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Reconfigurable Flood Wall Inspired by Architected Origami

Thesis

Completed in Partial Fulfillment of the Requirements for Graduation with Honors Research

Distinction in the Department of Civil Engineering at The Ohio State University

By

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The Ohio State University

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Abstract

Recent interest in the art of origami has opened a wide range of engineering applications and possibilities. Shape changing structures based on origami have had a large influence on the drive for efficient, sustainable engineering solutions. However, development in novel macro-scale utilization is lacking compared to the effort towards micro-scale devices. There exists an opening for environmentally actuated structures that improve quality for life of humans and the natural environment.

Specifically, resilient infrastructure systems could potentially benefit from the tailorable properties and programmable reconfiguration of origami-inspired designs. The realm of flood protection and overall water resources management creates a unique opportunity for adaptable structures. A flood protection system, or flood wall, is one application of the origami technique. In many situations, flood protection is visually displeasing and hinders an otherwise scenic natural environment within a cityscape. By applying a permanent, adaptable protection system in flood-prone areas, not only will general aesthetics be conserved, but quick deployment in disaster situations will be ensured. With a rapidly changing climate and an increase in storm disaster events, an efficient flood-protection system is vital.

In this study, simple rigid flood barriers are compared to adaptable wall systems that utilize multi-stable configurations. The flood event is characterized by a surcharge of water that is suddenly introduced–like that of a flash flood–and sustained at steady-state. Small-scale prototypes are tested in a hydraulic flume and compared to a numerical simulation for validation.

Acknowledgments

I would like to extend my sincerest gratitude to the many mentors, faculty, and friends that have contributed to my success at Ohio State. First, to my advisor Dr. Hu that inspired me to pursue graduate school and who also gave unending encouragement and support, even half way around the globe. Next, thank you to Dr. Shafieezadeh who first fostered my interest in research and exploring civil engineering outside of the classroom. To Dr. Zhao who graciously accepted me into her lab and assumed the role of academic advisor. A special thanks to Brady Hildebrand and Chunping Ma for assistance in the numerical simulation portion of this study.

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Vita

Education

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Publications

Ma, C., **Luce, B**., Long, Y., Morales, L., Stagge, J., & Hu, N. Exploiting Origami-inspired Adaptive Structures for Developing Sustainable Solutions in Overflow Control. Extreme Mechanics Letters (submitted)

Ma, C.*, Zhang, Z., **Luce, B**., Pusateri, S., Rafiei, M., & Hu, N. Design and Characterization of Tunable Architected Materials using a Machine Learning Based Algorithm, NPJ Computational Materials (submitted)

Presentations

POSTER

1. **Luce, B**., Hildebrand, B., Hu, N. 'Reconfigurable Flood Wall Inspired by Architected Origami'. 2020. Denman Research Forum. Columbus, OH, March 2020

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MGD – Millions of Gallons per Day

FSI – Fluid-Structure Interaction

CFD – Computational Fluid Dynamics

CEL – Coupled Eulerian Lagrangian

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Introduction

With the rise in climate change and increase of flooding events, flood protection has become a vital consideration in cityscapes. Traditional emergency flood mitigation–namely sandbags or concrete barriers seen in the figure below–can be easily overwhelmed by storm surges that produce upwards of 100x normal river flow. Flood water can then infiltrate homes, business, and inhibit emergency response. When this occurs, flood water and debris cause costly damage throughout the built environment.

Figure 1: Emergency Flood Barriers[1]

Current emergency flood barriers consist of sandbags and portable shields that are not efficient during crisis situations.

Background

The ample interest in origami inspired structures and metamaterials spurs from the wide range of geometric forms[2-4] and metamorphic properties. Applications include morphing structures[5], deployable structures[6], metamaterials[7], and self-folding robots [8]. The shape changing capability is the key factor in engineering interest. The ability of origami to physically alter the mechanical properties based on fold patterns gives rise to innumerable applications. Past studies into origami-inspired transformable materials[9], cellular metamaterials[10], and microscale deployable stents display the versatility in medical and engineering fields. Macroscale structures such as deployable solar panels in space[11] exemplify the other extreme of origami research. Currently, studies into deployable disaster relief structures[12] envelops most of macro-scale structures. Origami's influence on architectural design[13] can be seen throughout the built environment in the Figure 2: Origami Inspiration in Architecture below.

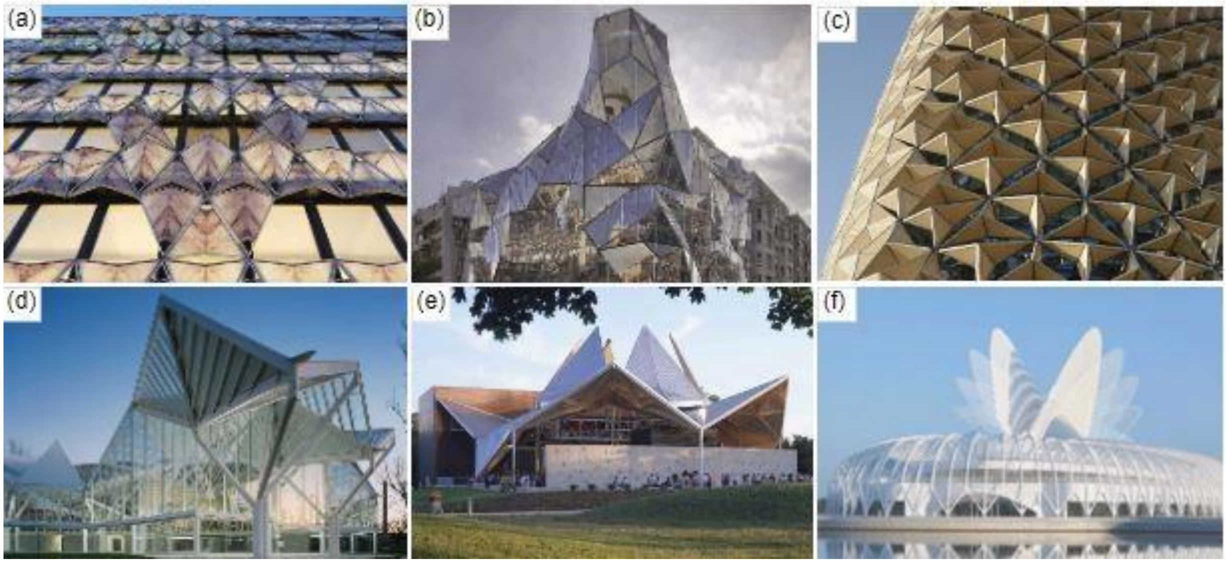

Figure 2: Origami Inspiration in Architecture

Origami inspiration in architectural design produces unique shapes and patterns in a multitude of locations and cultures.

A gap within origami-inspired structures lies within transformable macroscale structures that provide resiliency to natural disasters. Origami applied toward resilient infrastructure has a potential to alter not only the way natural disasters are mitigated, but also the visual aesthetic of urban areas. Specifically, retention walls and floodwalls provide significant protection from water overflow into urban areas. However, the current systems are either (i) inefficient and time consuming to install or (ii) visually displeasing to urban inhabitants. Inefficiency and time consumption in disaster situations are unacceptable to the potential for life threatening situations.

Significance

By developing a system that withstands flooding while fulfilling the additional objective of visual aesthetics, safety assurance greatly increases within high-risk environments. Current strategies of flood protection include sheet piling, sandbags, and portable shields and barriers[14]. While effective in most situations, these methods cannot adapt to different situations and altering weather patterns. In this study, the researcher hopes to provide an efficient dynamic structural system that can prevent flood-related disasters. Beyond developing a form of resilient infrastructure, it is the researcher's position that safety is paramount. Safety is tied directly into research and application as a civil engineer. Development of this system will ensure safety for the foreseeable future in which climate change causes more severe and repetitive weather patterns.

Implicit significance within the project exists under multiple objectives. Past studies have primarily focused on the micro-scale with few exceptions. In these past studies, zero-thickness origami patterns are traditionally used. However, in structural application, materials have non-negligible thickness, which provides further challenges. A relatively new field of non-zero-thickness study is therefore another objective within this project and can lay the foundation for further study.

Motivation of Work

The motivation behind this study was multi-part. Adaptable structures are by design sustainable solutions to engineering problems. By developing a modular system that is multi-purpose, efficient, and naturally actuated without artificial energy input, a sustainable solution is achieved. All parts of this study are scrutinized under a lens of sustainable development. The system will re-configure without human input and is made out of recycled materials. The material used in this study was ArmaForm (by armacell) structural foam that is manufactured using recycled PET plastics.

Figure 3: ArmaForm Foam by armacell[15]

The ArmaForm PET Structural Foam produced by armacell is recycled from plastics and can be used in a variety of applications including composite structures and insulation.

Further motivation stems from preventing degradation of building structures. An adaptable flood-mitigation system could potentially protect homes and businesses from costly damage caused by significant storm events. By withstanding intense storm surges, millions of dollars in damage could be prevented by the system outlined in this study.

Due to the complexity of the Fluid-Structure Interaction, physical testing of small-scale prototypes was used to validate numerical simulations performed in finite element software.

Goal of Research

The overall objective of the project was to design and characterize a baseline adaptive structure with tailorable properties and controllable reconfiguration under different levels of fluid pressure. The objective was based on the major hypothesis that the shape change of origami-inspired structural components and systems can be modified and controlled by tuning tessellation in targeted locations within the structure, thereby achieving the adaptive response feature. Development of this dynamic structure was focused on a modular level. While the main objective was to create a flood-resistant structure, the project has potential to create a multi-situational structure suitable for many applications. Instances such as adaptive weir walls in combined sewer systems and variable pressure piping are more potential areas of application.

Replacement of outdated and inefficient flood protection systems with the dynamic system will allow for control of water level in all situations. The final system will be able to raise and lower to a desired depth level in order to protect against over-flow. As a final structure, the prototype will be able to unfold quickly when deployed, refold dynamically, adapt the overall shape according to need, and easily re-form to a closed state.

Further optimization of the structure within a numerical analysis program will allow for scaling and simulation of real-world environments. While small-scale prototypes (tested in Flume) are valuable for testing mechanical properties of the basic structural components, real world application was the main goal of the study. In order to simulate real world flood conditions, an understanding of current flood patterns and fluid dynamics will be gained during the process of research. A further collaboration with in-house fluid mechanics researchers will allow for a deeper understanding in the subject and a comprehensive design of the flood prevention system.

Because of the exploration into non-zero-thickness origami, further research into appropriate materials must be considered. Traditional concrete, steel, or wood materials will most likely not be sufficient for the design based on current knowledge of bending and shape-changing abilities of each material. Thus, a composite material or combination of multiple materials was used.

Research Methodology

Physical Prototyping and Testing

In order to produce meaningful results, a combination of physical and numerical testing was utilized in this study. In this way, a comparison between simulated and observed behavior of the adaptable structures can be analyzed. The process for physical testing was as follows:

1. Conceptualize prototype using paper folding
2. Manufacture unit cells using ArmaForm Core recycled material and fiberglass matting
3. Fix tape to joints to cover from resin. Apply resin to bond/harden fiberglass to foam
4. Manually test the rotation of joints with applied pressure
5. Anchor modular unit to hydraulic flume.
6. Start flow of water into flume and observe actuation of weir with water pressure

Below is an example of fabrication:

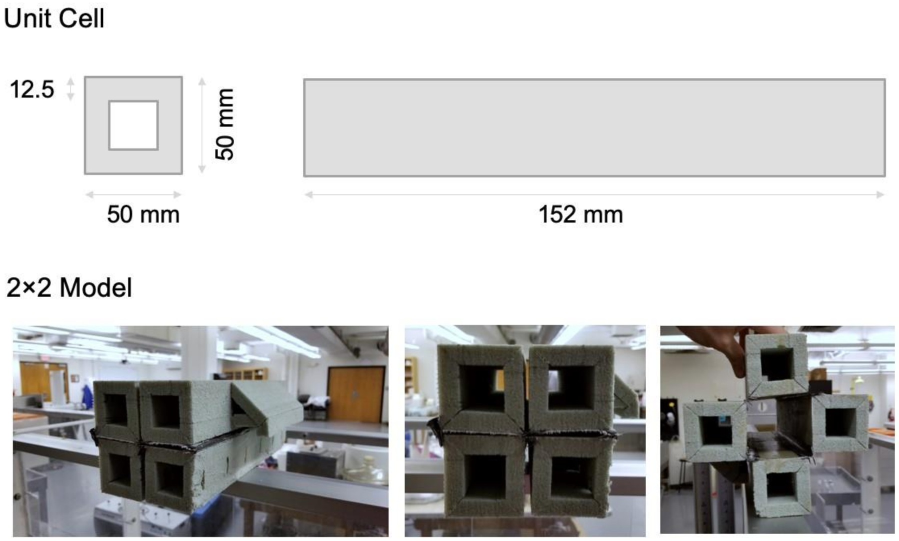

Figure 4: Unit Cell and Assembled 2x2 Structure

The designs were constructed with fiberglass overlay connecting the foam units.

Figure 5: Hydraulic Testing Flume

The flume consisted of 20 ft of plexiglass channeling that utilizes controllable water velocity to test different weir scenarios.

Numerical Simulation Approach

A numerical simulation was performed using commercial software ABAQUS to repeat observed results from the physical tests. The process of simulation was as follows:

1. Determine physical constraints from prototype and testing conditions: flow velocity, dimensions of units and flow path, etc.
2. Test a simple weir wall under flow conditions using Coupled Eulerian Lagrangian (CEL) simulation technique to observe deflection and flow over the structure
3. Create a system that couples fluid and structural dynamic deformations. This will be achieved using a Couple Eulerian Lagrangian (CEL) Technique.
4. Execute the two-way FSI in order to assess the deformations of the weir structure with changing velocities

Hydraulics and Fluid-Structure Interactions

In this study, a traditional rectangular sharp-crested weir was the control simulation in which to compare to the adaptable weir structures. However, due to the expandability of the adaptable weirs, simple hydrostatic pressure cannot be assumed. The alteration of initial shape changes the surface interaction of the structure and the fluid.

The dynamic structural adaptation combined with water velocity required a complex two-way FSI. A two-way FSI was modeled so the deformation of the structure was influenced in every time step by the flow of the fluid, and the flow was affected by the structural deflection in every time step.

For clarification, a one-way FSI involves the pressures on the surfaces of the structure being calculated in a separate CFD analysis. These pressures can then be transferred to the structural model. The limitation with this method is that the flow velocity and deflection of the structure do not interact, giving an inaccurate result in this study.

Simulation Conditions

Within ABAQUS/Explicit-CEL, an Eulerian domain was created to encompass the simulated flume. A single velocity boundary condition was used to specify the inflow of water at 0.5 m/s. Eulerian domains focus on the translation of material through the mesh and do not track the nodes of the mesh. Because of this, velocity of the material through the mesh was set to zero at all other boundaries. An initial set up for the CEL environment can be seen in Figure 6: ABAQUS CEL Simulation Environment below. The blocks were all modeled as rigid bodies and joints were modeled as deformable material with an Elastic Modulus of 9 MPa. The density for both the PET foam and the joints was modeled as 120 kg/m^3 according to the material specifications from armacell. This replicates the buoyant capability of the foam.

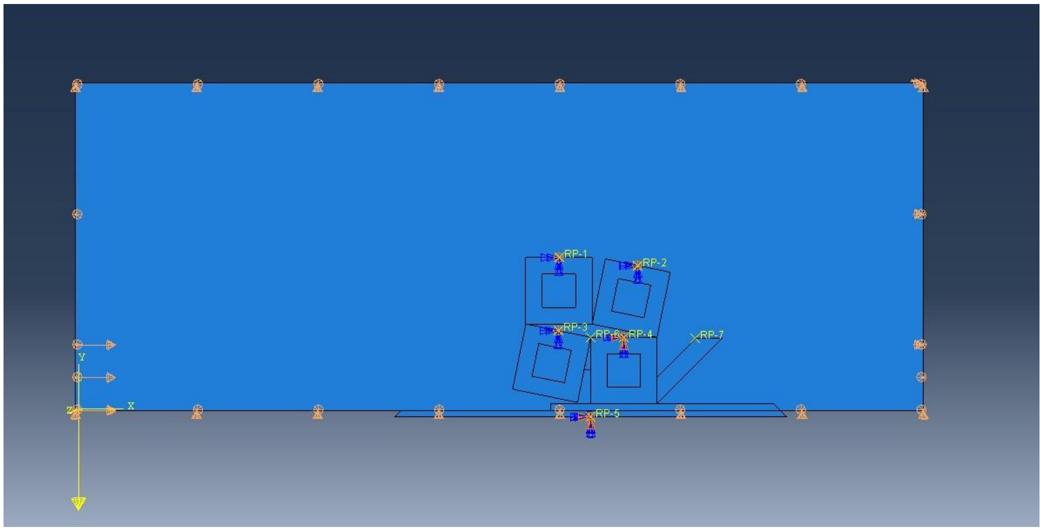

Figure 6: ABAQUS CEL Simulation Environment

The numerical simulation set-up was a Combined Eulerian-Lagrangian (CEL) simulation using boundary conditions to control velocity and the displacement.

A velocity boundary condition was specified to initiate water flow into the system that would replicate the water flume. The large Eulerian domain was constrained in all other directions using zero velocity boundary conditions. The Rigid bodies were constrained using traditional zero displacement boundary conditions except in targeted response directions.

Design, Fabrication, & Numerical Results

Design Concepts were broken down into two categories describing movement of the system: Single and Multi-Phase. A single phase design has two stable configurations. Multiphase designs can have either multiple stable configurations or continuously adaptable forms.

Single Phase:

With flood management as the goal, a re-configurable design was created to simply expand in height and width to halt flow. Initial rotation-inspired origami prototypes were built using 50x50mm units.

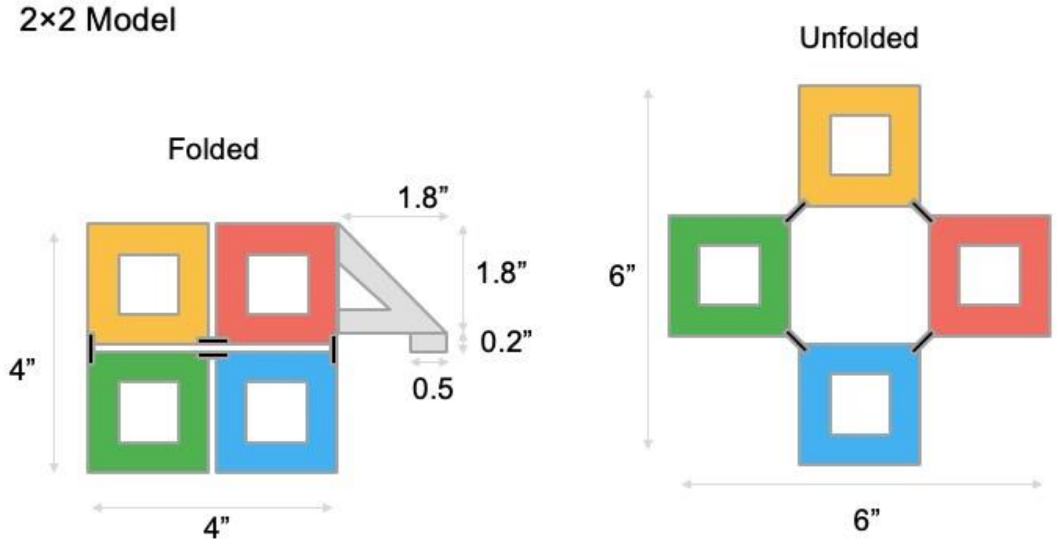

Figure 7: Single Phase 2x3 Unit Design Concept

The colored blocks represent the foam material and the black joints represent the flexible fiberglass material. The color represents the rotational path of the weir deflection.

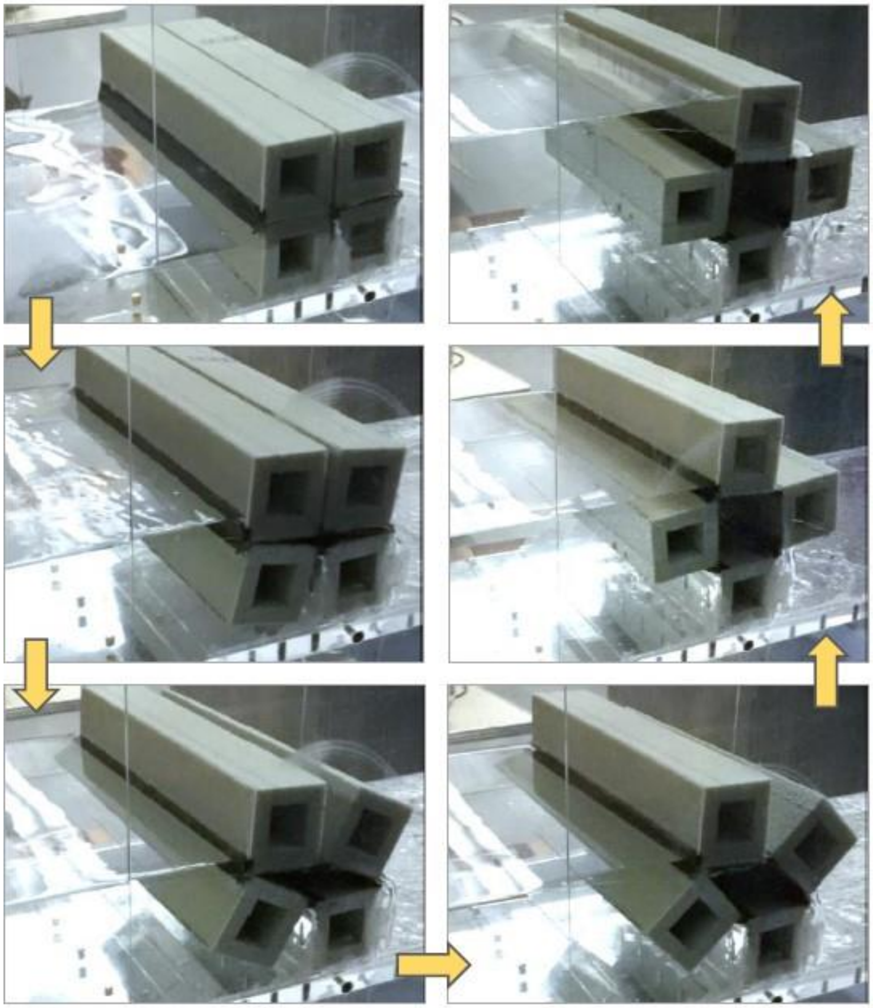

Figure 8: Physical Test of 2x2 Design

The physical testing of the 2x2 blocks confirmed initial predictions of deflection. Water flow was pooled behind the wall system and the wall was able to withstand the impact of water velocity.

The single-phase designs exhibited deflection in the expected fashion, expanding from the initial stable configuration to the second. However, initially the weir over rotated and shrunk into a mirror image of the first stage. The addition of a stopper remedied this, and the weir was able to withstand the full-height dynamic water pressure (seen in Figure 8). The weir expanded from a height of 2h, height of two blocks, to 3h. The numerical simulation produced similar results.

Figure 9: Numerical Simulation of 2x2 Design

The numerical simulation took effort to recreate physical behavior. The complex FSI created difficulties for the modeling environment, causing random blow-outs and pressure differentials.

The numerical simulation produced similar results for the 2x2 design. The lower density of the foam material allowed for the buoyant action to be replicated in the simulation. However, the initial uplift force had to be fabricated to start rotational action. Further study of the simulation will be needed to accurately replicate the behavior. This includes scaling up to simulate real-world flooding conditions. Currently, the 2x2 design is the only simulation available.

The same physical behavior was seen in the 3x3 Unit Design with some un-intentional over-deflection (Figure 10). This was due to the de-bonding of the fiberglass and the foam from increased water pressure. Overall, the 3x3 achieved an increase in height from 3h to 5h (33% increase).

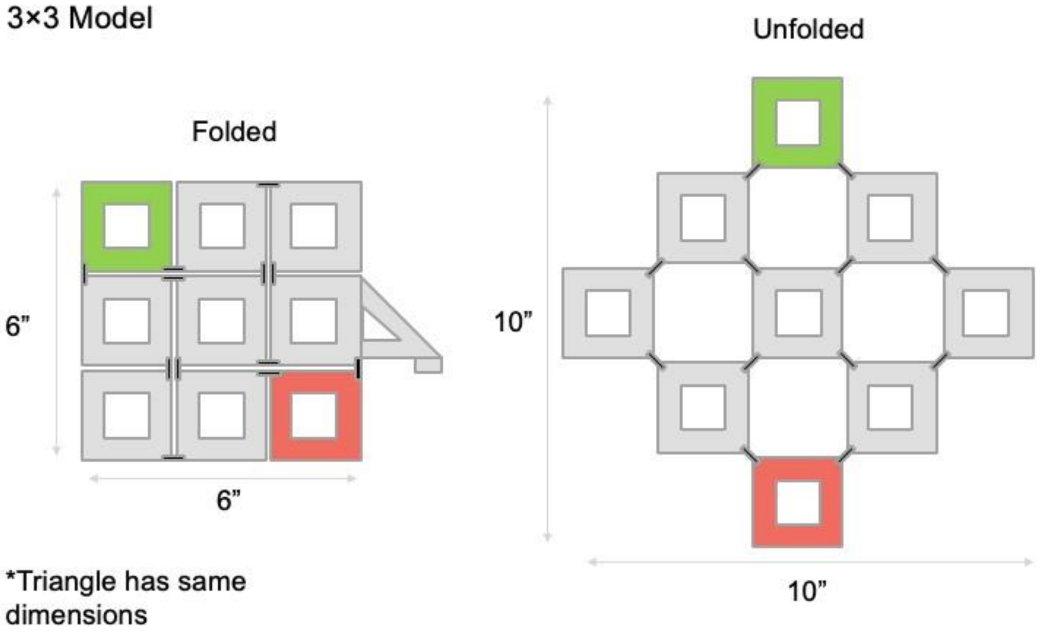

Figure 10: Single Phase 2x3 Unit Design

Similar blueprint to 2x2. Colored blocks represent the start and end location after deflection.

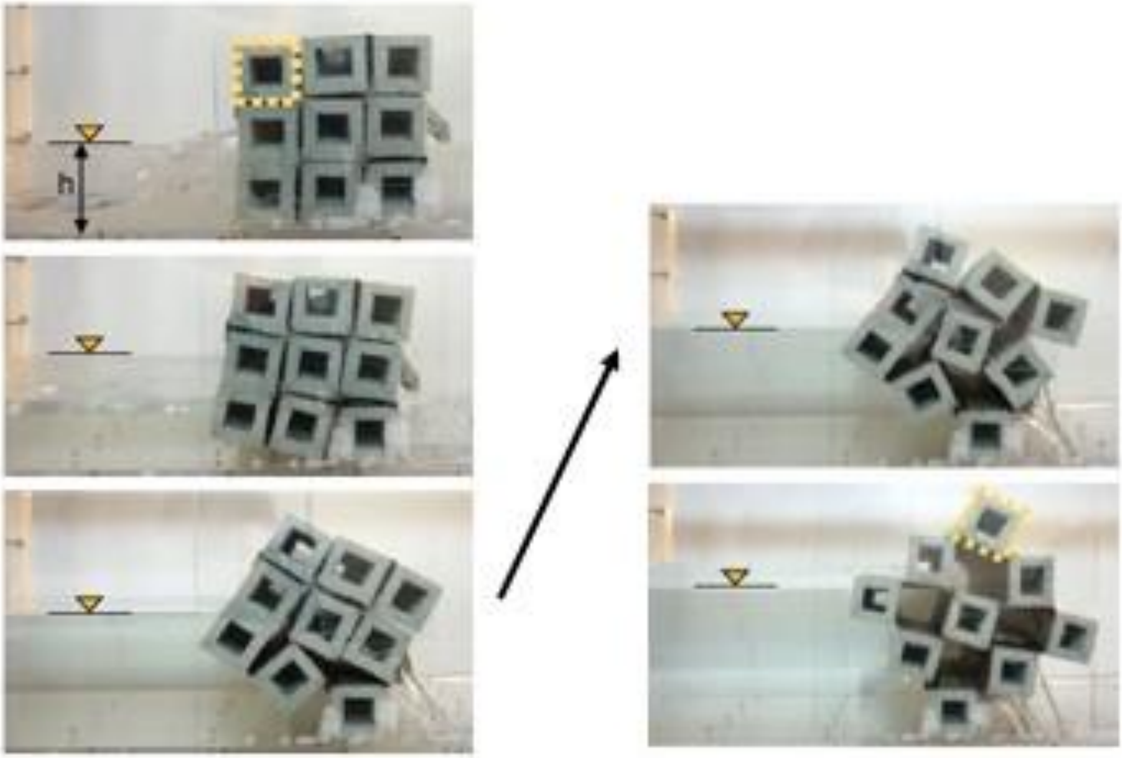

Figure 11: Testing of 3x3 Unit Design

Physical Testing produced similar results to the 2x2 design. Water was able to pool behind the structure at increased height.

Multi-Phase:

After experimentation with single-phase designs, further applications of modular origami-inspired water management were realized. The figures below demonstrate traditional weir systems and their functions within water management and flow mitigation.

Types of Weirs			
Sharp-Crested			Broad-Crested
Rectangular	Triangular (V-Notch)	Trapezoidal	Rectangular
Change Water Elevation	Measure Discharge	Change Elevation w/ Large Head	Flow Management and Regulation

Figure 12: Types of Weir Structures and Uses

Represents the common weir systems used in water management applications.

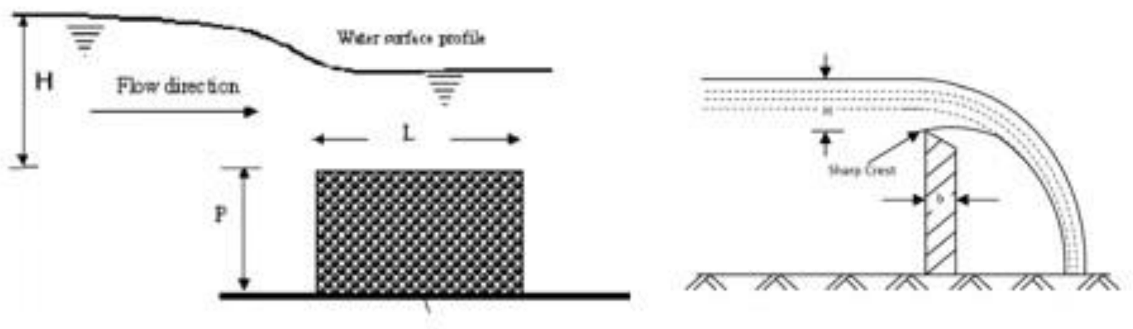

Figure 13: Broad-Crested Weir[16] (left) and Sharp Crested Weir[17] (right)

Target weir designs in this study. Altering water elevation and flow regulation are targeted water responses.

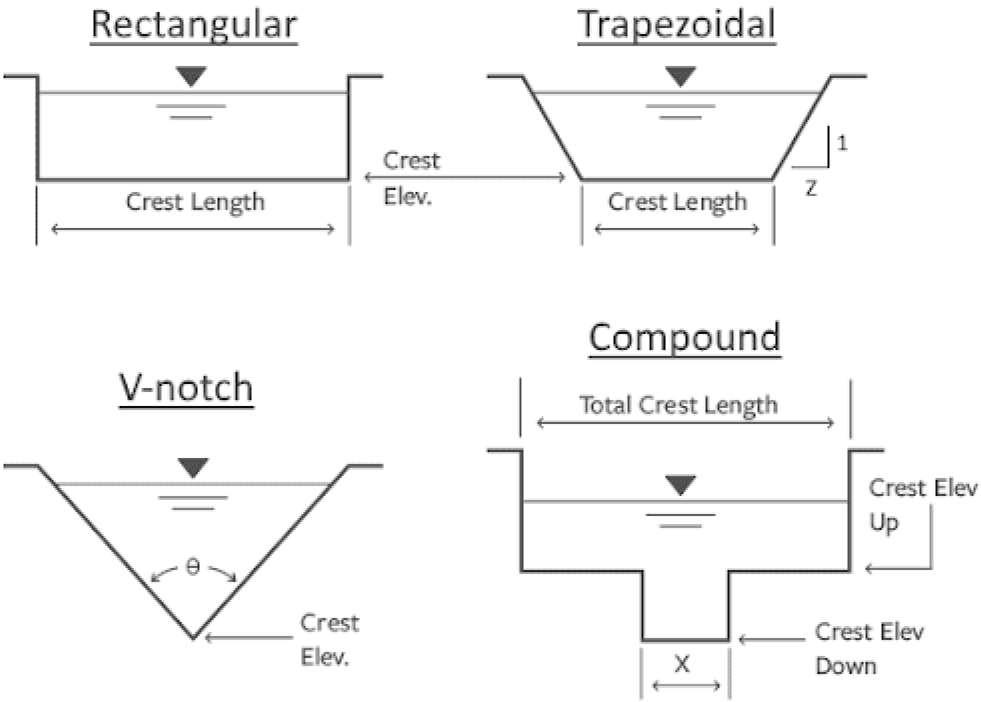

Figure 14: Weir Shapes[18]

The common weir shapes are used in different scenarios list in the flow chart above.

The potential for multiple, situational water management configurations in one adaptable structure drove the further conceptualization of the multi-phase design. Storm surcharges happen quickly and overwhelm flood barriers and sewer systems. This presents the need for extreme water elevation management and a rectangular sharp-crested weir. The multi-phase system, therefore, were designed to not only increase height but also alter from broad-crested orientation (flow management and regulation) to sharp-crested (elevation change management).

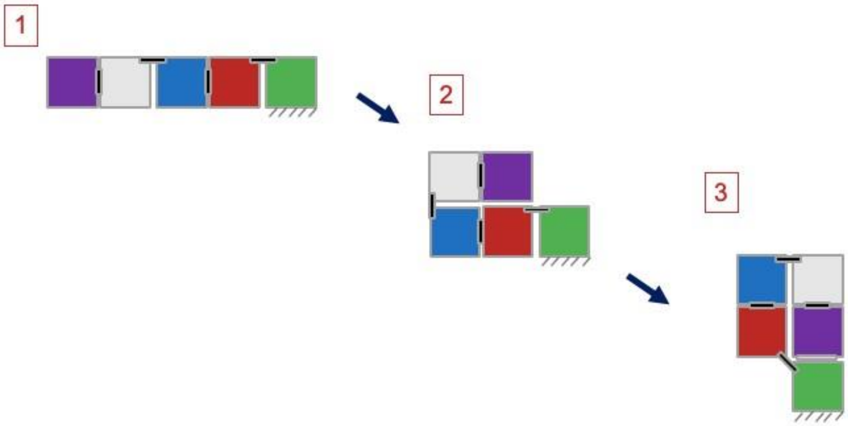

Figure 15: Stacking Multi-phase Design

The stacking design simulates an initial broad-crested weir but transforms into a sharp-crested design with increased height.

Figure 16: 1x5 Unit Design Test 1

Initial testing reflected the buoyancy of the foam material and joint placement strategy.

Figure 17: 1x5 Unit Design Test 2

Using forced actuation with a rod to hold down the units, the desired behavior was observed.

The 1x5, or "stacking," model was designed to increase in height at decrease in width during increased flow events. The flat phase (phase 1) is meant to be a broad-crested weir that has flow regulation capabilities but is also flat and un-obstructive to the aesthetics of the environment. A rectangular sharp-crested weir is used to change water elevation (phase 3) and could be used to mitigate storm surges. The design did not perform as expected in the physical tests due to the buoyancy of the material. The horizontal joints did not fold as planned, resulting in over-rotation of the entire weir system (Figure 16). With forced actuation using a rod to hold down blocks, the expected behavior was witnessed (Figure 17).

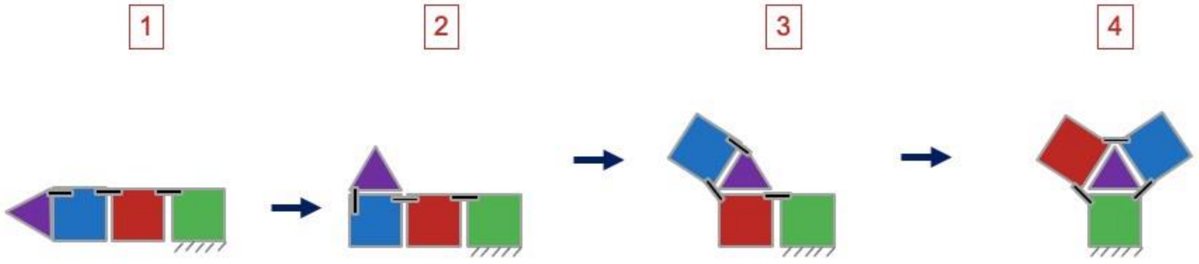

Figure 18: Y-Shape Design

The Y-Shape design consists of three square units and one triangular. The same dimensions are use for the square units as the 2x2 design.

Similar to the 1x5 Unit design, the "Y-Shape" weir starts as a broad-crested weir to reduce visual pollution and regulate flow. When storm surges increase, the weir becomes sharp-crested and increases height. Additionally, the Y-shape is used to disrupt flow twice during full actuation (phase 3). The double sharp-crested weir action serves to slow flow of water. Fabrication of the design was more difficult than previous due to the introduction of triangular base units and a "spiral" type reconfiguration (Figure 18).

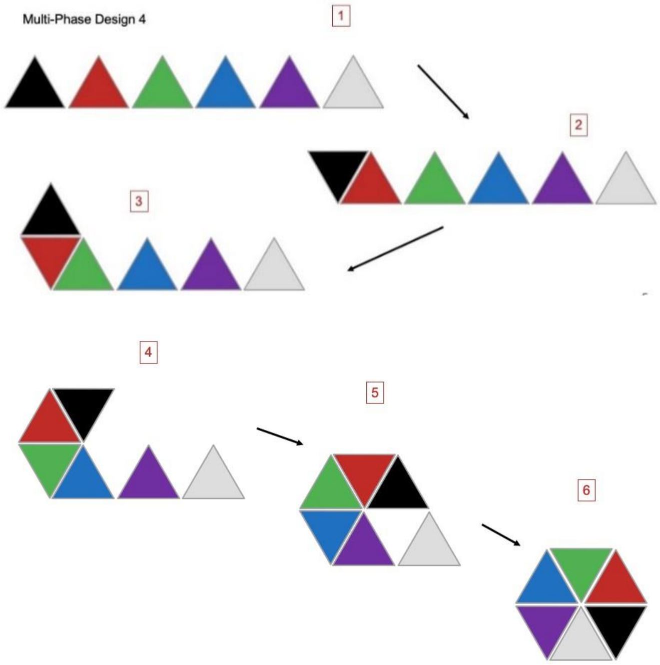

Figure 19: Hexagonal Design

The hexagonal design was conceptualized for turbid flow. The jagged surface area acts as multiple sharp crested weirs to slow water velocity. The increased height is included to pool water during flooding.

The design idea behind the Hexagonal concept centered on slowing the flow of water while increasing the height of the system. Similar to previous designs, the weir starts flat to avoid obstructing views but has a peaks and valleys to increase contact with water and therefore increase friction and slow velocity. When storm surges hit, the design is able to fold and increase height to a strong unit able to withstand intense pressure.

Figure 20: Fabrication Stages of Designs

The physical designs required special molds for fabrication to achieve desired final shape.

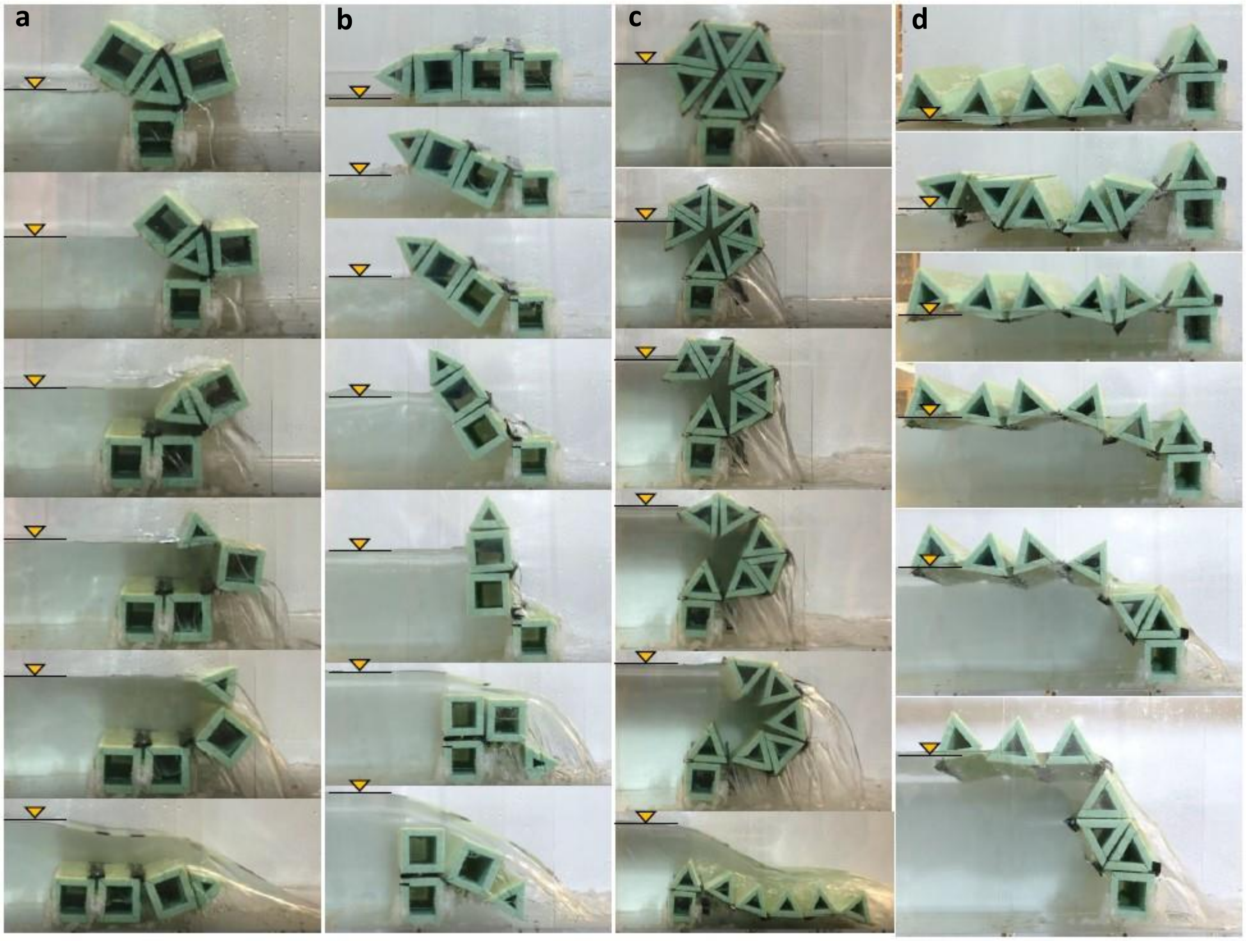

Figure 21: Testing of Multiple Multi-Phase designs with different orientations

The Y-Shape and Hexagonal designs were tested in the original orientation (b&d) and 180 degree flip (a&c) to test the step-wise action of the design.

For the purpose of exploration, the Hexagonal and Y-Shaped designs were re-oriented 180-degrees in the flume to test stopping behavior (Figure 21 a&c). The Y-Shape weir was unable to reconfigure in the expected steps due to the buoyancy of the material (Figure 21b). As seen in Figure 21d, the hexagonal design was able to withstand significant water pressure (water depth) due to the buoyancy of the material. This unexpected behavior was, in this case, beneficial as the design could potentially hold a larger depth of water based on the total number of additional triangular units attached to the end of the weir. This floating/stacking technique could be leveraged into a dynamic section of weir (first three units in Figure 19d) and rigid section (last three units in Figure19d). With changing water levels, the weir could unlock/unstack or continue to stack to withstand increasing water pressure.

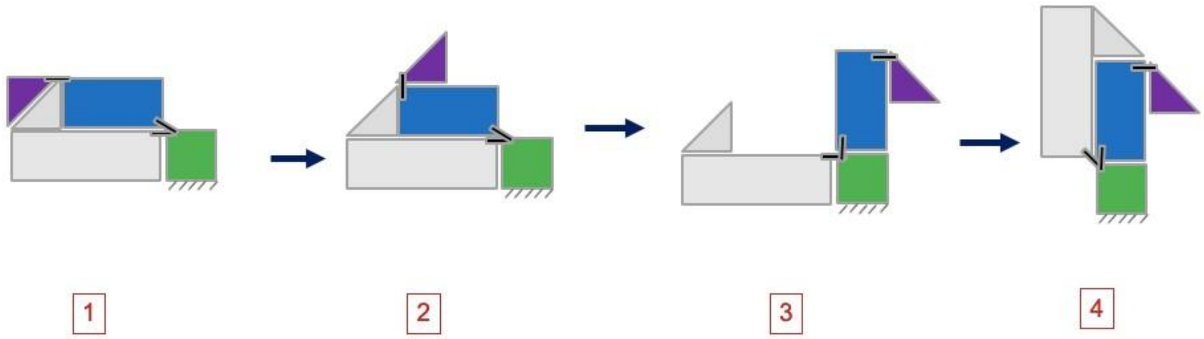

Figure 22: Irregular Four-Step Design

The design consists of four complex phases. Fabrication of the design was difficult do to non-regular joint placement and shape combination.

The Irregular Four-Step Design applies combines a complex reconfiguration for water management. Starting as a broad-crested weir (phase 1) and quickly extending to sharp-crested for water surges, the concept has a quick response ability. Phase 3 includes a height change and double sharp-crested weir action to further slow water. Lastly, phase 4 keeps the sharp-crested weir configuration, but also increases to full height of 4h, double the starting height.

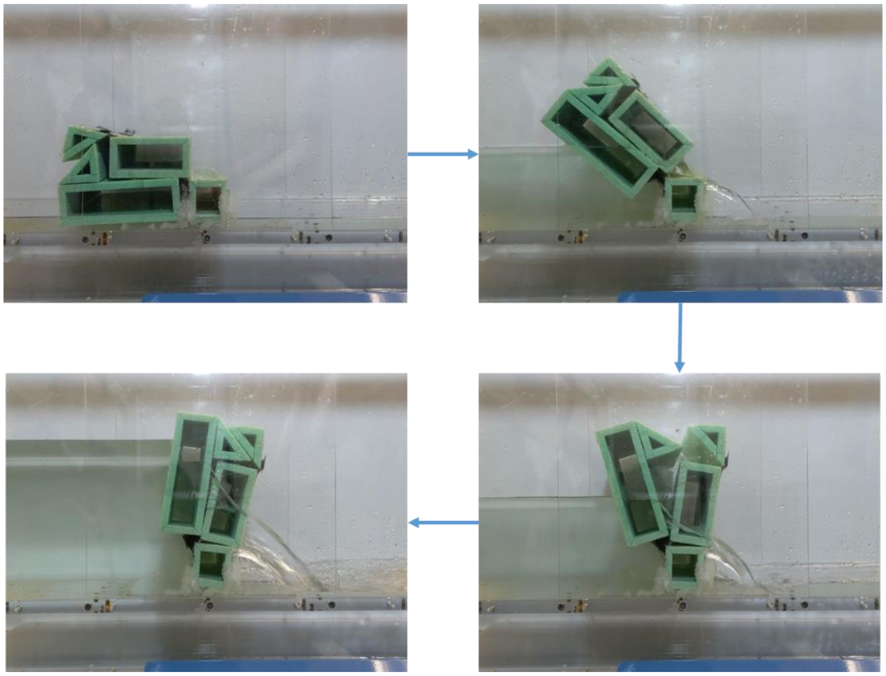

Figure 23: Irregular Four-Step Test

The irregular design consisted of complex joint placement that was difficult to fabricate. This translated to poor rotational displacement. The increased height of the weir is a route for future study.

The irregular design performed similarly to other multi-phase designs, exhibiting rotation only at the base joint (Figure 23). This did not allow for intended, step-wise adaptability.

The multi-phase design concepts, in theory, would allow for situational adaptability and mitigate more than one type of water flow. Ideally, the multi-phase system would be able to step through configurations. However, this was not seen in testing due to buoyancy of the ArmaForm material and joint placement. Further exploration of joint locking mechanisms could lead to proper reconfiguration. For example, the joints could be triggered to rotate with water pressure by increasing the joint stiffness towards the unit attached to the bracket. In this scenario, lower stiffness joints would rotate first and a step-wise reconfiguration behavior could be seen.

Conclusions and Future Work

While the results of the physical testing were promising in terms of expected behavior and unexpected, beneficial behavior, there were some issues with the testing environment. Water was able to penetration the foam units due to the porosity of the ArmaForm material and leak between the walls of the flume and the unit. Obviously, for flood protection, penetrating water is not acceptable and should be fixed in further study with a sealant or waterproof coating. The water leakage was not included in the numerical simulations that assumed ideal boundary and contact conditions. This greatly affected the results of the simulation because the uplift forces caused by internal water uplift were not included. Thus, the rotation of the weir structure was flawed. This was temporarily fixed with uplift pressure.

However, the ArmaForm material is recommended due to its low density. The ArmaForm foam can float on water allowing it to dynamically alter shape with the slightest water contact. The main area of focus in further studies should be on altering the stiffness of the joint material. By tuning the stiffness of the joints, the user can predict the rotation of the structure to a precise degree. This could be done using alternative adhesives for the foam material or within ABAQUS simulation.

The buoyancy of the material was most seen within the physical testing of the multi-phase designs. Most designs deflected unexpectedly due to the floating action and joint placement. Specifically, if a joint was placed to the rigid block (block attached to flume), rotation of this joint was almost always seen to actuate first. In some cases forced actuation with a rod was used to step through the expected phases. Because only water pressure actuation is wanted, solutions to this issue should be further studied. Potential joint locking or magnetic releases on certain joints could sole the unexpected behavior but would need to be tested.

The ability of the adaptable weirs could potentially be applied in different situations as stated in the Introduction. Some of the tested design would perform better in certain environments like flood protection where extremely high dynamic pressure is achieved. For example, the hexagonal design has potential to react to large water height due to the floating action. Other designs may perform better in sewer systems that experience a wide range of constant flow velocities. The single-phase systems could continuously adapt to water velocity but only reach a designated maximum height as to not complete close off sewer systems. Further exploration into tuning design to application could be done for multiple scales including microscale insertion into the human blood stream.

One of the driving goals in this study was to replicate the results observed in the physical tests to numerical simulation. This challenge proved difficult do to the highly dynamic FSI the adaptable weir undergoes. The use of ABAQUS CEL was sufficient for testing basic interaction and the deflection of the joint material, further analysis must be done in order to fully capture the behavior of the problem. Additionally, multi-phase designs must be modeled in the simulation. For this future study, the author recommends using a coupled simulation with ABAQUS/Explicit and Star-CCM+ CFD. Star-CCM+ CFD software gives a more detailed and accurate modeling environment for fluid dynamics. A co-simulation between the structural model in ABAQUS and the CFD Analysis in Star-CCM+ could capture accurate deformation of the weir structure and the resulting flow.

References

[1] Temporary barriers: https://cbs2iowa.com/news/local/flash-flood-emergency-issued-for-burlington-after-temporary-flood-protection-failure

[2] L. H. Dudte, E. Vouga, T. Tachi and L. Mahadevan, Nat Mater **15** (5), 583-588 (2016).

[3] J. L. Silverberg, A. A. Evans, L. McLeod, R. C. Hayward, T. Hull, C. D. Santangelo and I. Cohen, Science **345** (6197), 647-650 (2014).

[4] X. Zhou, H. Wang and Z. You, Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences **471** (2181) (2015).

[5] S. Li and K. W. Wang, Smart Materials and Structures **24** (10), 105031 (2015).

[6] J. Kim, D.-Y. Lee, S.-R. Kim and K.-J. Cho, presented at the Robotics and Automation (ICRA), 2015 IEEE International Conference on, 2015 (unpublished).

[7] C. Lv, D. Krishnaraju, G. Konjevod, H. Yu and H. Jiang, Scientific Reports **4**, 5979 (2014).

[8] S. Felton, M. Tolley, E. Demaine, D. Rus and R. Wood, Science **345** (6197), 644-646 (2014).

[9] J. T.B. Overvelde *et. al*, Nature Communications, **7**, 10929 (2016).

[10] K. C. Cheung *et al* 2014 Smart Materials and Structures **23**, 094012 (2014).

[11] Y. Nishiyama, International Journal of Pure and Applied Mathmatics, **79** (2), 269-279 (2014).

[12] C.P. Quaglia, A.J. Dascanio, A.P. Thrall, Engineering Structures, **75**, 276-287 (2014).

[13] P. M. Reis, F. L. Jimenez, J. Marthelot, Proceedings of the National Academy of Science **112** (40), 12234-12235 (2015).

[14] C. A. Richardson (1995) *United States Patent No. 5439316.* Retrieved from http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PALL&p=1&u=%2Fnetahtml%2FPTO%2Fsrchnum.htm&r=1&f=G&l=50&s1=5439316.PN.&OS=PN/5439316&RS=PN/5439316

[15] ArmaFORM PET Core. (n.d.). Retrieved from https://www.virtualmarket.innotrans.de/de/ArmaFORM-PET-Core,p1502572.

[16] Broad-Crested Weir Schematic. (n.d.). Retrieved from https://www.researchgate.net/figure/View-of-solid-broad-crested-weir-used-in-the-study_fig2_236122097

[17] Sharp-Crested Weir Schematic. (n.d.). Retrieved from https://theconstructor.org/water-resources/what-is-weir-types-flow-over-weirs/11873/

[18] Types of Weir Diagrams. (n.d.). Retrieved from http://learn.hydrologystudio.com/studio-express/knowledge-base/weirs/