HGC Window Prototyping - Carbonfiber Testing Series

Samip Basnet
Rory Evans
Ryan Ambrose Derek Gervais Garth Huber Geremy Lague
Wenliang Li Dilli Paudyal Lorenz Weber
Ahmed Zafar
University of Regina

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As part of the prototyping process for the SoLID Heavy Gas Cherenkov detector (HGC), a suitable material for the entrance window must be found. The HGC will be filled with gas at a pressure of approximately 1.5 atm, or 22.0 psi (that is, 0.5 atm or 7.35 psi over-pressure), and must fit in the SoLID assembly at Jefferson Lab Hall A. As such, the material must not only withstand the pressure difference, but do so with minimal bulging (no more than approximately 10 cm). In this series of trials, a miniature version of the HGC window is tested with 3 different material configurations along with a full-sized shell prototype. The procedures followed to make these configurations are detailed in this report, along with the results from the pressure test for each window shell.

1 Fabrication

Due to the failure of previous design configurations[1] and the availability of excess carbon fiber from Hall C HGC construction, we decided to develop shell designs with the carbon-fiber. The list of materials used to make these shell designs are listed below.

- 3 Layers Carbon Fiber (Fiber Glast - 1069 3K, 2x2 Twill Weave Carbon Fiber Fabric)
- Epoxy Resin (2000 and 2020)
- Mylar
- Kevlar
- Mid-density Fiber (MDF) board
- Aluminum frames

[1] Evans et. al, "HGC Window Prototyping - July Testing Series", July 2017.

For the configurations tested (except for the small mock-up windows), the ratio of Epoxy Resin 2020 to 2000 was 23:100. The total amount of epoxy mixture used for small and full-sized shells were $\sim$190 g and $\sim$470 g respectively. Additionally, as shown in Figure 1, the desired shape of the shell was pre-formed using MDF board on a flat wooden board (unless otherwise specified).

Figure 1: Pre-formed shape of the window-shell (Note: The shape of this mold was modeled after the small window-shell shape at $\sim$ 10 psi pressure.)

1.1 Flat mock-up windows

Before finalizing the fabrication procedure with carbon fiber, two small mock-up windows were prepared. For these mock-ups, only two layers of carbon fiber and flat shape were used. Unlike rest of the design configurations that use Epoxy Resins 2000 and 2200 mixture, these two windows only use about 150g of pure Epoxy Resin 2000. For the first mockup, we did not pre-stretch the mylar layer while the second mock-up used mylar after pre-stretching it at $\sim$10 psi overnight. We learned from these mock-ups testing that the lesser thickness and rigidity in addition to the flat shape of the windows caused them to fail miserably under pressure.

1.2 Small shell #1

The first of the three miniature (14 in by 17 in) window shell design uses 3 layers of carbon fiber and epoxy mixture as well as a layer of Kevlar on the outer surface of the shell and a layer of pre-stretched mylar as the innermost layer of the shell. This design has depth of about 1 inch and only uses one metal frame. It is also worth noting that the small window need to hold four times the pressure to equal the same stress as large window[1].

For the first design, the desired shape of the window was modeled after the small mylar window-shell shape under pressure. Once the shape was pre-formed, the following steps were taken to fabricate the window-shell.

[1]Evans et. al, "HGC Window Prototyping - July Testing Series", July 2017.

1. Put first layer of carbon-fiber on top of the desired window-shell shape.
2. Apply around $\frac{1}{3}$ of the total epoxy mixture and spread it evenly throughout the shell as shown in Fig. 2.

Figure 2: Applying epoxy to carbon layer. (Note that this was done without vacuum bagging.)

3. Add the second layer of carbon-fiber, apply the same amount of epoxy mixture, and spread it evenly throughout the layer.
4. Repeat step #3 with another layer of carbon-fiber and the remaining epoxy mixture.
5. After the final layer of epoxy mixture is applied, let it cure for 8 hours or more.
6. Once cured, sand down both sides of the window shell. This is necessary to help the outer Kevlar layer stick on it easily.
7. Take the outermost metal window frame and place it on top of the shell.
8. With half an inch spacing, cut the around the edges, cut the shell and drill five holes (one in the middle and around four corners) with 1mm drill bit. This helps release air between the Kevlar and carbon fiber layers.
9. Punch the holes in the shell for mounting the metal frame using quarter inch hole drill bit.

Finally, the inner mylar layer was pre-stretched at 10 psi pressure overnight and everything was put together before testing.

Figure 3: Cured window shell and Kevlar before applying the final layer.

Figure 4: Drilling 1mm hole in the middle.

1.3 Small shell #2

Similar to small shell design #1, this design also uses 3 layers of carbon fiber and epoxy mixture along with an outer layer of Kevlar and an inner layer of pre-stretched mylar. The depth for this design is 1.5 inches, which is about half as much greater than that for the first window shell design. This design also uses one metal frame.

The second design for the window shell more or less follows the same procedure as the first one. The only difference between the two designs is desired shape of shells. For the small shell #1, the shape was modeled after the mylar layer under 10 psi of pressure however for this design, dimensions of the Klopper head, mostly used for pressure vessels[2], were used (see Fig. 5). The breadth (14 in) of miniature window was used as the reference diameter for the Klopper head design.

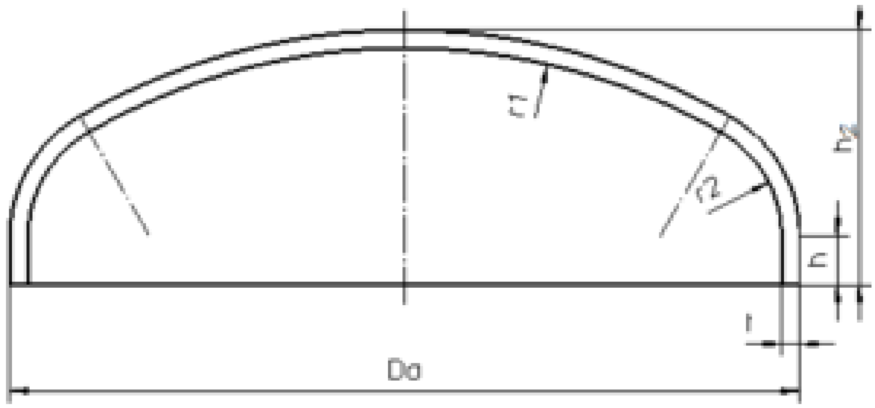

Figure 5: Schematic diagram of Klopper-head taken from Wikipedia.(Note that this design assumes a cylindrical base, however the window is rectangular so some changes had to be made.)

It is also worth noting that during the manufacturing process for this design, we faced some difficulties removing the cured shell from the mold. Even though mold-release wax was applied before placing the first layer of carbon fiber on top it, the cured shell and the mold bonded together so a pry-bar and compressed air was used to separate them. The shell therefore endured some fractures. Thus, a layer of carbon fiber and epoxy mixture was added later, as described in the steps 1-3 above. This time a wax cloth was used between carbon fiber and the mold.

1.4 Small shell #3 (sandwich design)

The configuration of the third design is pretty much identical with respect to the layers of carbon fiber, epoxy mixture, Kevlar and mylar used and the procedure followed to fabricate them. The depth of the shell is 1.5 inches, same as the second small shell design. The previous designs only used one aluminum flange. However, for the window shell #3 the cured carbon fiber shell was sandwiched between two aluminum frames along with epoxy mixture around the edges for each layer, as suggested during the SoLID collaboration meeting. Apart from that, this design follows the same procedure to make the shell and uses Klopper head dimensions for the shape similar to the small shell #2. Once all the window shell components (two metal frames, cured shell, and pre-stretched mylar) are ready, we followed the procedure listed below to put together the window-shell.

1. Lay the bottom frame on a flat surface with wax cloth, after sanding it down with a Scotch-Brite pad to help prepare the bonding surface. Note that the frame should contain O-ring before applying epoxy.

2. Apply epoxy to the surface of the frame to bond with mylar as shown in Fig. 6

[2]Pressure vessel information in Wikipedia.

Figure 6: Applying epoxy mixture on the metal frame.

3. Prepare both sides of the pre-stretched mylar by lightly sanding the edges around the flange area with Scotch-Brite pad to provide better bonding surface for the epoxy mixture as shown in Fig. 7.

Figure 7: Sanding the mylar layer for better bonding with epoxy mixture.

4. Place mylar on the frame with epoxy mixture on it and brush a layer of epoxy mixture on top of the mylar layer as shown in Fig. 8.

5. Wet the bottom edges around the cured shell with the mixture before placing it on top of the mylar and bottom metal frame.

6. Brush the top layer of the shell as well as bottom part of the top frame with some epoxy and place the frame on top rest of the shell.

7. Insert some bolts through the entire sandwich to ensure the alignment is correct.

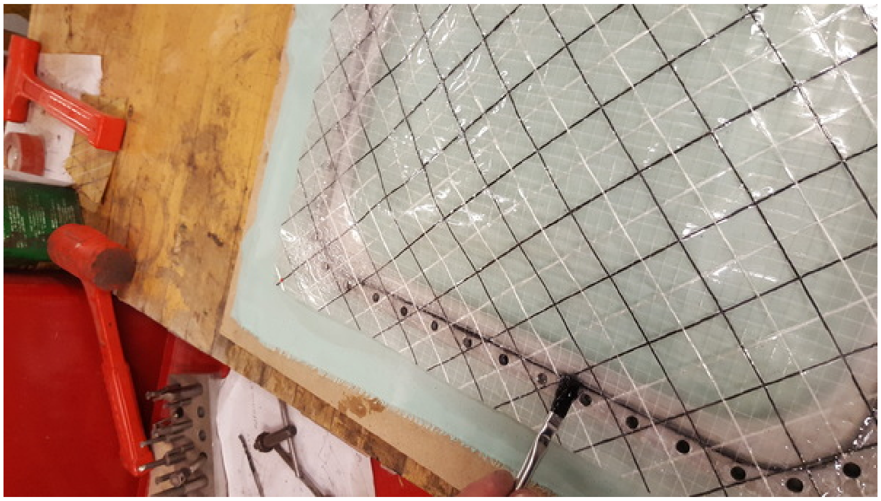

Figure 8: Applying epoxy to the mylar.

Figure 9: Metal blocks used as weight after applying epoxy mixture.

8. Apply some weight on top of the entire assembly and let the epoxy cure. C-clamps are preferred for such purposes but due to lack of large enough C-clamps in the machine shop, we improvised by using metal blocks as shown in Figure 9.

1.5 Full-sized shell #4

This design is essentially a full-scale version of the design #3. However, unlike the small window shells, the full scale window is not rectangular in shape[1], thus some changes had to be made while making the mold (a variation of Klopper head design had to used with breadth at half-length as the reference radius (∼32 in) for the design). Since the quantity of MDF board to make mold for full sized window is enormous, we decided to use wooden frame and foam cloth to make the mold.

[1]Evans et. al, "Heavy Gas Cherenkov Detector: Window Material Pressure Test", Dec 2016.

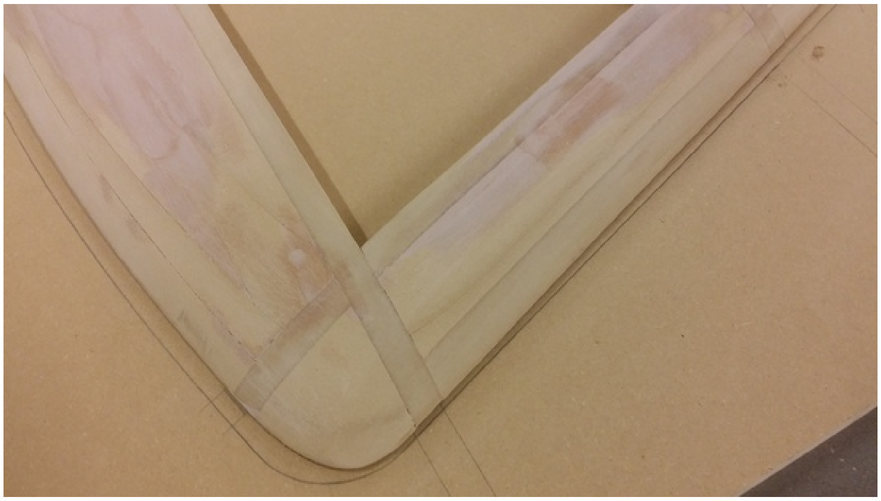

Figure 10: Completed frame edge

First, the frame was cut out using cardboard and sanded down (see Fig. 10). Then, a layer of foam cloth was placed on top of the frame. The foam cloth was then tightened using staples as shown in Fig. 11.

Figure 11: Tightening the foam cloth on the wooden frame.

With the tightened foam cloth, it should now take the desired shape. Next, one thin layer of epoxy mixture was used on the foam and let it cure for overnight before following the same steps taken for sandwich design to fabricate the complete assembly.

Figure 12: The end product after applying a thin epoxy mixture layer left to cure overnight.

2 Experimental Procedure

Each window was mounted to a steel plate with vacuum grease to provide an airtight seal. A ruler was fixed above the window in an apparatus which allows the ruler to slide up and down, resting against the window. Air was pumped through a hole in the underside of the plate using a bicycle pump attached to a pressure gauge and valve. Figs. 13 and 14 show the setup for the miniature and full-size windows respectively.

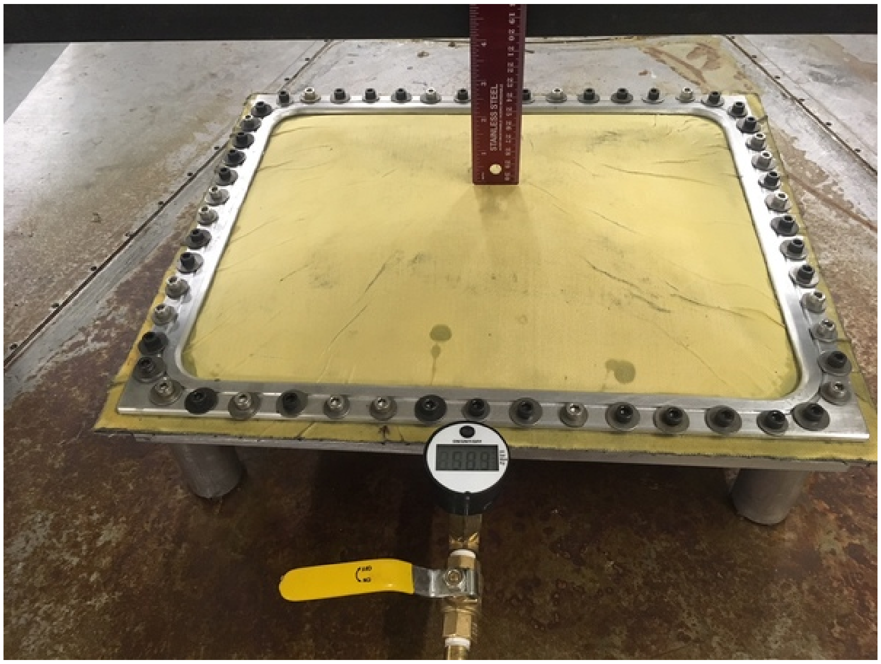

Figure 13: Experimental setup for miniature window.

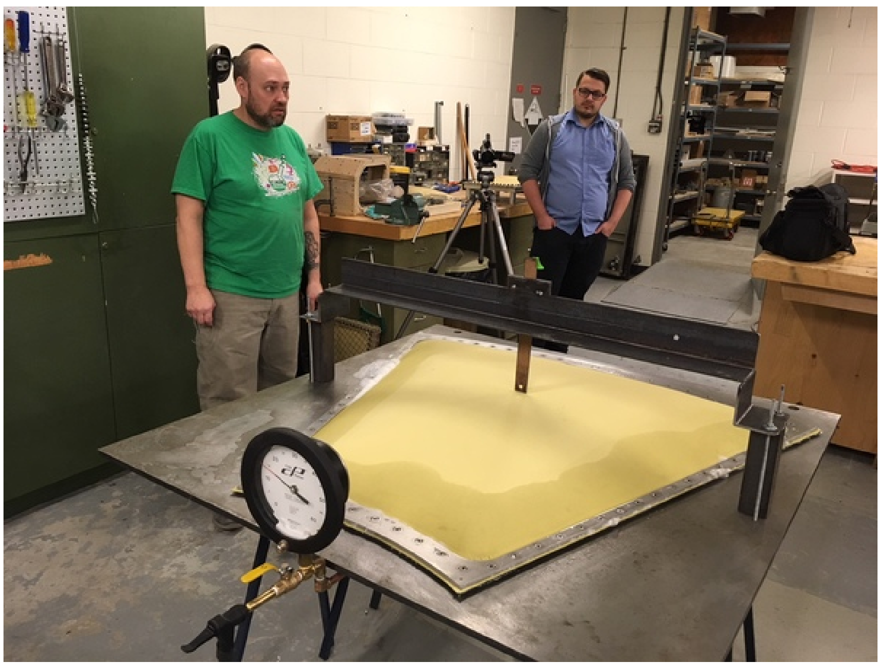

Figure 14: Experimental setup for full-size window.

3 Results

3.1 Miniature Window

The two flat carbon fiber windows failed at less than 40 psi. These initial mock-ups indicated that a harder epoxy was needed, and that the shell should be given some initial depth.

Multiple tests were performed with each carbon fiber shell under different configurations. Tests were done with and without the 1/8” clamping wire due to its suspected interference with the seal against the o-ring. These tests are summarized in Table 1.

Test #	Shell #	Material Layers	Remarks
1	1 (Sec.1.2)	3mil Mylar, 3xCF, Kevlar, 1” depth	No wire, bolt leaks at 40 psi, c-clamps on frame reduced (but did not eliminate) leaking.
2	1 (Sec.1.2)	Pre-stretched 3mil Mylar, 3xCF, Kevlar, 1” depth	Wire in. Loud creaking followed by rapid increase in deflection. Suspected compromise in shell.
2.5	1 (Sec.1.2)	Same as Test 2	Catastrophic failure at 60 psi.
3	2 (Sec.1.3)	3mil Mylar, 3xCF, Kevlar, 1.5” depth	Wire in, noticable leaking through bolts at 60 psi.
4	3 (Sec.1.4)	3mil Mylar, 3xCF, Kevlar, 1.5” depth	Reached 60 psi with no issue. Held pressure for multiple weeks.

Table 1: Summary of miniature window testing.

The deflection data for these tests are shown in Fig. 15.

3.1.1 Test 1

Throughout this test, shell #1 was observed to make creaking and popping sounds as pressure was increased. At around 40, psi the window was found to be leaking between the frame and bolt holes, and by 60 psi, the leak rate was outpacing the pump. C-clamps were applied around the edge to try to reduce leaking (Fig. 16), and was moderately successful, though leaking was still significant. This suggested that while the window was holding the stress, the pressure seal was failing due to poor contact with the o-ring.

3.1.2 Test 2

When retesting shell #1 with the clamping wire in place and a new Mylar sealing layer, the creaking was noticeably louder, and after a large pop, deflection began to rise much more rapidly. The shell was suspected to have been compromised and testing was halted. The decision was made to force a failure of this window to observe failure mode (Test 2.5). The window was inflated to 60 psi, where it remained briefly before the carbon fiber burst, tearing the Kevlar with it. The Mylar remained briefly intact before bursting. Fig. 17 shows the aftermath of the window failure.

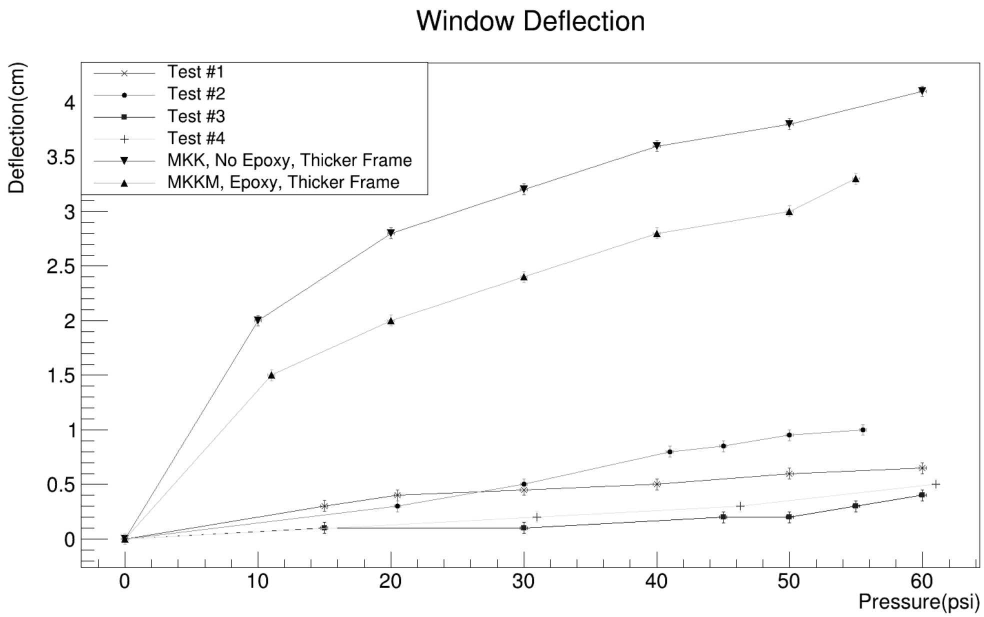

Figure 15: Deflection past the original depth of the four miniature window tests, and comparison with best of previous Mylar-Kevlar tests.

3.1.3 Test 3

During this test, the creaking sounds were greatly reduced, indicating an improvement in the deeper shell design. However the pressure seal again failed at 60 psi, leaking air through the bolt holes. Upon disassembly, the carbon fiber was noted to have cracked underneath the flange, which possibly caused the seal to fail, while maintaining the integrity of the load bearing part of the window.

3.1.4 Test 4

The "sandwich" design of the fourth test seems to have addressed the pressure seal issues. The window reached 60 psi with only minor creaking and had no noticeable leaking. The window maintained this pressure for just over 3 weeks before it was deflated for inspection. The shell and Mylar were both found to be intact. At this point, this test was the most significant success thus far, however this design has the drawback of the window material being permanently fixed to the frame. This may be acceptable for the final manufacturing of the HGC, however it is undesirable during the prototyping phase.

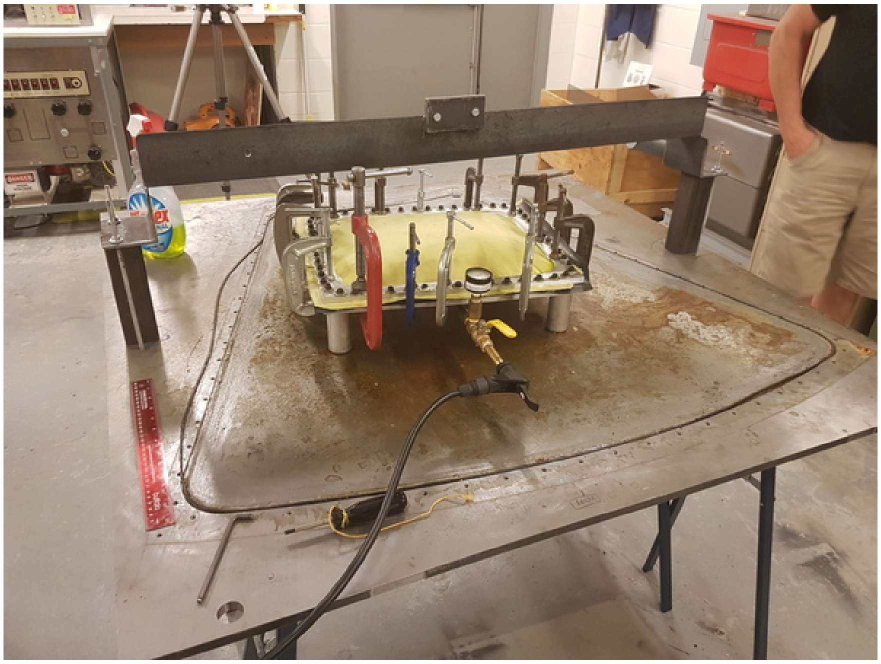

Figure 16: Reinforcement of window frame using c-clamps.

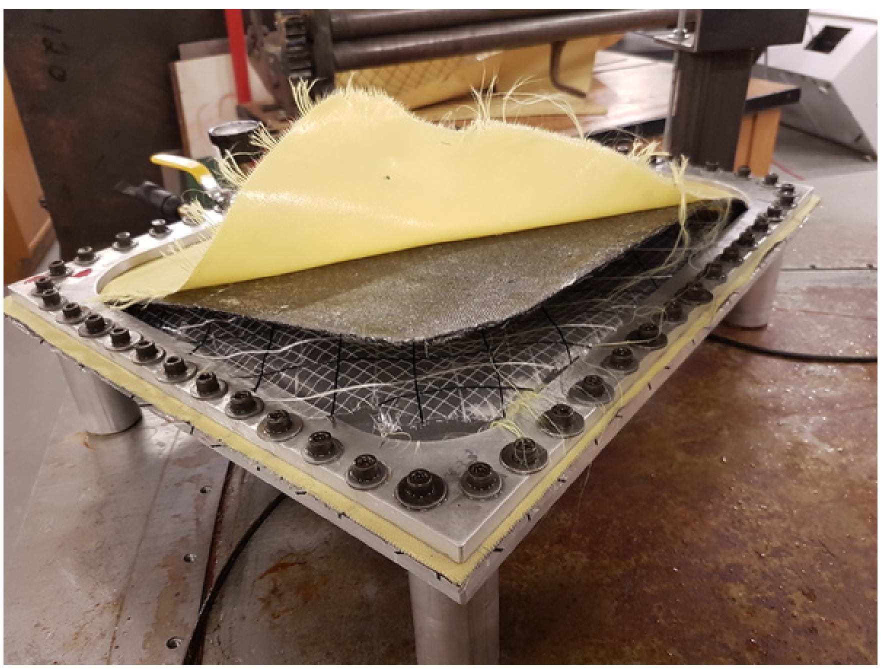

Figure 17: Aftermath of test #2.5.

3.2 Full Size Window

The deflection of the window during the two full size window tests is shown in Fig. 18. In the first test, the window began to leak from the long, straight sides underneath the flange above 12.0 psi, losing about 0.5 psi before stopping. The window reached a maximum pressure of 14.5 psi with no damage to the shell, however leaking continued through the side, so testing was discontinued.

In order to address the side leaking, 1/4" thick Aluminum bars were added to the straight sides of the window frame in order to simulate a thicker frame and increase the force on the o-ring (Fig. 19). During this test, the window reached a maximum of 15 psi with no detectable leaking. The window was left in this state on December 1st. By December 4th (three days later), the pressure had decreased to 14.4 psi, however it had also expanded by an additional 4 mm. At this time, the window was reinflated to 15 psi. By December 8th, the pressure decreased again to 14.8 psi, but it remained at this point until at least Dec. 21. At some time after this date, while unattended, the window pressure decreased to 5 psi and was unable to maintain pressure again. This indicates that the pressure seal had failed. Analysis after dissassembly showed no obvious cause.

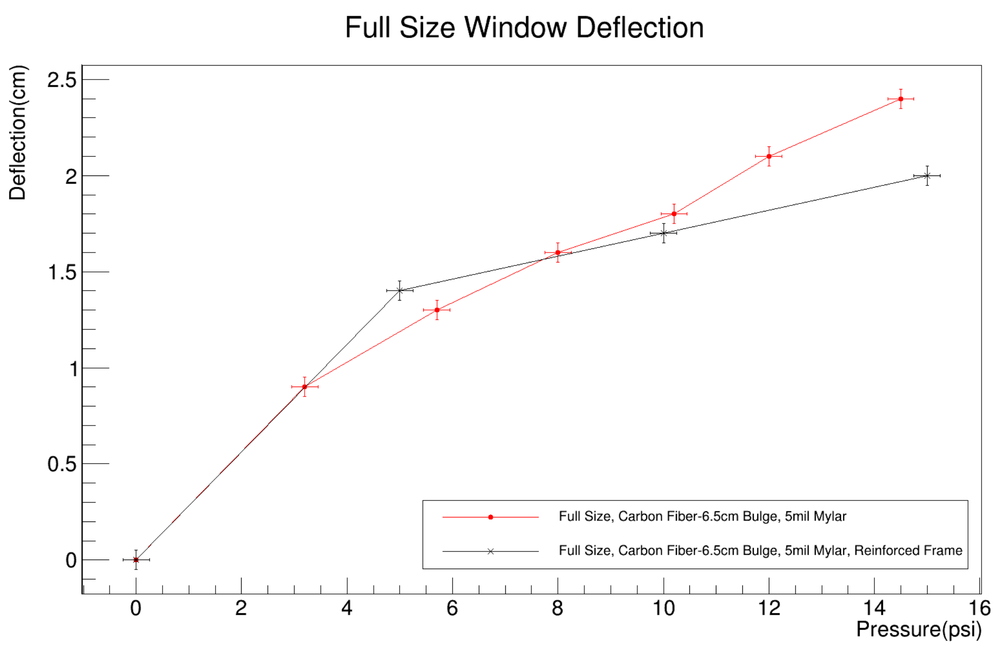

Figure 18: Raw deflection data of the two full size window tests.

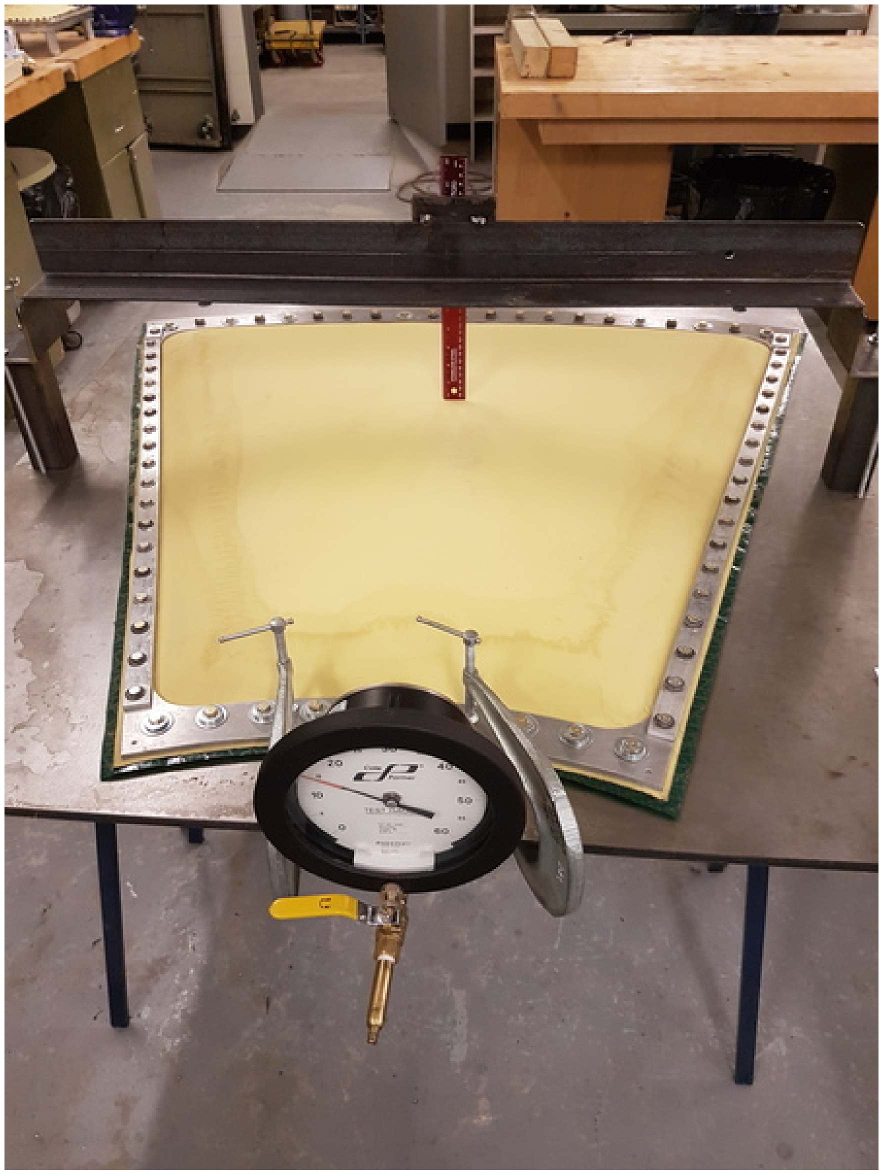

Figure 19: Reinforced full-size window.

4 Conclusions

These tests have proved to be conclusive in showing the viability of carbon fiber as the load bearing component of the HGC window. The second full-size test in particular satisfied almost all requirements for the window. Only the eventual failure of the pressure seal must be addressed.

A few questions remain with the respect to the vaccuum sealing component.The 3 mil Mylar proved to be sufficient during the second full-size test, but has failed in others. Variables such as pre-stretching, use of the wire and use of adhesives my require further testing. Tedlar also remains a possible candidate. Replacement of the O-ring by a gasket is also being investigated.

It would be preferable to eliminate the creaking of carbon fiber, perhaps by optimizing the shape of the shell. More detailed tests including a profiles of the window's shape at multiple pressures are currently planned, in order to learn how the shell is changing shape as the window is inflated.