ABSTRACT
Research into self-assembly systems has been growing in recent years, focusing on the design and engineering of materials to react to environmental factors, which trigger a chain of reactions promoting the components to build themselves. This paper attempts to expand this field with the design and testing of a full-scale structure that could be dropped high above the ground, self-assemble in the air in a matter of seconds, and form an inhabitable space on the ground.

This system uses spline-based fiberglass rods, folded in specific configurations and connected with parachute surfaces as the main material system, enabling the global aerial performance. A series of drop tests were conducted from a 100’ crane to investigate the unfolding sequence, the release mechanisms, and the parachute configurations, leading to its successful aerial assembly.
1. INTRODUCTION
This research began as part of a design studio interrogating current notions of construction and assembly in architecture, further framed by the design and construction of a quickly deployable architectural structure by the end of the class. By looking at disaster relief, concert venues, inflatables, canopies, or other transformable and temporary structures, this research questioned the speed, cost, and ease of assembly in large-scale construction. Precedent works include the Mongolian ger and the Quechua 2-Second Tent by Decathlon USA, as examples in nomadic architecture; Le Pont Trampoline by AZC and PneUI by the Tangible Media Group, as examples of inflated constructions; and systems developed by Wood Skin® and Fold Finding by tal friedman, as example of origami-inspired structures. These examples were chosen according to the research’s three guiding principles: cost, speed, and ease of assembly. Cost refers to the material, labor, and transportation requirements for construction. Speed refers to how fast and easily a significant volume of enclosure could be built. Ease of assembly relates to the prefabrication of parts, which are embedded with a certain behavior, geometry, and connectivity prior to their arrival to the construction site. Based on these principles, the Aerial Pop-Up Structures research explores the structural and transformative potential of torsional springs in spline-based assemblies to enable a pop-up behavior and aerial assembly.

This research focuses on the structural properties of the simple and economically accessible fiberglass rod, which can bend and twist, easily connecting to itself to form strong geometries with embedded spring forces for transformation. The material system builds on existing knowledge of lightweight, self-erecting and self-standing tents (Brady 1992). In contrast to the pneumatic and origami systems, the spline-based system requires nothing more beyond the first motion of release to assemble, using potential energy in the material to self-construct versus that of an outside source. These properties allow the pavilion to deploy “instantaneously,” in the span of a few seconds, while falling one hundred feet to the ground. This paper will first provide an understanding of spline behavior in fiberglass rods before proceeding with a sequence within the applied research project’s lifecycle.

2. METHODS
2.1 SPLINE BEHAVIOR
This research began with experimentation into the elasticity and mechanics enabled by fiberglass rods, specifically their ability to bend, twist, and elastically deform, ultimately regaining their original shape (Quinn et al. 2009). A simple working module was developed to repeatedly test these functional mechanics and global geometries. The working module is a cube composed of four fiberglass rods spliced into rings and joined with aluminum sleeves at the quadrants (“knots”). The fifth face of the cube is a “popping ring,” which can drive the expansion of the collapsed cube (“quad”). This popping ring differs from the rest in the way it is attached to the system. It is only connected at two points, allowing for twisting in half and folding (“figure-eighting”), which
collapses the module, while also charging it with a high amount of potential energy, dictated by the diameter and torsional strength of the fiberglass rod. It is this energy that then unfurls the packaged structure when released (Figure 2). To ensure the process of folding/unfolding, while also preventing the collapse of the structure under self weight, experimentation tested the following variables:

- the diameter of the rod that made up the quad ring;
- the diameter of the rod that made up the popping ring;
- the ratio of the diameters of the popping ring versus the quad rings;
- the length of the four fixed joints of the quad;
- the length of the two fixed joints attaching the popping ring to the quad;

2.2 AGGREGATION AND FOLDING

The structural and flexural properties of the module translated to the pavilion's overall design: a space large enough to accommodate up to 15 adults that a team of five individuals could easily collapse, transport to another location, and then deploy to reproduce the same structure. Translation from the singular module to a larger, global geometry composed of multiple modules increased the folding and popping behavior significantly. It became clear that the sequence of folding was crucial to ensure the full, successful expansion of the structure from a collapsed state. While some folding methods made the structure prone to entanglement, others proved to be more successful. The "book-folding method" (Figure 4) consisted in flattening the structure and folding it in half at every step, which brought entanglement issues. The most successful folding sequence was the "quad folding method" (Figure 5), which flattened each of the four outer quads first and then flattened the central quad. This allowed the structure to easily collapse down into a single 6' diameter ring and then jump into an overall structure with dimensions of 18' x 18' x 6'.

2.3 PARACHUTE AND ENCLOSURE

Imagining the structure's potential to function as a temporary shelter raised questions about the enclosure. While providing privacy for the occupants, this enclosure would also have to work seamlessly with the structure's folding and unfolding sequences. This steered the design towards a fabric envelope, which also enabled the potential for an aerial deployment and parachute effect.

The parachute was designed with two states in mind: the free-fall condition and the ground state (Figure 6). During free fall, the fabric would act as a parachute to slow and soften the structure's descent, as well as provide upward force to help release the
popping structure. Once on the ground, the envelope could be reconfigured into different forms, which would also aid in tethering the structure. Nylon ripstop fabric, nylon threading, and high-performance velcro were chosen as lightweight, inexpensive and high-strength materials.

3. RESULTS

3.1 FINAL DESIGN

The final full-scale configuration is a cross made of four quads and a central void. The final ring diameter is six feet, with a rod diameter of 3/8” and 5/16” for the popping rings. Each quad required two popping rings to create the correct force for expansion and stability, due to the weight of the structure. The length of the joints between quad rings was 8”, while the length of the joints between quads and popping rings was 12”. These lengths were important to resist the forces of the rods springing back into a straight line and to create the accurate tangency of the two rods as they circle around to meet one another. These dimensions collectively proved to be the most successful in balancing 1) the necessary stiffness to maintain the structure under self-weight, 2) enough spring force to set the structure into place, and 3) the bending radius to create the overall form.

The final design for the parachute was divided into three components: the caps (attached to the top rings), the wings (attached
to the outer faces of the cross), and the veils (attached between quads). These components (Figure 7) were designed based on experiments to maximize the surface area of the parachute in order to provide a soft landing for the structure. Tests in pilot cute mechanisms prompted the incorporation of centralized vents on the cap surfaces to minimize gliding, producing a fall closer to the vertical. Prototypes at half and quarter scale confirmed the effectiveness of this full assemblage of parts in free-fall testing. However, high winds on the final testing day created too much lateral force on the structure, requiring the removal of all but the fabric caps to ensure a successful drop.

3.2 TEST RESULTS

For the final drop, a crane lifted the structure to a height of 100′ (Figure 8). A release hook held the folded geometry until triggered to release by a pull from a rope, which connected the hook to the tester on the ground. Through a series of drop tests, the concept was proven; an 18′ x 18′ space could be folded down to a 6′ diameter ring, raised to a height of 100′, then released to aerially self-assemble and land on the ground without encountering major damage to its structure.

The 100′ drop tests demonstrated both successful drops (Figure 9) as well as a number of points of failure in the materials, folding sequence, parachute design, and construction techniques. Multiple rod failures (splintering and deformation) and joint failures (due to torsion and tension on the joints) were observed. According to structural calculations, each test stressed the fiberglass rods beyond their 80% capacity. This might explain why the structure was prone to long-term failures. These results call for further research on:

- Variable rod diameters to withstand high torsion at specific moments, while allowing flexibility
- Splice joints and ring joints that can also withstand these forces and allow very specific moments of flexibility
- Aerodynamic design. The current parachute "caps" created enough drag to slow down the fall without the need for the other parachute components, which actually hindered the deployment due to the lateral wind forces deforming the structure of the cross

4. CONTRIBUTIONS

This research shows that room-sized, quickly deployable structures can be built with inexpensive materials and designed to drop from high above the ground before self-assembling in time for landing (Figure 10). There are potential applications in humanitarian and disaster relief efforts, or military applications, where substantial damage to road networks makes it difficult to get people, machinery, or equipment on site. In such cases, the structures could serve as temporary shelters, mobile tents for aid distribution, or act as operation bases. The prospect of combining them opens up the potential for more complex communal configurations; this could take form as a temporary space of spirituality to practice religion while communities are reforming, or even as the shelter for a concert event. These
simple fiberglass rod and parachute assemblies demonstrate that architectural spaces can be packed, collapsed to a fraction of their volume, and dropped to site without skilled labor, complex construction, or expensive machinery. Further, these structures could deploy repeatedly, as a group may easily fold, transport, and drop them indefinitely due to the rod’s elasticity. Finally, the aerial assembly of lightweight structures uses only the embedded material energy and forces of gravity/wind during free-fall for construction, avoiding the typical electromechanical, pneumatic, or other robotic mechanisms for architectural transformation.

Continuation of this research by linking digital and physical experiments could lend greater understanding of the material properties and the delicate balance of stiffness versus flexibility. Additionally, further development of the fabric system to address variable wind conditions and to improve performance in the shelter configuration is needed. Lastly, there is the possibility of expanding the current modular system by differing spline geometry along the rod, the overall form of the assembled structure, and the parachute configurations for both aerial and ground states. Considering the vast possibilities present in these lines of inquiry, the current work is but the beginning to true enablement of the fast, cheap, and aerial self-construction of future architectural structures.

ACKNOWLEDGEMENTS
The studio’s research was made possible through MIT’s School of Architecture and Planning, the MIT Museum, and Autodesk Inc. We thank Aran Chadwick and Neil Thomas of Atelier One for their collaboration to structurally engineer the project. Many thanks goes out to our friends and classmates as well, for their continuing inspiration.

REFERENCES

IMAGE CREDITS
Figure 1, 8-10: James Addison
All other drawings and images by the authors.
Danniely Staback obtained her bachelor’s degree in Environmental Design from the University of Puerto Rico School (’13), where she graduated as Summa Cum Laude. She then worked in several local design and architectural firms, including Muuuaa and Díaz Paunetto Arquitectos, where she collaborated in several award-winning projects. She was admitted at MIT SA+P for her masters as a Graduate Fellow. At MIT, she has been Teaching Assistant and Shop Monitor, and worked in New York, Cambridge, and Zurich. She was recently awarded the M. Pierce / Dean W. Emerson Fellowship Award, and a research travel award for her thesis on the implications of automation for the future of architecture.

MỹDung Nguyễn thinks of space a lot, held by cultural patterns that animate it, by construction systems that form it. She attained a Bachelor of Design in Architecture and a minor in anthropology from the University of Florida, graduating with Summa Cum Laude in 2014. Under the guidance of Doctor Esther Obonyo, MỹDung worked as part of a research analyst team for the National Housing and Building Research Agency of Tanzania. She is a graduate fellow at MIT SA+P, pursuing her Master’s in Architecture while working as a Fabrication Shop Monitor. Her thesis researches imaginings for unincorporated towns in California’s Central Valley.

James Addison is from Charleston, Illinois, a small town in the central part of the state. After graduating from the University of Illinois at Urbana-Champaign with university honors in 2014, James began pursuing a Masters of Architecture at MIT. James’ work has broadly centered around socially-minded design in the developing contexts of central and east Asia. While at MIT, he has worked on urban-rural revitalization projects in the Jiangsu province of China and in West Bengal, India, has researched cost-effective roofing strategies in disaster-prone regions of India, and was the lead design instructor for a technology-based entrepreneurship course in Mongolia.

Zain Karsan is currently pursuing a Master of Architecture at MIT. He received his bachelor’s degree in architecture from the University of Waterloo School of Architecture in 2013. Zain has designed and built a variety of installations with GLD, WOJR, and the Self Assembly Lab and worked for a number of professional practices in Toronto, New York, and Boston. Zain’s interests have revolved around computational processes as they relate to materials, with work spanning from laminar assemblies using thin shell geometries of breglass, to the subtractive processes of machining hardwood. His current research focuses on the design of fabrication tools to reconsider our interaction with materials.

Skylar Tibbits is a Co-Director and the Founder of the Self-Assembly Lab housed at MIT’s International Design Center. The Self-Assembly Lab focuses on self-assembly and programmable material technologies for novel manufacturing, products and construction processes. Skylar is an Assistant Professor of Design Research in the Department of Architecture where he teaches graduate and undergraduate design studios.

Zachary Angles is a M.Arch candidate at MIT. His research interests are located at the intersections between architecture, fiction, and world-building. His thesis, “Narrative Tactics for Making Other Worlds Possible,” explores how architectural design can use world-building to address societal and ecologic externalities in our uncertain times of resource scarcity and climatic crisis. He edited thresholds 45: MYTH published by the MIT Press in 2017 which brought together disciplinary voices to explore how architecture makes myth and myth makes architecture. He founded a research group, The Storytelling Space Group, which has conducted workshops and organized symposia on world-building around the globe.
Anchored structure after landing, only displaying the CAP components.