Origami-Inspired Additive Manufacturing: Architectural Aerodynamics in Hurricane Wind Loads

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Introduction

- Hurricanes and natural disasters are among the largest construction challenges today. Aerodynamic mitigation of tall buildings are subdivided into local and global shape mitigation.
- Local shape mitigation focuses on corner shape configurations while global shape mitigation has a major effect on architectural form and structural design as it looks at optimizing the overall shape of the building.
- Providing an infinite amount of possibilities, origami-inspired structures has been used to solve small scale engineering problems (Tolman et. al., 2014).
- By taking dynamic building envelopes designed using origami principles, a new generation of smart structures can be built to sustain impacts by high winds.

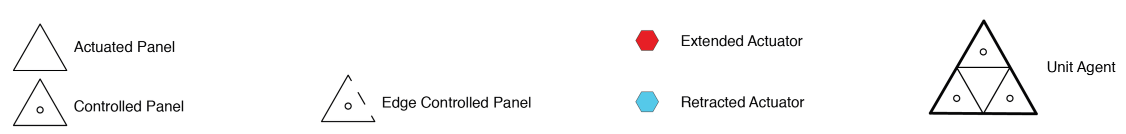

Figure 1: Legend showing activation symbols for below diagrams. Controlled Panels remain static, while actuated panels to either extended or retracted states *(Courtesy of Amanda Bellamy)*

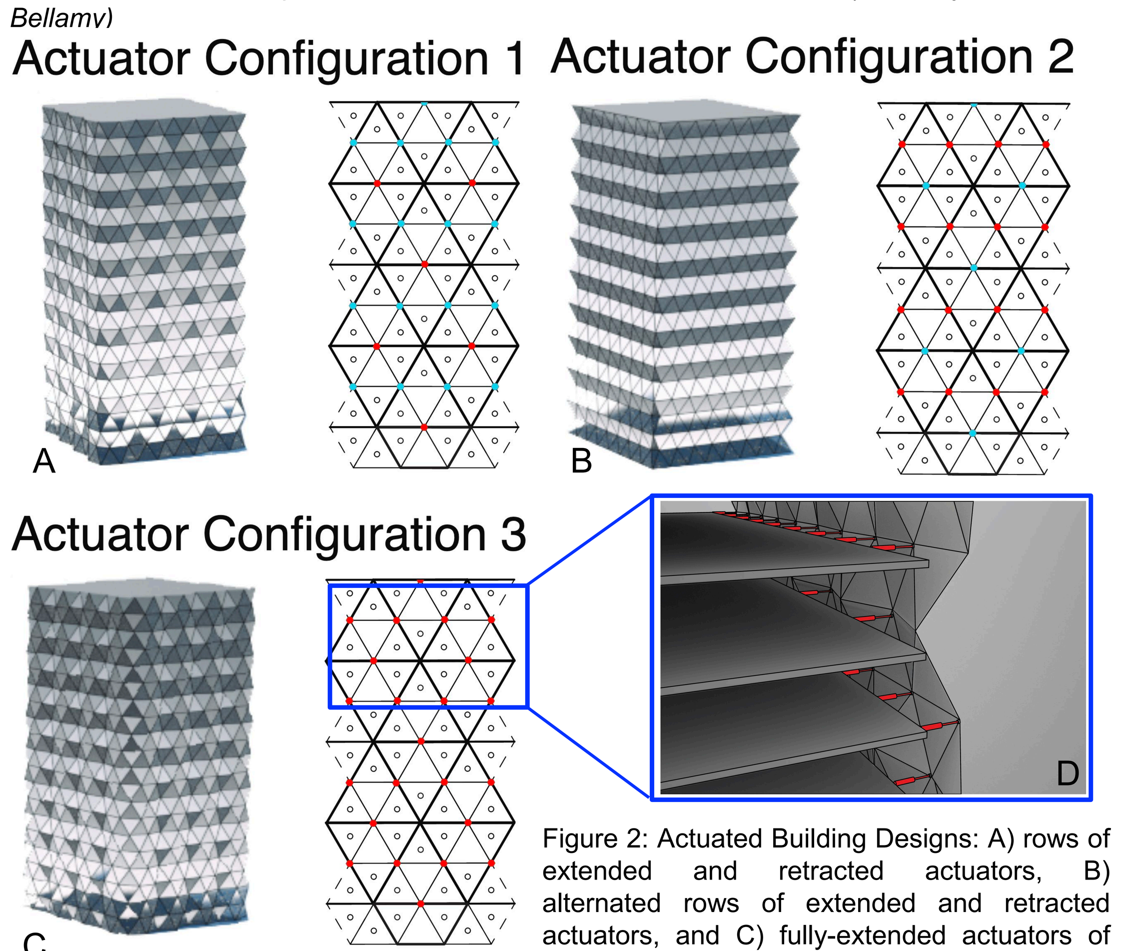

Figure 2: Actuated Building Designs: A) rows of extended and retracted actuators, B) alternated rows of extended and retracted actuators, and C) fully-extended actuators of the unit agent. D) close-up to the fully-actuated unit agent *(Courtesy of Amanda Bellamy)*

Origami used with paper has differences from several engineering design goals, including:

- stress/strain of creased materials,
- the curvature involved with folding,
- distribution of a crease over a non-zero area, the high strength required for materials,
- gravity and intra-molecular forces (Lang, et. al. 2018).

- A balance of effectiveness and simplicity can be created by combining different joints together (Lang, e. a. 2018).
- For engineering projects, the feasibility of the construction, as well as the effectiveness of the material must be balanced out in order to create the best solution (Lang, et. al. 2018).

Objectives

The objectives of this research investigation are to:

1. Review background information on adaptive envelopes and origami-inspired architecture.
2. Compare small scale wind-tunnel testing to large scale computational fluid dynamic analysis.
3. Evaluate performance of different wind tunnels in generating desired wind speed.
4. Determine if dynamic envelope prototypes are a feasible step in adaptive building design.

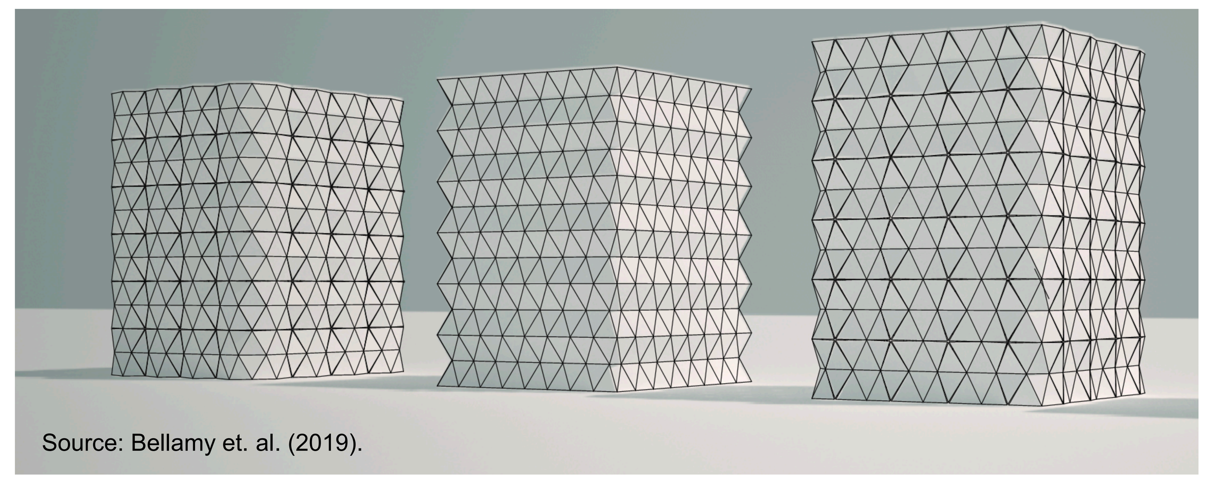

Figure 3: AutoCAD modeling of actuated building designs, going from left to right: Actuated Configuration 1, Actuated Configuration 2, Actuated Configuration 3.

Methods

To create the small-scale adaptive envelopes would require not only a manufacturing mechanism that was cost effective, but also capable of making the complicated shapes as seen during computational analysis. Additive manufacturing using the Maker Select Plus printer was chosen to create models.

Three adaptive envelopes were made, at two scales: 24 mm and 80 mm. There were small imperfections in the surfaces of the prints, but the small size made it difficult to detect if these lead to performance changes.

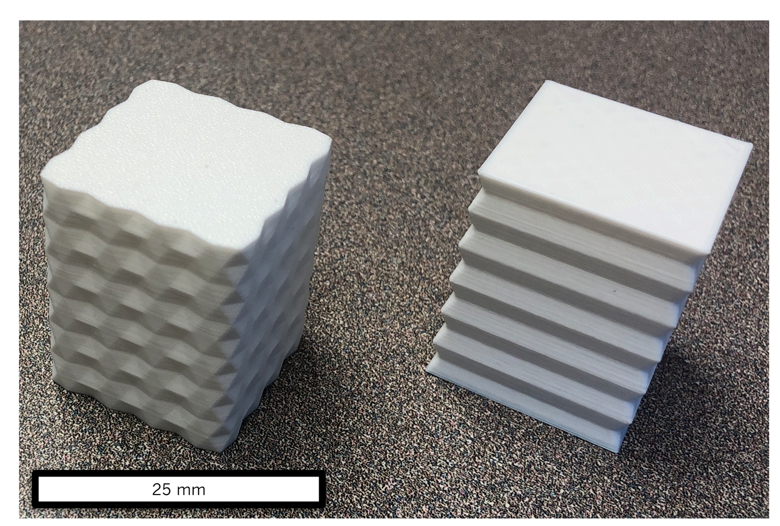

Figure 4: Small Scale Building 3D prints of Actuated Configurations 1 and 2.

To test these designs experimentally two wind tunnels were used. For the 25 mm scale buildings a hot wire anemometer was used over 30 seconds intervals to calculate the average wind speed versus the wind tunnel voltage, and buildings were compared against the unobstructed wind speeds.

Buildings were testing at 0 and 45 degree angles to the wind crossflow to observe the flat surface performance versus wind coming off at an angle.

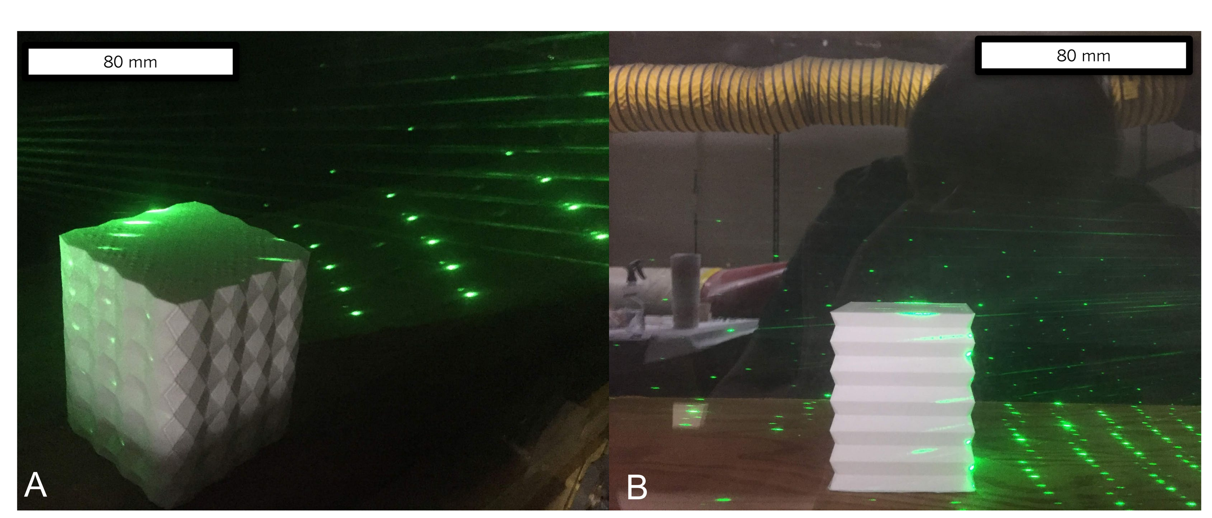

Figure 5: Wind flow set up of 3D printed mid-scale 80 mm buildings. A) Actuated Configuration 1 in wind flow testing, isometric view. B) Side view of Actuated Configuration 2 in wind flow testing.

To look at wind flow, the 80 mm buildings were set in a separate wind tunnels, and smoke was move through the structure to examine wind patterns.

Originally the smoke could not be seen due to the relative high wind speeds. Only on wind speeds of approximately 1m/s could the smoke be seen. By decreasing ambient light and using a multi directional laser, the smoke particulates could further be refined and analyzed.

Results and Discussion

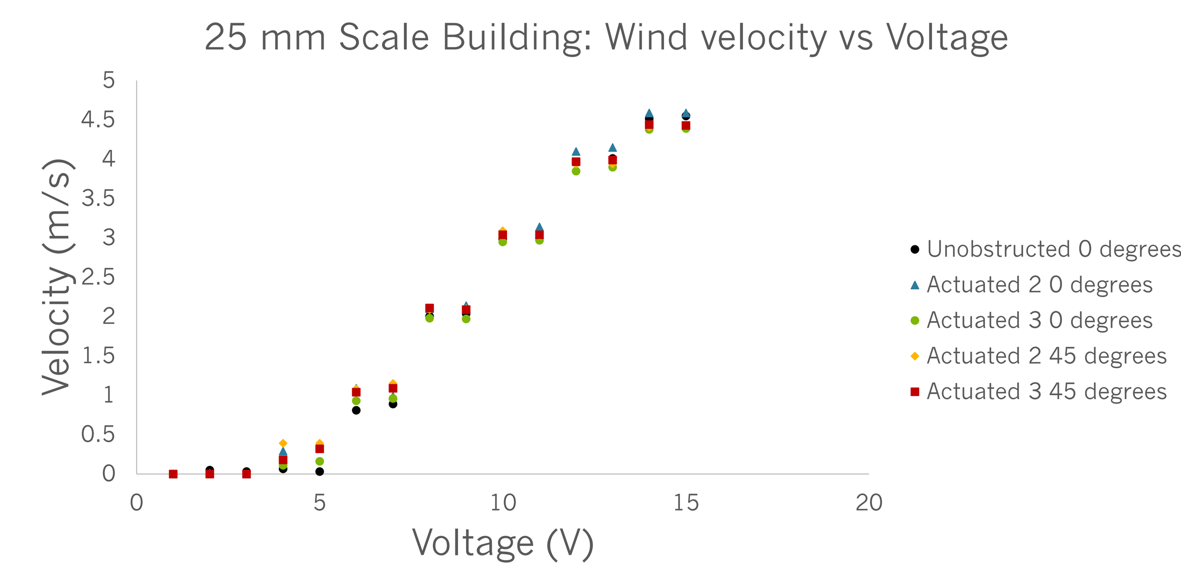

Figure 6. Wind flow speeds captured by unobstructed, actuated 2 at 0 and 45 degrees, and actuated 3 at 0 and 45 degrees. For each test the wind speed has a linear relationship with the voltage used by the wind tunnel, except in the 0-20 volt range, where the wind speed follows an exponential relationship. This low voltage performance is more likely due to the fan having low power rather than wind flow irregularities.

The small scale wind tunnel testing showed higher wind speeds after actuated building 2 at 0 degrees, even though building two is obstructed direct wind flow.

- This could be caused by wind flow patterns around the building, pushing wind behind to higher speeds than the wind tunnel originally produces.
- This is also seen at the large scale simulations, as shown in Figure 7.

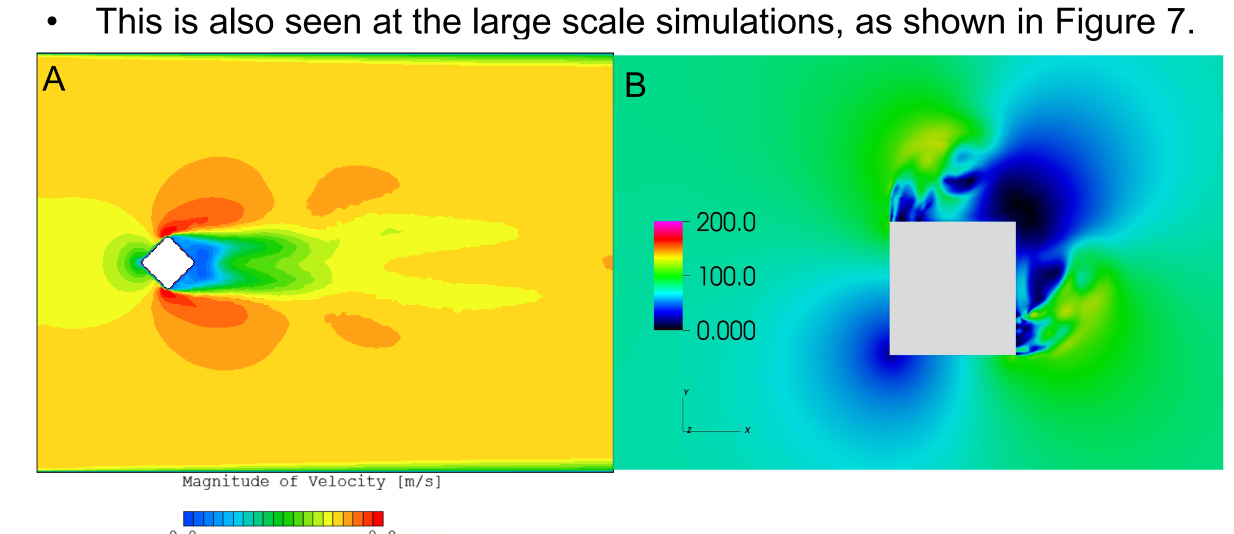

Figure 7. Wind Flow contour mapping of A) small scale versus B) large scale computational fluid dynamics for Actuated Configuration 2. Both images show high windspeeds behind the building due to warpage of wind flow.

- Wind flow turbulence on top of the building has a large impact. During computation analysis, both large and small scale had the highest velocities on the top end of the building.
- When analyzing the top flow in the wind tunnel, this fast air could also be viewed moving about. The highest wind speeds were observed at the corners of the building.

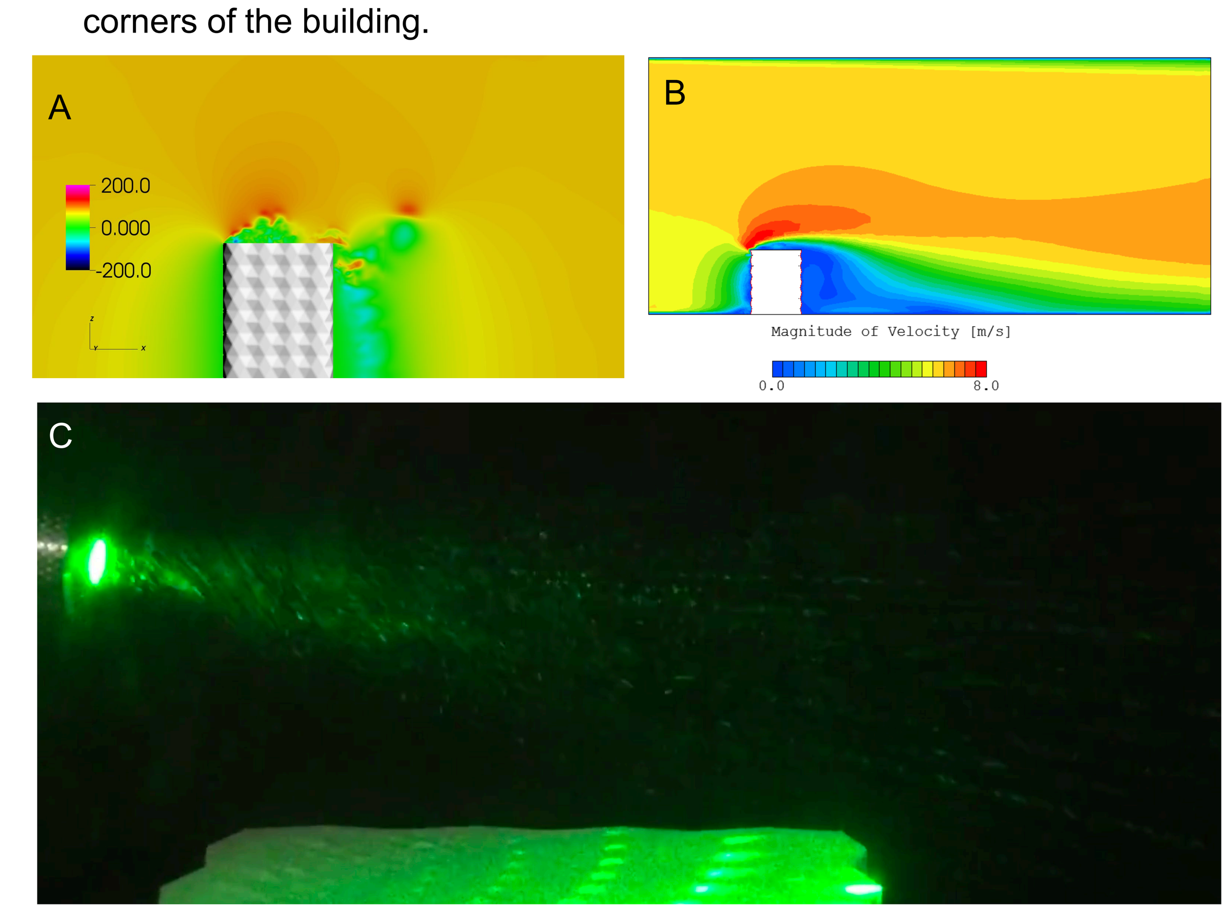

Figure 8. A) large scale side view of actuated configuration 1 vs B) side view of small scale actuated configuration 1. C) shows the above surface wind flow shown in the two computational predictions.

Conclusion

Through this pilot project, it can be observed how the wind speed changes based on different building envelope shape configurations. Understanding which shape provides best aerodynamic performance will provide the necessary information for future structural designs.

For small scale experimentation versus large large computation, there is a great deal of variance with the difference in scales.

- Wind speeds, forces, and aerodynamic properties all have slight differences that make each building unique. However, by using both analysis together, behaviors can be predicted and seen on each meaning experimental test can inform and calibrate computation models.

Establishing aerodynamic performance provides to the next step for multiple projects, including:

- Building dynamic envelopes out of shape memory polymers and shape memory alloys using additive manufacturing.
- Behavior response to various electrochemical energy signals.
- Real-time morphing envelopes subjected to wind loading.

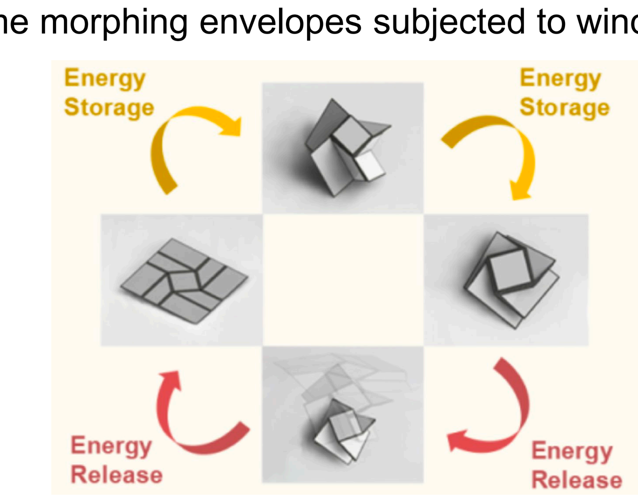

Figure 9. Potential Energy storage designs using shape memory polymers in origami inspired designs. (Source: Wang, et. al. 2019)

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