

## Abstract

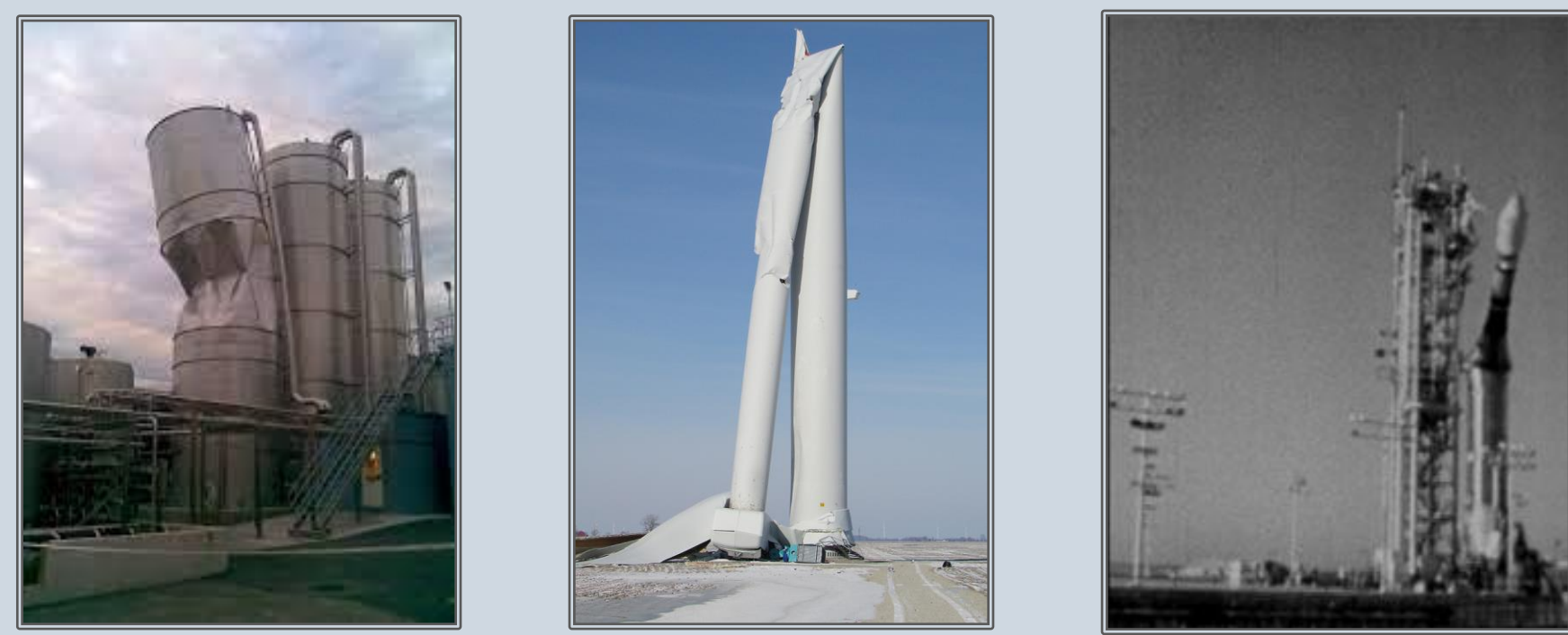
Under uniaxial compression, a thin cylindrical shell, such as aluminum can, buckles in unpredictable ways associated with microscopic imperfections on its surface. Horton and Durham (1965) demonstrated that the cylindrical shell can produce a predictable periodic buckling pattern that resembles a diamond-like lattice structure when the shell is constrained by an internal mandrel. We report here an experiment with a thin cylindrical shell made of Mylar wrapped around a PVC tube. Using X-ray imaging, we investigate the regular buckling profile of this shell when compressed along its major axis with greater precision than before. We focus on the gap between the shell and the tube to compute the wavelength of the buckled mode. The reconstruction of the surface pattern will help us understand the stresses that lead to failure in grain silos, rockets and other tubular structures or interest.

## Motivation

- Buckling is usually associated with the failure modes of various structures under load.
- Horton and Durham showed that a thin shell under compression forms a diamond like lattice structure uniaxially.
- Can this buckling behavior be utilized?

- X-ray imaging of a buckled shell under compression allows for the experimenter to acquire the wavelength of the buckled mode and the gap distance, unlike other methods of data acquisition.

Understanding the behavior of buckled cylinders under compression may be the gateway towards new technologies which utilize their shapeshifting properties. Applications can include haptic feedback surfaces to simulate feel on a electronic display, as well as implementing this behavior on control surfaces.



## Experimental Set Up

The mylar shell was created separately then slides on to the inner mandrel like a sleeve. We chose a mylar sheet of thickness 0.127 mm for this experiment. Figure 1 shows the gap between the shell and the inner mandrel, chosen and measured to be  $\delta = 3$  mm. The height of the shell is 7.0 mm taller than the mandrel. The mylar sheet was cut to size using a laser cutter and assembled by hand. Figure 2 shows the final product.

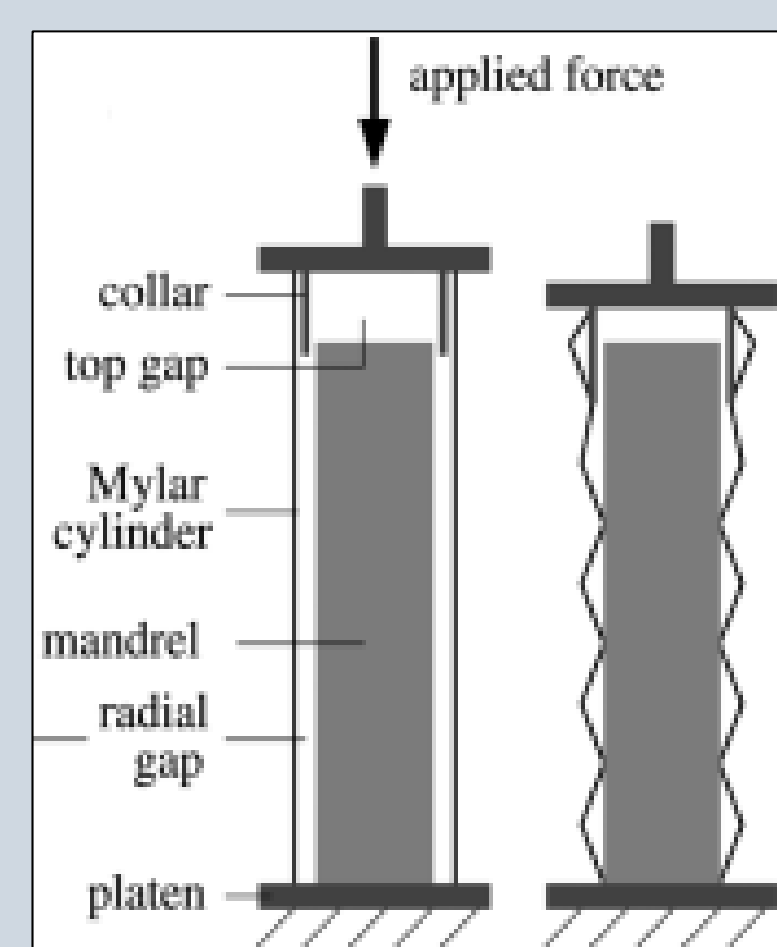


Figure 1

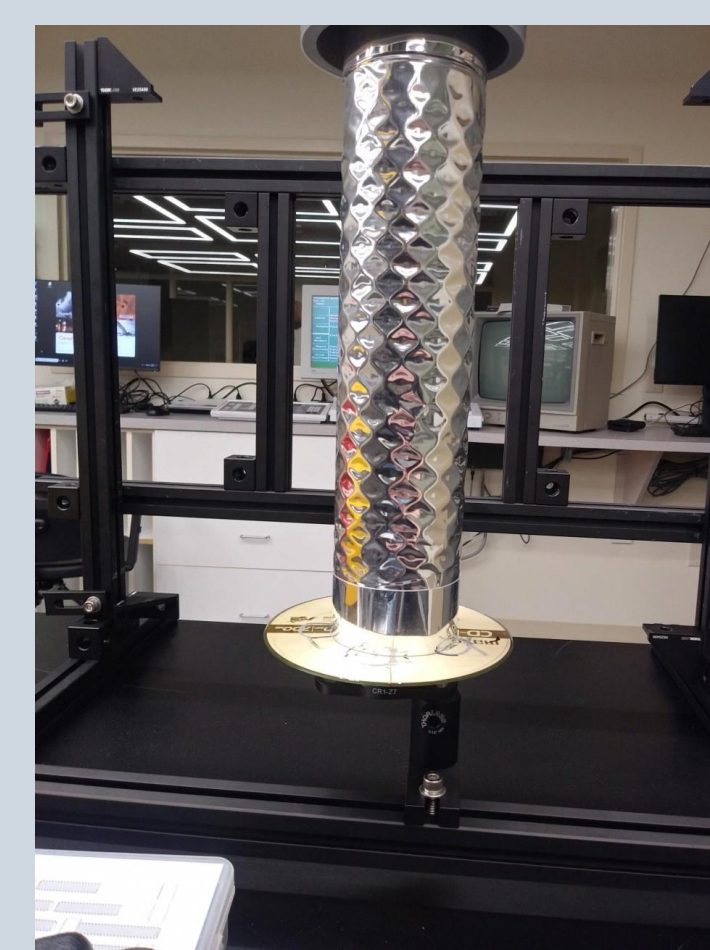


Figure 2

## X-ray imaging

After it has been compressed, we imaged the buckled mylar shell by using the X-ray facility at the Madison Accelerator Lab as illustrated in fig. 3.

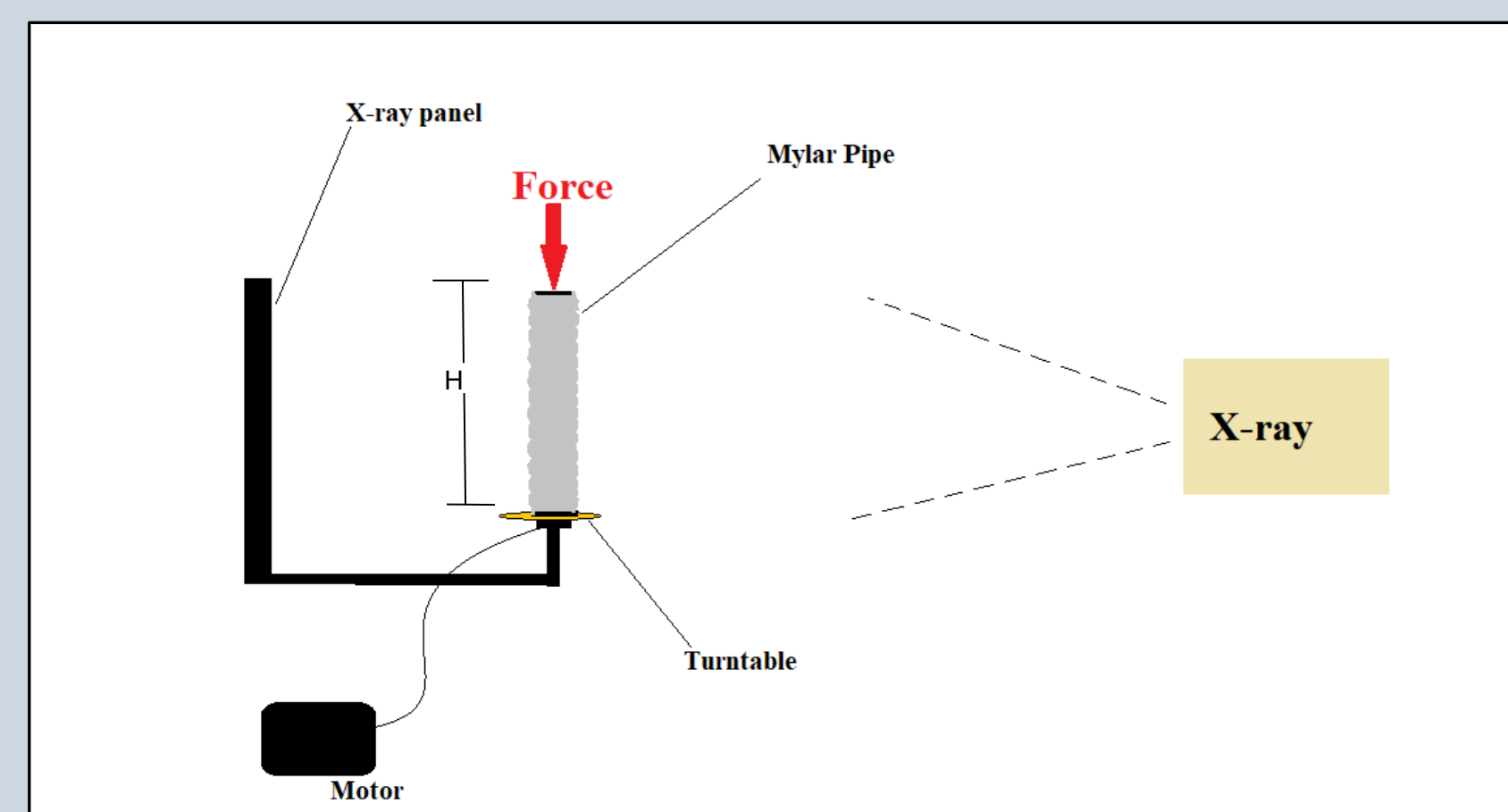


Figure 3

**Procedure:** The motor turns a turntable which rotates the set up one degree after every image taken by the X-ray. In this way, a full 360 degree reconstruction can be done with 180 images which display the cross section of the mylar pipe.

## Image Analysis

A series of images were obtained at each rotation of the shell. Each new image corresponds to a rotation of 1 degree. In this way all 360 degrees of the shell can be captured by the X-ray. As seen from fig. 4(a), the shell appears to be quite transparent because the shell is thin and not as many X-rays are absorbed by the mylar compared to the thick PVC, which makes the inner mandrel.

To get a clear image of the shell, we use multiple techniques and tools from the open source software, ImageJ. First the gradient profile of the background of the image is removed (fig. 4(b)); this allows a threshold to be applied evenly to the histogram of pixel values of the image. The image is sharpened and then a threshold is applied which allows the contour of the buckled shell to stand out better. From here we convert the images to binary, and apply a despeckler filter to output a cleaner outline of the shell and remove noise as shown in figure 4(c).

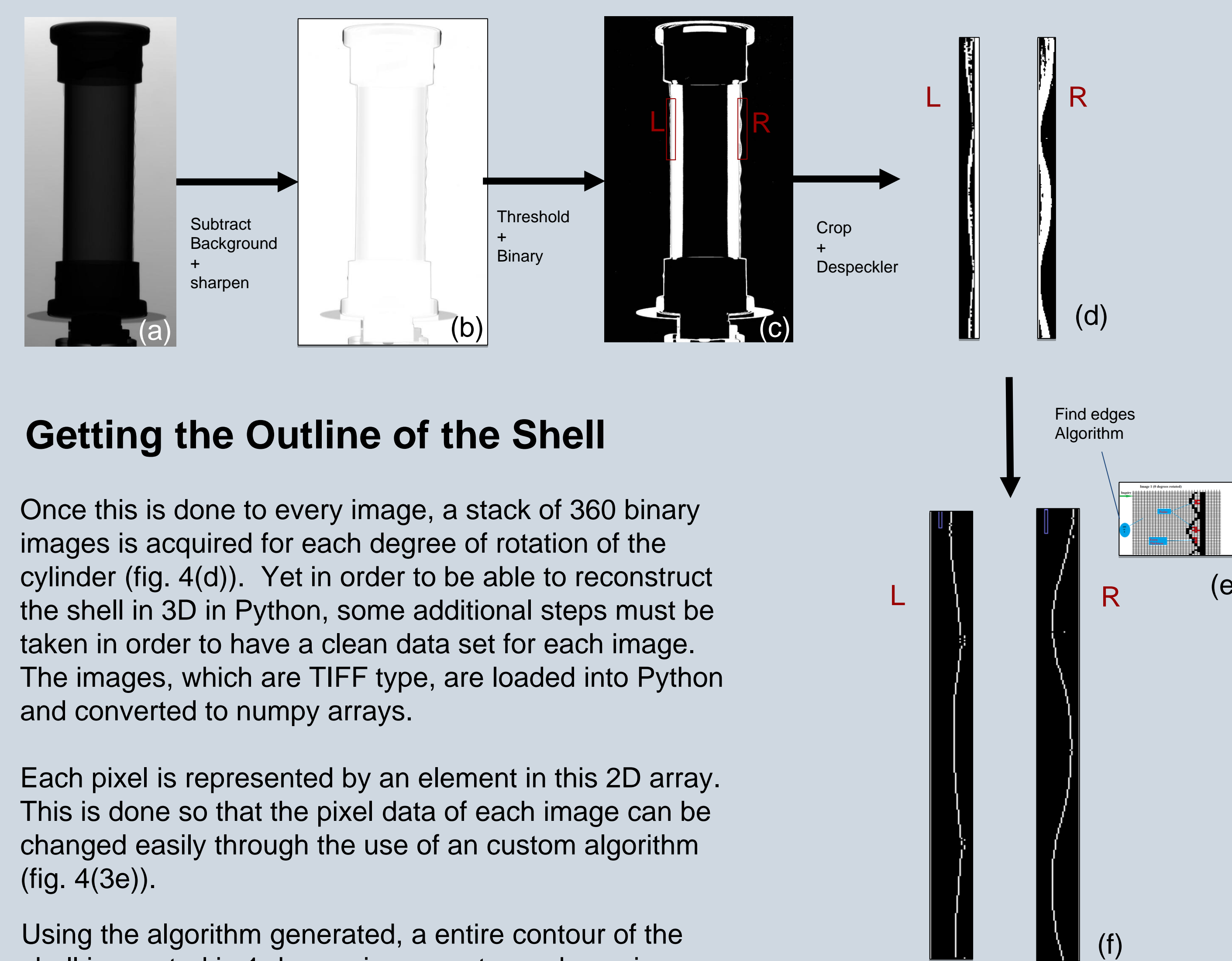


Figure 4

## Getting the Outline of the Shell

Once this is done to every image, a stack of 360 binary images is acquired for each degree of rotation of the cylinder (fig. 4(d)). Yet in order to be able to reconstruct the shell in 3D in Python, some additional steps must be taken in order to have a clean data set for each image. The images, which are TIFF type, are loaded into Python and converted to numpy arrays.

Each pixel is represented by an element in this 2D array. This is done so that the pixel data of each image can be changed easily through the use of a custom algorithm (fig. 4(3e)).

Using the algorithm generated, a entire contour of the shell is created in 1 degree increments as shown in figure 4(f). These new images acquired from the algorithm is fed back into ImageJ where radius and height (z) coordinates are extracted into a text file.

## Matching theory with observation

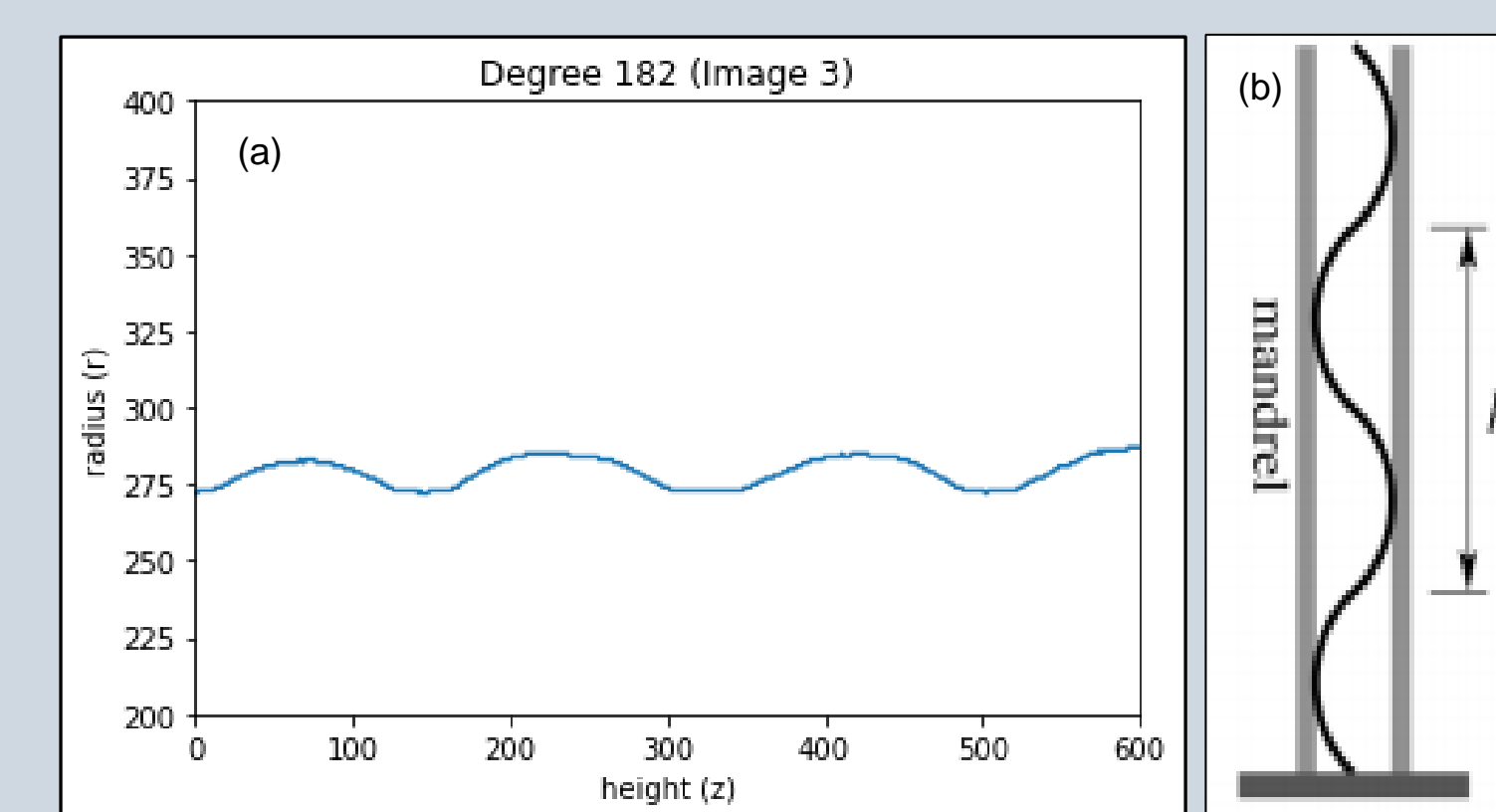


Figure 5

Figure 5(a) shows a segment of the contour for angle 182 degrees. Fitting a function onto each contour acquired provides information about the Wavelength,  $h$  in figure 5(b), and gap size.

In the future we will use the fit data to acquire the number of facets there should be and verify it by counting.

$$\frac{\text{perimeter}}{\text{wavelength}} = \text{number of circumferential diamonds facets}$$

$$\frac{H}{\text{wavelength}} = \text{number of diamond facets along z direction}$$

## 3D reconstruction

Figure 4 shows the radius (R) and height (z) coordinates for each image are combined with the known degree of rotation to form the cylindrical coordinates of the exterior shell. Figure 5 shows an optical scanning reconstruction of the same shell.

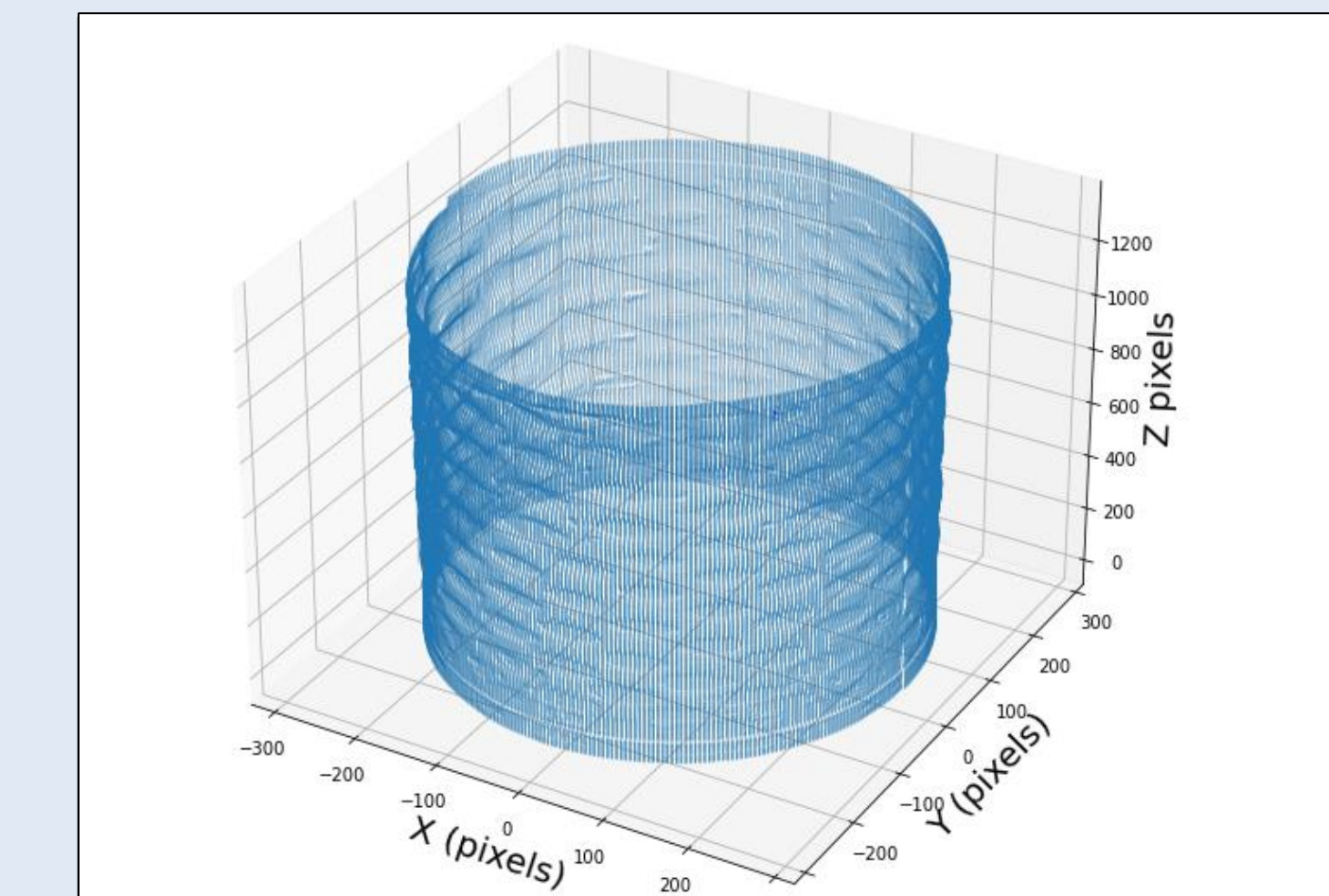


Figure 4

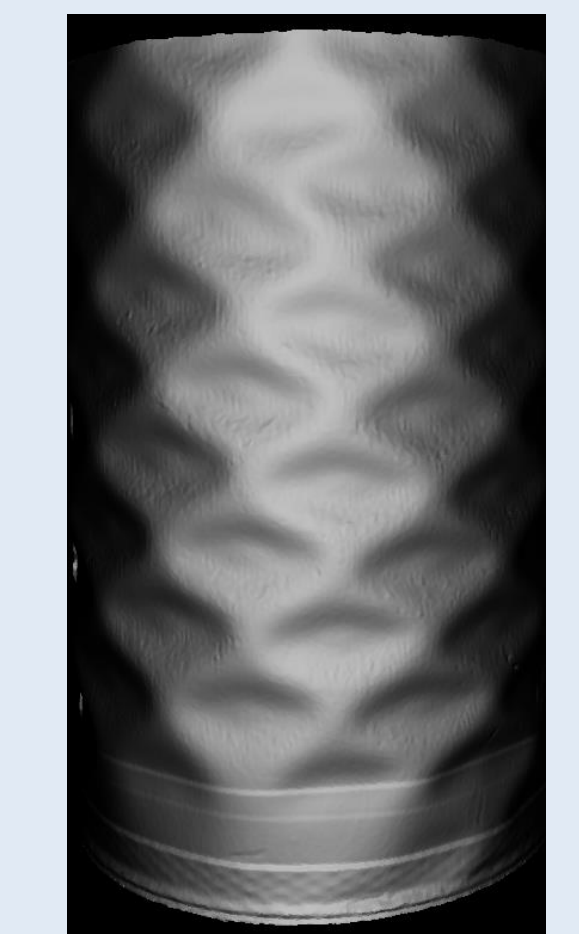


Figure 5

## Conclusion

Through X-ray imaging, a new data acquisition method has been developed that allows the experimenter to see in between the inner core and the buckled shell. In this way, an amplitude of the buckled wave mode can be determined through fitting and help verify theoretical predictions. Going forward, a novel way to make the mylar material appear thicker in the X-ray might be needed for improved results. Methods have been proposed such as spraying the mylar with X-ray absorbing material; in this way, the contours of the buckled shell are preserved and will come out sharper.

## Outlook

Soft matter form a class of materials that under low applied stress behave as a solid, but above a threshold flow as liquids. In the future we plan to study the twisting motion of the shell and connect this investigation to the movement of dry foam. When twisted a buckled shell (fig. 6) and a aqueous foam (fig. 7) will both undergo what is called a "T1 event," which occurs when four pairs of faces/bubbles switch places. This similarity may be the first step in linking these two different systems.

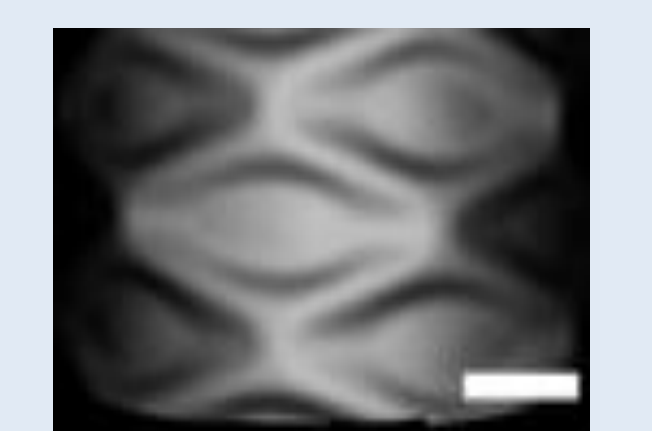


Figure 6

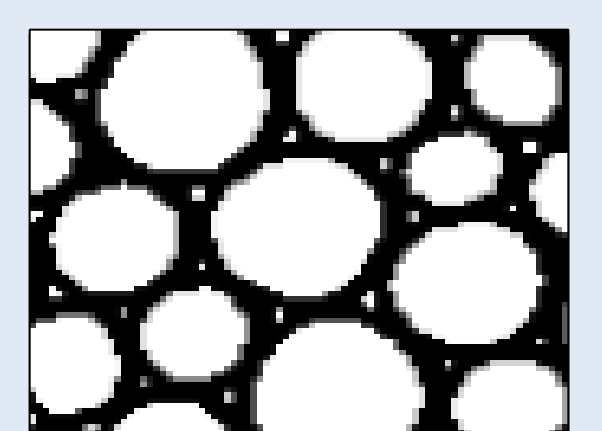


Figure 7

## Summary

- X-ray imaging for buckled cylinders offers a unique perspective; to be able to see between the inner mandrel and shell allows the experimenter to accurately retrieve desired parameters from theory
- A greater resolution has allowed for the buckled cylinder to be reconstructed more accurately than before
- Future work is planned to get the mylar to appear thicker in the X-ray imaging and improve data quality.

## References

- [1] K.A. Seffen, S.V Stott, *Surface Texturing Through Cylinder Buckling*, Journal of Applied Mechanics **81**, 6 (2014)
- [2] N. Voce, K. Feitosa, *Curvature in Compressed Thin Cylindrical Shells Approaching the Isometric Limit*, James Madison University (2020)

## Acknowledgements



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