Measuring Deformation in Pneumatic Cushions: Determining Accuracy Through Comparitive Digital Modeling with Simulated Physics

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ABSTRACT

Using a digital model with a simulated physics engine as a comparative measure, to what degree of accuracy can a physical model produce precise and reliable measurements of a pneumatic membrane's deformation when subjected to different physical conditions? To answer this question, a rigid chamber will be constructed of MDF. This chamber is a stand-in for one exterior chamber within a multi-layer pneumatic cushion. A foil or foils will be attached to a single open side of the MDF chamber and fastened in an air-tight manner around the perimeter. To obtain a measurement, a LiDAR sensor, known as a time-of-flight (TOF) sensor, is moved vertically at approximately one-inch intervals (a quarter rotation of the stepper motor) pausing between each movement for 500 milliseconds to take a distance reading. These distance readings are graphed and plotted into a curve. This curve is then compared to a section curve derived from a digital model, created parametrically in Grasshopper, utilizing the Kangaroo physics engine. Finally, the area between the measured and digital curves is calculated. The anticipated results are that the data confirm to be measured curves to be closely aligned with the digitally derived curves. For the purposes of this paper, a maximum area of 25 square inches between the curves will be considered closely aligned. This is derived from the length of the curves, which is approximately 25 inches; in other words, the measured curve will need to remain, on average, within one inch of the digital curve to be considered closely aligned.

1. Introduction

As membrane building envelopes become increasingly popular in design and construction, the capabilities of the materials used in these facades will be pushed further and further. In recent years, ethylene tetrafluoroethylene (ETFE) has solidified its place as the plastic of choice in membrane envelope construction. ETFE has been in the spotlight recently for its inclusion in prominent architectural designs such as Diller Scofidio Renfro's The Shed at New York's Hudson Yards and the Beijing National Aquatics Center in Bejing, China, designed by PTW Architects.

This rise in popularity of ETFE, as well as other plastics such as polytetrafluoroethylene (PTFE) and polyvinyl chloride (PVC), has lead to more frequent innovations in their application. One example is the inclusion of water in a performative ETFE cushion being studied at the Islamic Azad University in Tehran, Iran[1]. As these innovations become increasingly complex, simultaneously dealing with the challenges presented by pneumatics, the architects and engineers will need reliable methods of testing the physics that accompany their novel envelope technologies.

This highlights the primary question this research seeks to address. *Using a digital model with a simulated physics engine as a comparative measure, to what degree of accuracy can a physical model produce precise and reliable measurements of membrane materials under different physical stresses and conditions?*

More specifically, as an initial focus, this research will attempt to understand the degree of accuracy a physical model, utilizing relatively inexpensive materials, is capable of measuring the section curve of an inflated membrane foil to determine its degree of deformation. The section curve will be measured via a LiDAR sensor located on a linear motion track traveling along the Z-axis (up/down). The digital model, against which accuracy will be measured, will be modeled in Rhinoceros and, through Grasshopper, will run Kangaroo's live physics engine to simulate the forces acting upon the foil. Accuracy will be determined by calculating the area between two curves: the section cut measured on the real-world model by the LiDAR sensor, and a section curved extracted from the digital model.

The physical model is designed to measure either the interior foil of a multi-layer pneumatic cushion or an exterior foil of a two-foil cushion. Because the interior layer of a multi-layer cushion is typically concealed and inaccessible to typical measuring devices, this capability is key to this research as it adds significant potential to the viability of its inclusion in future research.

2. Background

The author of this paper was unable to locate previous research on this specific topic but did find a significant amount of research that validated the relevance and necessity of an investigation into this topic.

Kheybari et al. (2016)[1] published a paper at the FacadeTectonics2016 conference in which they detail the design and feasibility of an adaptive building envelope that incorporates performative water-filled ETFE cushions as the primary feature of their integrated design strategy. Inspired by human skin and blood circulation's response to temperature stresses, their paper delineates how the inclusion of water bladders within a multi-layer ETFE cushion could regulate the thermal and visual properties of a building through the manipulation of a pneumatic system to direct heat flow, thus reducing energy demand.

Within their paper, Kheybari et al.[1] describe the deformative characteristics of the water-filled bladder and postulates the need for increased air pressure and a secondary reinforcement provided via tensile fibers or a net of cables. The viability of these secondary supports is precisely the type of challenge the research presented in this paper seeks to address.

Another paper, written by Hinz et al. from the Technical University of Munich[2], explores an alternative means of measuring ETFE foils. They describe how, utilizing photogrammetry, they were able to obtain precise measurements of the deformation of ETFE foils. They laid out a grid on each ETFE foil prior to subjecting it to pneumatic pressure. They then inflated the ETFE foil and photographed from a variety of angles and submit the photographs to photogrammetric software, which provides them with an accurate 3D model of the deformed foil.

While their paper proves this as a viable method for measuring the deformation of an ETFE foil, it will only work on a foil that is accessible to be photographed. Therefore it would be insufficient to measure an interior foil of a multi-layer cushion. One aim of this paper is to provide a method of measuring ETFE deformation that is capable of assessing both interior and exterior foils.

3. Fabrication and Methodology

To successfully measure the interior foil of a multi-layered pneumatic cushion, a rigid chamber was constructed of MDF. This chamber is a stand-in for one of the exterior chambers the pneumatic cushion. It is a rectangular prism, open on one side. The open side is where a single foil, or multiple foils, can be attached. Within the rigid MDF box, a linear motion track is oriented along the Z-axis, where a sled is moved up and down vertically at controlled intervals. Attached to the sled of this track carries a LiDAR sensor that fires a laser and measures how long the light takes to bounce off of the membrane foil and return to the sensor. In doing so, it is able to calculate the distance from the sensor to the foil.

The decision to used MDF was derived from its smooth surfaces and uniform thickness, both factors that lend themselves to the need for individual components of the box to meet each other in a flush manner - an aid in guaranteeing the ability of the box to remain air-tight when exposed to pneumatic pressure. Other factors that influenced the selection of MDF include its price and the quality finish achieved on a CNC mill; relative to plywood, MDF is generally less expensive and it mills with greater ease due to its lack of granular structure.

The scale of the MDF chamber was determined jointly by the constraints of the standard available size of the material (4’ x 8’ sheets) and by the necessity to maximize the scale of the membrane testing space, allowing for the greater resolution of detail; typical ETFE cushions span as far as 3.5 meters in their short direction and as long as necessary in the other direction[3]. Therefore, the size of the MDF chamber is ultimately determined

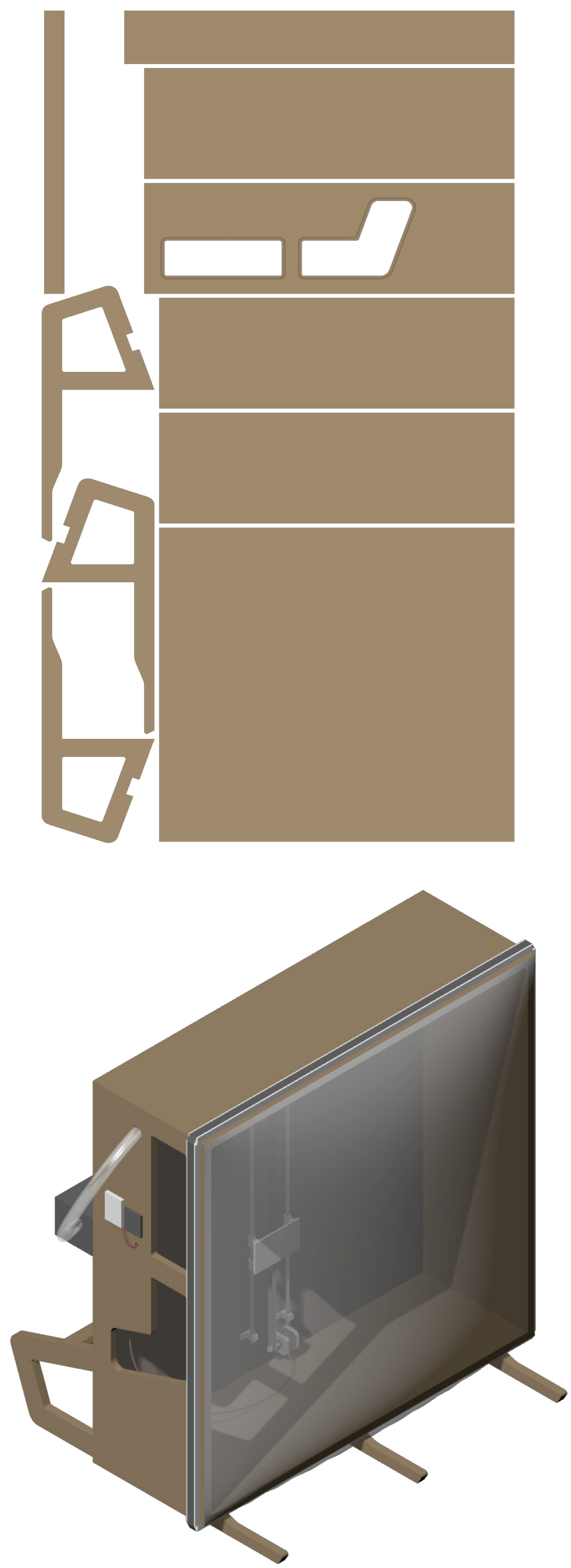


Figure 1 | Depiction of cnc milled pieces and finished model by what can maximally be crafted from an individual 4’ x 8’ sheet of material. After a number of iterative considerations, this was determined to be a box 37” x 37” x 11”, with the 37” square side being left open for foil measurement. The box also features a base that accounts for the weight of the box itself, as well as any off-centered weight of the plastic membranes and liquid bladders they might hold.

A viewport was incorporated into the side of the box so that the sensor and linear motion track could be monitored. Should any failures or obstructions arise, this would allow the operator to see them regardless of the opacity of the material being measured.

The linear motion track is comprised of two guide rails on which a sled of layered cardboard slides. Attached to this sled is the LiDAR sensor, an Adafruit VL53L0X Time of Flight Distance Sensor capable of measuring between 30mm and 1000mm in distance within an accuracy of ±3%. The entire length of the linear motion track is 80 cm which is approximately 31.5 inches. The full range of motion of the sensor is limited to 25 linear inches due to the mounting hardware as well as the height of the sled itself, approximately 2 inches. The motion of the track is controlled by a stepper motor, model 28BYJ-48, which is attached to a timing belt affixed to the bottom of the sled. The stepper motor and timing belt are attached to the MDF chamber with custom 3D-printed hardware.

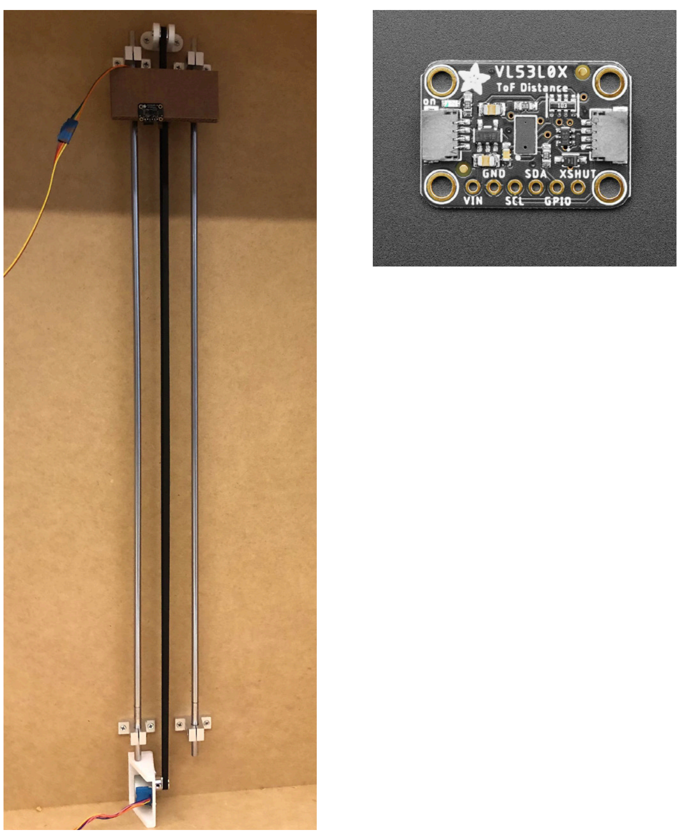
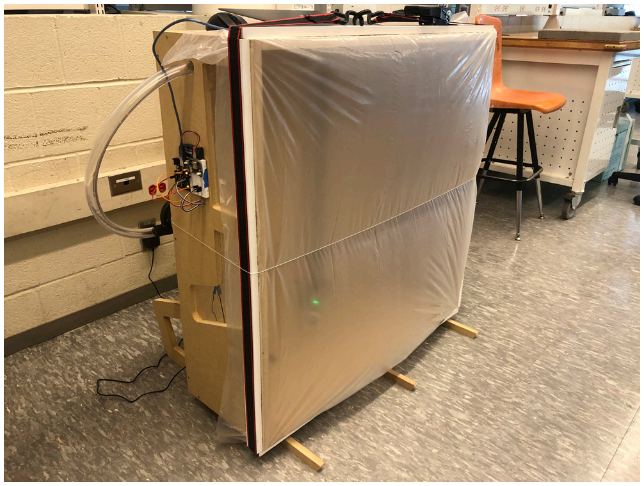
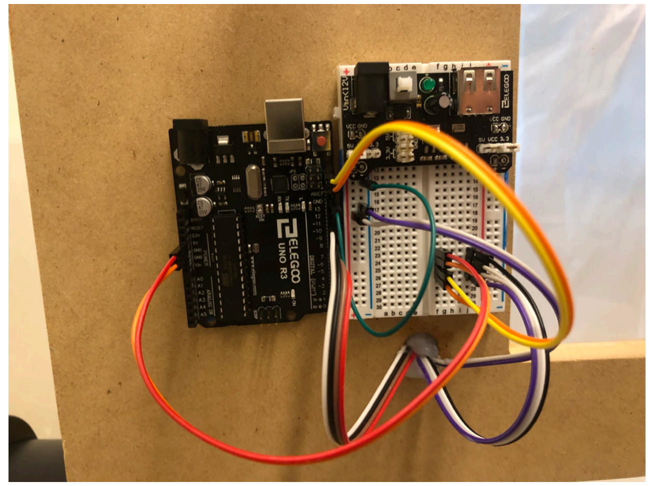


Figure 2 | Linear Motion Track and TOF Sensor

The plastic foil is secured to the box by clamping the material around the exterior of the box utilizing strips of MDF molding and a ratchet strap. This proved to be sufficient in maintaining relative air-tightness for testing. There are two holes in the box, one an inch in diameter which accepts a tube connected to an electric air pump, and the other that allows the wiring from the sensor and stepper motor to pass through the MDF and reach the microcontroller affixed to the exterior of the box.

To obtain a measurement, the time-of-flight (TOF) sensor is moved vertically at approximately one-inch intervals (a quarter rotation of the stepper motor) pausing between each movement for 500 milliseconds to take a distance reading. This interval was selected because it produced an acceptably high-resolution representation of the curve, while still allowing a complete measurement of the curve to be taken in an amount of time that allowed for a reasonable number of iterations; the interval could be reduced to further, as low as one motor step, which would translate to .002 inches and would provide an incredibly high-resolution representation of the curve. The distance readings obtained by the TOF sensor are recorded as points in space, the vertical placement of the sensor translating to the Y coordinate, and the distance from the sensor to the foil indicating the X coordinate. Together, these points are connected to form the measured section curve of the inflated





Figures 3 and 4 | Completed Physical Model and Microcontroller with Breadboard

foil.

This curve is then compared to a section curve derived from a digital model, created parametrically in Grasshopper, utilizing the Kangaroo physics engine. A control simulation was established to calibrate material properties; Both in the real-world model and in the digital model, a single sheet of plastic material was placed over the opening of the box. For the purposes of this experiment, 2 mil plastic drop cloth was used due to its affordability and accessibility. The material was inflated and measured by LiDAR. The modulus of elasticity is adjusted in the model to match that of the testing material, such that the apex of the inflated foil was equal to that of the real-world test. In this case, the modulus of elasticity was very low, as the 2 mil drop cloth was not very elastic. This calibration needs to be performed for any material that is to be tested.

Additionally, horizontal bands are tied around the box and foil as a means of introducing variations of deformation. The bands are made of a nylon cord. Measurements were taken with different band placements and the deformation compared to that caused by identical band placements within the digital model. For the purposes of this experiment, bands were placed and measured at the following locations: at the midpoint of the box, one-third of the way up from the bottom of the box, one-quarter of the way up from the bottom of the box, and at both thirds of the box. They are oriented horizontally in order to remain perpendicular to the motion of the LiDAR sensor.

Finally, the coordinates of both the measured and digital curves are plotted and the absolute difference between the curves is calculated using the formula:

$$A = \int_a^b |f(x)-g(x)|dx$$

This is how the accuracy of the measured curve is determined. The maximum acceptable area between the two curves, in order to be considered closely aligned, is 25 square inches. This is derived from the approximate lengths of both curves, 25 inches; so generally, a measured curve must remain within one inch, on average, of the digital curve to be considered closely aligned.

4. Expected Results and Discussion

The anticipated results were hypothesized to be measured curves that closely approximated the digitally derived curves but were anticipated to be imperfect due to human error. This is very accurate to what ultimately arose in the data.

There were several commonalities that emerged between tests. One notable difference between the measured curve and the digital curve is that deformation caused by the horizontal bands was less defined in the real-world measurements. In other words, the dip or valley present on the real-world curves was less sharp than that in the digital curve. This is likely due to the use of nylon chord as the horizontal band, which in itself was a somewhat elastic material. A more rigid material, such as a metal bar clamped across the foil would likely produce results more closely aligned with those of the digital model.

Another common anomaly was that the portion of the curve measured towards the top of the box was consistently less aligned with the digital model than the portion measured towards the bottom of the box. This may be due to the method with which the plastic was clamped onto the box and subsequently adjusted. To ensure that the plastic was not deforming in a twisting manner simply due to it not being clamped evenly and symmetrically around the box, the material was adjusted several times, always at the top of the box. This occurred in some instances after the horizontal bands had already been affixed. It is likely that in making these adjustments, the plastic re-clamped less tightly than prior to attaching of the bands, therefore leaving an excess of the material above the band, allowing the top portion to inflate beyond the limits of the equivalent section of the digital model. This could be solved by introducing registration marks to the plastic so that the material is consistently clamped to the box.

The results indicated that the relative location of the horizontal obstruction did not affect the degree of accuracy to which the real-world model replicated the deformation. Multiple measurements were taken at each of the band locations. The absolute difference between the measured and digital

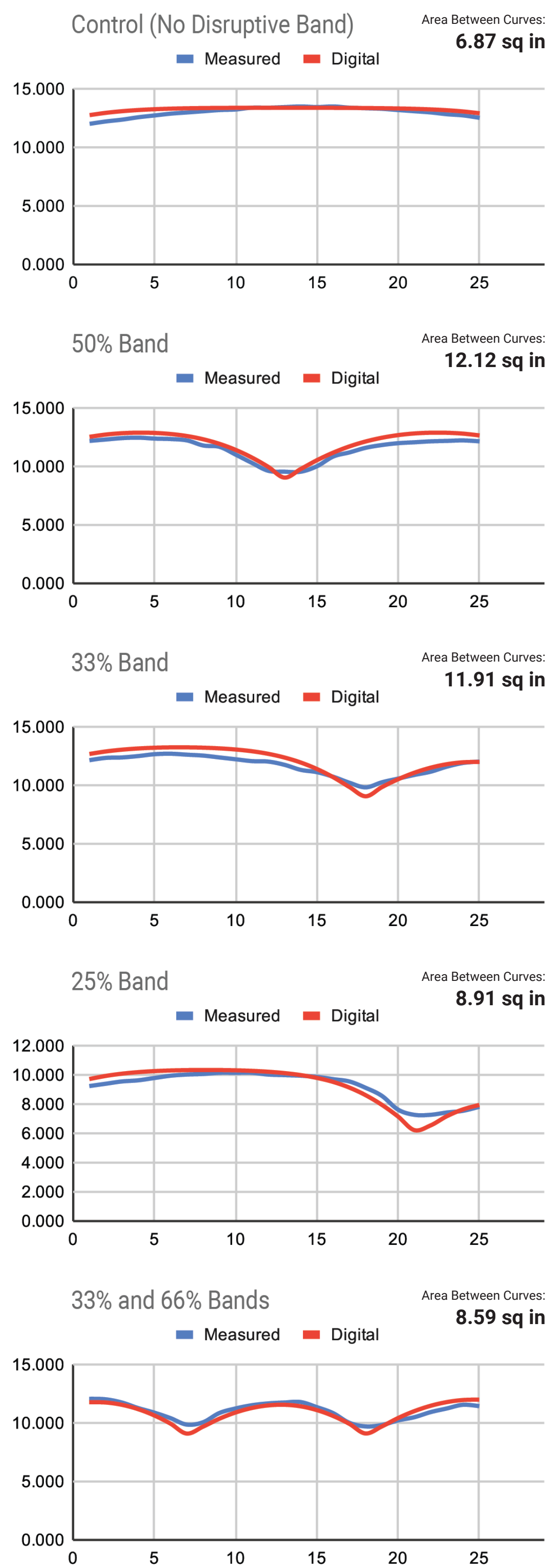


Figure 5 | Comparitive Graphs

curves consistently fell between the values of 8.59 and 12.12 square inches. There is, however, an indication that introducing a horizontal obstruction slightly reduces the accuracy of the replicated curve when compared to the control configuration which had no horizontal obstruction. Multiple measurements of the control curve returned absolute differences between the values of 6.87 and 7.08 square inches.

Ultimately, the results show that the model successfully measures deformation when compared to digital simulations that utilize physics engines. The model could be fine-tuned to reduce measured curves and their corresponding digital curves, however, the data consistently shows a convincing relationship between measured and digital curves.

5. Conclusion and Next Steps

In moving forward with the research, one could begin to introduce additional foils so that the material being measured is truly an inner foil. As the experiment currently stands, the measurement is successfully taken from within the pneumatic chamber, but it has only be run in a single-chamber configuration. To achieve a multi-layered cushion arrangement, a second air supply would need to be introduced to a new chamber, requiring the splicing of a new branch into the existing air supply line or the addition of another air pump and supply line altogether. An option second linear track could be introduced outside of the MDF chamber to measure exterior pneumatic foils, or alternative methods such as Hinz et al.'s[2] use of photogrammetry could be used instead, in conjunction with the linear motion track housed in the MDF chamber.

Testing a wider array of materials would also be a logical next step for this research. Certainly, measuring the deformation of ETFE would be a more natural progression into an actual building material. That said, this experiment is set up to work with any pneumatic membrane material.

Another potential improvement would be the introduction of an atmospheric pressure sensor, such as the Adafruit BMP280 which is capable of measuring barometric pressure with ±1 hPa absolute accuracy. This addition would be useful if testing elastic failure points in materials or measuring the impact of air pressure on the plastic deformation of a liquid-filled bladder.

If greater pressures and increased weight is going to be introduced, it would make sense to redesign how the plastic is secured around the MDF chamber. As it exists, four 37” strips of MDF molding are clamped around the MDF box, the plastic tightly pinched between the two, and a ratchet strap holding it in place. To better secure the plastic, and to ensure a more air-tight and water-tight seal, a rectangular channel could be routed into the box below where the MDF molding sits currently. The channel would need to be slightly larger than the molding itself. This would allow the molding to slot into the MDF and still have room to enclose the plastic. In doing so, three new 90 degree turns would be introduced into the plastic to better prevent leaks.

A final improvement would be to upgrade the linear motion track to a dual-axis motion track that allowed the sensor to move freely along the entirety of the XY plane. In doing so, a field of points would be produced rather than a single curve, which would allow for the measurement of more complicated forms of deformation (ie. asymmetrical, etc).

As this work is carried forward, it is the aspiration of the researcher that it be improved upon and utilized in innovative technological developments within the field of membrane building envelopes. Perhaps it could be used in testing how secondary support structures, as proposed by Kheybari et al.[1], could be introduced to control and influence deformation.

Along those lines, the researcher intends to further study how a material with a smaller modulus of elasticity could be extruded via 3D printing technology onto ETFE to constrain expansive deformation on portions of the material, enabling the creation of formally irregular ETFE cushions. If such a method of fabrication was proven feasible, it would open the door to unprecedented formal explorations in architecture, utilizing the already successful ETFE as a lightweight medium. This research directly relates to such an inquiry, as it would provide an accurate real-world measurement of resultant deformation and allow precise modifications to be made without relying on simulated physics engines, the limitations of which are already tested by such complex physical problems.

Furthermore, the researcher is also interested in the incorporation of a photobioreactor into a pneumatic facade system. Because photobioreactors are largely comprised of water, the ability to measure the deformation of an interior foil is crucial in understanding the viability of such a system. Beyond measuring the deformation of a liquid-bearing foil, combining the aforementioned ability to manipulate deformation through the introduction of a secondary support system could be the determining factor as to whether a photobioreactor integrated pneumatic facade is a realistic technology at this point, or if it isn't.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available on the course website, buildtestbuildtest.com.

References

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