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Design of Blowout Mechanisms for a Large Fabric Windscreen

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Abstract

The design, testing, and evaluation of the fabric panels for a large windscreen are studied in the paper. The fabric panels are stacked in arrays seven high, and supported by tubular steel towers and horizontal aluminum spars that can be raised and lowered in the manner of a Roman shade. The fabric panels are designed to resist a critical wind speed of 27 m/s, at which point a motor and winch system will retract the panels into the structure's base to prevent overloading of the supporting structure. The panels are designed to blowout and dissipate load at higher wind speeds in the event of operator error or mechanical failure. The design team conducted extensive analytical studies on the full-size panels, as well as on half-size models used to test blowout failure mechanisms. These mechanisms include two general approaches to causing fabric panel blowout at a target wind pressure: sewn "zippers" that rupture across the full width of the fabric panel, and metal "fuses" that fracture to release the load in panel edge ropes. Test results on alternate designs have been evaluated for membrane deformations, loading on the supporting structure, effectiveness in limiting air leakage between the edges of the fabric panels and the vertical supporting members, and for reliability of blowout mechanisms.

Keywords: fabric structures, windscreens, fuses, deployable structures, vacuum chamber testing

1. Introduction

The author's firm is working in collaboration with a fabric specialty contractor to design a deployable windscreen. The name of the windscreen owner and its use are confidential. The screen is an assembly of 4.64m high by 9.79m wide fabric panels. The panels are supported by a system of tubular steel columns joined by horizontal aluminum spars that secure the top and bottom edges of each panel. Panels are stacked seven high into 34.35m high towers, and multiple towers are in turn joined to each other to form the complete screen. The screen rests on wheeled steel "bogies" (similar to those of a rail car), which may be moved along a circular track in order to orient the wind screen perpendicular to the wind. A typical tower with its seven fabric panels is shown in Figure 1.

The fabric panels are raised into position using a motorized winch and cable system that raises the horizontal spars along the tubular columns in the manner of a Roman shade. While the windscreen may be employed in regions subject to hurricane wind speeds, the screen's supporting structure is designed to resist lateral wind forces associated with a 27 m/s wind speed acting on the full windscreen area. The spars are lowered in order to retract the fabric panels when winds exceed this speed, so that member forces and overturning moments on the supporting structure are kept within acceptable limits.

The windscreen requires a backup system to relieve load from the supporting structure in high winds in the event of operator error, mechanical malfunction, or a sudden increase in wind speed that

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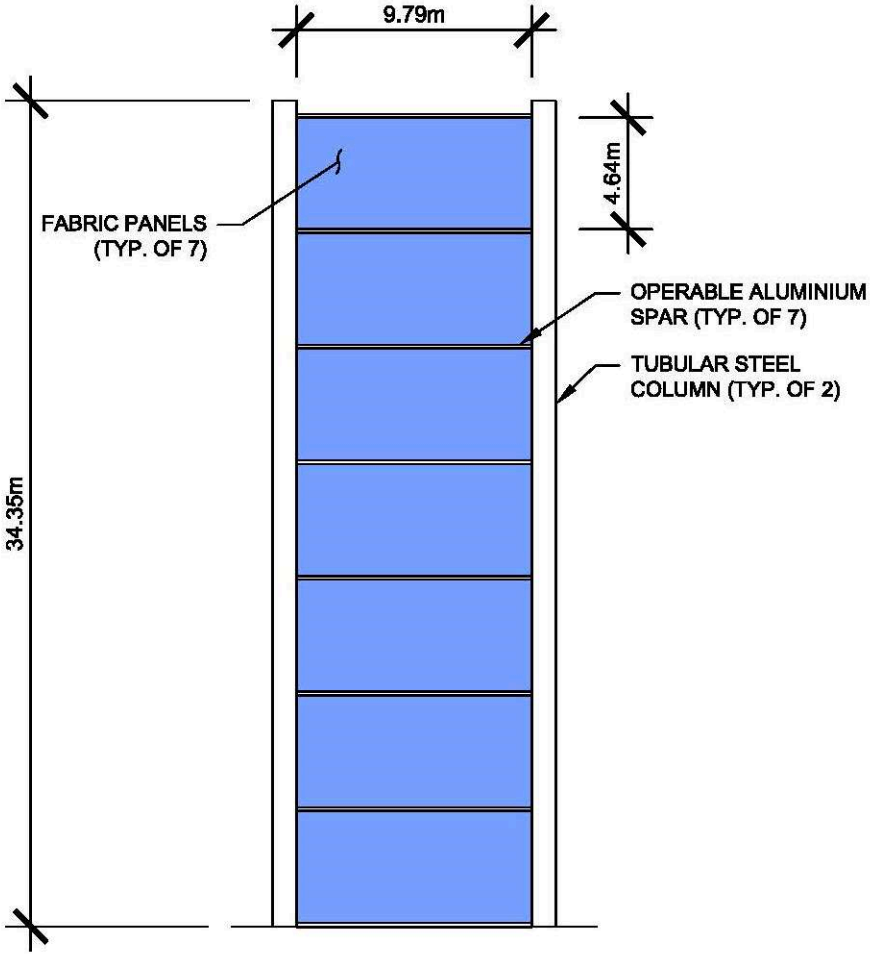

Figure 1: Typical seven panel tall windscreen tower elevation

prevents the screen being lowered in high winds. This backup is provided by a fuse mechanism that allows the fabric panels to break away from the spars to dissipate wind load at the maximum horizontal wind pressure associated with the 27 m/s wind speed. This horizontal pressure was determined from the governing results of ASCE7-10 Code-level design [1], computational fluid dynamics, and wind tunnel testing. The design goal is for the panels to blowout at loads as close as possible to those associated with the target wind speed, in order to prevent either overload of the supporting structure or operational issues associated with early blowout.

Achieving blowout close to the target pressure is made more difficult by the fact that the load bearing efficiency of the initially uncurved fabric membrane increases as the membrane deflection grows larger under increased loading. Stated another way, the internal forces in the membrane and rope edges increase more slowly than the applied loading increases. Since membrane zippers and rope fuses are the mechanisms initiating the blowout, modest errors in the strength of the zipper or fuse may result in relatively large deviations in blowout load. Accurate evaluation of the strength of the zippered or fused blowout mechanism and accurate analysis of element loads are therefore both critical to achieving blowout at wind speeds close to the target speed.

Material selection for the project was governed by the need for a system that is robust and adaptable to frequent deployment and retraction of the shade system. A minimum lifespan of 3-5 years is required, with moderate fabric translucency a desirable feature for daylighting. Ferrari 902 vinyl-coated polyester fabric was selected. For the ropes incorporated into the panels, high strength and stiffness are both required, as is dimensional stability under repeated load cycling and the ability to accommodate tight bend radii both for fit-up into the supporting framework and for storage of the retracted shade system. Wire rope has insufficient flexibility for use in the deployable system, and ropes selected are therefore manufactured using Dyneema fibers [2]. These ropes have much greater strength and stiffness than polyester rope, as well as low creep deformations and high flexibility that facilitate tight bend radii. Model generation, analysis, and patterning were all done using software developed by Fabric Technology for Structures.

The design of the fuse system and its calibration so as to provide reliable blowout at the 0.78 kPa horizontal loading associated with the 27m/s wind speed is the focus of this paper. The sections below outline the performance requirements of the fuse system, describe the fuse testing program undertaken, and outline ongoing developments in the design of the system.

2. Alternate Fabric Panel Breakaway Systems

There are several goals of the panel blowout system design, as described below:

1. Panel blowout should occur at loading close to the 0.78 kPa wind load. Lower blowout load impedes operation of the windscreen and risks unnecessary damage to the fabric panels. Higher blowout loads carry the more serious risk of overstressing or overturning the supporting structure.
2. The panels should sustain repeated loadings approaching the design load without damage to hardware, breaking of threads or elongation at sewn seams, separation of heat-sealed seams, fraying of ropes, or other damage requiring repair.
3. Panel blowout should be sudden and relieve nearly all load on the fabric panels.
4. Panel blowout should not result in hazards related to metal parts that act either as projectiles or which remain attached to a loose panel which whips about in the wind.
5. The cost and complexity of repairs associated with panel blowout should be limited.

Breakaway mechanisms are of two general types. Zippers are designed to come apart across the width of a planar element, as in the failure of a sewn seam across the width of a fabric panel, while fuses are designed to cause a point failure in a rope or other linear load-bearing element. Both types of breakaway mechanism are designed to fail at a specified load, so that the panel blows out at the targeted wind speed. Both types of breakaway mechanism were analyzed and tested as part of the project development. The designs that were developed using these two approaches described in the following sections.

3. Zippered Panel Blowout System

The structural elements of the zippered panel design are shown in Figure 2. The fabric panel is oriented with the warp fibers in the horizontal direction, in order to maximize fabric usage and prevent the unwanted strengthening effect of doubled fabric thickness where the seams cross the horizontal zipper. This orientation also reduces the stiffness of the membrane in the primary (vertical) load bearing direction. The resulting increase in membrane deflection serves to reduce fill fabric stresses and vertical reactions on the spars.

Prestress of 0.44 N/mm is provided in the warp fibers and 0.88 N/mm in the fill, as appropriate to hold the panel taut without increasing reaction loads unnecessarily. Membrane stresses increase to a maximum of 7.7 N/mm in the warp and 8.5 N/mm in the fill under the design wind pressure – values that are still well below allowable for the specified fabric. The top and bottom edges of the fabric panel are continuously attached to the adjoining horizontal spars with keder track, while the two side edges are formed by 50mm wide polyester webbing that resists small catenary edge tension forces. Webbing tension is equal to 6.7 kN under prestress and doubles to 13.4 kN under the design wind pressure. A slender horizontal aluminum batten at the middle of the panel halves the span of the vertical edge webbing, and assures narrow gaps between the fabric and the adjacent steel tube column in order to reduce air leakage through the windscreen.

Analysis indicated that fill (vertical) membrane stresses vary little over the height of the panel, so that the placement of the horizontal breakaway zipper is not structurally critical. It was positioned near the bottom of the panel, so that a failed panel will hang from the top keder edge, without falling into the panel below.

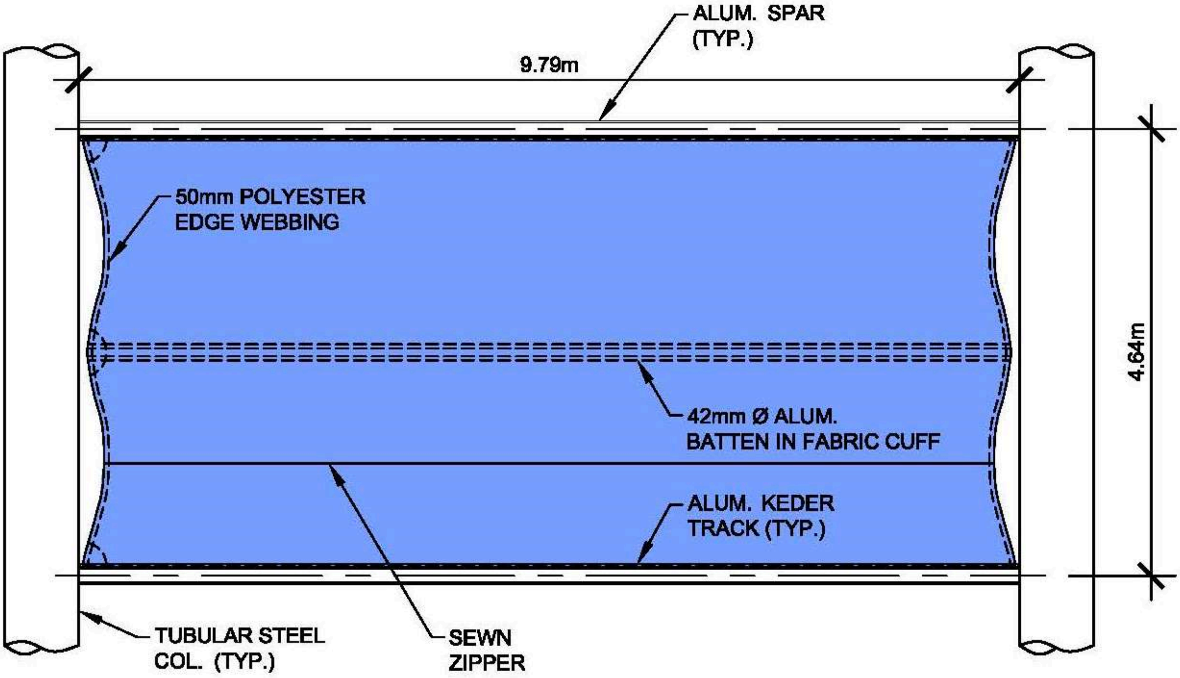

Figure 2. Typical zippered fabric panel elevation

The zippered breakaway design has the assets of simple construction and easy installation. The concern with its design lies in the ability to accurately predict the maximum fill fabric stress and to accurately regulate the strength of the sewn zipper, so that blowout occurs at the intended pressure level. Analysis indicated fill stress under the design pressure to be approximately 8.5N/mm over the full height of the panel and over approximately the center 60% of panel width. The pull tests made on fabric samples to establish the appropriate thread and stitching pattern to achieve this strength are discussed in Section 5, below.

4. Fused Rope Breakaway System

A typical panel using this alternate design scheme is shown in Figure 3. The main fabric panel is ringed with Dyneema ropes. 12mm diameter ropes at the top and bottom of the panel gather the primary membrane stresses that run in the vertical fill direction, and carry them to shackles anchored to each end of the spars. 10mm ropes at the sides of the panel carry the smaller horizontal warp stresses to the corner shackles.

In order to limit air leakage through the panel, the gaps between the horizontal ropes and the spars are infilled with fabric closure panels that attach to keder extrusions running the length of the spar. The top closure may be heat sealed to the main panel. In order to allow blowout of the panel, though, the bottom closure is attached to the main panel with continuous strips of 3M Dual Lock - a high capacity variant of the ubiquitous Velcro product. The closures are oversized to provide up to 100mm of slack width under presstress, so that they provide a wind seal without imposing significant load on the spars. The closures do not fully straighten and carry significant load prior to blowout of the main panel. When the metal fuse breaks to initiate panel blowout, the forces in the side and bottom ropes reduce to zero, and the fill membrane stresses transfer into the top and bottom closure panels. This overloads the Dual Lock on the bottom closure, which tears loose to break the main panel free of the closure. The closure remains attached to the spar along its keder edge, where it can flap freely without resisting wind load. Similar closures are provided at the two sides of the panels.

In order to allow the spars and fabric panels to be raised and lowered, the side closures are attached to the vertical safety ropes rather than to a keder rail connected directly to the columns. Field installation is facilitated by securing the cuff to the safety rope using a Dual Lock cuff, and securing the other edge of the closure to the main panel with Dual Lock.

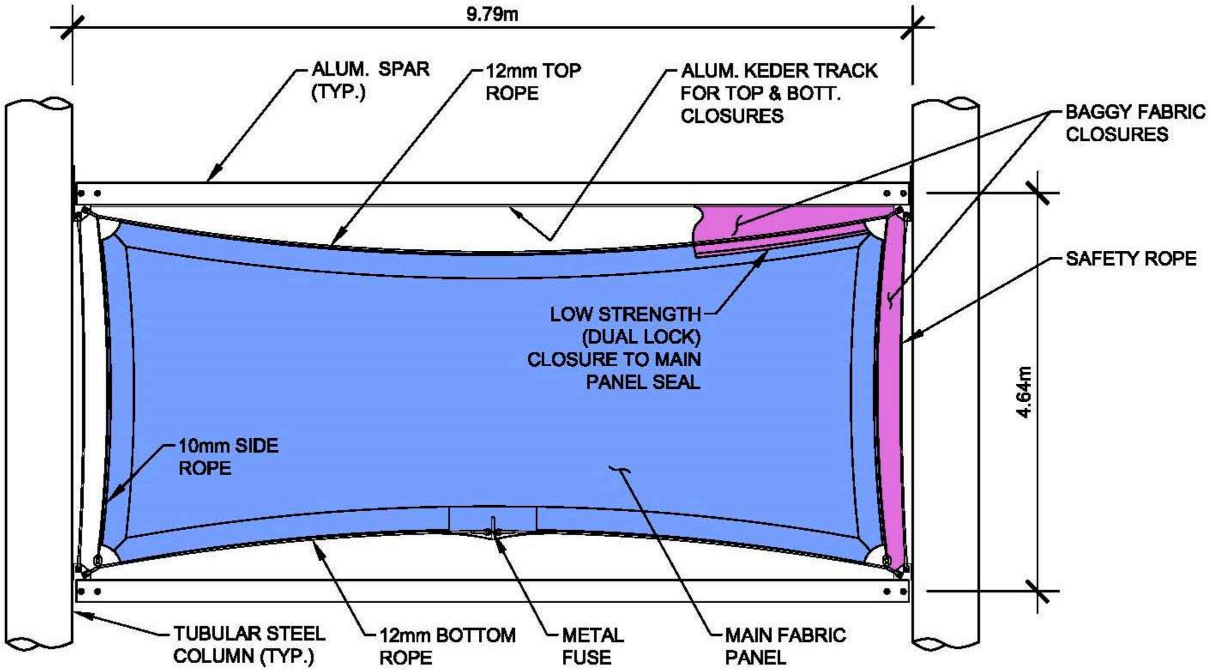

Figure 3. Typical fused fabric panel elevation

Complete panel blowout must initiate with failure at a single fuse point in order to assure that there is no partial blowout that would relieve only a portion of the wind loading. If fuses were positioned at the rope attachment points in each panel corner, for example, overload would be likely to cause failure at a single corner of the panel, leaving three of the four panel corners attached, with a triangular area encompasing one-half of the original rectangle remaining in place to resist wind.

To assure complete blowout, the bottom rope is divided at its midpoint, and a single fuse is placed at this location, as shown in Figure 3. The tensile fracture of the fuse allows the bottom rope to slip out through its cable cuff, so that the panel then hangs freely from the intact rope along the top edge. Different configurations of edge rope were considered in order to address the demands of field installation and the differing force levels in the ropes along the long top and bottom edges relative to the shorter side edges, as shown in Figure 4.

Our initial fused rope concept is termed the “rope stop” design, and its rope configuration is shown schematically on the left side of Figure 4. The top and bottom ropes are shaped to provide a 20kN prestress load, with 6 kN prestress in the smaller side ropes. The side ropes are connected to each other with a single chain link that is positioned on the side rope side (rather than the bottom rope side) of the corner shackle. The chain link is too bulky to pass through the shackle, and thereby provides a “stop” that prevents the rope from translating through the shackle and equilibrating the two prestress levels.

An alternate rope configuration adopts the terminology and techniques of yachting ropes to create the “block and tackle” design. In this scheme, the rope cuffs at the main fabric panel edges are shaped so that the 16kN prestress in the top and bottom ropes is exactly double that in the side ropes. The continuous ropes double back on themselves along the top and bottom of the panel to form the block and tackle mechanism which effectively doubles the prestress level in the top and bottom ropes to achieve the desired force level.

In order to create the bottom rope fuse, the design team initially considered manipulations in the fabrication of the rope itself to create a point with well-calibrated weakeness. These included the following:

1. Splicing a short piece of 8mm rope between the two sections of 12mm bottom rope.

2. Cutting a fraction of the 12 strands comprising the rope and braiding them back into the intact portion of the rope to create a weak point in the rope.

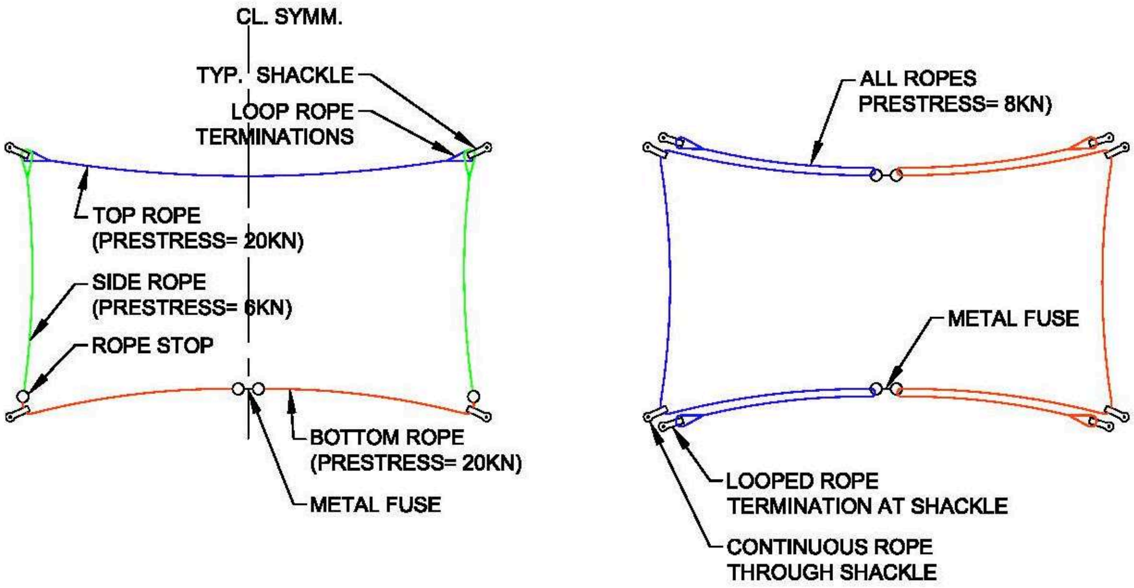

Figure 4. Fused fabric panel rope configuration. Rope stop design (left), block & tackle design (right)

Accurate calibration of the fuse strength is critical to blowout of the panel at the target wind pressure, and we concluded that these methods did not provide sufficiently accurate calibration of the fuse strength to the targeted failure load. The fuses are instead compact parts machined from 17-4 HT900 heat-treated stainless steel. This material has an ultimate tensile strength very close to its yield strength, which assures the desired brittle fuse failure, and final fuse geometry was determined based on the tested strength of the billet from which the fuses were made. Together with careful machining and finishing to eliminate local stress increases, this assures reliable tensile strength.

In the rope stop design, the two bottom rope halves terminate at the fuse, so the looped terminations on the bottom rope are attached to small shackles which are in turn pinned to a dog bone shaped metal fuse. In the block and tackle design, the ropes must turn back on themselves and continue back to the panel corner, so the rope is passed through the circular hole in the metal fuse, and allowed to ride freely across the fuse to equilibrate the forces in the pair of rope halves.

An asset of the fused rope system is that the primary fill membrane stresses are carried by the top and bottom ropes, thereby relieving the majority of bending moment from the spars. Installation of the fabric panels into the steel frame used in the vacuum testing program described below was made difficult by the fact that the straight line length of the untensioned top and bottom ropes is slightly less than the straight line distance between the rope anchorage points on the shackles at the ends of each spar. Using the rope stop design, the curvature of the ropes within the cuffs at the edges of the main panel will therefore be increased slightly, so that the ropes can be installed by hand under minimal tension, thus easing panel installation. The block and tackle rope layout has the advantage of providing ample rope slack for installation of the fabric panel whenever the spars are positioned close together prior to raising the fabric windscreen panels.

5. Testing Program

Initial testing on fabricated parts of the panel assembly included the following:

1. Biaxial tests on fabric samples as required to establish prestress compensation values.
2. Tension tests on 100mm and 200mm wide fabric samples with sewn seams, as required to establish fabric zipper strength. Pull tests were performed on 100mm and 200mm wide fabric

strips, with narrow fabric “wings” each side, as required to anchor the stitching detail. A 200mm specimen at failure is shown in Figure 5 (left). Testing indicated substantial variability in zipper strength, even with test specifimens carefully fabricated to the same specification.

3. Tension tests on polyester webbing, to determine webbing tension strength.
4. Tension tests on machined steel fuses. Fractured fuses are shown in Figure 5 (right).

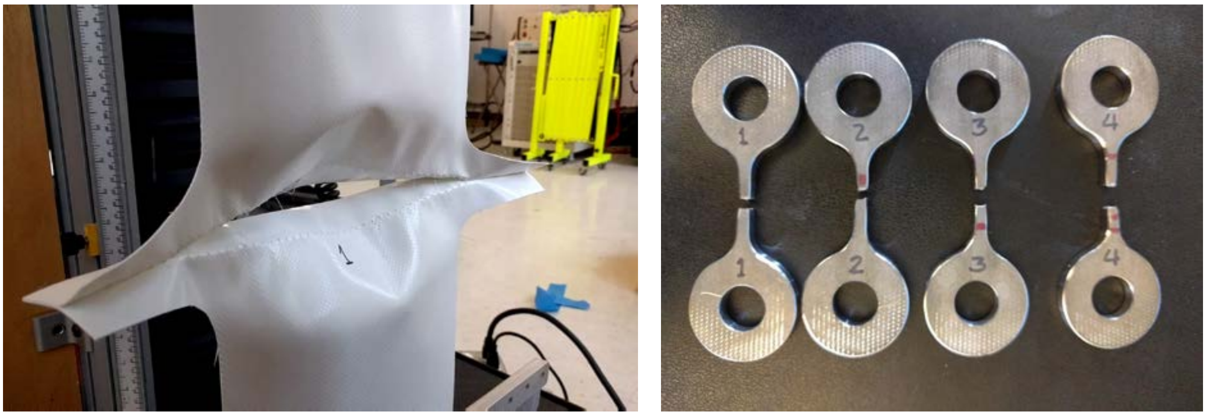

Figure 5. Tests to failure of sewn fabric seams for the zippered panel design (left) and machined metal fuses for the rope stop design (right)

A second testing program was conducted on complete fabric assemblies using a vacuum chamber methodology similar to that used to test curtain wall assemblies, as shown in Figure 6. A half-size testing frame was designed and constructed to support a scaled fabric panel and provide a tensioning mechanism for test panels constructed with the zippered panel and fused rope schemes. The test frame is supported on posts that elevate it approximately 800mm above the floor, and the space beneath the panel is enclosed by plywood in order to create the vacuum chamber beneath the panel. There are air gaps on the two side edges of the fabric panel in both the zippered and fused rope schemes. These gaps were closed with baggy fabric skirts anchored between the fabric panel and the surrounding steel frame, and the panel assembly and frame were then covered with a 0.25mm polyethylene sheet, which was taped to the testing facility floor to create a sealed chamber. Pumping the air out of the sealed chamber creates the measured negative presesures that simulate the required wind loading.

Scaling effects vary for different elements and properties of the test assembly. (Spar stiffness can be adjusted by reducing spar size in the half size model, for example, but the testing required use of the

Figure 6. Vacuum chamber and zippered panel prior to testing (left), zippered panel following rupture of zipper and polyethylene cover (right)

same Ferrari 902 fabric material that will be used in the full size structure.) Similarly, ropes and metal fuses can be readily scaled, but scaling the strength of the stitched fabric fuse was problematic in practice and was not attempted. Additional scaling complications result from the highly non-linear rates at which fabric span, tension stress, and deflection vary under load. Our predictions for the load capacity and deformation of the test panels were therefore derived from a separate analysis based on the properties of the test assembly, rather than by scaling the analytical results of the full-sized panel.

Testing of the zippered panel system was watched closely in real time, with live observations confirmed by subsequent study of video recordings. These demonstrated blowout in the desired mode: large out-of-plane deformation of the membrane, followed by initiation of the zipper failure near the middle of the panel that propogated to the each side of the panel, where the edge webbing tore completely to relieve the vacuum loading. Three tests all produced vacuum pressure at blowout approximately double the target pressure, with substantial variability between tests, as reflective of the variability in testing of fabric zipper samples conducted earlier. By adjusting the thread and stitching design of the sewn seam and correcting inaccuracies in the modeling of spar deflection in the analysis of the test panel, we expect that zipper strength can be adjusted to bring the zipper strength down to the desired level. The variability in strength between tests of panels constructed to the same specification may remain an issue, however.

An initial test of the fused rope design produced blowout at pressure well above the target pressure. The test overload is believed to be the result of deviations in rope length in the test assembly. Two subsequent tests with corrrected rope lengths produced blowout at plus or minus 15% of the target pressure. The results on these two final tests provide a fairly satisfactory level of performance and a solid basis for further refinement of the design.

6. Conclusions

Design, analysis, and testing completed to date have demonstrated the viability of both zippered and fused panel blowout schemes, but the difficulty in calibrating the failure load of the fabric zipper has led the design team to focus on the fused rope approach for further development. Additional design, analysis, and testing is required in order to perfect details of the design and fabrication process as required to assure reliable blowout at pressures close to the target pressure. This work will include refinements in the test panel analysis and improvements in the design of fuses and other hardware as required to achieve the required strength using parts that are readily assembled on site.

Testing on the fused rope concept will be expanded from the rope stop approach to include the block and tackle system. When vacuum chamber testing has demonstrated reliable performance and predictible blowout pressure, a final design will be selected, and an initial full sized panel will be constructed to finalize evaluation of the blowout system and to test the deployment system used to raise and lower the fabric panels.

References

[1] *ASCE Minimum Design Loads for Buildings and Other Structures*, ASCE Standard 7-10, 2010

[2] *Fibers for Cable, Cordage, Rope and Twine*, Cordage Institute CI 2003, 2005