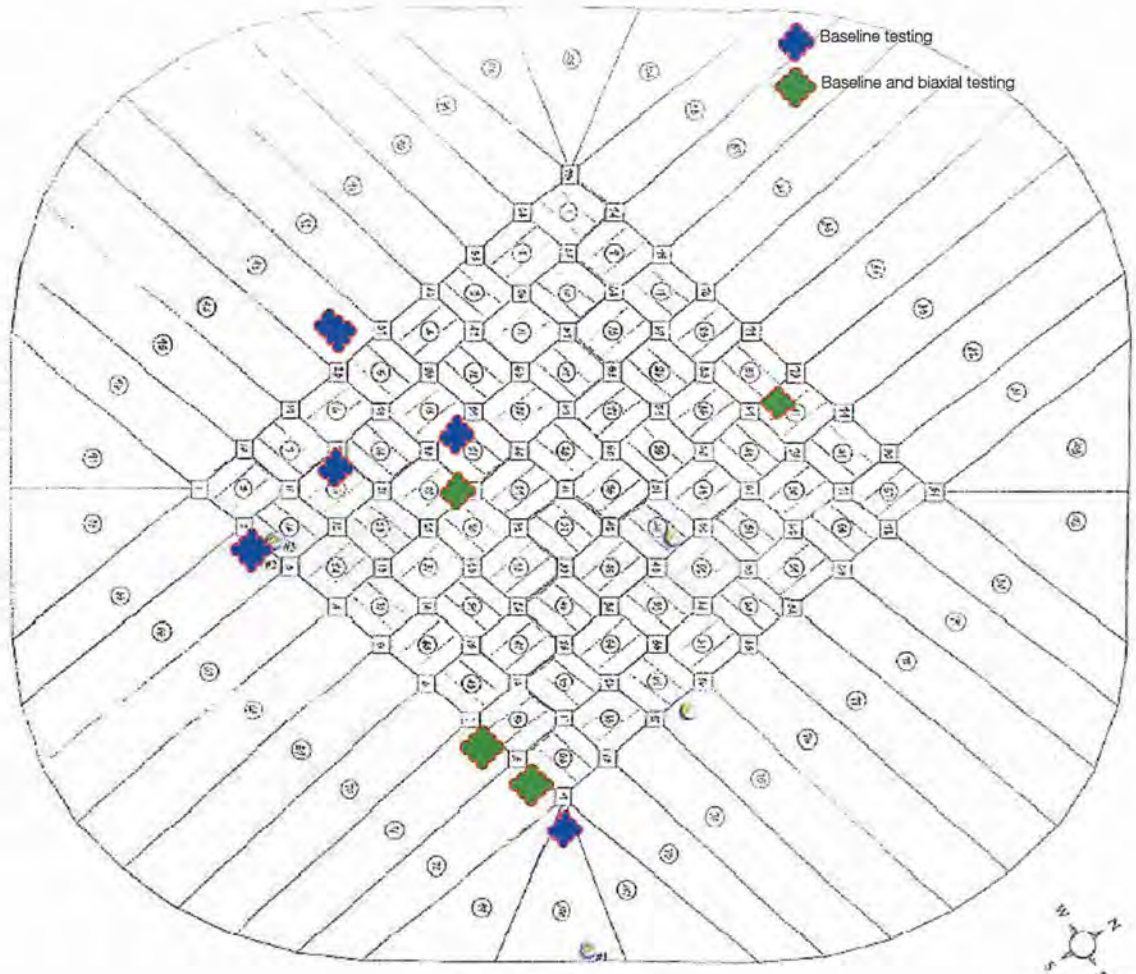
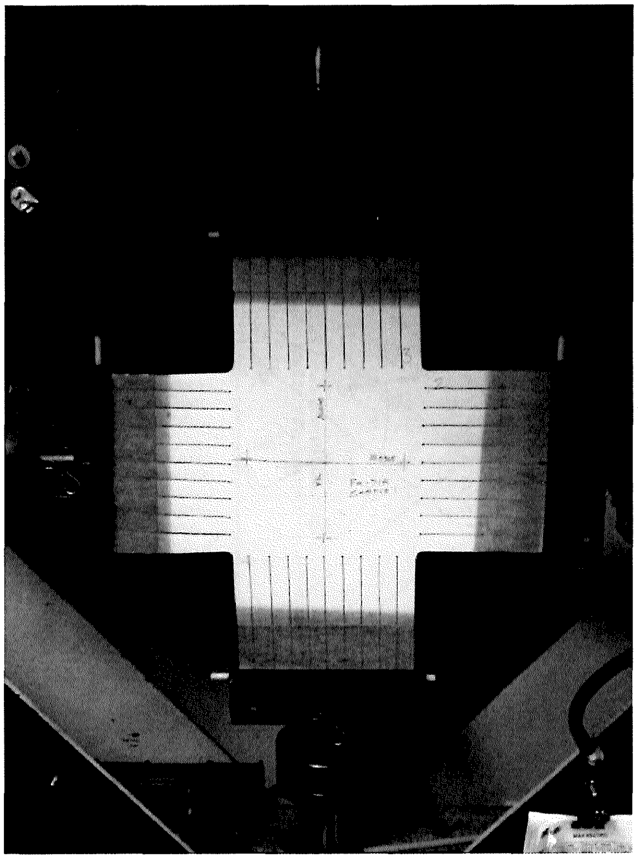


Figure 1: Test Sample Locations



FABRIC STRESS	
WARP (PLI)	FILL (PLI)
20	***20***
20	***50***
20	***80***
20	***110***
20	***140***
20	***20***
50	***20***
50	***50***
50	***80***
50	***110***
50	***140***
20	***20***
80	***20***
80	***50***
80	***80***
80	***110***
80	***140***

FABRIC STRESS	
WARP (PLI)	FILL (PLI)
20	***20***
110	***20***
110	***50***
110	***80***
110	***110***
110	***140***
20	***20***
140	***20***
140	***50***
140	***80***
140	***110***
140	***140***

FABRIC STRESS	
WARP (PLI)	FILL (PLI)
20	***20***
20	***50***
50	***50***
80	***50***
110	***50***
140	***50***
20	***20***
20	***80***
50	***80***
80	***80***
110	***80***
140	***80***
20	***20***
20	***110***
50	***110***
80	***110***
110	***110***
140	***110***
20	***20***
20	***140***
50	***140***
80	***140***
110	***140***
140	***140***

Figure 2: Biaxial Test Setup and Procedure

Table 1: Panel 15 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-80-17 Metro Dome
FABRIC TYPE: SH-II
UNIT: Diamond Assy 15 - Panel 2 - ROLL #3131

DATE TESTI 12/28/2010-12/29/2010

For control panel 21; actual panel 15 not tested

TEST			RESULTS											1980 Spec	% Strength Retention	2003 Testing Average	Reduction from 2003 Test	Actual Roll 1980 Testing	Reduction from 1980 Roll
														37.50	N/A	38.25	N/A	37.90	N/A
(All per ASTM D 4851, unless noted)			A	B	C	D	E	F	G	H	Sample Received From Site Testing Average	2002 Saint-Gobain Spec Avg	% Strength Retention Using The 2002 Spec	0.032	N/A	0.030	N/A	0.030	N/A
		Warp	826.4	845.1	811.9	843.3	890.5	906.6	836.7	862.3	853	825	103%	520	164%	734	116%	988	86%
Strip Tensiles			FF	JB	JB	JB	FF	JB	JB	JB									
(# / in)	Dry	Fill	628.9	700.5	671.8	692.4	677.3	695.5	577.7	678.4	665	600	111%	420	158%	673	99%	667	100%
			JB	JB	FF	JB	JB	JB	JB	JB									
		Warp	617.2	615.4	504.8	752.1	734.3	844.6	745.6	768.1	698	625	112%	440	159%	642	109%	972	72%
Strip Tensile			JB	FF	FF	JB	FF	JB	JB	JB									
(# / in)	Wet	Fill	599.3	640.2	575.9	615.6	614.4	607.8	557.0	623.4	604	465	130%	360	168%	566	107%	649	93%
			JB	JB	FF	JB	JB	JB	JB	JB									
		Warp	563.0	504.7	492.0	474.4	579.2	622.7	541.3	587.4	546	680	80%	440	124%	559	98%	766	71%
Strip Tensile			BF	BF	BF	BF	BF	BF	BF	BF									
(# / in)	Flexfold	Fill	319.7	310.5	276.9	266.1	207.9	255.5	335.8	298.5	284	415	68%	300	95%	421	67%	449	63%
	10 lbs.		BF	BF	BF	BF	BF	BF	BF	BF									
Trapezoidal Tear		Warp	61.0	55.4	58.2	58.4	58.3	58.5	57.5	59.1	58	75	78%	35	167%	56	104%	68	86%
(lb.)		Fill	56.5	57.7	54.0	54.2	52.8	54.3	55.8	54.8	55	70	79%	38	145%	51	108%	72	76%

AF - ADHESIVE FAILURE CF - COHESIVE FAILURE FF - FABRIC FAILURE JB - JAWBREAK BF - BREAK AT FOLD

COMMENTS:

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 12/29/2010

Table 2: Panel 21 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome
FABRIC TYPE: Sheerfill-II
UNIT: Diamond 21 - Subpanel 2
ROLL #: Roll # 3132 Birdair # 26

DATE TESTED: 1/7/2011-1/10/2011

TEST (All per ASTM D 4851, unless noted)			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Weight (oz/yd²)			37.91															
Thickness (in.)			0.028															
Strip Tensiles (lb/in)	Dry	Warp	806.7	869.1	842.8	845.1	838.9	865.3	807.4	860.5	886.9	822.2	852.7	876.2	770.2	806.8	830.7	745.1
			JB	JB	JB	FF	JB	JB	FF	JB	FF	FF	JB	JB	FF	JB	JB	JB
		Fill	626.7	667.2	582.7	592.3	668.5	634.1	700.0	661.7	670.2	588.3	640.3	695.1	559.2	668.0	627.6	658.5
			JB	JB	JB	JB	JB	FF	JB	JB	FF	FF	JB	JB	JB	JB	JB	JB
Strip Tensiles (lb/in)	Wet	Warp	746.8	810.0	802.0	812.9	788.7	722.9	736.8	796.8	792.3	725.3	763.5	787.1	739.6	749.0	743.9	722.2
			JB	JB	JB	JB	JB	FF	JB	JB	JB	JB	JB	JB	JB	FF	JB	JB
		Fill	588.8	609.1	553.7	531.0	570.4	558.1	615.4	641.7	598.1	630.8	487.1	584.5	561.8	567.4	619.3	594.9
			JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	FF	JB	JB	JB	JB	JB
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	307.3	479.2	459.2	414.5	460.2	483.2	456.6	493.4	526.0	379.4	495.8	540.5	460.3	483.0	453.1	359.1
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
		Fill	408.3	326.5	299.7	356.3	402.6	293.4	347.9	355.2	324.0	277.7	332.7	396.5	374.9	257.8	290.4	375.3
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
Trapezoidal Tear (lb.)		Warp	54.9	48.7	53.1	51.0	53.9	52.3	55.7	54.3	52.0	50.3	50.5	55.5	49.8	52.2	49.8	50.3
		Fill	54.0	51.9	56.0	54.8	52.9	51.1	53.2	51.5	54.3	55.9	53.9	54.2	52.1	53.9	52.7	52.5

TEST			Sample Received From Site Testing Average	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec	1980 Spec	% Strength Retention Using The 1980 Spec	2003 Testing Average	Reduction from 2003 Test	Actual Roll 1980 Testing	Reduction from 1980 Roll
Weight (oz/yd²)			37.91	38.50	N/A	37.50	N/A	38.25	N/A	37.90	N/A
Thickness (in.)			0.028	0.030	N/A	0.032	N/A	0.030	N/A	0.030	N/A
Strip Tensiles (lb/in)	Dry	Warp	833	825	101%	520	160%	734	113%	988	84%
		Fill	640	600	107%	420	152%	673	95%	667	96%
Strip Tensiles (lb/in)	Wet	Warp	765	625	122%	440	174%	642	119%	972	79%
		Fill	582	465	125%	360	162%	566	103%	649	90%
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	453	680	67%	440	103%	559	81%	766	59%
		Fill	339	415	82%	300	113%	421	80%	449	75%
Trapezoidal Tear (lb.)		Warp	52	75	70%	35	149%	56	93%	68	77%
		Fill	53	70	76%	38	141%	51	105%	72	74%

AF - ADHESIVE FAILURE CF - COHESIVE FAILURE FF - FABRIC FAILURE JB - JAWBREAK BF - BREAK AT FOLD

COMMENTS:

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 1/11/2011

Table 3: Panel 22 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome
FABRIC TYPE: Sheerfill-II
UNIT: Diamond 22 - Subpanel 1
ROLL #: Roll # 3131 Birdair # 36

DATE TESTED: 1/8/2011-1/10/11

TEST (All per ASTM D 4851, unless noted)			RESULTS A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Weight (oz/yd²)			38.19															
Thickness (in.)			0.028															
Strip Tensiles (lb/in)	Dry	Warp	786.6	855.6	788.2	739.1	845.4	778.0	863.4	738.3	771.9	806.3	751.2	795.0	764.0	800.9	845.1	857.5
			JB	JB	JB	JB	JB	JB	JB	FF	FF	JB	JB	JB	FF	JB	JB	JB
		Fill	666.6	674.4	720.3	747.5	667.1	723.2	626.2	724.7	741.0	667.7	710.3	692.9	639.6	659.1	688.4	724.5
			FF	JB	JB	JB	JB	JB	FF	JB	JB	FF	JB	JB	JB	JB	JB	JB
Strip Tensiles (lb/in)	Wet	Warp	732.7	794.6	773.4	694.6	792.9	737.3	765.0	765.9	725.3	781.8	679.1	623.9	726.4	798.6	792.4	747.4
			JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	FF	JB	JB	JB	JB	JB
		Fill	625.3	633.0	536.2	676.6	615.2	685.8	620.5	675.5	682.7	652.3	681.7	577.9	669.5	572.9	642.1	665.5
			JB	JB	FF	JB	JB	JB	JB	JB	FF	JB	JB	JB	JB	FF	JB	JB
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	527.4	571.6	463.6	512.6	565.3	453.2	463.2	551.3	475.6	574.0	487.0	517.5	468.7	498.2	524.0	453.3
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
		Fill	376.3	334.0	323.7	352.5	332.1	293.8	410.5	405.4	376.2	417.8	379.3	390.9	328.0	285.3	362.7	305.3
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
Trapezoidal Tear (lb.)		Warp	64.4	56.6	61.1	59.7	57.7	57.2	58.6	57.6	54.7	56.8	52.1	58.9	59.8	56.2	61.4	60.7
		Fill	58.4	53.0	55.9	55.8	53.8	52.5	49.6	56.4	57.4	50.5	53.1	47.6	54.0	52.6	55.2	57.5

TEST (All per ASTM D 4851, unless noted)			Sample Received From Site Testing Average	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec	1980 Spec	% Strength Retention Using The 1980 Spec	For control panel 21; actual panel 22 not tested: 2003 Testing Average	Reduction from 2003 Test	Actual Roll 1980 Testing	Reduction from 1980 Roll
Weight (oz/yd²)			38.19	38.50	N/A	37.50	N/A	38.25	N/A	37.90	N/A
Thickness (in.)			0.028	0.030	N/A	0.032	N/A	0.030	N/A	0.030	N/A
Strip Tensiles (lb/in)	Dry	Warp	799	825	97%	520	154%	734	109%	988	81%
		Fill	692	600	115%	420	165%	673	103%	667	104%
Strip Tensiles (lb/in)	Wet	Warp	746	625	119%	440	169%	642	116%	972	77%
		Fill	638	465	137%	360	177%	566	113%	649	98%
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	507	680	75%	440	115%	559	91%	766	66%
		Fill	355	415	85%	300	118%	421	84%	449	79%
Trapezoidal Tear (lb.)		Warp	58	75	78%	35	167%	56	104%	68	86%
		Fill	54	70	77%	38	142%	51	106%	72	75%

AF - ADHESIVE FAILURE CF - COHESIVE FAILURE FF - FABRIC FAILURE JB - JAWBREAK BF - BREAK AT FOLD

COMMENTS:

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 1/11/2011

Table 4: Panel 41 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome
FABRIC TYPE: Sheerfill-II
UNIT: Rectangle 41 Subpanel 1
ROLL #: Roll # 3131 Birdair # 36

Date Tested 1/28/2011-2/1/2011

TEST (All per ASTM D 4851, unless noted)			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Sample Received From Site Testing Average	Original Roll Test Results (1980) Avg	% Strength Retention Using The 1980 Test Results	1980 Released Spec Avg	% Strength Retension Using the 1980 Spec	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec
Weight (oz/yd²)			37.78	37.7	37.7	38.0													37.80	40.20	N/A	37.50	N/A	38.50	N/A
Thickness (in.)			0.037	0.037	0.038	0.038													0.037	0.031	N/A	0.032	N/A	0.030	N/A
Strip Tensiles (lb/in)	Dry	Warp	867.7	719.9	786.2	730.9	810.2	783.6	763.7	770.4									779	1005	78%	520	150%	825	94%
			JB	JB	JB	FF	JB	JB	JB	JB															
		Fill	688.2	615.3	594.4	629.4	689.9	685.4	672.1	723.9									662	687	96%	430	154%	600	110%
			JB	JB	JB	JB	JB	JB	FF	JB															
Strip Tensiles (lb/in)	Wet	Warp	753.1	775.6	666.5	762.6	739.0	752.4	760.4	722.2									741	925	80%	440	169%	625	119%
			JB	JB	JB	JB	JB	JB	JB	JB															
		Fill	602.1	561.7	555.3	583.5	650.3	600.9	606.2	631.4									599	690	87%	360	166%	465	129%
			JB	JB	JB	JB	JB	JB	JB	JB															
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	476.6	486.1	470.1	537.9	375.7	510.2	423.2	537.9									477	908	53%	440	108%	680	70%
			BF	BF	BF	BF	BF	BF	BF	BF															
		Fill	296.0	307.0	319.3	291.6	532.9	412.0	383.5	333.1									359	522	69%	360	100%	415	87%
			BF	BF	BF	BF	BF	BF	BF	BF															
Trapezoidal Tear (lb.)		Warp	55.0	52.3	56..526	57.7	56.6	53.4	56.6	50.6									55	70	78%	35	156%	75	73%
		Fill	48.6	51.3	46.3	46.8	58.3	46.4	47.2	51.6									50	83	60%	38	130%	70	71%

			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P							
Special Strip Tensiles (lb/in) Wet Tensile from this combination identified SP was soaked for 96 hrs	Dry	Warp	812.2	832.5	779.7	830.6	818.7	836.8	781.5	830.2									815					825	
			JB	JB	JB	JB	JB	JB	JB	JB															
		Fill	603.8	636.9	636.5	644.1	670.0	651.0	611.2	642.0									637					600	
			FF	JB	FF	JB	JB	JB	JB	JB															
Special Strip Tensiles (lb/in) Wet Tensile from this combination identified SP was soaked for 96 hrs	Wet	Warp	675.7	756.5	708.3	791.5	751.6	641.2	701.9	736.3									720					825	
			FF	JB	JB	JB	JB	JB	JB	JB															
		Fill	567.5	588.4	546.2	577.0	617.4	573.6	565.1	627.3									583					600	
			JB	JB	FF	JB	JB	JB	JB	JB															

AF - ADHESIVE FAILURE CF - COHESIVE FAILURE FF - FABRIC FAILURE JB - JAWBREAK BF - BREAK AT FOLD

COMMENTS:

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 2/1/2011

Table 5: Panel 66 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome
FABRIC TYPE: Sheerfill-II
UNIT: Rectangle 66 - Subpanel 1
ROLL #: # 2807 Birdair # 35

DATE TESTED: 1/10/2011-1/11/2011

TEST (All per ASTM D 4851, unless noted)			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Weight (oz/yd²)			38.37															
Thickness (in.)			0.028															
Strip Tensiles (lb/in)	Dry	Warp	778.2	737.9	766.7	692.6	876.6	723.1	769.1	742.8	807.7	748.5	825.9	878.0	828.4	857.9	848.1	856.0
			JB	JB	JB	JB	JB	JB	JB	JB	FF	JB	JB	JB	JB	JB	JB	JB
		Fill	627.5	663.3	722.2	662.1	478.6	537.9	578.4	594.4	676.6	637.5	644.9	566.9	773.0	647.3	615.2	597.3
			JB	JB	JB	FF	JB	FF	FF	FF	FF	JB	JB	FF	JB	JB	JB	FF
Strip Tensiles (lb/in)	Wet	Warp	722.6	723.5	663.9	734.4	803.4	699.0	730.8	766.3	766.7	754.2	760.5	755.4	745.8	747.4	791.5	769.0
			JB	JB	JB	JB	JB	JB	JB	JB	JB	FF	JB	JB	JB	JB	JB	JB
		Fill	605.2	540.9	615.4	541.4	541.0	573.1	569.8	518.2	648.3	647.0	537.4	581.2	659.2	572.8	593.3	588.7
			JB	JB	JB	JB	JB	JB	JB	JB	JB	FF	FF	JB	JB	JB	JB	JB
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	481.4	526.1	534.5	471.1	584.7	458.0	458.8	426.5	590.0	555.2	554.6	565.9	549.2	579.5	640.5	533.0
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
		Fill	322.7	291.5	329.7	293.4	317.1	267.2	291.9	281.6	382.8	324.9	307.3	311.0	352.1	296.8	322.3	282.2
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
Trapezoidal Tear (lb.)		Warp	49.8	47.7	53.6	55.7	61.6	53.6	53.7	55.7	56.8	54.4	52.8	52.8	54.2	55.7	55.3	56.5
		Fill	45.2	49.2	49.0	50.6	49.5	51.3	48.7	49.1	48.7	50.4	50.3	50.1	49.6	49.3	51.4	48.9

From control sample panel 21, 1980 roll date not available at panel 66

TEST			Sample Received From Site Testing Average	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec	1980 Spec	% Strength Retention Using The 1980 Spec	April 2010 testing avg	Reduction from April 2010 Test	Actual Roll 1980 Testing	Reduction from 1980 Roll
Weight (oz/yd²)			38.37	38.50	N/A	37.50	N/A	38.09	N/A	37.90	N/A
Thickness (in.)			0.028	0.030	N/A	0.032	N/A	0.028	N/A	0.030	N/A
Strip Tensiles (lb/in)	Dry	Warp	796	825	96%	520	153%	769	104%	988	81%
		Fill	626	600	104%	420	149%	627	100%	667	94%
Strip Tensiles (lb/in)	Wet	Warp	746	625	119%	440	170%	717	104%	972	77%
		Fill	583	465	125%	360	162%	589	99%	649	90%
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	532	680	78%	440	121%	409	130%	766	69%
		Fill	311	415	75%	300	104%	271	115%	449	69%
Trapezoidal Tear (lb.)		Warp	54	75	72%	35	155%	53	103%	68	80%
		Fill	49	70	71%	38	130%	49	101%	72	69%

AF - ADHESIVE FAILURE CF - COHESIVE FAILURE FF - FABRIC FAILURE JB - JAWBREAK BF - BREAK AT FOLD

COMMENTS:

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 1/11/2011

Table 6: Panel 71 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome
FABRIC TYPE: Sheerfill-II
UNIT: Rectangle 71 Subpanel 1
ROLL #: Roll # 12908 Birdair # 45

Date Tested 1/28/2011-2/1/2011

TEST (All per ASTM D 4851, unless noted)			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Sample Received From Site Testing Average	Original Roll Test Results (1980) Avg	% Strength Retention Using The 1980 Test Results	1980 Released Spec Avg	% Strength Retension Using the 1980 Spec	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec
Weight (oz/yd²)			38.74	38.8	40.1	39.8													39.35	41.30	N/A	37.50	N/A	38.50	N/A
Thickness (in.)			0.037	0.037	0.038	0.038													0.037	0.031	N/A	0.032	N/A	0.030	N/A
Strip Tensiles (lb/in)	Dry	Warp	802.2	786.8	773.4	659.2	867.2	782.9	815.6	790.4									785	960	82%	520	151%	825	95%
			JB	JB	JB	FF	JB	JB	JB	JB															
		Fill	574.4	790.7	713.7	677.9	644.8	660.2	715.9	667.3									681	645	106%	430	158%	600	113%
			FF	JB	JB	JB	JB	JB	JB	JB															
Strip Tensiles (lb/in)	Wet	Warp	756.8	745.3	686.8	743.4	812.0	509.2	758.8	732.8									718	915	78%	440	163%	625	115%
			JB	JB	JB	JB	JB	JB	JB	JB															
		Fill	655.4	647.1	672.5	628.5	633.9	613.0	661.4	611.7									640	643	100%	360	178%	465	138%
			JB	JB	JB	JB	JB	JB	JB	JB															
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	511.6	497.0	466.6	535.6	548.7	510.1	510.0	593.6									522	812	64%	440	119%	680	77%
			BF	BF	BF	BF	BF	BF	BF	BF															
		Fill	328.5	309.6	334.6	426.4	334.9	419.8	378.1	397.0									366	431	85%	360	102%	415	88%
			BF	BF	BF	BF	BF	BF	BF	BF															
Trapezoidal Tear (lb.)		Warp	67.5	64.2	57.0	57.7	59.7	57.5	58.3	63.1									61	74	82%	35	173%	75	81%
		Fill	57.1	51.8	55.3	60.0	56.1	55.7	51.8	53.0									55	83	66%	38	145%	70	79%

			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Sample Received From Site Testing Average	Original Roll Test Results (1980) Avg	% Strength Retention Using The 1980 Test Results	1980 Released Spec Avg	% Strength Retension Using the 1980 Spec	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec
Special Strip Tensiles (lb/in) Wet Tensile from this combination identified SP was soaked for 96 hrs	Dry	Warp	765.4	763.0	814.0	749.9	795.3	816.2	805.6	718.0									778						
			JB	JB	FF	JB	JB	JB	JB	FF															
		Fill	699.7	578.8	621.6	669.6	698.6	696.2	664.5	615.7									656						
			JB	FF	JB	JB	JB	JB	JB	JB															
Special Strip Tensiles (lb/in) Wet Tensile from this combination identified SP was soaked for 96 hrs	Wet	Warp	687.8	739.6	775.1	690.6	719.0	756.6	719.7	742.5									729						
			JB	JB	JB	JB	JB	JB	JB	JB															
		Fill	603.1	547.1	546.2	622.3	621.8	635.5	623.0	594.4									599						
			JB	JB	FF	JB	JB	JB	JB	JB															

AF - ADHESIVE FAILURE CF - COHESIVE FAILURE FF - FABRIC FAILURE JB - JAWBREAK BF - BREAK AT FOLD

COMMENTS:

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 2/1/2011

Table 7: Panel 72 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome
FABRIC TYPE: Sheerfill-II
UNIT: Rectangle 72 - Subpanel 1
ROLL #: # 12928 Birdair # 21

DATE TESTED: 1/12/2011-1/13/2011

RESULTS

TEST (All per ASTM D 4851, unless noted)	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Weight (oz/yd²)	38.47															
Thickness (in.)	0.028															
Strip Tensiles (lb/in) Dry Warp	779.7	780.4	753.7	816.3	778.3	807.1	783.3	764.9	764.7	756.6	742.5	720.5	730.8	713.9	733.8	756.0
	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB
Strip Tensiles (lb/in) Dry Fill	687.9	685.2	769.3	710.1	732.2	798.4	725.0	689.7	770.6	564.1	703.3	396.7	684.5	626.8	624.0	672.2
	JB	JB	FF	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB
Strip Tensiles (lb/in) Wet Warp	695.5	679.0	702.2	729.8	691.0	676.0	731.6	669.1	686.7	747.1	699.3	359.7	637.9	702.6	486.7	706.9
	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	FF	JB	JB	FF	JB
Strip Tensiles (lb/in) Wet Fill	705.8	629.5	665.1	628.2	618.0	446.1	644.1	618.9	663.2	613.0	653.8	410.6	548.3	656.2	606.7	589.5
	JB	JB	JB	JB	JB	FF	JB	JB	JB	JB	JB	FF	JB	JB	JB	JB
Strip Tensiles (lb/in) Flexfold 10 lbs Warp	441.6	433.1	427.2	446.1	470.7	496.6	464.0	432.7	313.6	375.4	488.7	386.1	405.9	447.4	250.1	541.0
	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
Strip Tensiles (lb/in) Flexfold 10 lbs Fill	397.3	399.7	452.3	324.1	523.3	438.1	359.0	355.1	380.9	376.9	412.6	380.9	352.9	404.3	335.5	315.2
	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
Trapezoidal Tear (lb.) Warp	66.7	57.6	57.1	61.7	58.3	64.6	63.6	65.1	44.4	58.9	61.8	60.0	63.9	62.7	67.5	71.0
Trapezoidal Tear (lb.) Fill	58.9	58.4	65.5	64.2	60.4	56.1	57.1	77.7	63.4	68.9	63.6	60.5	54.9	51.3	59.7	13.2

TEST (All per ASTM D 4851, unless noted)	Sample Received From Site Testing Average	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec	1980 Spec	% Strength Retention Using The 1980 Spec	For control panel 21; actual panel 72 not tested: 2003 Testing Average	Reduction from 2003 Test	Actual Roll 1980 Testing	Reduction from 1980 Roll
Weight (oz/yd²)	38.47	38.50	N/A	37.50	N/A	38.25	N/A	37.90	N/A
Thickness (in.)	0.028	0.030	N/A	0.032	N/A	0.030	N/A	0.030	N/A
Strip Tensiles (lb/in) Dry Warp	761	825	92%	520	146%	734	104%	988	77%
Strip Tensiles (lb/in) Dry Fill	677	600	113%	420	161%	673	101%	667	102%
Strip Tensiles (lb/in) Wet Warp	663	625	106%	440	151%	642	103%	972	68%
Strip Tensiles (lb/in) Wet Fill	606	465	130%	360	168%	566	107%	649	93%
Strip Tensiles (lb/in) Flexfold 10 lbs Warp	426	680	63%	440	97%	559	76%	766	56%
Strip Tensiles (lb/in) Flexfold 10 lbs Fill	388	415	93%	300	129%	421	92%	449	86%
Trapezoidal Tear (lb.) Warp	62	75	82%	35	176%	56	110%	68	91%
Trapezoidal Tear (lb.) Fill	58	70	83%	38	154%	51	114%	72	81%

AF - ADHESIVE FAILURE CF - COHESIVE FAILURE FF - FABRIC FAILURE JB - JAWBREAK BF - BREAK AT FOLD

COMMENTS: Samples were tested to the astm standard. Results may be misleading on the samples that are Highlighted. These samples all had weak areas as shown on the attached graphs. See Graphs for details - work sheets identified I Warp, J Warp, M Warp, J Fill & P Fill Trap Tear.

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 1/13/2011

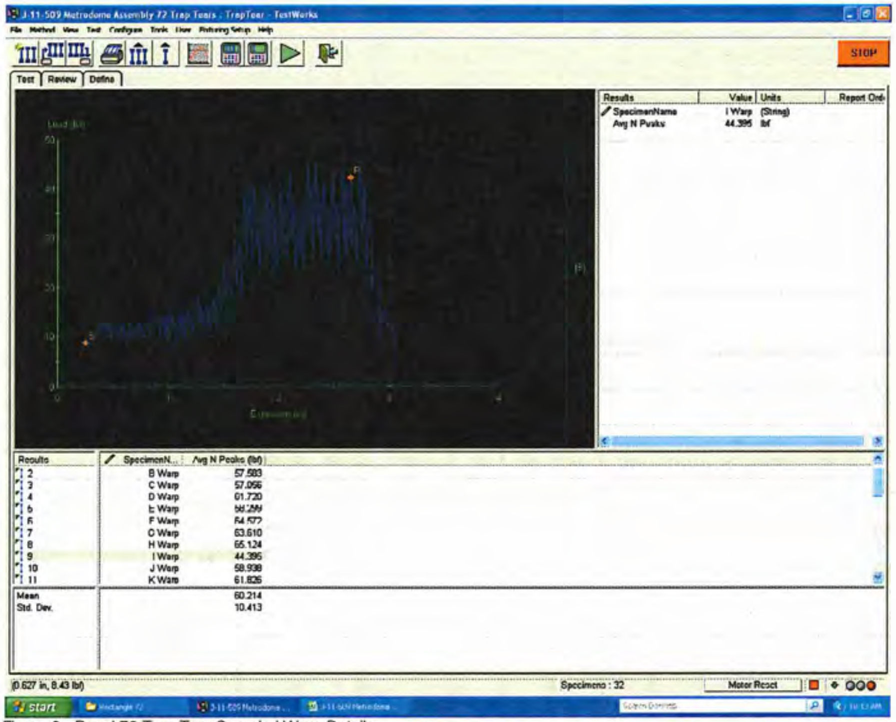


Figure 3: Panel 72 Trap Tear Sample I Warp Details

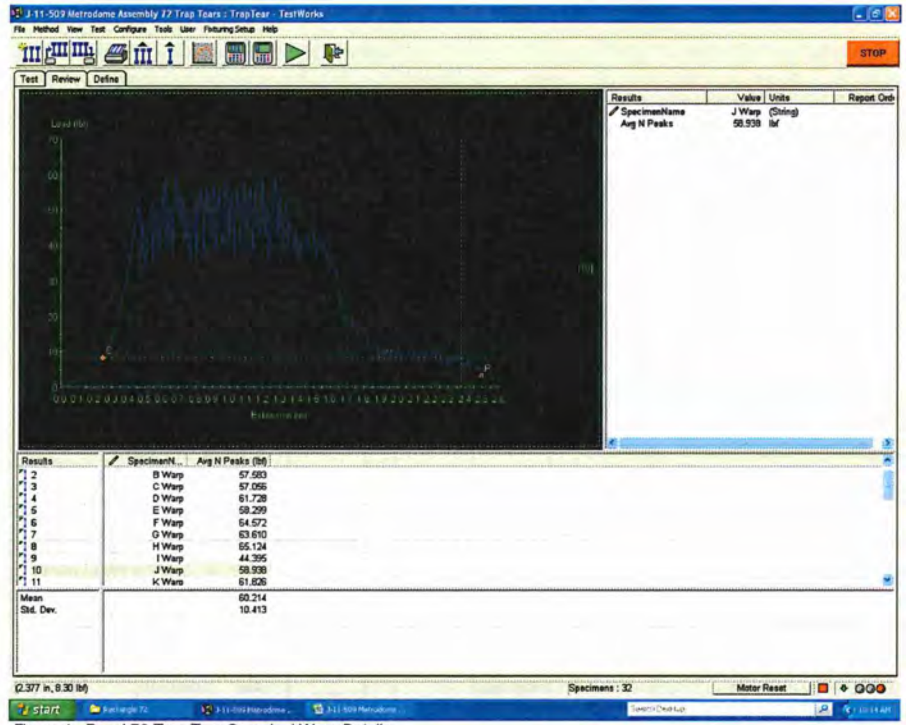


Figure 4: Panel 72 Trap Tear Sample J Warp Details

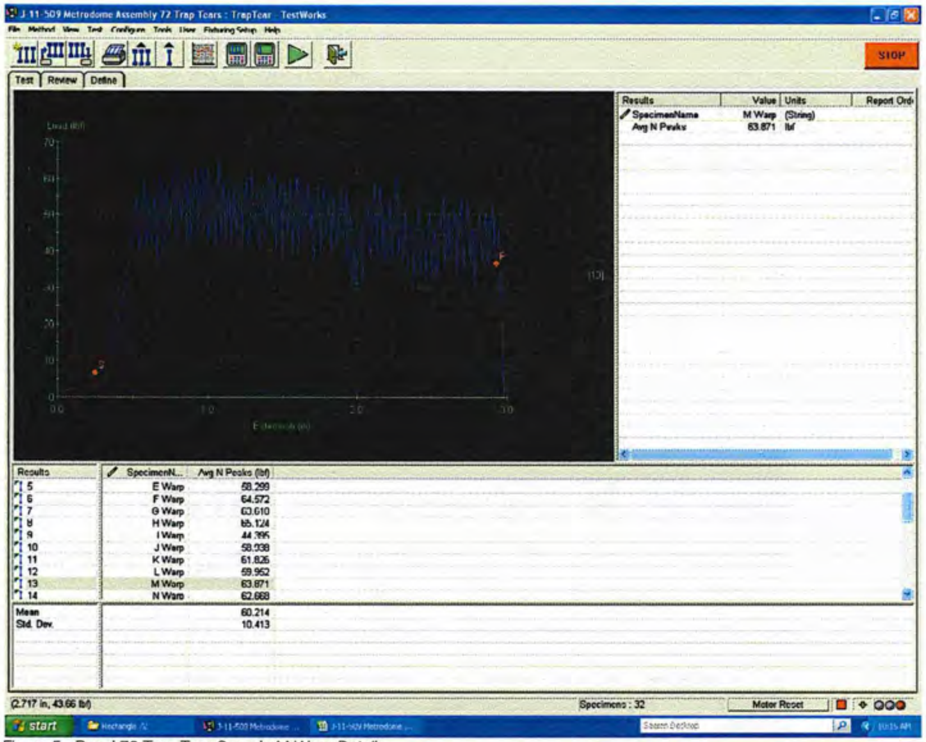


Figure 5: Panel 72 Trap Tear Sample M Warp Details

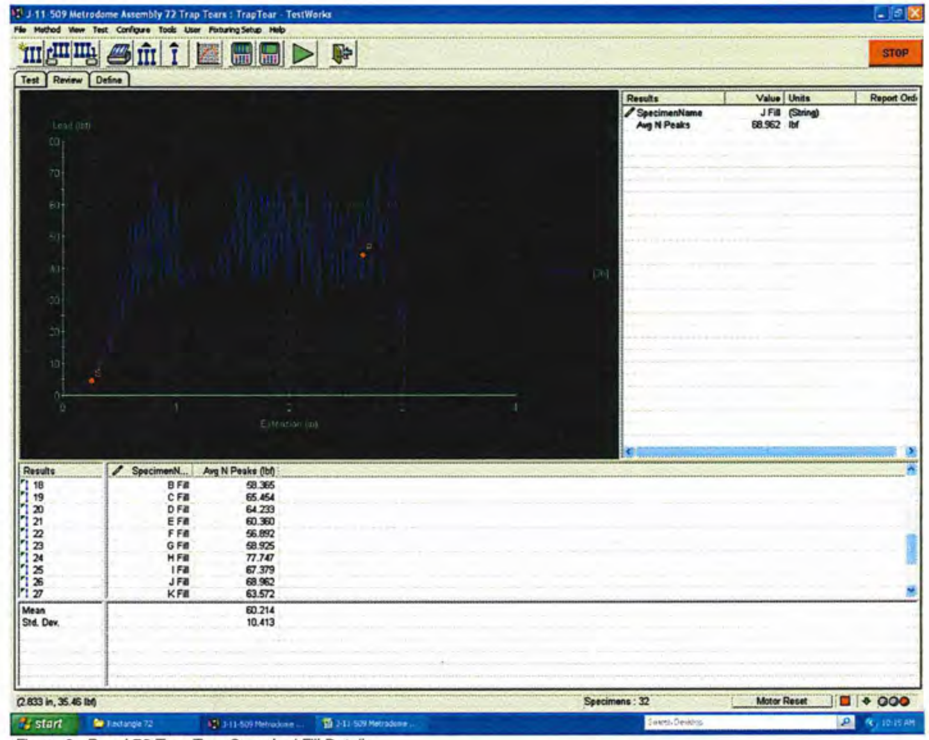


Figure 6: Panel 72 Trap Tear Sample J Fill Details

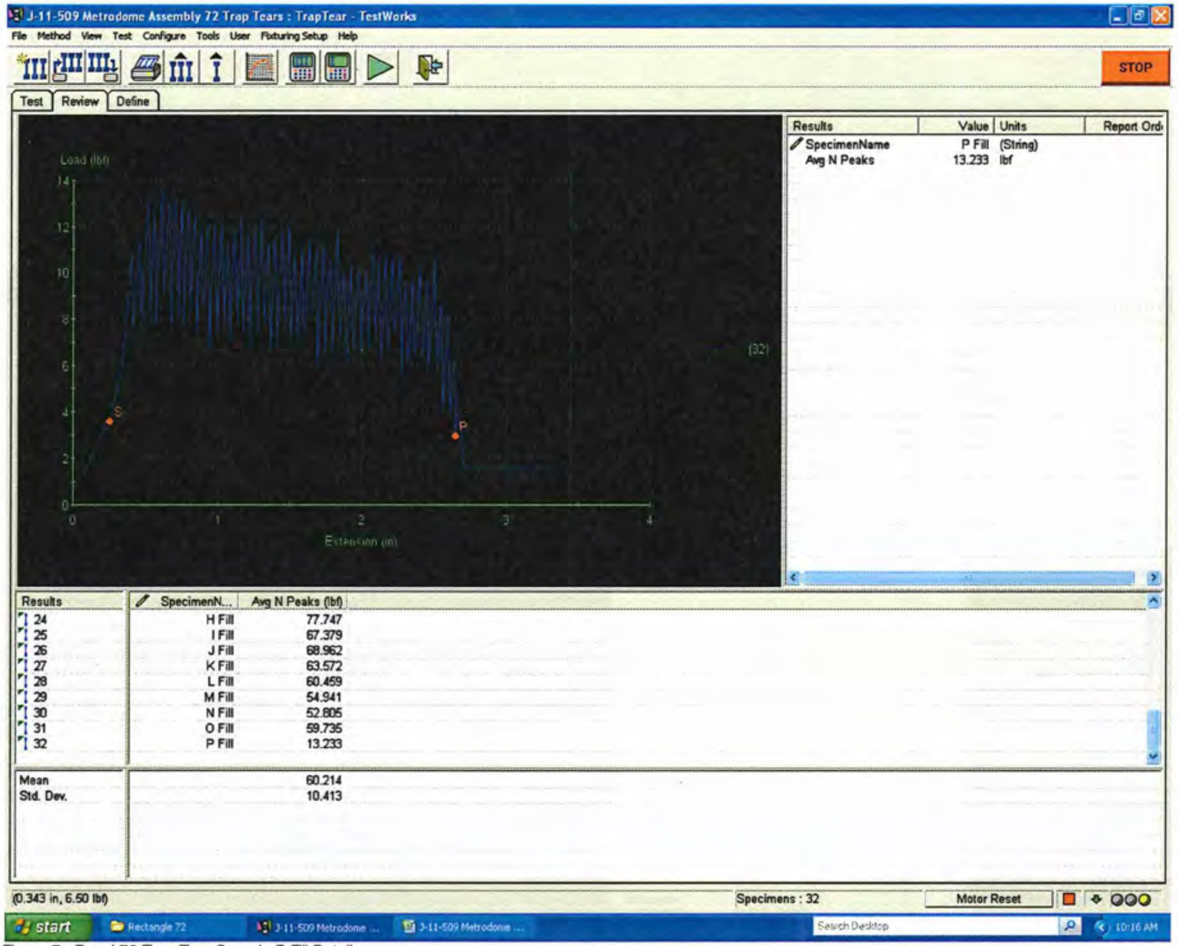


Figure 7: Panel 72 Trap Tear Sample P Fill Details

Table 8: Panel 93 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome
FABRIC TYPE: Sheerfill-II
UNIT: Rectangle 93 - Subpanel 1
ROLL #: Roll # 4400 Birdair # 73

DATE TESTED: 1/10/2011-1/11/2011

TEST			RESULTS																								
(All per ASTM D 4851, unless noted)			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Sample Received From Site Testing Average	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec	1980 Spec	% Strength Retention Using The 1980 Spec	2003 Testing Average	Reduction from 2003 Test	Actual Roll 1980 Testing	Reduction from 1980 Roll
Weight (oz/yd²)			37.74																37.74	38.50	N/A	37.50	N/A	38.03	N/A	39.10	N/A
Thickness (in.)			0.028																0.028	0.030	N/A	0.032	N/A	0.030	N/A	0.028	N/A
Strip Tensiles (lb/in)	Dry	Warp	750.6	771.1	742.3	689.4	775.9	826.0	801.1	768.8	787.5	791.2	726.3	763.9	821.4	816.3	827.3	797.0	778	825	94%	520	150%	753	103%	977	80%
			JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	FF	FF									
		Fill	581.4	706.6	689.6	630.6	651.2	672.7	720.6	756.8	717.3	687.4	700.0	703.1	680.1	644.1	673.9	677.7	681	600	113%	420	162%	523	130%	647	105%
			JB	JB	JB	FF	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	FF	JB									
Strip Tensiles (lb/in)	Wet	Warp	714.7	692.8	665.0	698.7	658.2	733.5	747.1	718.2	667.9	707.1	667.6	718.9	725.2	699.3	753.5	767.0	708	625	113%	440	161%	695	102%	815	87%
			JB	JB	FF	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB									
		Fill	602.1	545.6	565.2	642.8	657.1	586.9	624.2	606.4	624.3	614.3	546.4	607.2	612.2	620.3	612.3	584.8	603	465	130%	360	168%	541	112%	618	98%
			JB	JB	FF	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB									
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	443.3	482.1	478.3	407.6	557.5	529.8	575.0	542.9	468.4	430.6	499.8	495.6	569.1	510.9	510.1	484.7	499	680	73%	440	113%	511	98%	not available	#VALUE!
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF									
		Fill	369.2	327.0	307.1	421.6	365.0	396.7	413.6	381.1	386.0	351.2	369.0	328.0	346.2	353.9	311.0	381.9	363	415	87%	300	121%	351	103%	not available	#VALUE!
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF									
Trapezoidal Tear (lb.)		Warp	55.7	59.5	59.8	65.3	66.0	59.2	56.0	57.6	58.9	53.0	57.9	58.0	54.4	50.6	57.5	55.9	58	75	77%	35	165%	49	118%	69	84%
		Fill	55.4	57.0	54.5	49.9	48.6	52.4	49.3	54.7	55.6	54.5	53.2	50.9	51.0	49.7	48.2	49.9	52	70	75%	38	137%	48	109%	73	71%

AF - ADHESIVE FAILURE   CF - COHESIVE FAILURE   FF - FABRIC FAILURE   JB - JAWBREAK   BF - BREAK AT FOLD

COMMENTS:

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 1/11/2011

Table 9: Panel 100 Test Results

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome
FABRIC TYPE: Sheerfill-II
UNIT: Triangle 100 - Subpanel 2
ROLL #: # 4001-8 Birdair # 82

DATE TESTED: 1/15/2011-1/17/2011

TEST (All per ASTM D 4851, unless noted)			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Weight (oz/yd²)			39.48															
Thickness (in.)			0.028															
Strip Tensiles (lb/in)	Dry	Warp	775.6	807.6	783.1	757.6	599.2	773.7	835.1	793.0	791.1	862.2	885.1	821.4	803.9	825.0	800.6	791.9
			JB	FF	JB	JB	JB	FF	FF	JB	FF	JB	JB	FF	FF	FF	JB	FF
		Fill	679.6	437.7	536.0	579.5	645.8	627.8	578.8	630.8	569.6	530.2	631.5	652.1	629.5	575.8	246.1	516.5
			JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	FF
Strip Tensiles (lb/in)	Wet	Warp	729.3	706.5	810.0	786.4	765.2	782.9	743.8	775.2	742.4	801.6	819.9	750.7	759.6	738.9	748.5	750.4
			JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB	JB
		Fill	518.0	514.5	515.8	549.2	543.5	620.7	606.7	385.0	562.5	525.8	476.9	507.5	539.9	559.6	532.6	534.4
			JB	JB	JB	FF	JB	JB	JB	FF	JB	JB	FF	JB	JB	JB	FF	JB
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	520.2	476.5	469.9	443.1	437.8	321.4	419.9	321.3	480.5	395.0	406.9	373.9	501.2	364.6	354.8	287.7
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
		Fill	243.3	323.5	257.4	271.8	286.2	263.6	311.5	293.2	314.1	253.7	274.5	325.8	252.9	276.9	291.4	272.1
			BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF	BF
Trapezoidal Tear (lb.)		Warp	45.5	51.6	50.5	46.8	46.9	52.9	44.1	49.1	52.3	50.3	40.3	41.5	42.5	46.6	46.2	50.1
		Fill	51.7	53.8	64.8	72.7	49.6	56.9	57.2	52.5	47.7	48.4	58.9	55.5	53.6	50.1	50.0	52.4

TEST			Sample Received From Site Testing Average	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec	1980 Spec	% Strength Retention Using The 1980 Spec	2003 Testing Average	Reduction from 2003 Test	2010 Testing Average	Reduction from 2010 Test	Actual Roll 1980 Testing	Reduction from 1980 Roll
Weight (oz/yd²)			39.48	38.50	N/A	37.50	N/A	38.50	N/A	37.87	N/A	40.40	N/A
Thickness (in.)			0.028	0.030	N/A	0.032	N/A	0.028	N/A	0.028	N/A	0.030	N/A
Strip Tensiles (lb/in)	Dry	Warp	794	825	96%	520	153%	687	116%	754	105%	932	85%
		Fill	567	600	94%	420	135%	606	94%	652	87%	626	91%
Strip Tensiles (lb/in)	Wet	Warp	763	625	122%	440	173%	691	110%	714	107%	835	91%
		Fill	531	465	114%	360	147%	535	99%	608	87%	536	99%
Strip Tensiles (lb/in)	Flexfold 10 lbs	Warp	411	680	60%	440	93%	518	79%	407	101%	717	57%
		Fill	282	415	68%	300	94%	376	75%	265	106%	396	71%
Trapezoidal Tear (lb.)		Warp	47	75	63%	35	135%	56	85%	54	88%	65	73%
		Fill	55	70	78%	38	144%	57	96%	52	105%	72	76%

AF - ADHESIVE FAILURE CF - COHESIVE FAILURE FF - FABRIC FAILURE JB - JAWBREAK BF - BREAK AT FOLD

COMMENTS: Samples were tested to the astm standard.
Results may be misleading on the samples that are Highlighted. These samples all had weak areas as shown on the attached graphs. See Graphs for details - work sheets identified D Warp and K Warp

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 1/17/2011

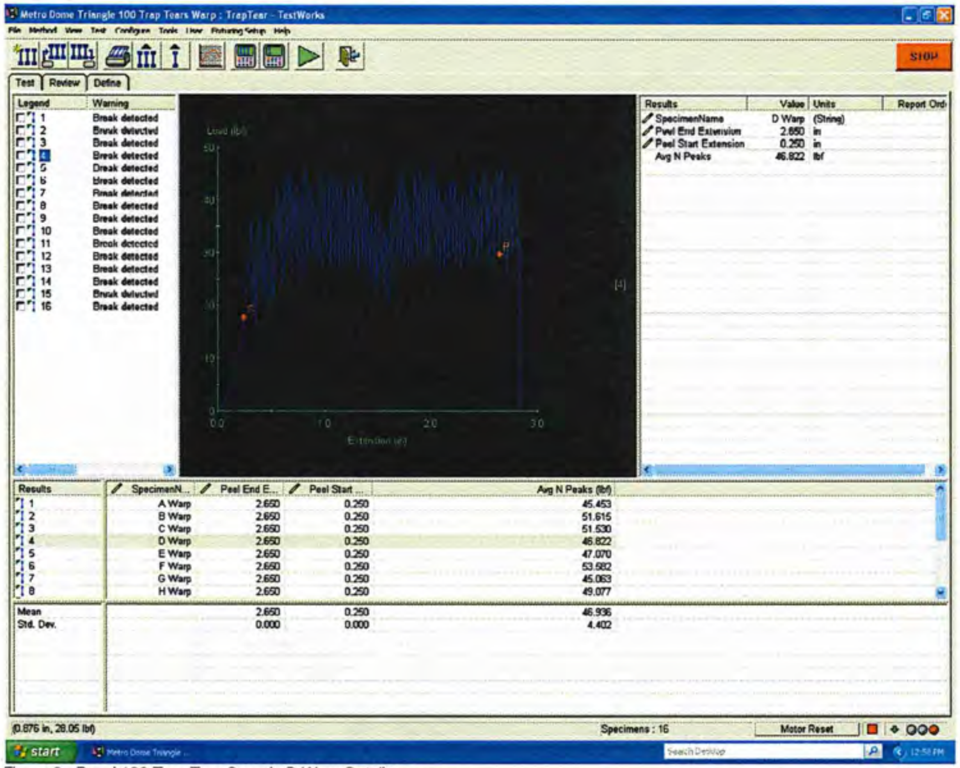


Figure 8: Panel 100 Trap Tear Sample D Warp Details

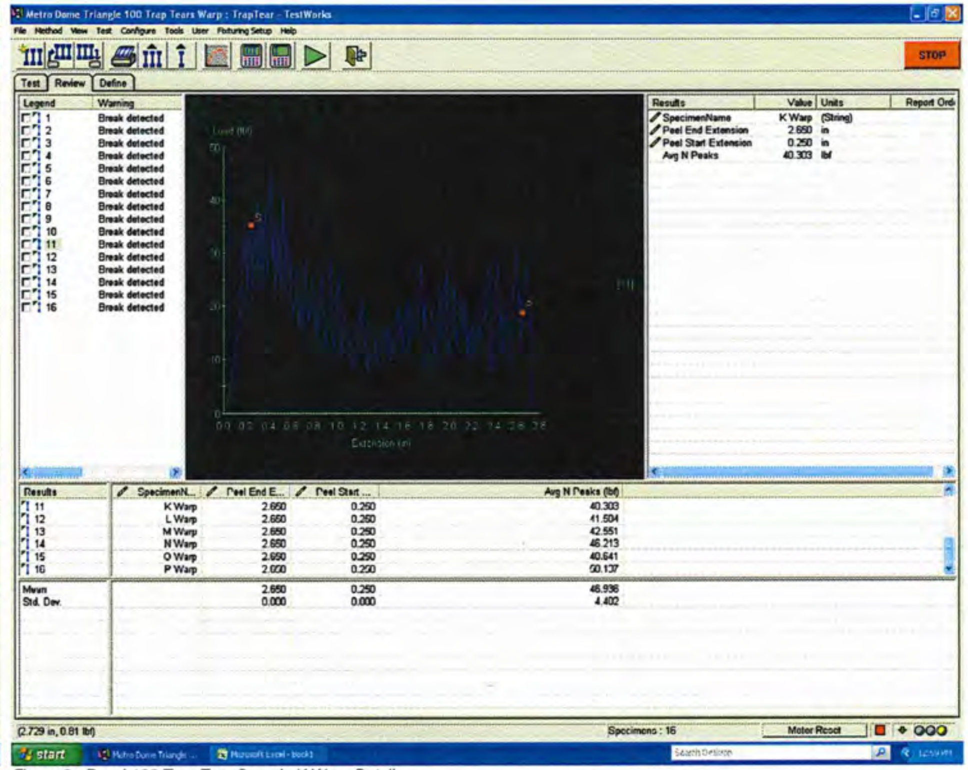


Figure 9: Panel 100 Trap Tear Sample K Warp Details

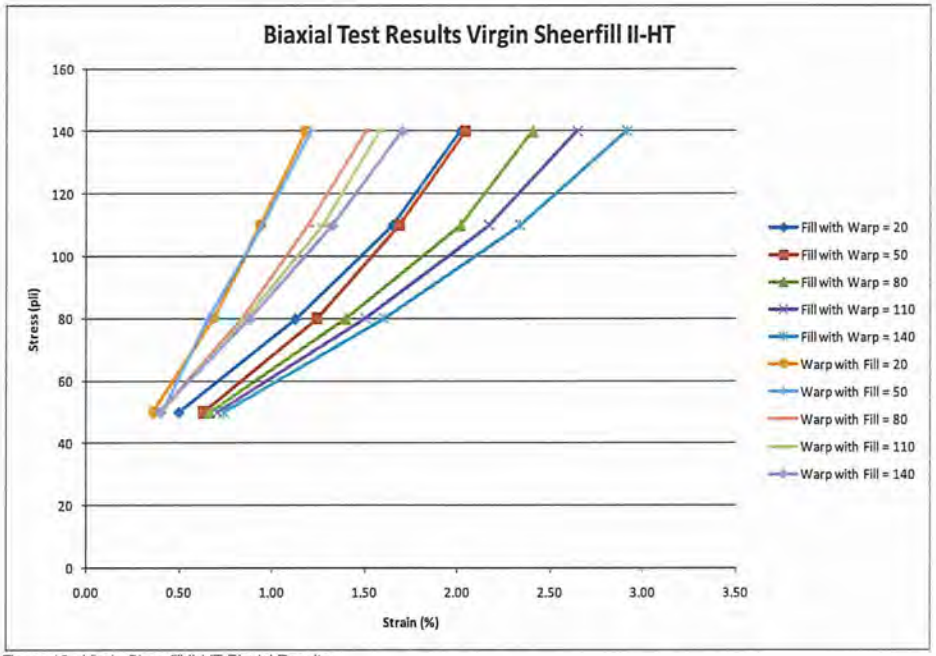


Figure 10: Virgin Sheerfill II-HT Biaxial Results

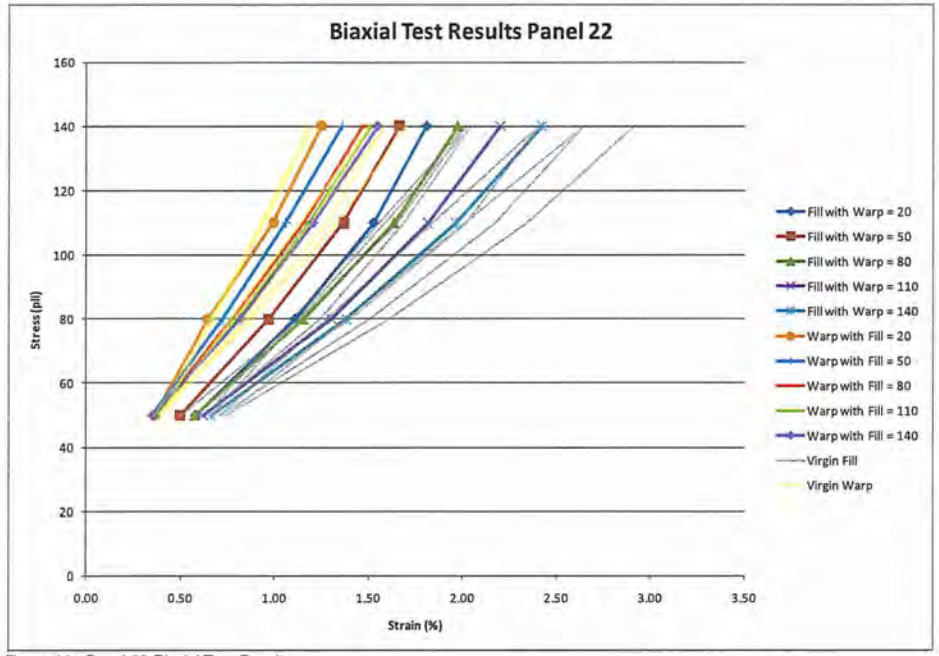


Figure 11: Panel 22 Biaxial Test Results

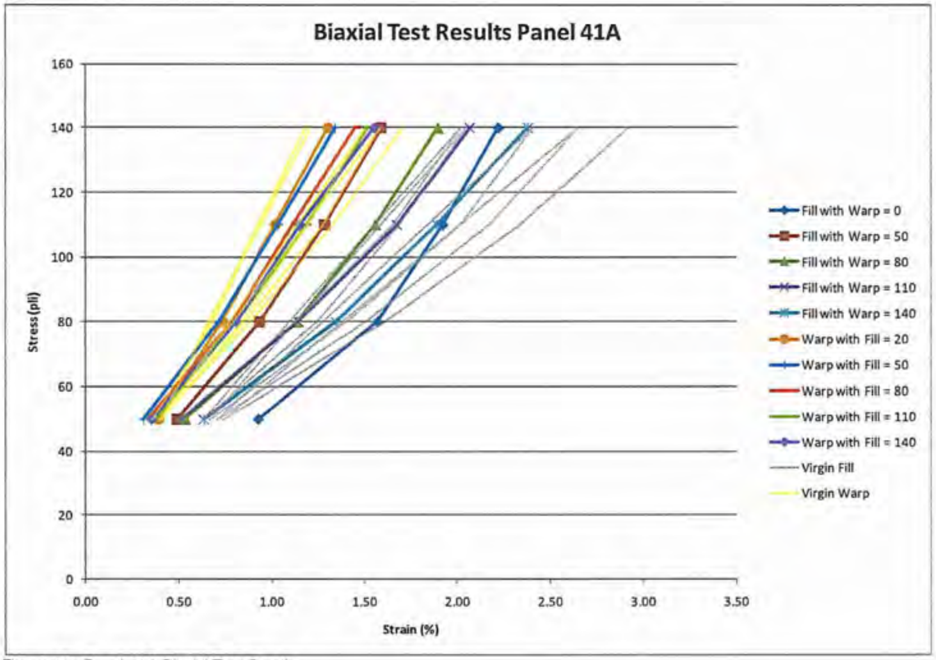


Figure 12: Panel 41A Biaxial Test Results

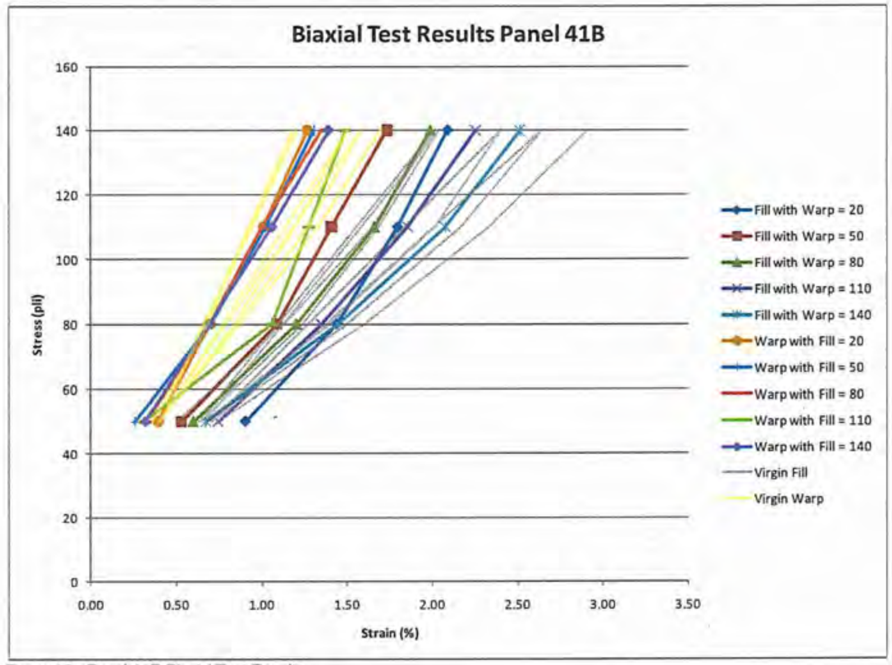


Figure 13: Panel 41B Biaxial Test Results

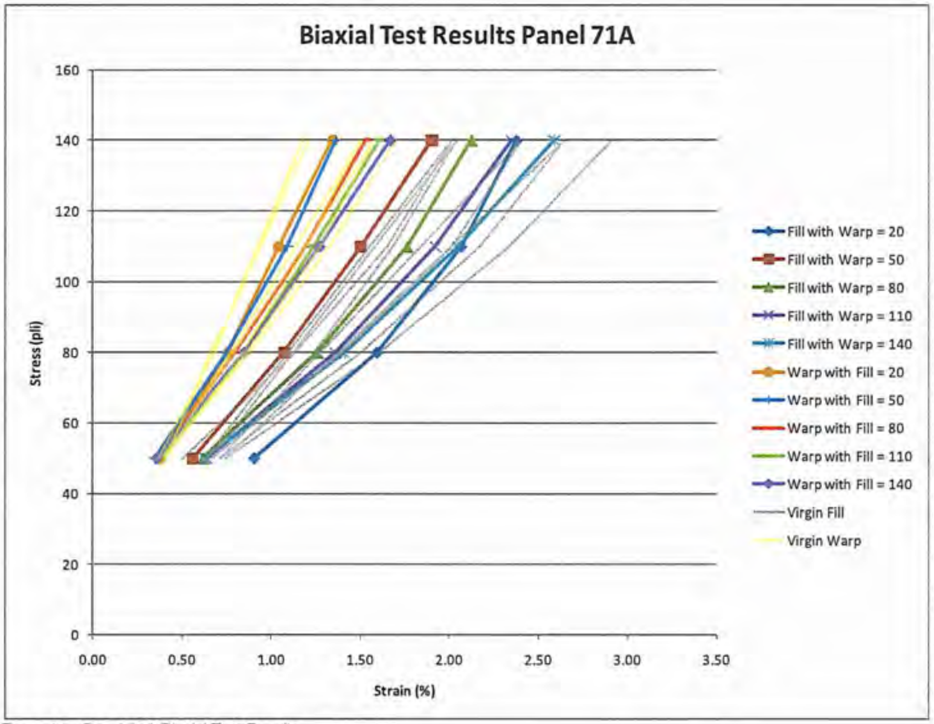


Figure 14: Panel 71A Biaxial Test Results

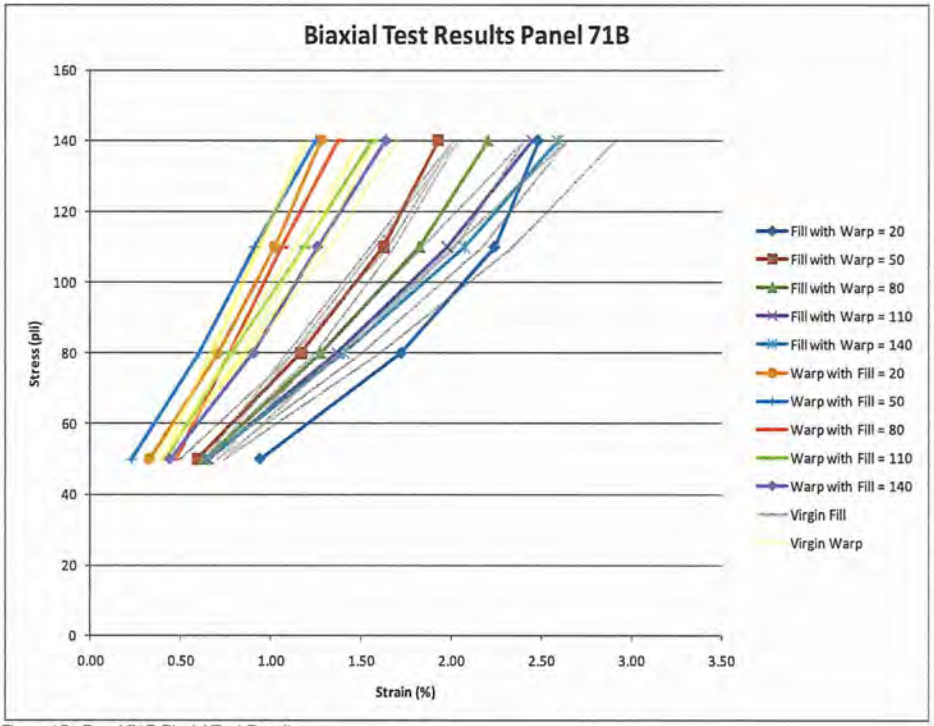


Figure 15: Panel 71B Biaxial Test Results

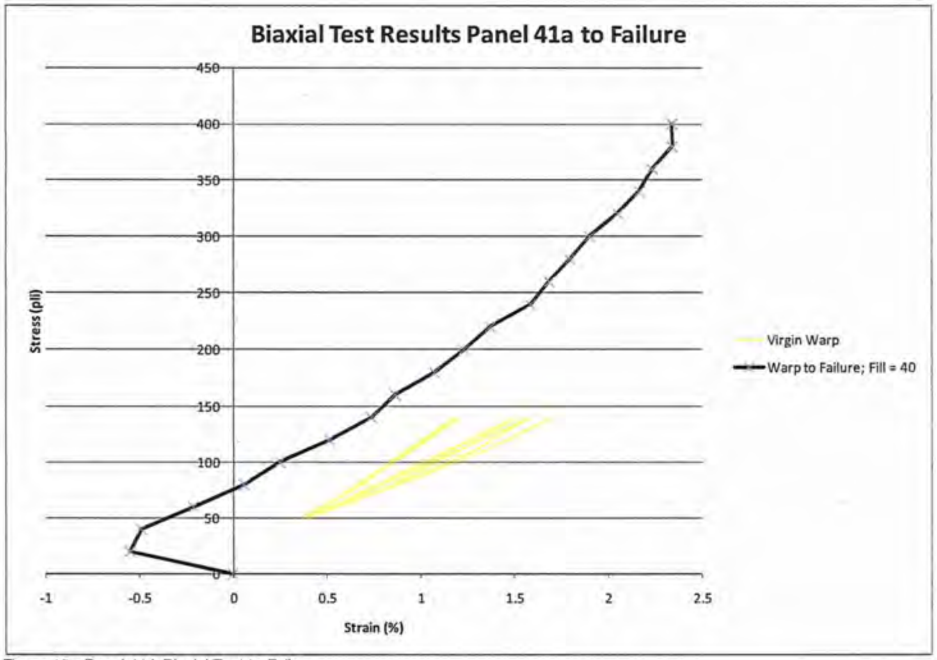


Figure 16: Panel 41A Biaxial Test to Failure

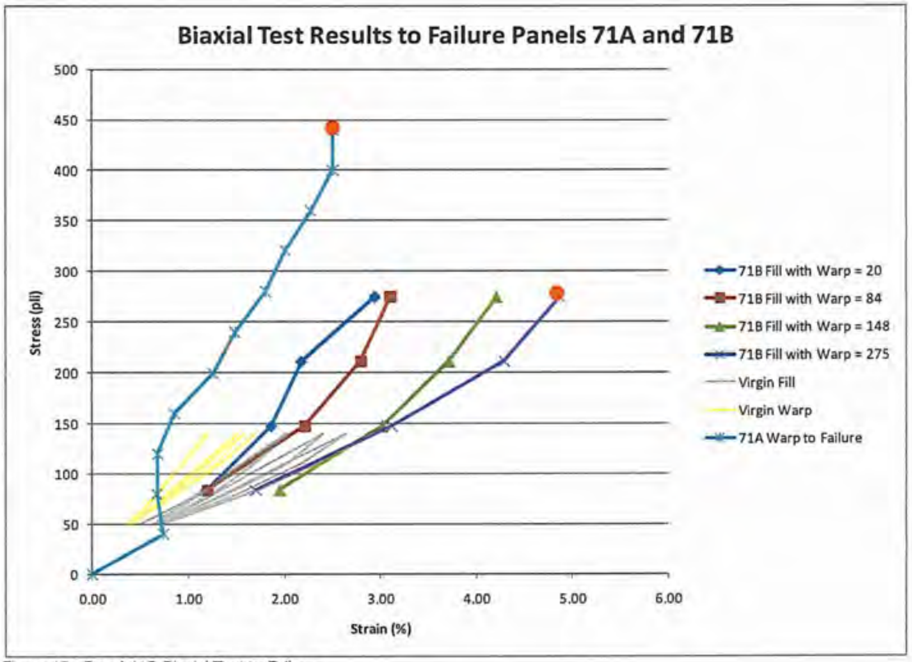


Figure 17: Panel 41B Biaxial Test to Failure

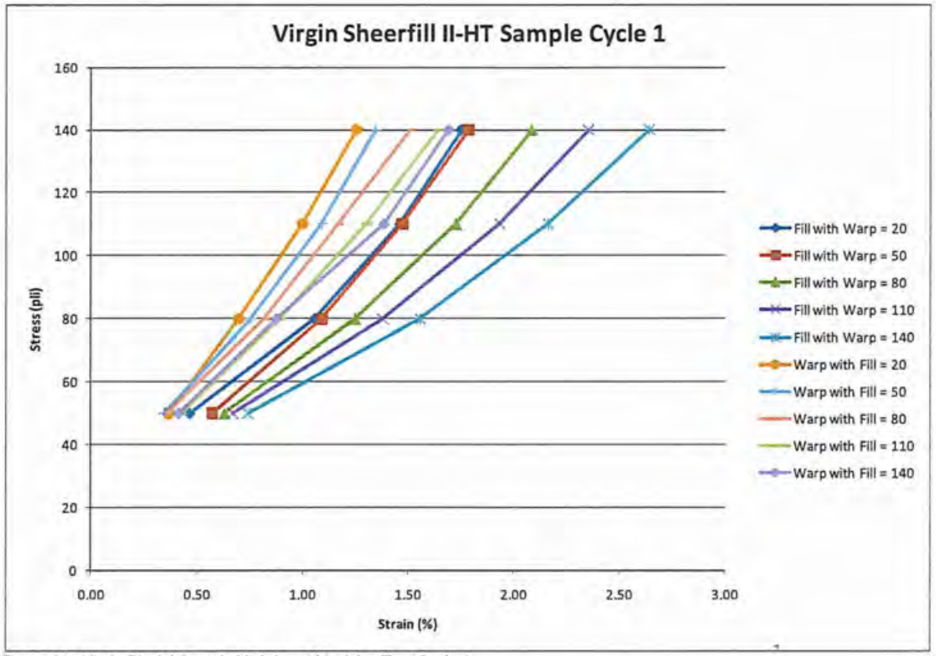


Figure 18: Virgin Biaxial Sample High Load Modulus Test Cycle 1

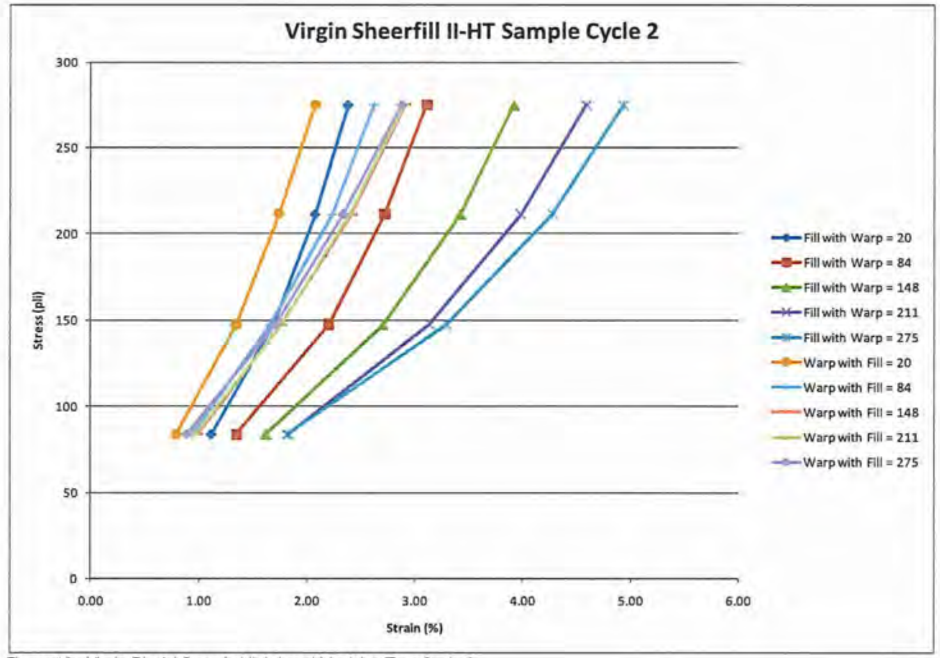


Figure 19: Virgin Biaxial Sample High Load Modulus Test Cycle 2

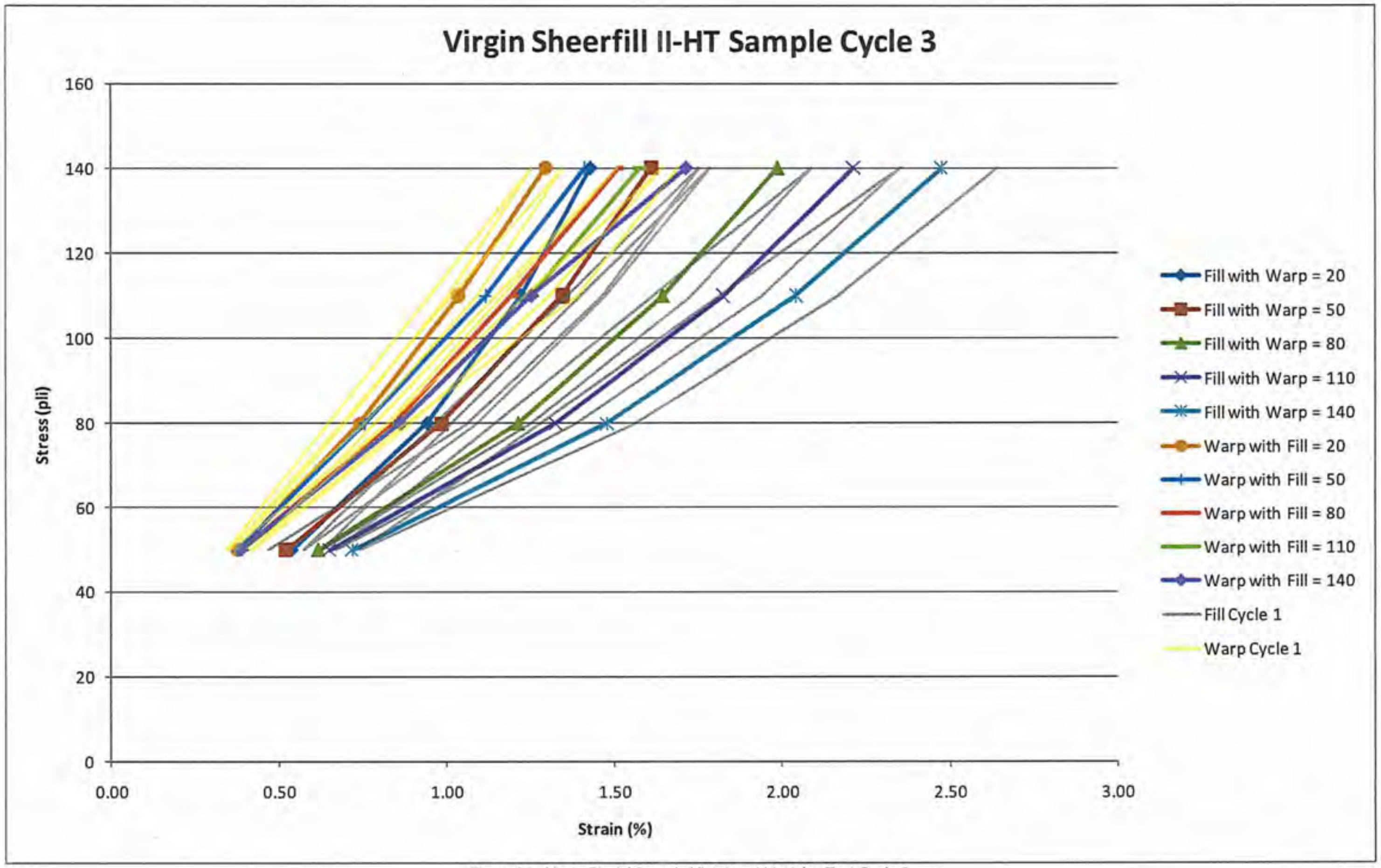


Figure 20: Virgin Biaxial Sample High Load Modulus Test Cycle 3

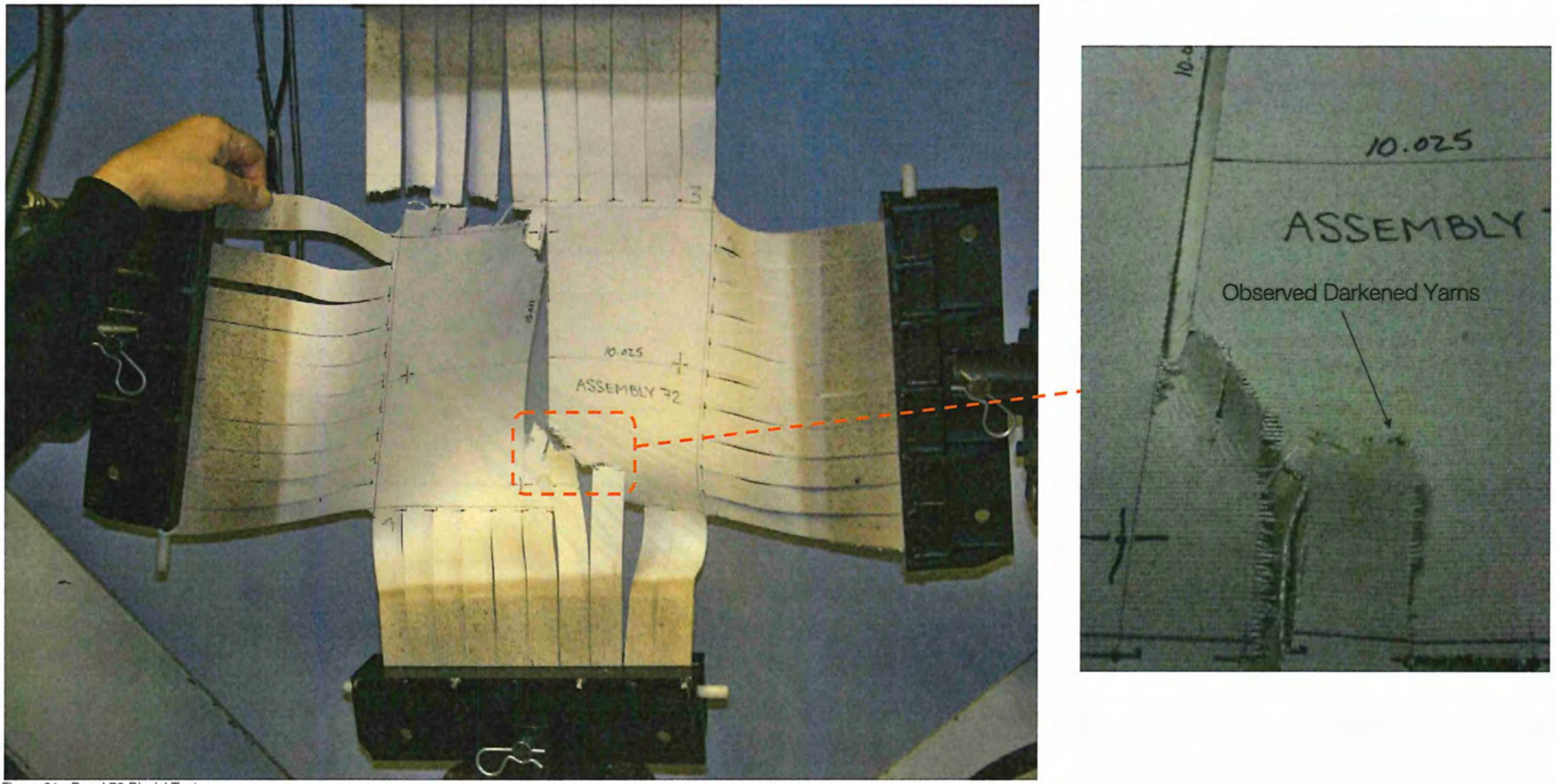
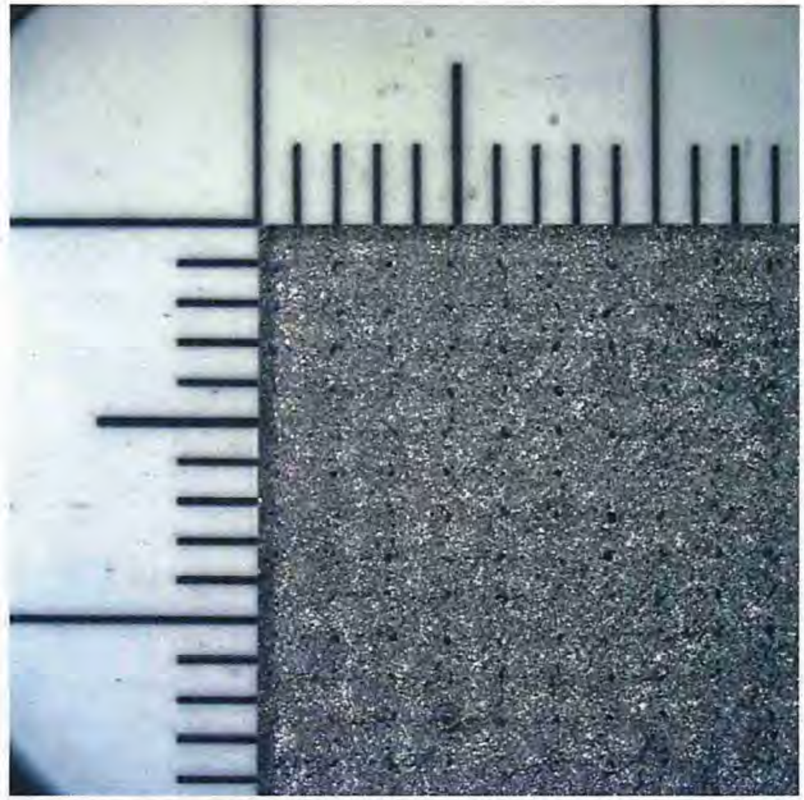


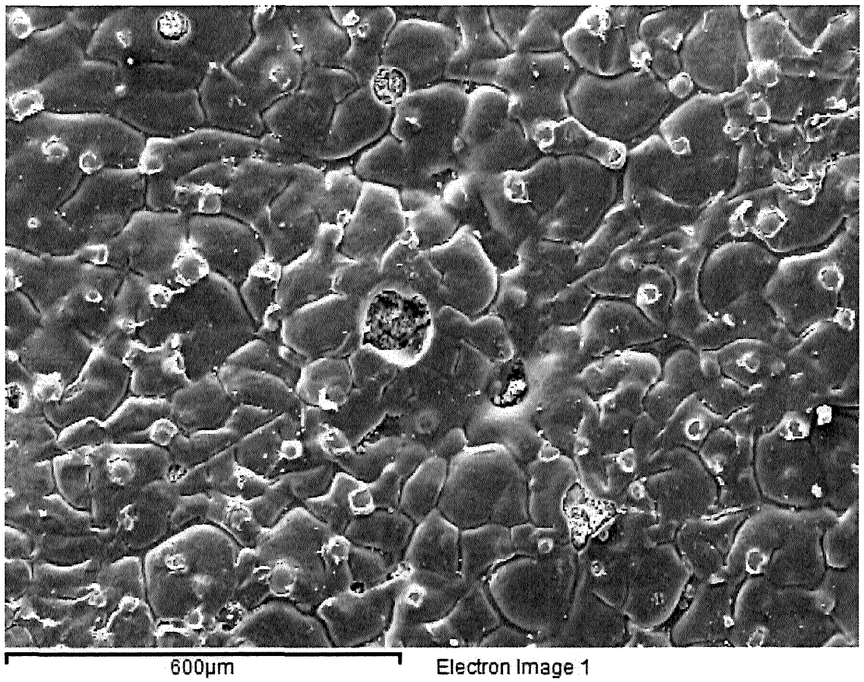
Figure 21: Panel 72 Biaxial Test

Figure 22: Microscopic Image Panel 72



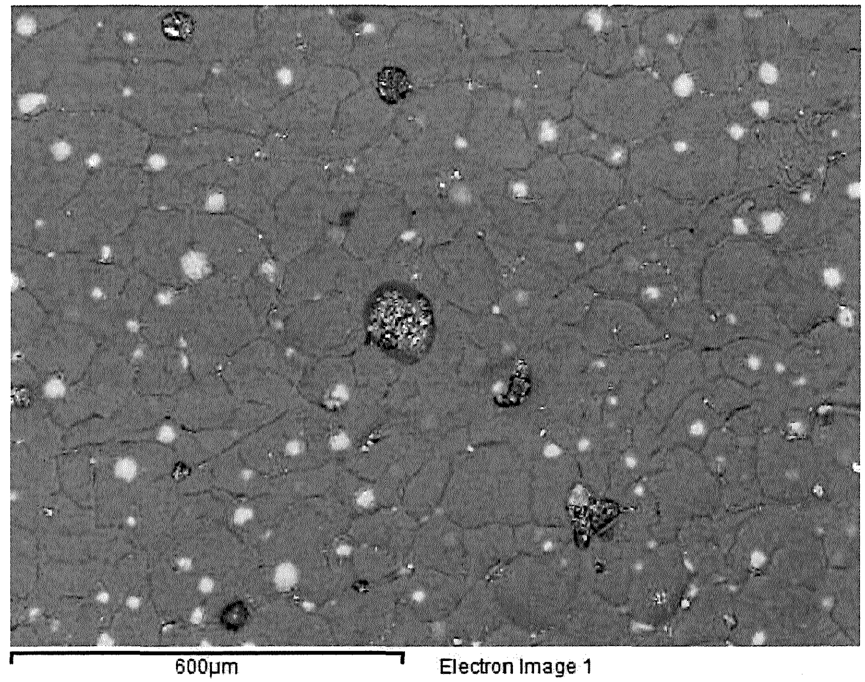
vertical spacing as 10 holes in 10.5mm = 1.05mm o.c.
horizontal spacing as 8 holes in 10.6mm = 1.32mm o.c.
SF2 has 24 warp yarns, 19.5 fill yarns per inch
1/24 inches – 1.06mm o.c.
1/19.5 inches – 1.30mm o.c.
Fill yarns are running vertically in the photo, warp yarns are horizontal

Figure 23: Microscopic Image Panel 72 Aligned with Scale



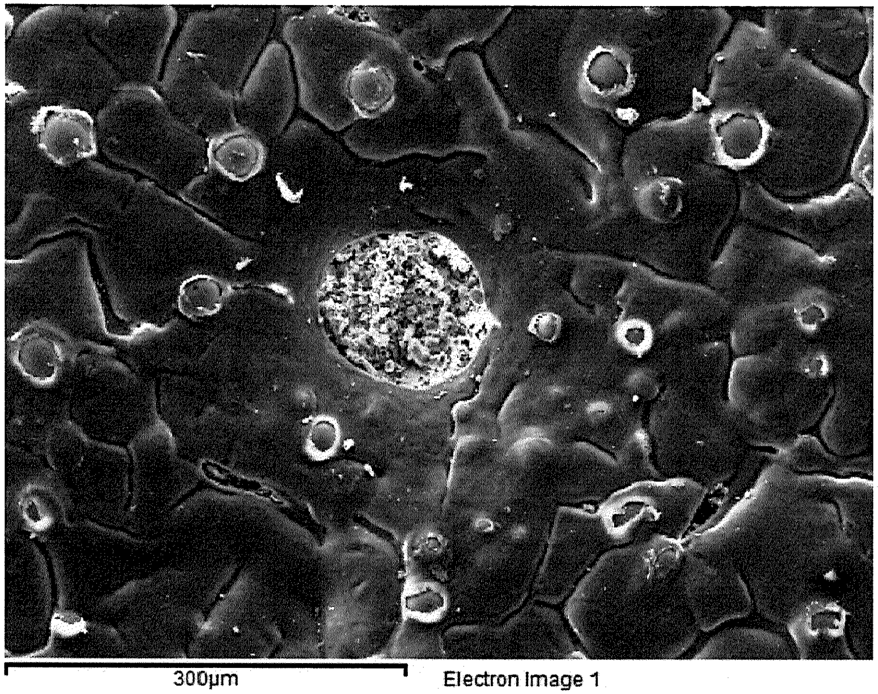
Comment: weathered 100x sec

Figure 24: Panel 72 Microscopic Image 600 µm Scale



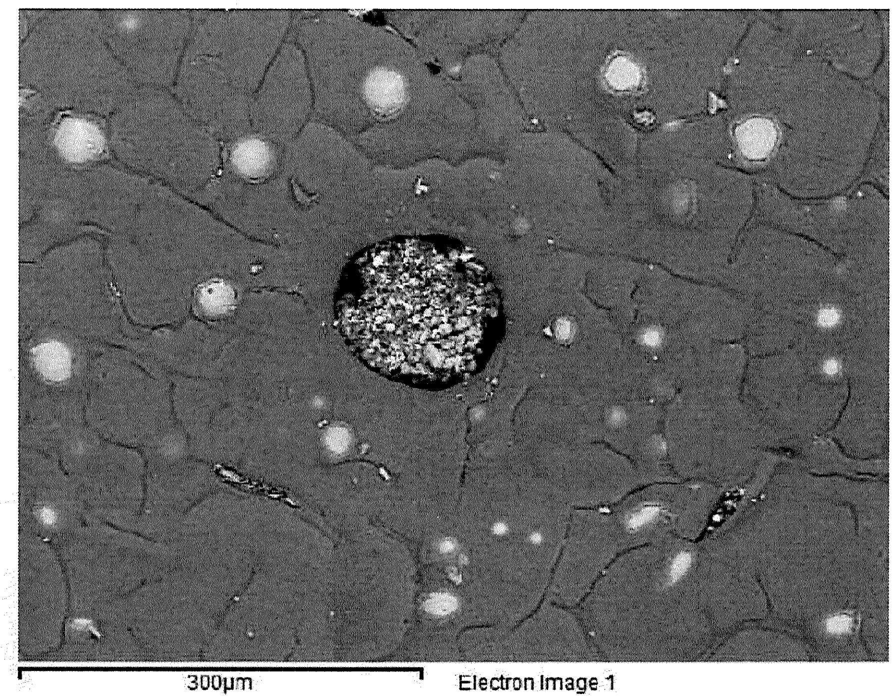
Comment: weathered 100x sec

Figure 25: Panel 72 Microscopic Image 600 µm Scale Alternate Light



Comment: weathered 200x sec

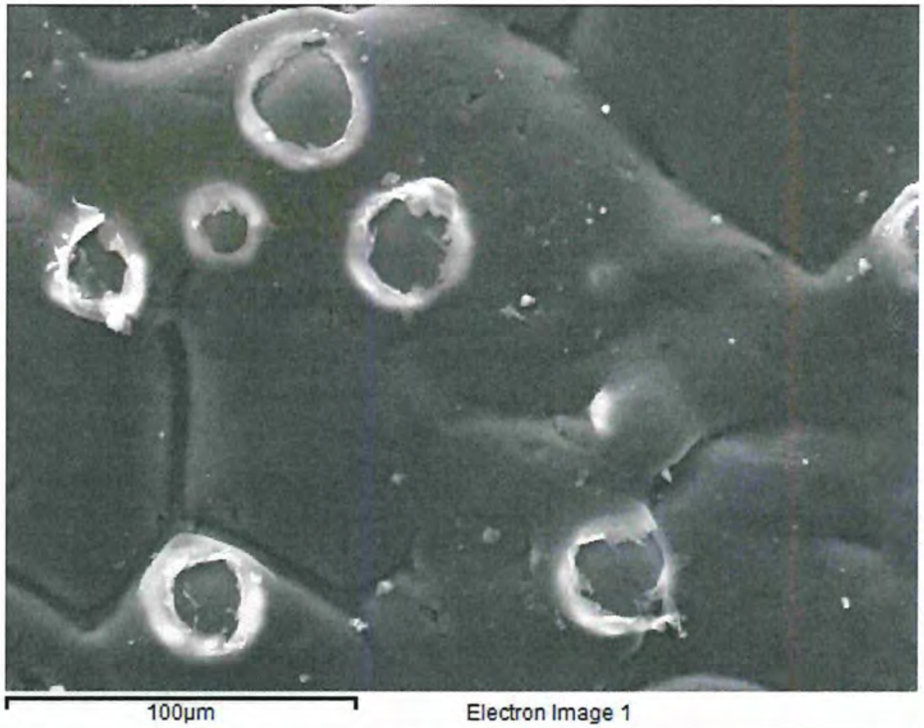
Figure 26: Panel 72 Microscopic Image 300 µm Scale



Comment: weathered 200x sec

Figure 27: Panel 72 Microscopic Image 300 µm Scale Alternate Light

Y



Comment: weathered 500x sec

Figure 28: Panel 72 Microscopic Image 100 µm Scale

Figure 29: Cross Section of PTFE-Fiberglass Fabric from BC Place Showing Ink Penetration Test

Table 10: Water Absorption Tests

BIRDAIR

PHYSICAL TEST DATA

PROJECT: J-11-509 Metro Dome DATE TESTED: 2/1/2011

FABRIC TYPE: Sheerfill-II

	TEST	RESULTS						
	(All per ASTM D 4851, unless noted)	Sample Received From Site Testing Average	Original Roll Test Results (1980) Avg	% Strength Retention Using The 1980 Test Results	1980 Released Spec Avg	% Strength Retension Using the 1980 Spec	2002 ASTM Released Spec Avg	% Strength Retention Using The 2002 Spec
Diamond 21	Weight (oz/yd²)	37.91	38	N/A	37.50	N/A	38.50	N/A
	Water Absorption Weight (oz/yd²)	38.14	N/A	N/A	N/A	N/A	N/A	N/A
	% Water Absorption	0.59%	N/A	N/A	N/A	N/A	0.5%	118%
	Thickness (in.)	0.028	0.030	N/A	0.032	N/A	0.030	N/A
Diamond 22	Weight (oz/yd²)	38.19	40.20	N/A	37.50	N/A	38.50	N/A
	Water Absorption Weight (oz/yd²)	38.37	N/A	N/A	N/A	N/A	N/A	N/A
	% Water Absorption	0.48%	N/A	N/A	N/A	N/A	0.5%	95%
	Thickness (in.)	0.028	0.031	N/A	0.032	N/A	0.030	N/A
Rectangle 66	Weight (oz/yd²)	38.37	39.20	N/A	37.50	N/A	38.50	N/A
	Water Absorption Weight (oz/yd²)	38.73	N/A	N/A	N/A	N/A	N/A	N/A
	% Water Absorption	0.95%	N/A	N/A	N/A	N/A	0.5%	190%
	Thickness (in.)	0.028	0.029	N/A	0.032	N/A	0.030	N/A
Rectangle 72	Weight (oz/yd²)	38.47	40.10	N/A	37.50	N/A	38.50	N/A
	Water Absorption Weight (oz/yd²)	38.81	N/A	N/A	N/A	N/A	N/A	N/A
	% Water Absorption	0.86%	N/A	N/A	N/A	N/A	0.5%	172%
	Thickness (in.)	0.028	0.029	N/A	0.032	N/A	0.030	N/A
Rectangle 93	Weight (oz/yd²)	37.74	38.90	N/A	37.50	N/A	38.50	N/A
	Water Absorption Weight (oz/yd²)	38.08	N/A	N/A	N/A	N/A	N/A	N/A
	% Water Absorption	0.89%	N/A	N/A	N/A	N/A	0.5%	178%
	Thickness (in.)	0.028	0.028	N/A	0.032	N/A	0.030	N/A
Triangle 100	Weight (oz/yd²)	39.48	40.30	N/A	37.50	N/A	38.50	N/A
	Water Absorption Weight (oz/yd²)	39.74	N/A	N/A	N/A	N/A	N/A	N/A
	% Water Absorption	0.65%	N/A	N/A	N/A	N/A	0.5%	130%
	Thickness (in.)	0.028	0.030	N/A	0.032	N/A	0.030	N/A

QA TECHNICIAN: GJ Panfil / Dan Thornton

DATE: 2/1/2011

Minneapolis Metrodome

December 2010 Roof Deflation Assessment

Part 3

Review of Visual Survey and Risk Assessment

Prepared for:

Metropolitan Sports and Facilities Commission

900 South 5th St.

Minneapolis, MN 55415

Prepared by

WALTER P MOORE

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Chase Building, 221 West 6th Street

Suite 800

Austin, TX 78701

Walter P Moore Project S02.10026.01

February 10, 2011 Final Report

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EXECUTIVE SUMMARY

Walter P Moore has conducted a limited independent assessment of the condition of the Metrodome roof structure following the December 12, 2010 deflation event. This assessment has been performed by Walter P Moore and Associates, Inc. acting as an independent consultant to the Metropolitan Sports Facilities Commission. The purpose of this report is to assist the Metropolitan Sports Facilities Commission in evaluating the condition of the roof structure so that it can make an informed decision about the future use of the Metrodome as it relates to public safety.

Part 3 of our report addresses our review of the visual survey conducted by Birdair. We have independently evaluated all available images and data provided by Birdair inspectors in the survey, and conducted our own categorization of the extent of the damage at each panel. Of particular concern is the presence of damage that exposes glass yarns in combination with large amounts of moisture on the roof.

In order to rationally evaluate the observed damage, we have conducted a qualitative risk assessment of the damage on a panel by panel basis. Using standard risk and hazard analysis techniques, relative relationships between the likelihood of occurrence of certain damage and the consequence of that damage in the reinflated roof configuration are evaluated.

The risk assessment has identified 30 diamond panels, 22 rectangular panels, and all ten triangular panels as the minimum extent of replacement. This includes the four diamond panels and one triangular panel that failed in the initial deflation. Refer to the Summary and Recommendations document for consideration of other issues that affect the roof globally.

REVIEW OF VISUAL SURVEY

A visual survey of the top surface of the Metrodome roof tensile membrane has been conducted by representatives of Birdair, Inc. who are trained in PTFE fiberglass membrane assessment. This survey was completed on February 3. At the time of writing this report, detailed cataloged survey suitable for independent evaluation is available for all diamond panels, rectangular panels 65 through 72, and triangular panels 97 and 98. Verbal reports of panel condition were provided for the remaining panels.

Walter P Moore has conducted an independent review of the available cataloged photographs. Our evaluation is cataloged in Appendix A on a panel by panel basis. Appendix A also catalogs various other aspects of the entire roof evaluation as summarized in other parts of this report.

Damage Assessment Criteria

The review of the visual survey data focused on the following possible damage items:

1. Overall panel condition as rated by Birdair. This assessment is made by the roof inspector and is consistent with the approach used in the prior roof inspections conducted by Birdair. During the last inspection in April 2010, the overall fabric condition was rated as "good-fair". In the current review, the Birdair inspectors have rated the fabric condition on a panel by panel basis. The diamond panels are all rated "fair-poor", and all remaining panels are rated as "poor".
2. Exposed yarns. Exposed yarns present a strong risk for infiltration of water to the yarns which are degraded by moisture contact. Refer to Part 2 of our report for a detailed discussion of the moisture damage phenomenon. In particular, exposed yarns in the presence of the significant amounts of retained water are a major concern.
3. Holes and tears. Numerous holes and tears were observed in the roof. These are likely caused by sharp edges of sliding ice. If not repaired, tears are a major risk to future damage of the panels. In addition, at tear locations usually yarns are left exposed, which presents the same risks as discussed in item 2 above. A large number of tears in an individual panel usually requires replacement.
4. Spider webbing and scratches. So called "spider webbing", or localized distortion of yarns due to creasing or other external actions, is indicative of weak locations in the membrane. Scratches of the PTFE coating also present potential moisture intrusion paths.
5. Moisture. A large number of retained pools of water and ice have been observed on the roof. These are generally from accumulation of snow in a manner that does not reach a roof panel drain. With the high heat provided under the roof, the snow melts and forms water pools, some of which have ice layers on top. For reasons of moisture intrusion to glass yarns, long term exposure to moisture pools in the presence of damaged areas presents a high risk.

6. Other conditions. Instances of seam separation, creasing, severe wrinkling, and other damage have been observed.

QUALITATIVE RISK ASSESSMENT

In order to provide a logical framework for evaluating the various observed damage conditions, a qualitative risk assessment has been conducted. Risk assessments are a common means of establishing relative weighting of importance of certain conditions by relating relative consequence of a certain adverse action to the relative probability of that action occurring. The procedure used herein generally follows Eurocode Part 1-7, General Actions – Accidental Actions, Annex B. The basic procedure is outlined in Figure 1.

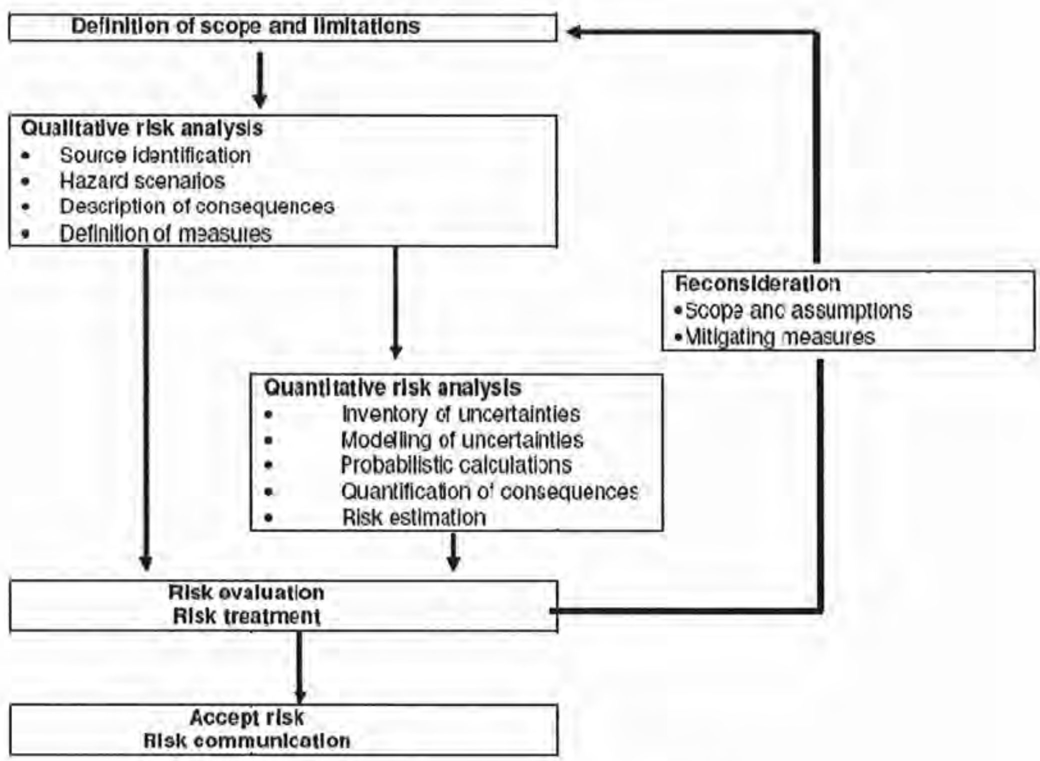

Figure 1: Risk Assessment Flowchart

The fundamental mechanism for carrying out a risk assessment is a relation of the applicable likelihood of occurrence of a certain action to the consequence of occurrence. When sufficient statistical data is available, this can be conducted quantitatively. Where it does not, a relative qualitative ranking is used. Because the Metrodome survey relies on observations that largely cannot be quantified, a qualitative approach is used here.

The proposed hazard matrix is shown in Figure 2. This table may be subjected to further modification based upon the input of various stakeholders, but the version presented represents our professional judgment of a reasonable approach.

HAZARD CLASSIFICATION MATRIX		LIKELIHOOD of Flaw Occurrence					
		High A	Moderate B	Low C	Very Low D	Remote E	Negligible F
CONSEQUENCE of Occurrence	**Full Roof Deflation or Collapse** 1	Unacceptable Replace 1	Unacceptable Replace 2	Unacceptable Replace 4	Unacceptable Replace 7	Marginal Stakeholder Review Required 11	Acceptable As Designed Or Mitigated 16
	Partial Roof Collapse causing impairment to building operation and occupancy 2	Unacceptable Replace 3	Unacceptable Replace 5	Unacceptable Replace 8	Marginal Stakeholder Review Required 12	Acceptable As Designed Or Mitigated 17	Acceptable As Designed Or Mitigated 21
	Major Patching Effort or Repair requiring external contractor assisted repairs 3	Unacceptable Replace 6	Unacceptable Replace 9	Marginal Stakeholder Review Required 13	Acceptable As Designed Or Mitigated 18	Acceptable As Designed Or Mitigated 22	Acceptable As Designed Or Mitigated 25
	Minor Patching Effort or Repair capable of being repaired by Metrodome staff 4	Unacceptable Replace 10	Marginal Stakeholder Review Required 14	Acceptable As Designed Or Mitigated 19	Acceptable As Designed Or Mitigated 23	Acceptable As Designed Or Mitigated 26	Acceptable As Designed Or Mitigated 28
	Minimal Effect on normal occupancy, operation, and maintenance 5	Marginal Stakeholder Review Required 15	Acceptable As Designed Or Mitigated 20	Acceptable As Designed Or Mitigated 24	Acceptable As Designed Or Mitigated 27	Acceptable As Designed Or Mitigated 29	Non Hazard No Effect 30

Figure 2: Hazard Classification Matrix

The likelihood of flaw occurrence is categorized by using a scoring system based on the presence of various elements of damage in the panels. One point each is assigned for the presence of any of the following conditions:

- Rating of "red" on the 12/21/2010 hot zone map.
- Panel condition of "fair-poor" or "poor".
- Presence of exposed yarns.
- Presence of holes or tears.

- Presence of spider webbing or scratches.
- Presence of moisture pools through late January.
- Finding of overstress in the Part 1 study.

The maximum possible score for any one panel is 7 points. Likelihood of flaw occurrence categories are then assigned as shown in Table 1.

Table 1: Scoring Categorization for Likelihood Class

Category	ID	Points
High	A	5 or higher
Moderate	B	4
Low	C	3
Very Low	D	2
Remote	E	1
Negligible	F	0

Assignment of consequence class is made based on exposure to loading as evaluated by roof position. Classification is shown in Figure 3.

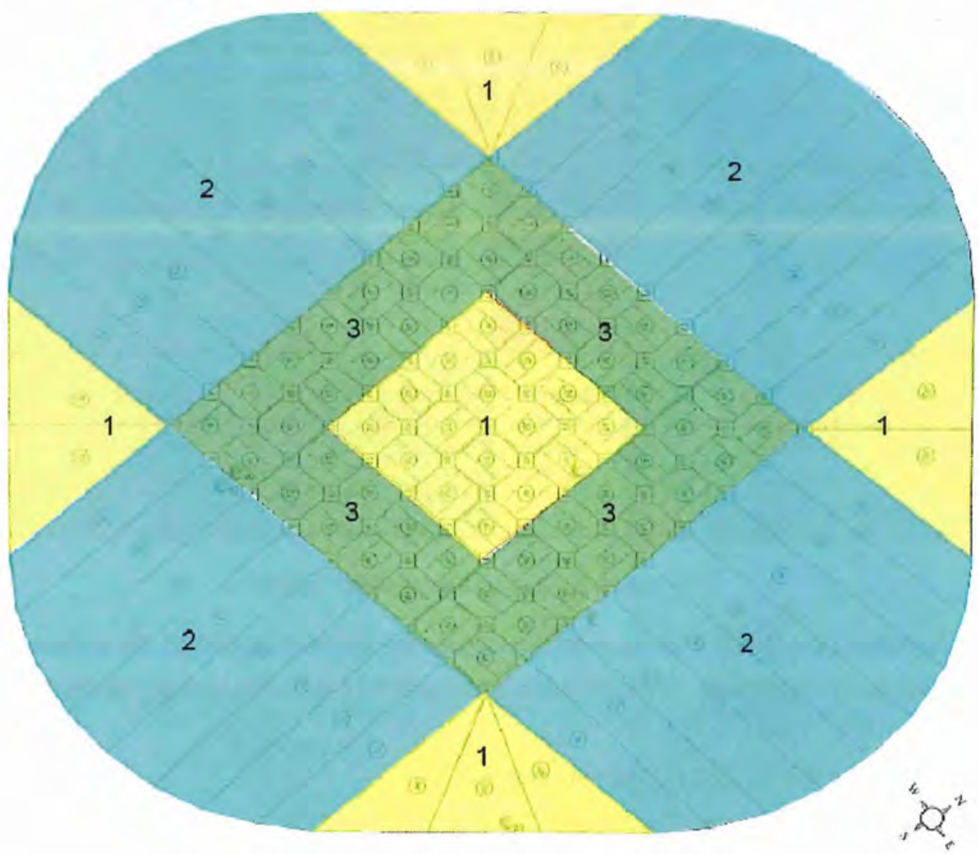

Figure 3: Consequence Categories

Assignment of consequence categories is made on the following considerations:

- Category 1 are the central 16 diamond panels and the triangular panels. The central 16 diamond panels are the locations that are most likely to accumulate and trap snow, leading to panel inversions. The triangular panels are the most highly stressed panels and have demonstrated significant risk of failure in both snow and wind events.
- Category 2 is the rectangular panels. The rectangular panels are not subjected to higher snow loads due to their slope, but are exposed to wind loads. Because of the more transient nature of wind loading, they are assigned to Category 2.
- Category 3 is the outer band of diamond panels outside Category 1. These panels have less risk of snow accumulation and generally have lower stresses under wind loading.

Based on the assignment of a Likelihood Class and a Consequence Class, an outcome is found for each panel based on Figure 2. Results are tabulated in Appendix A.

CONCLUSIONS

Based upon the results of the visual survey and the risk assessment alone, 30 diamond panels, 22 rectangular panels, and all 10 triangular panels are recommended as the minimum extent of replacement. This includes the 4 diamond panels and 1 triangular panel that failed in the initial deflation. The qualitative risk assessment results only address condition of individual panels, and do not account for global issues that affect the confidence in the restored roof. Refer to the Summary and Recommendations document for our complete recommendations on extent of replacement.

Appendix A

				Part 1 Deflated Fabric Stresses: Stress (pli)		Part 1 Deflated Fabric Stresses: Stress Ratio		Testing Status			Visual Survey												
Panel #	Panel Type	Status	Status 12/21 Hot Zone	Warp	Fill	Warp	Fill	Strength	Biax	Prior	Complete	Indexed Photos	Condition	Exposed Yarn	Hole/ Tears	Spider Web or Scratch	Water	Other	Condition Score	Likelihood Class	Consequence Class	Hazard Classification	Action
1	Diamond	Intact	Yellow	55	50	0.52	0.57				Yes	Yes	Fair/Poor	Yes		Yes	Yes		4	Moderate	3	9	Replace
2	Diamond	Intact	Yellow	60	55	0.57	0.63				Yes	Yes	Fair/Poor			Yes	No		3	Low	3	13	Review
3	Diamond	Intact	Red	60	65	0.57	0.75				Yes	Yes	Fair/Poor	Yes		Yes	Yes		5	High	3	6	Replace
4	Diamond	Intact	Red	75	55	0.71	0.63				Yes	Yes	Fair/Poor	Yes		Yes	Yes		5	High	3	6	Replace
5	Diamond	Intact	Yellow	75	50	0.71	0.57				Yes	Yes	Fair/Poor	Yes	Yes	Yes	Yes		5	High	3	6	Replace
6	Diamond	Intact	Yellow	60	75	0.57	0.86				Yes	Yes	Fair/Poor	Yes		Yes	Small		4	Moderate	3	9	Replace
7	Diamond	Intact	Yellow	50	65	0.47	0.75				Yes	Yes	Fair/Poor			Yes	Small		3	Low	3	13	Review
8	Diamond	Intact	Yellow	90	100	0.85	1.15				Yes	Yes	Fair/Poor			Yes	No		4	Moderate	3	9	Replace
9	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor				Yes		2	Very Low	3	18	Acceptable
10	Diamond	Intact	Red	110	100	1.04	1.15				Yes	Yes	Fair/Poor	Yes		Yes	Yes		6	High	3	6	Replace
11	Diamond	Intact	Red	40	55	0.38	0.63				Yes	Yes	Fair/Poor			Yes			3	Low	3	13	Review
12	Diamond	Intact	Yellow	25	20	0.24	0.23				Yes	Yes	Fair/Poor			Yes		Seam separation	2	Very Low	3	18	Acceptable
13	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor						1	Remote	3	22	Acceptable
14	Diamond	Intact	Red	75	40	0.71	0.46	Future			Yes	Yes	Fair/Poor	Yes			Small		4	Moderate	3	9	Replace
15	Diamond	Failed	NA	NA	NA	NA	NA	Yes			NA	NA	NA						2	Very Low	1	7	Replace
16	Diamond	Intact	Yellow	45	70	0.43	0.80			2010	Yes	Yes	Fair/Poor				Yes		2	Very Low	3	18	Acceptable
17	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor			Yes	Yes		3	Low	3	13	Review
18	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor			Yes	Small	Seam - photo 145	3	Low	3	13	Review
19	Diamond	Intact	Yellow	25	25	0.24	0.29	Future			Yes	Yes	Fair/Poor			Yes	Small		3	Low	1	4	Replace
20	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor						1	Remote	1	11	Review
21	Diamond	Intact	Yellow	60	60	0.57	0.69	Yes		2003, 1980	Yes	Yes	Fair/Poor			Yes	Small		3	Low	1	4	Replace
22	Diamond	Intact	Red	90	100	0.85	1.15	Yes	Yes		Yes	Yes	Fair/Poor				Yes	Vent Crushed	4	Moderate	1	2	Replace
23	Diamond	Intact	Yellow	40	25	0.38	0.29				Yes	Yes	Fair/Poor	Yes		Yes		Many Wrinkles	3	Low	3	13	Review
24	Diamond	Intact	Yellow	40	65	0.38	0.75				Yes	Yes	Fair/Poor			Yes	Yes		3	Low	3	13	Review
25	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor			Yes	Yes		3	Low	3	13	Review
26	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor						1	Remote	3	22	Acceptable
27	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor			Yes			2	Very Low	1	7	Replace
28	Diamond	Intact	Red	35	25	0.33	0.29				Yes	Yes	Fair/Poor			Yes	Small		4	Moderate	1	2	Replace
29	Diamond	Intact	Red	90	90	0.85	1.03	Future			Yes	Yes	Fair/Poor			Yes	Yes		5	High	1	1	Replace
30	Diamond	Intact	Yellow	50	50	0.47	0.57				Yes	Yes	Fair/Poor			Yes	Yes	Many Wrinkles	3	Low	1	4	Replace
31	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor						1	Remote	3	22	Acceptable
32	Diamond	Intact	Yellow	90	70	0.85	0.80	Future			Yes	Yes	Fair/Poor			Yes	Yes	Loose Patches	3	Low	3	13	Review
33	Diamond	Intact	Yellow	55	50	0.52	0.57				Yes	Yes	Fair/Poor			Yes	Yes		3	Low	3	13	Review
34	Diamond	Intact	Red	50	50	0.47	0.57				Yes	Yes	Fair/Poor					Minor creasing	2	Very Low	3	18	Acceptable
35	Diamond	Intact	Red	70	40	0.66	0.46	Future			Yes	Yes	Fair/Poor			Yes	Yes	Seam separation	4	Moderate	1	2	Replace
36	Diamond	Failed	NA	NA	NA	NA	NA				NA	NA	NA						2	Very Low	1	7	Replace
37	Diamond	Intact	Red	110	110	1.04	1.26				Yes	Yes	Fair/Poor			Yes		Many Wrinkles	4	Moderate	1	2	Replace
38	Diamond	Intact	Red	110	110	1.04	1.26				Yes	Yes	Fair/Poor			Yes		Many Wrinkles	4	Moderate	1	2	Replace
39	Diamond	Intact	Yellow	70	60	0.66	0.69				Yes	Yes	Fair/Poor			Yes		Many Wrinkles	2	Very Low	3	18	Acceptable

WALTER P MOORE

Metrodome Roof Deflation Assessment
Part 3: Review of Visual Survey and Risk Assessment
February 10, 2011

Appendix A

S02.10026.00

				Part 1 Deflated Fabric Stresses																			
				Stress (pli)		Stress Ratio		Testing Status			Visual Survey												
Panel #	Panel Type	Status	Status 12/21 Hot Zone	Warp	Fill	Warp	Fill	Strength	Biax	Prior	Complete	Indexed Photos	Condition	Exposed Yarn	Hole/ Tears	Spider Web or Scratch	Water	Other	Condition Score	Likelihood Class	Consequence Class	Hazard Classification	Action
40	Diamond	Intact	Yellow	70	70	0.66	0.80				Yes	Yes	Fair/Poor	Yes		Yes	Yes	Yarn flaw - photo 80	4	Moderate	3	9	Replace
41	Diamond	Intact	Red	80	80	0.76	0.92	Yes	Yes		Yes	Yes	Fair/Poor	Yes		Yes	Yes		5	High	3	6	Replace
42	Diamond	Intact	Red	50	60	0.47	0.69				Yes	Yes	Fair/Poor	Yes		Yes	Yes	Wrinkles and creasing	5	High	3	6	Replace
43	Diamond	Failed	NA	NA	NA	NA	NA				NA	NA	NA						2	Very Low	1	7	Replace
44	Diamond	Failed	NA	NA	NA	NA	NA				NA	NA	NA						2	Very Low	1	7	Replace
45	Diamond	Intact	Red	80	100	0.76	1.15				Yes	Yes	Fair/Poor			Yes	Small		5	High	1	1	Replace
46	Diamond	Intact	Red	90	90	0.85	1.03				Yes	Yes	Fair/Poor			Yes		Creasing	4	Moderate	1	2	Replace
47	Diamond	Intact	Yellow	50	50	0.47	0.57				Yes	Yes	Fair/Poor			Yes	Small		3	Low	3	13	Review
48	Diamond	Intact	Yellow	50	50	0.47	0.57				Yes	Yes	Fair/Poor				Yes	Seam separation, wrinkles, creases	2	Very Low	3	18	Acceptable
49	Diamond	Intact	Yellow	65	60	0.62	0.69				Yes	Yes	Fair/Poor			Yes	Small	Wrinkles and creasing	3	Low	3	13	Review
50	Diamond	Intact	Yellow	80	85	0.76	0.98				Yes	Yes	Fair/Poor		Yes		Yes	Seam tear, wrinkles, creases	3	Low	3	13	Review
51	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor	Yes		Yes	Yes		4	Moderate	3	9	Replace
52	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor			Yes		Many Wrinkles	2	Very Low	3	18	Acceptable
53	Diamond	Intact	Yellow	50	25	0.47	0.29				Yes	Yes	Fair/Poor					Loose Patches	1	Remote	3	22	Acceptable
54	Diamond	Intact	Yellow	25	40	0.24	0.46				Yes	Yes	Fair/Poor				Yes	Corner Wrinkles, Creasing	2	Very Low	3	18	Acceptable
55	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor			Yes	Yes		3	Low	3	13	Review
56	Diamond	Intact	Yellow	50	50	0.47	0.57				Yes	Yes	Fair/Poor			Yes	Yes	Wrinkles and creasing	3	Low	3	13	Review
57	Diamond	Intact	Yellow	40	60	0.38	0.69				Yes	Yes	Fair/Poor			Yes	Small	Loose patches, wrinkles, creases	3	Low	3	13	Review
58	Diamond	Intact	Yellow	25	25	0.24	0.29				Yes	Yes	Fair/Poor				Small	Wrinkles and creasing	2	Very Low	3	18	Acceptable
59	Diamond	Intact	Yellow	25	40	0.24	0.46				Yes	Yes	Fair/Poor	Yes		Yes	Yes		4	Moderate	3	9	Replace
60	Diamond	Intact	Yellow	35	25	0.33	0.29				Yes	Yes	Fair/Poor		Yes		Yes		3	Low	3	13	Review
61	Diamond	Intact	Yellow	25	65	0.24	0.75				Yes	Yes	Fair/Poor	Yes		Yes	Yes	Wrinkles and creasing	4	Moderate	3	9	Replace
62	Diamond	Intact	Yellow	50	25	0.47	0.29				Yes	Yes	Fair/Poor			Yes	Yes	Wrinkles and creasing, Linear yarn flaw - photo 085	3	Low	3	13	Review
63	Diamond	Intact	Yellow	25	25	0.24	0.29	Future			Yes	Yes	Fair/Poor				Small	Loose patches, wrinkles	2	Very Low	3	18	Acceptable
64	Diamond	Intact	Yellow	60	50	0.57	0.57				Yes	Yes	Fair/Poor			Yes	Yes	Loose patch	3	Low	3	13	Review

				Part 1 Deflated Fabric Stresses				Testing Status			Visual Survey												
				Stress (pli)		Stress Ratio																	
Panel #	Panel Type	Status	Status 12/21 Hot Zone	Warp	Fill	Warp	Fill	Strength	Biax	Prior	Complete	Indexed Photos	Condition	Exposed Yarn	Hole/ Tears	Spider Web or Scratch	Water	Other	Condition Score	Likelihood Class	Consequence Class	Hazard Classification	Action
65	Rectangle	Intact	Red	75	65	0.71	0.75				Yes	Yes	Poor	Yes		Yes	Yes	Deep water pool	5	High	2	3	Replace
66	Rectangle	Intact	Yellow	110	80	1.04	0.92	Yes		2010	Yes	Yes	Poor	Yes		Yes	Yes	Dark exposed yarns near clamps - photo 0158	5	High	2	3	Replace
67	Rectangle	Intact	Red	140	90	1.33	1.03				Yes	Yes	Poor	Yes		Yes			5	High	2	3	Replace
68	Rectangle	Intact	Red	140	90	1.33	1.03				Yes	Yes	Poor	Yes	Yes	Yes	Yes		7	High	2	3	Replace
69	Rectangle	Intact	Yellow	110	10	1.04	0.11				Yes	Yes	Poor	Yes	Yes	Yes	Yes		6	High	2	3	Replace
70	Rectangle	Intact	Red	90	40	0.85	0.46				Yes	Yes	Poor	Yes		Yes	Yes		5	High	2	3	Replace
71	Rectangle	Intact	Red	110	65	1.04	0.75	Yes	Yes		Yes	Yes	Poor	Yes		Yes	Yes		6	High	2	3	Replace
72	Rectangle	Intact	Red	125	120	1.19	1.38	Yes	Yes		Yes	Yes	Poor		Yes	Yes	Yes	Tear at eliminator frame adjacent 99	6	High	2	3	Replace
73	Rectangle	Intact	Yellow	115	65	1.09	0.75				Yes	No	Poor				Yes		3	Low	2	8	Replace
74	Rectangle	Intact	Red	115	50	1.09	0.57				Yes	No	Poor				Yes		4	Moderate	2	5	Replace
75	Rectangle	Intact	Red	120	90	1.14	1.03				Yes	No	Poor				Yes		4	Moderate	2	5	Replace
76	Rectangle	Intact	Red	115	100	1.09	1.15				Yes	No	Poor				Yes		4	Moderate	2	5	Replace
77	Rectangle	Intact	Red	90	65	0.85	0.75				Yes	No	Poor				Yes		3	Low	2	8	Replace
78	Rectangle	Intact	Red	65	50	0.62	0.57				Yes	No	Poor				Yes		3	Low	2	8	Replace
79	Rectangle	Intact	Yellow	40	35	0.38	0.40				Yes	No	Poor				Yes		2	Very Low	2	12	Review
80	Rectangle	Intact	Green	25	25	0.24	0.29				Yes	No	Poor				Yes		2	Very Low	2	12	Review
81	Rectangle	Intact	Green	40	30	0.38	0.34				Yes	No	Poor						1	Remote	2	17	Acceptable
82	Rectangle	Intact	Yellow	70	60	0.66	0.69				Yes	No	Poor						1	Remote	2	17	Acceptable
83	Rectangle	Intact	Red	110	90	1.04	1.03	Future			Yes	No	Poor						3	Low	2	8	Replace
84	Rectangle	Intact	Red	120	75	1.14	0.86				Yes	No	Poor						3	Low	2	8	Replace
85	Rectangle	Intact	Yellow	100	25	0.95	0.29				Yes	No	Poor						1	Remote	2	17	Acceptable
86	Rectangle	Intact	Yellow	80	25	0.76	0.29				Yes	No	Poor						1	Remote	2	17	Acceptable
87	Rectangle	Intact	Green	65	25	0.62	0.29	Future			Yes	No	Poor						1	Remote	2	17	Acceptable
88	Rectangle	Intact	Green	25	15	0.24	0.17				Yes	No	Poor				Yes		2	Very Low	2	12	Review
89	Rectangle	Intact	Green	40	25	0.38	0.29				Yes	No	Poor				Yes		2	Very Low	2	12	Review
90	Rectangle	Intact	Yellow	90	65	0.85	0.75				Yes	No	Poor				Yes		2	Very Low	2	12	Review
91	Rectangle	Intact	Red	110	65	1.04	0.75				Yes	No	Poor						3	Low	2	8	Replace
92	Rectangle	Intact	Red	120	65	1.14	0.75				Yes	No	Poor						3	Low	2	8	Replace
93	Rectangle	Intact	Red	140	90	1.33	1.03	Yes		2003, 1980	Yes	No	Poor						3	Low	2	8	Replace
94	Rectangle	Intact	Red	120	90	1.14	1.03	Future			Yes	No	Poor						3	Low	2	8	Replace
95	Rectangle	Intact	Red	120	110	1.14	1.26				Yes	No	Poor						3	Low	2	8	Replace
96	Rectangle	Intact	Red	110	110	1.04	1.26				Yes	No	Poor						3	Low	2	8	Replace
97	Triangle	Intact	Yellow	90	110	0.85	1.26				Yes	Yes	Poor			Yes			3	Low	1	4	Replace
98	Triangle	Intact	Red	60	80	0.57	0.92				Yes	Yes	Poor	Yes	5, severe	Yes		Folded onto self by flutter - photo 226	5	High	1	1	Replace
99	Triangle	Intact	Yellow	70	25	0.66	0.29				Yes	No	Poor		Yes	Yes		Tear at eliminator frame adjacent 72	3	Low	1	4	Replace
100	Triangle	Intact	Green	70	25	0.66	0.29	Yes		2010, 2003, 19	Yes	No	Poor			Yes			2	Very Low	1	7	Replace
101	Triangle	Intact	Green	70	25	0.66	0.29				Yes	No	Poor			Yes			2	Very Low	1	7	Replace
102	Triangle	Intact	Green	25	25	0.24	0.29				Yes	No	Poor			Yes			2	Very Low	1	7	Replace
103	Triangle	Intact	Green	40	40	0.38	0.46				Yes	No	Poor		5	Yes			3	Low	1	4	Replace
104	Triangle	Failed	NA	NA	NA	NA	NA				NA	NA	NA						2	Very Low	1	7	Replace
105	Triangle	Intact	Yellow	25	20	0.24	0.23				Yes	No	Totaled			Yes			2	Very Low	1	7	Replace
106	Triangle	Intact	Green	25	20	0.24	0.23				Yes	No	Poor			Yes			2	Very Low	1	7	Replace

MINNEAPOLIS METRODOME

DECEMBER 2010 ROOF DEFLATION ASSESSMENT

PART 4

QUANTITATIVE RELIABILITY ANALYSIS

Prepared for:

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Walter P Moore Project S02.10026.01

February 10, 2011 FINAL REPORT

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EXECUTIVE SUMMARY

Walter P Moore has conducted a limited independent assessment of the condition of the Metrodome roof structure following the December 12, 2010 deflation event. This assessment has been performed by Walter P Moore and Associates, Inc. acting as an independent consultant to the Metropolitan Sports Facilities Commission. The purpose of this report is to assist the Metropolitan Sports Facilities Commission in evaluating the condition of the roof structure so that it can make an informed decision about the future use of the Metrodome as it relates to public safety.

A reliability analysis is performed to establish the level of safety of the roof membrane structure. For structures in which the nature and extent of flaws cannot be predetermined, a reliability analysis provides a quantitative measure of failure probability assuming that the flaws are randomly distributed in the structure. It is especially important for structural elements where the local presence of flaws can lead to a brittle facture and cause widespread structural failure. Fabric structures that are partially torn can spread the tear when stressed even to nominal load levels and cause failure of the entire roof surface. The reliability analysis conducted in this study is based on the approach suggested by (Iacopino, 2006) and (Todinov, 2005). Note that this study only focuses on the probability of failure of the fabric component of the structure under the presence of flaws. Other sources of failure are ignored in this study.

The results of the reliability analysis indicate high levels of probability of localized roof failure leading to overall deflation in the presence of randomly distributed flaws. This finding underscores the importance of having absolute confidence that all existing flaws are discovered and repaired if the existing membrane material is to be put back into service. In absence of this confidence, which we do not believe is practical to reasonably achieve in a timeframe to serve the Metrodome use needs, a full membrane replacement is recommended.

RELIABILITY ANALYSIS

Background

The probability of failure of a component containing random flaws under any load condition can be expressed as

$$P_f = 1 - e^{-\lambda V F_c} \qquad (1)$$

P_f: Probability of failure

λ: mean density of flaws

V: volume of the component

F_c: probability of failure of the component given there is a single flaw in the component or conditional probability of failure

In order to study the failure probability we first establish a failure criteria for fabric panels. Fabric panels containing flaws exhibit stress concentrations around the flaws. The level of stress concentration is related to the flaw size. This stress concentration is expressed as factor to be applied to the state of stress under any given load at the location of the flaw. For this study the relationship between the flaw size and the stress concentration factor is adapted from (Komatsu) and is reproduced in Figure 1. Therefore the stress levels at any flaw location x having a flaw size a can be expressed as follows:

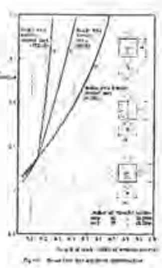

Figure 1 Thread Loss Rate and Stress Concentration

$$\sigma_{uw}(x,a) = \sigma_w(x) C_f(a) \qquad (2)$$

$$\sigma_{uf}(x,a) = \sigma_f(x) C_f(a) \qquad (3)$$

where σ_w and σ_f are the warp and fill stresses at location x under the applied load in the absence of flaws, C_f is a stress concentration factor dependent on flaw size a, and σ_{uw} and σ_{uf} are the warp and fill stresses at location x amplified by the presence of a flaw.

A membrane element is considered to have failed if at the location of a flaw the stress concentration exceeds the allowable stress limits. So the failure criteria, I, can be expressed as

$$I(x,a) = \begin{cases} 1 \; if \; (\sigma_{uw}(x,a) > \sigma_{aw} \vee \sigma_{uf}(x,a) > \sigma_{af}) \\ 0 \; otherwise \end{cases} \qquad (4)$$

The failure criteria depends on flaw location x, and flaw size a, each of which can be expressed as a independent random variable. Flaws are equally likely to be present at any location in the fabric and therefore the flaw location is represented by a uniform random variable. Flaw size is assumed to be a normally distributed random variable. Using Monte Carlo simulation techniques several sets of (x, a) are generated and the resulting conditional probability of failure can be estimated as follows

$$F_c = \frac{1}{N}\sum_{i=1}^{N} I(x_i, a_i) \qquad (5)$$

Since the mean density of flaws for the roof structure is unknown we have assumed different mean densities and established the failure probability under each assumption.

Methodology

The process can be described in the following steps:

a. Establish a load level *L*
b. Establish stress levels in a single fabric panel at the load level selected using a FEM analysis
c. Generate several thousand sets of random variables, x and a
d. For each set calculate failure, *I*, using equation 4 and for the entire simulation establish conditional probability of failure, F_c, using equation 5.
e. Assume a flaw density and then using equation 1 calculate the total probability of failure of a single panel
f. Assuming a load intensity distribution integrate the probability of failure over the entire roof to establish probability of failure for the roof structure
g. Repeat this over several load levels to generate a failure curve for the entire roof

For the purpose of this study three different mean flaw sizes 0.2 (12 mm), 0.3 (18 mm) and 0.4 (24 mm) representing small, medium and large size flaws were selected. For flaw density we assumed one to five flaws per panel.

Simulation Size and Accuracy

The accuracy of estimates obtained using Monte Carlo simulations are dependent on the size of the simulation sets. Events that have a low probability of occurrence require orders of magnitude higher number of simulations to achieve similar levels of confidence as events with higher probability of occurrence. The number of simulations required to obtain estimates within ±10% of the true value with 95% confidence is given by

$$N_{reqd} = \left(\frac{196}{10}\right)^2 \frac{(1-p)}{p} \tag{6}$$

where p is probability being estimated. For example if the estimated probability is 0.001 then N_{reqd} is 383,776 and if the estimated probability is 0.00001 then N_{reqd} is 38,415,616 which can be computationally intensive. Acceptable levels for structural reliability or probability of failure are given in Table C1.3.1a (ASCE/SEI 7-10, 2010) for various conditions which is reproduced in Figure 2. In the case of the fabric roof structure, failure can be described as one that is sudden or leads to wide-spread progression of damage for which the failure probability is given as $2.0\text{x}10^{-6}$/yr under occupancy category III. This annual probability of failure (P_F) can be separated into structural probability of failure at a given load level ($P_{FS|L}$) and the annual probability of exceedance of that load level (P_L).

$$P_F = P_{FS|L} \times P_L \tag{7}$$

When using a load and resistance factor approach for designing occupancy category III structures, typical annual probability of exceedance of load levels is 0.000588, therefore the structural probability of failure at the ultimate load level using nominal strengths reduced by resistance factors is expected to be in the range $2.0\text{x}10^{-6}/0.000588 = 0.0034$. However, fabric structures are typically designed using allowable stress design methods. If we assume that the target reliability levels are same for structures designed using either allowable stress design method or the load and resistance factor design method we can expect that the structural probability of failure at service load levels using allowable stress levels would be in the same range. For this reason we selected to run approximately 400,000 simulations for each case to estimate the failure probabilities within ±10% of true probabilities with 95% confidence.

Allowable stress levels for the fabric panels are established following ASCE/SEI 55-10 Section 4.4.

$$\sigma_{aw} = \beta L_t T_{sw} \tag{8}$$
$$\sigma_{fw} = \beta L_t T_{fw}$$

where β is defined as a strength reduction factor, L_t is defined as a life-cycle factor which adjusts the member capacities to allow for the effects of aging caused either by environmental effects or by the effects of wear and tear on membrane protective coatings T_{sw} and T_{fw} are the specified tensile strengths in the warp and fill directions respectively and σ_{aw} and σ_{af} are the allowable stresses in the warp and fill directions respectively. Allowable stress levels for the fabric panels are listed in Table 1 and Table 2 below. For the purposes of this study, the original project specification material strength values are used. While these are known to be somewhat conservative, the original strip tensile specification strengths are observed to be similar to those found via current testing for flexfold tensile strength (See Report Part 2). Due to widespread observed creasing, it appears reasonable to use values consistent with current tested flexfold strengths.

Table 1 Allowable stresses under snow load

Orientation	Specified stress T_s (pli)	L_t	β	Allowable stress limit
Warp	520	0.75	0.27	105.3
Fill	420	0.75	0.27	85.0

Table 2 Allowable stresses under wind load

Orientation	Specified stress (pli)	L_t	β	Allowable stress limit
Warp	520	0.75	0.33	128.7
Fill	420	0.75	0.33	103.9

RESULTS

Snow Loads

The probability of failure against snow loads was established using stress results from the analysis of diamond panels as they are most likely to pond and invert. Original design of the roof structure was based on a uniform snow load of 25 psf in the down hanging position (Liddel, 1992). The stress resultants for a diamond panel were obtained using an analysis model of an isolated panel with an assumed load coefficient approach to simulate the snow load shape on an individual panel. We performed the analysis for snow loads ranging from 10 – 80 psf which should cover the most common snow load levels expected during the lifetime of the roof structure. The snow load intensity distribution used for this study is shown as a histogram in Figure 3. The results of the analysis are presented in a graphical form in Figure 4 to Figure 6. At the design load level of 25 psf the probability of failure in the presence of flaws ranges from about 0.05 to 0.5 which is much higher than that of expected range of reliability for structures of about 0.0034.

Wind Loads

The probability of failure against wind uplift loads was established using stress resultants from the analysis of the rectangular panels as they are most likely to experience the peak wind loads. Original design of the roof structure was based on a 12 psf maximum internal pressure and wind uplift of 18 psf (Liddel, 1992). The stress resultants for a rectangular panel were obtained using an analysis of uniform load on a quarter model of the roof structure. We performed the analysis for wind loads varying from 5 psf – 55 psf of uniform uplift which should cover the most common wind loads levels expected during the lifetime of the roof structure. The wind load intensity distribution used for this study is shown as a histogram in Figure 7. The results of the analyses are presented in a graphical form in Figure 8 to Figure 10. At the design load level of 18 psf the probability of failure under the presence of flaws ranges from about 0.45 to 0.85 which is much higher than the expected range of reliability for structures of about 0.0034.

CONCLUSIONS

The results of the quantitative reliability analysis indicate unacceptable levels of structural reliability of the membrane system in the presence of randomly distributed flaws. By evaluating a wide ranges of scenarios, different possible flaw distributions can be studied for confidence in the structural condition under re-inflation of the existing fabric.

For the diamond panels, the critical condition of failure relates to local panel inversions under snow. In the presence of one to five flaws per panel of various sizes the reliability ranges from 0.05 to 0.5, the smallest of which is approximately 15 times higher than that allowed for a stadium structure in the building code.

For the rectangular panels, the critical condition of failure relates to uplift forces caused by wind loads. In the presence of one to five flaws per panel of various sizes the reliability ranges from 0.45 to 0.85, the smallest of which is 132 times higher than that allowed for a stadium structure in the building code.

The results of this study underline the importance of having a high level of confidence that all existing flaws in the roof membrane material are discovered and repaired prior to re-inflation of the structure. In absence of such confidence, the only prudent course of action in our opinion is the full replacement of the roof membrane.

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APPENDIX A

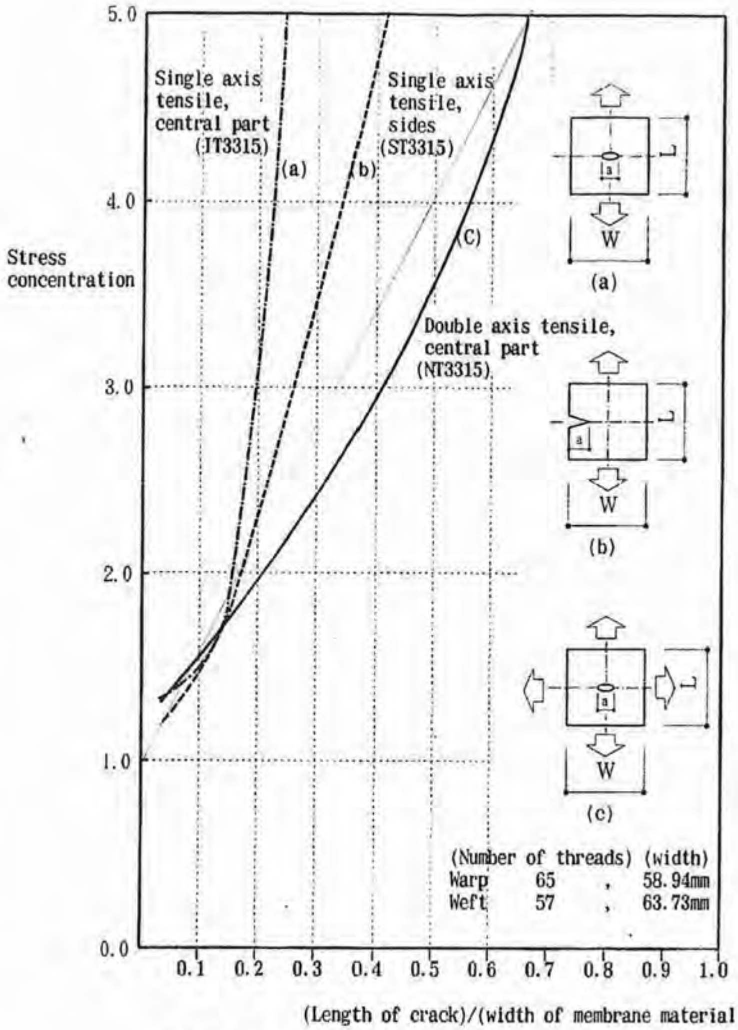

Fig.-15 Thread Loss Rate and Stress Concentraction

Figure 1 Thread Loss Rate and Stress Concentration (Komatsu)

Table C.1.3.1a Acceptable reliability (maximum annual probability of failure) and associated reliability indexes[1] (β) for load conditions that do not include earthquake[2]

Basis	Occupancy Category			
	I	II	III	IV
Failure that is not sudden and does not lead to wide-spread progression of damage	$P_F = 1.25 \times 10^{-4}$/yr $\beta = 2.5$	$P_F = 3.0 \times 10^{-5}$/yr $\beta = 3.0$	$P_F = 1.25 \times 10^{-5}$/yr $\beta = 3.25$	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$
Failure that is either sudden or leads to wide-spread progression of damage	$P_F = 3.0 \times 10^{-5}$/yr\ $\beta = 3.0$	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$	$P_F = 2.0 \times 10^{-6}$/yr $\beta = 3.75$	$P_F = 7.0 \times 10^{-7}$/yr $\beta = 4.0$
Failure that is sudden and results in wide spread progression of damage	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$	$P_F = 7.0 \times 10^{-7}$/yr $\beta = 4.0$	$P_F = 2.5 \times 10^{-7}$/yr $\beta = 4.25$	$P_F = 1.0 \times 10^{-7}$/yr $\beta = 4.5$

[1]The reliability indices are provided for a 50-year service period, while the probabilities of failure have been annualized. The equations presented in Section 2.3.6, Load Combinations for Non-Specified Loads, are based on reliability indices for 50 years because the load combination requirements in 2.3.2 are based on the 50-year maximum loads.
[2]Commentary to Section 2.5 includes references to publications that describe the historic development of these target reliabilities.

Table C.1.3.1b Anticipated reliability (maximum probability of failure) for earthquake[1]

Risk Category I and II	
Total or partial structural collapse	10% conditioned on the occurrence of Maximum Considered Earthquake shaking
Failure that could result in endangerment of individual lives	25% conditioned on the occurrence of Maximum Considered effects
Risk Category III	
Total or partial structural collapse	6% conditioned on the occurrence of Maximum Considered Earthquake shaking
Failure that could result in endangerment of individual lives	15% conditioned on the occurrence of Maximum Considered Earthquake shaking
Risk Category IV	
Total or partial structural collapse	3% conditioned on the occurrence of Maximum Considered Earthquake shaking
Failure that could result in endangerment of individual lives	10% conditioned on the occurrence of Maximum Considered Earthquake shaking

[1]Refer to the NEHRP Recommended Provisions Seismic Regulation for Buildings and Other Strucures, FEMA P750, for discussion of the basis of seismic reliabiltiies.

S100-07 North American Specification for the Design of Cold Formed Steel Structural Members

AF&PA
American Forest & Paper Association
1111 Nineteenth Street, NW, Suite 800
Washington, DC 20036

Supplement Special Design Provisions for Wind & Seismic

ANSI/AF&PA NDS-2005 National Design Specification for Wood Construction
ANSI/AF&PA SDPWS-2008 Special Design Provisions for Wind & Seismic

AA
Aluminum Association
1525 Wilson Blvd, Suite 600
Arlington, VA 22209

Specification for Aluminum Structures

Figure 2 Table C1.3.1a Acceptable reliability for load conditions that do not include earthquake

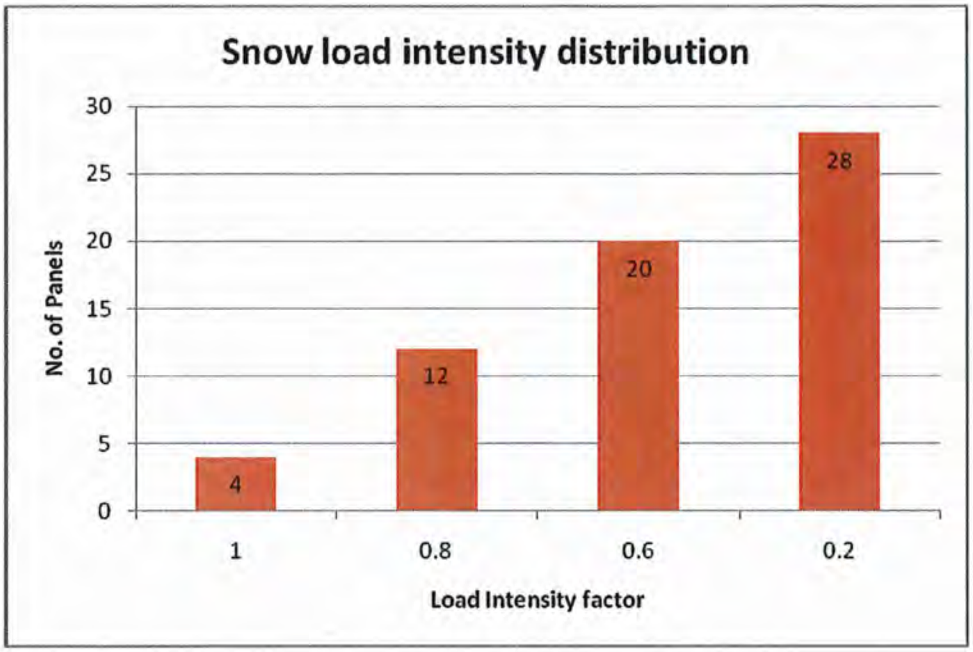

Figure 3 Snow load intensity distribution – Diamond Panels

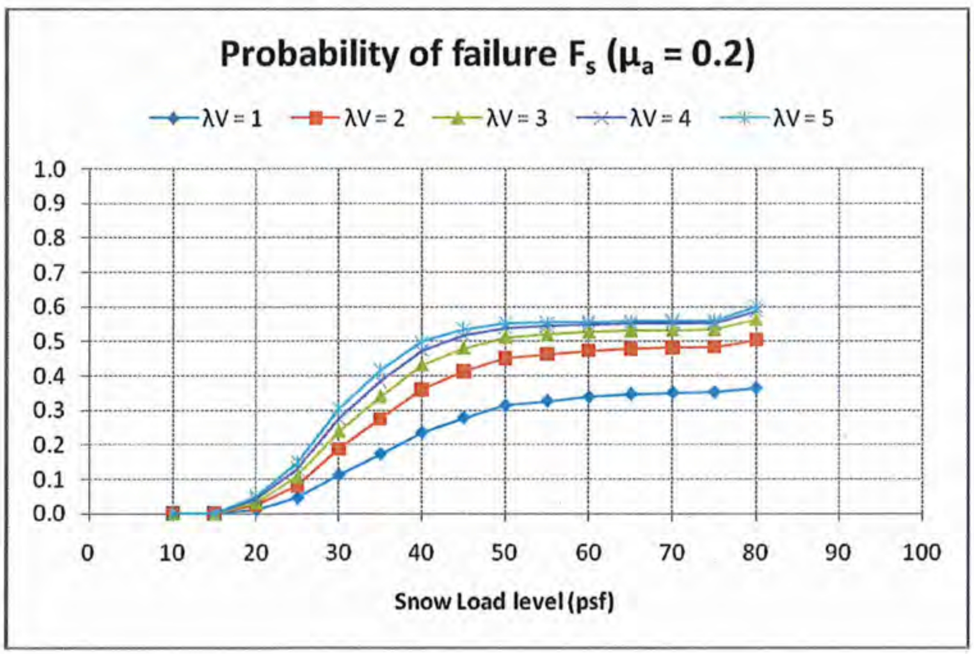

Figure 4 Probability of diamond panel failure under snow load, mean flaw size 12 mm

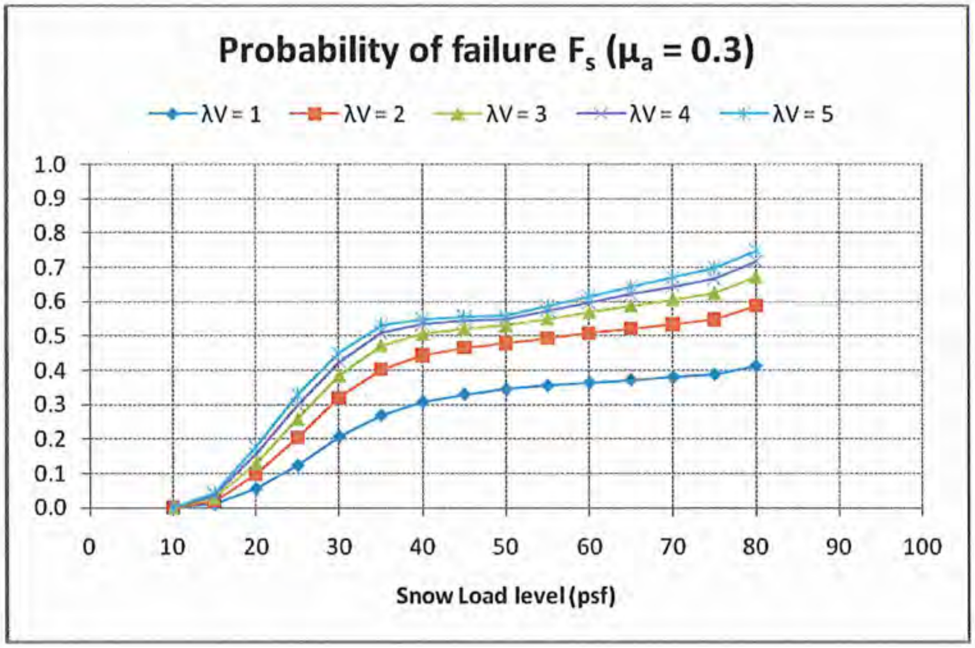

Figure 5 Probability of diamond panel failure under snow load, mean flaw size 18 mm

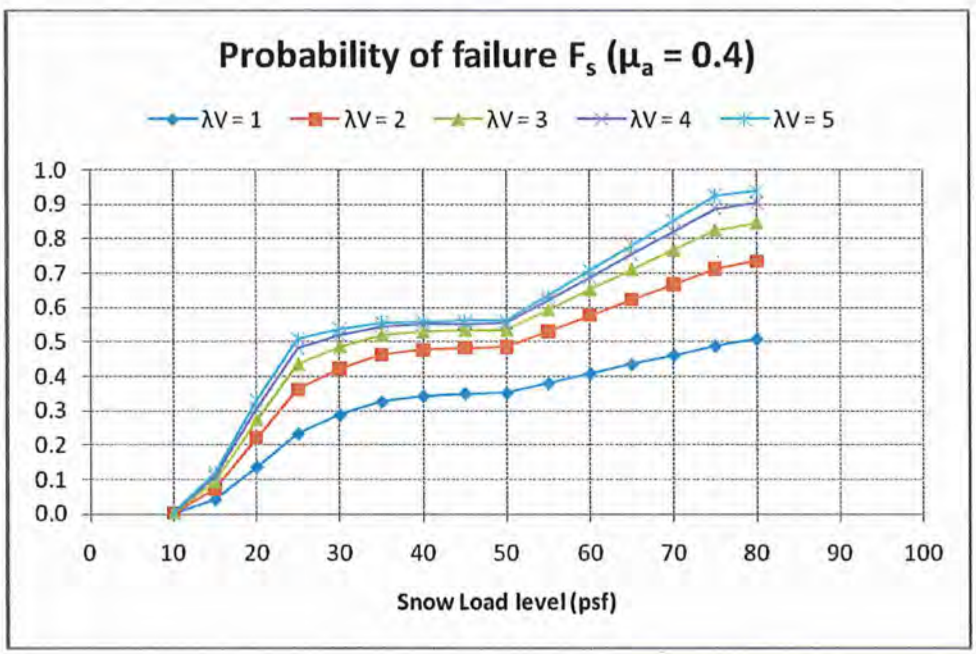

Figure 6 Probability of diamond panel failure under snow load, mean flaw size 24 mm

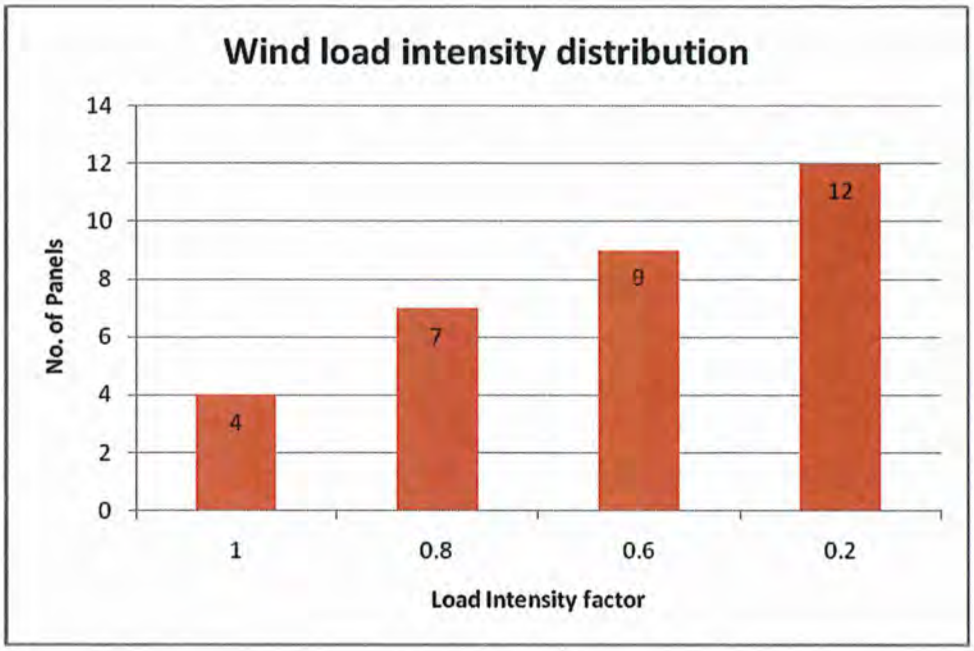

Figure 7 Wind load intensity distribution for Rectangular Panels

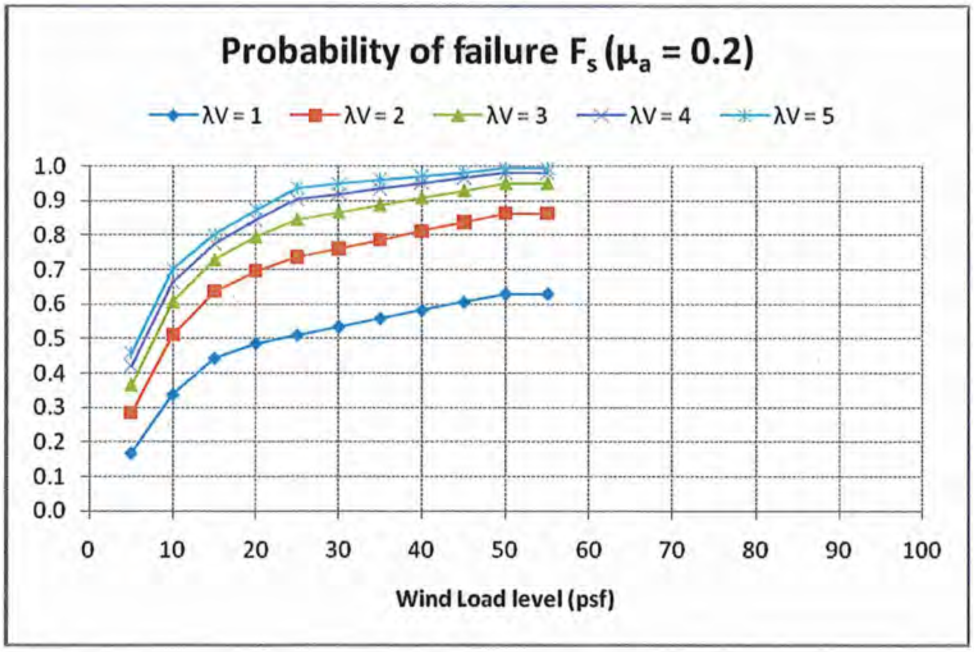

Figure 8 Probability of rectangular panel failure under wind load, mean flaw size 12 mm

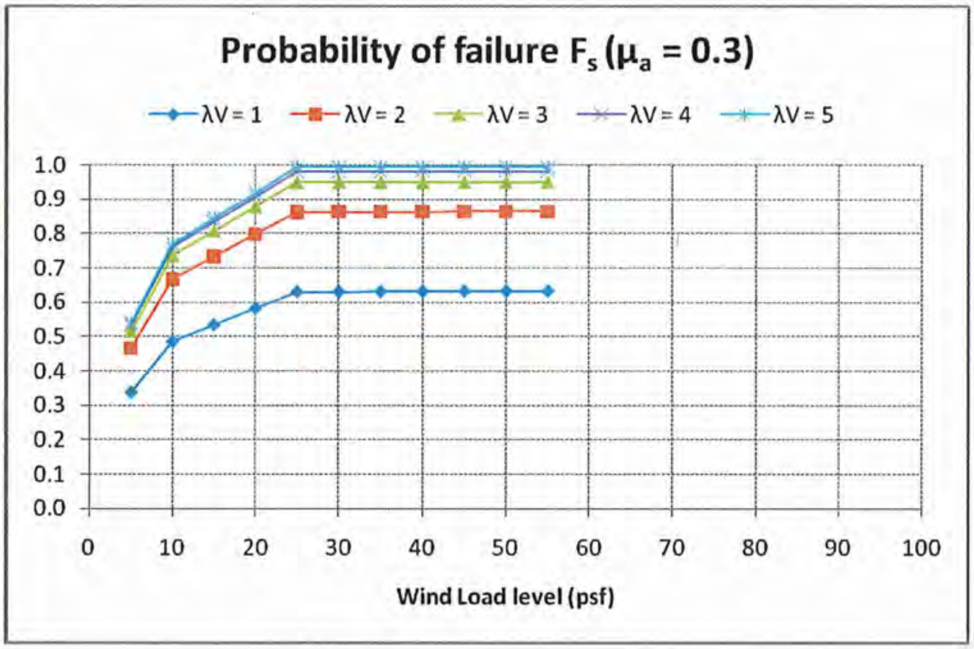

Figure 9 Probability of rectangular panel failure under wind load, mean flaw size 18 mm

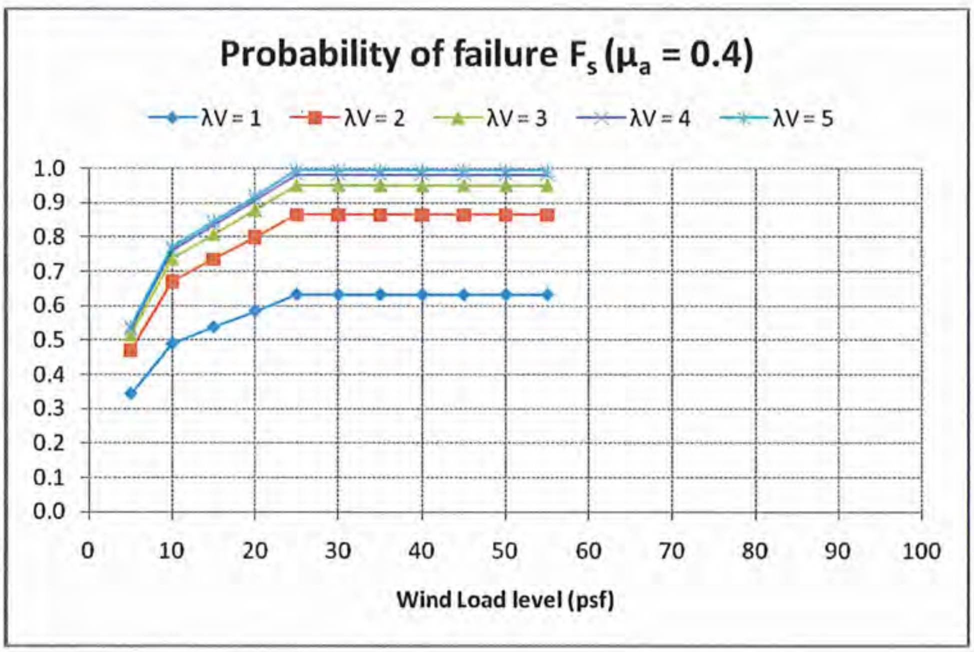

Figure 10 Probability of rectangular panel failure under wind load, mean flaw size 24 mm