Rapid Deployable Shell Structures: Bi-layer Bending Systems for Pop-Up Architectural Morphologies

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Abstract. Architects have often employed nature as a tool for design. However, it is not until recently nature has been examined as a system of complex mechanisms. This area of study is known as Biomimetics. This research situates itself within this field by deeply investigating one such biological system, the bi-layer bending mechanism in coiling tendrils, and exploring its relevance in architectural design. This mechanism uniquely integrates the flexibility of pliable materials with the strength of rigid materials to create rapid curling responses when stimulated. When this mechanism is translated into an architectural system, it provides the opportunity to leverage two opposing materials to create self-bending structures. Particularly, the authors found a great advantage in utilizing this system for rapidly deployable shell structures. The inventive use of this bending mechanism creates bespoke morphologies with a few simple elements, creating versatile solutions which can adapt to various conditions. Through this research, the authors investigate this mechanism in a design setting and explore its potential applications at an architectural scale. This work highlights the significance of the application of biological principles in the architecture and design discipline.

Keywords: Biomimetics, Bio-digital design, Bi-layer bending system, Deployable architecture, Multi-objective optimization

1 Introduction

Nature provides an enormous library of techniques and mechanisms which can be leveraged across design fields, yet Biomimetics is still an emerging topic in architectural design due to the lack of a systematic design process model to guide the design process (Samy et al., 2020). Architects have often been inspired by natural systems in their design methods. However, this was initiated as morphological inspiration, rather than an investigation of the intricate mechanisms and processes involved. It is not until recently architects have examined nature as a complex network of processes and interrelationships. To take full advantage of these biological advancements, designers should abstract principles from nature's structures, dissecting their biological rules with a systematic approach. Abstraction reveals the underlying principles, making adaptation into design fields stronger (Vincent, 2001).

Building on this domain, the research investigates the mechanisms of natural systems and their significance in architecture. Specifically, the authors studied the coiling tendril plant and its bi-layer bending mechanism. This principle was tested on physical materials to understand synthetic material behavior and material experiments were conducted to control workability. Once these behaviors were understood, a multi-objective optimization process was used to create a set of performative designs. The authors applied this principle in an architectural setting to the design of rapidly deployable shell structures due to its ability to easily create bespoke morphologies with a few simple elements by exploiting the mechanism's natural bending behavior. These shell structures were then tested through a small-scale prototype to understand the bi-layer bending mechanism's functionality in an architectural setting.

2 Literature Review

Drawing inspiration from biological systems, (Sung et al., 2011) leveraged the adaptability of skin to create self-ventilating building systems using thermal bimetals (TBM). By recreating the skin's specific mechanisms with TBMs, the authors were able to improve upon existing standards in the building industry and develop a more efficient breathable façade system.

Building upon this biomimetic approach, a more detailed study on biological bending systems was conducted by (Gerbode et al. 2012), focusing on the bi-layer bending principles observed in tendril plants. The researchers replicated the coiling mechanisms of a cucumber tendril using elastic bands as a model and suggested designs for biomimetic twist-less springs with tunable mechanical responses. The paper explained in detail the coiling process of the tendril and developed a synthetic coiling system which is molecularly accurate to the biological system.

(Zhan et al., 2023) further explored the trigger-based bi-layer bending system by introducing a time-based actuator. This research replicated the bi-layer hygroscopic movement in plants to trigger a bending mechanism with moisture change. The authors carefully studied the precise changes in bending in respect to a change in the system's parameters and detailed the composite configurations required to take full advantage of this mechanism. While this study had some architectural uses, the research found difficulty in maintaining a bent form for long periods, which limited its scope of application.

All papers showcased a strong consideration for principal abstractions of various biological bending mechanisms. The authors of this paper carefully studied these existing experiments and extracted several key elements which have been integrated into the presented work. (Sung et al., 2011) showed the relevance in leveraging biological bending mechanisms at an architectural scale using industrial materials. (Gerbode et al., 2012) displayed the necessity in utilizing two opposing materials to enact synthetic bending behaviors. Finally, (Zhan et al., 2023) showcased the optimization of designed systems to induce variation and precision in the bending system.

However, while all papers provided a comprehensive study of biological bending mechanisms, their domains largely remained in the replicability of the coiling process rather than an abstraction of it. When applying these mechanisms in architecture, however, a level of abstraction is required to take full advantage of the core biological principles at an architectural scale (Vincent, 2001). As such, the primary objective of this paper is to broaden the practical application of bending mechanisms observed in coiling tendrils and bi-layer systems by abstracting and thoroughly examining the fundamental biological principles at play. This research is particularly oriented towards their integration into architectural designs and structures, aiming to explore how these natural mechanisms can be adapted and utilized within the architectural domain.

3 Abstraction of Biological Mechanisms

To properly translate the coiling tendril's trigger-based bending behavior into an architectural application, the authors carefully studied the biological principles and abstracted their core mechanisms for application on a large scale. Coiling tendrils are observed in short plants which have very little access to sunlight due to shade from their surroundings. As such, tendrils employ a biological bending mechanism to wrap around nearby objects and reach the sun (Darwin, 1875). The coiling mechanism takes place because of an integrated bi-layer system containing two materials with different properties of elasticity: one which is flexible and can contract and the other which is rigid but bendable (Gianoli, 2015). The contracting material initiates a bending which the other follows.

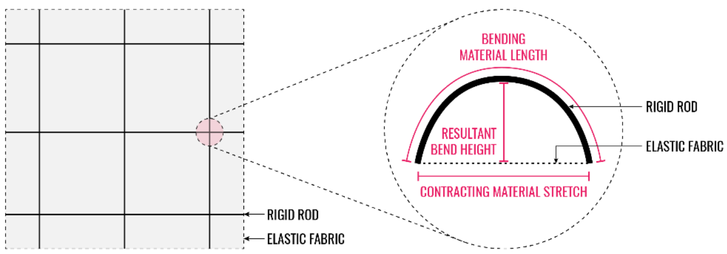

Figure 1. Abstraction of Bi-Layer Bending System (Credit: Authors)

To abstract this concept, the authors experimented with two material qualities which had opposing elasticities. When these materials are joined, they perform the bending action. This bending is highly controllable based on the strengths and dimensions of the two materials, producing a precise bending configuration. The trigger-based initiator was also integrated into the architectural system. This idea was extracted by using a releasing mechanism to cause the structure to bend. When stretched, the system does not bend, but when released, the elastic material’s contraction force causes the rigid material to bend into shell volume. The bi-layer system and the trigger initiator collaborate to create a rapidly deployable shell structure.

4 Methodology: Material Experiments

In order to utilize the bi-layer bending system in an architectural setting, it was first necessary to develop the proper material pairing for the bending system through a series of material tests. The underlying principle of two materials with rigid and elastic properties was maintained for each material pairing. These material pairings were first tested on a small scale. Then, this data was utilized to speculate which material pairing may work on an architectural scale.

4.1 Material Explorations

Spandex, known for its elasticity in all four directions, was chosen as the elastic material for all experiments. It was combined with three relatively rigid materials: PLA, metal wire, and acrylic rod. To enact a bending behavior, the elastic material (spandex) was stretched to the length of the rigid material which induced a bending behavior. The authors conducted multiple experiments to investigate the behavior of two materials with opposing properties. The outcomes provided insights on the use of synthetic materials to abstract a tendrils' bending behavior, showcasing its potential in architectural design.

All experiments maintained the same parameters and dimensions (500mm rigid material length, 1000mm spandex length) to ensure a level of comparability amongst all tests. Each experiment was conducted three times to ensure a level of accuracy among the tested samples. The first material experiments combined spandex and 3D-printed PLA to achieve bending upon fabric release. Observations showed that PLA strips resulted in reduced curvatures and ripples, due to its lack of rigidity and ability to stick to the fabric. Concerns included fabrication challenges, size restriction, and scalability. The accuracy of the 3D printers improved results, but the practicality remained questionable. Metal wire was tested next, due to its higher rigidity (1mm aluminum). The aluminum rod was too rigid, and thus was unable to bend.

Figure 2. Initial Material Explorations (Credit: Authors)

While the other material pairings were unsuccessful in creating a controllable bend, the acrylic rod experiments showed greater results, offering flexibility and controllability without deformation. As such, spandex and acrylic rods were the most promising materials for the bending system. Figure 2 showcases a small sample of the material tests and resultant bending behavior.

4.2 Material Variable Control

After selecting spandex and acrylic for the bi-layer system, experiments were conducted to analyze spandex's elasticity and gain control over the degree of curvature created. These investigations played a vital role in understanding both materials' capabilities and limits, as well as calibrating the digital model.

Spandex Elasticity Test

The experiment aimed to determine the fabric's elasticity. The fabric's original length was 150mm, and it was subjected to a 600g linear load, stretching it to its maximum capacity. After three trials, the average calculated fabric elasticity was 0.012GPa using Hooke's Law. This metric provided crucial material property information for the computational framework and for guiding the selection of architectural-scale materials.

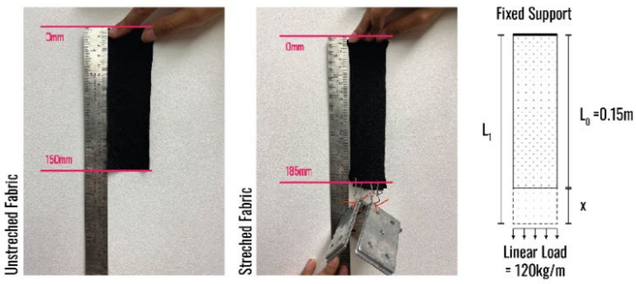

Figure 3. Spandex Elasticity Test (Credit: Authors)

Bending Control Test

To control the system's curvature, the authors tested the relationship between acrylic rods and spandex fabric with varied lengths. Keeping the acrylic rod length constant at 1000m, fabric lengths were incrementally varied to observe the resultant bending. Two experiments were conducted using 4mm and 5mm

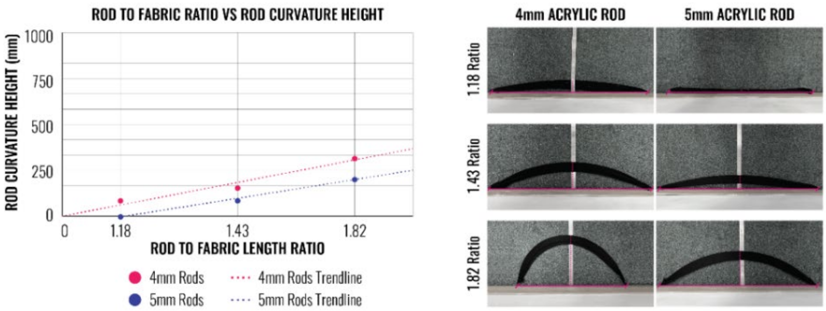

Figure 4. Bending Control Test (Credit: Authors)

thick rods and each experiment was conducted three times to increase accuracy. The authors found that increasing the rod length to fabric length ratio led to higher bending. The optimal curvature, which is the maximum achievable bend without plastic deformation or breakage, occurred at a length ratio of 1.82, while below 1.18 or above 1.82, consistency diminished. Rod thickness also affected curvature, where 4mm rods showed more bend than 5mm rods. This data was used to calibrate the computational bending model.

4.3 Translation of Small-Scale Materials to Architectural-Scale Materials

Transitioning from the small-scale materials to an architectural scale posed challenges due to material functionality differences. However, the authors discovered the ratio between the two materials' elasticities was a transferable property between scales. This comparability of ratios was determined through digital experiments on one small-scale and one architectural-scale material system using Kangaroo, a physics engine. A spandex and acrylic rod system was compared against a nylon and carbon fiber rod system. Both systems had very different elasticities but had the same elasticity ratio between the materials.

The observations showed that the carbon fiber and nylon system bent in a remarkably similar manner to the acrylic and spandex system. The ratios of rod length to bending depth were nearly identical, indicating proportionality in the bending produced. Based on these findings, the authors concluded that the elasticity ratio was a transferable variable. Additionally, this experiment showed a carbon fiber and nylon system would be suitable at the architectural scale.

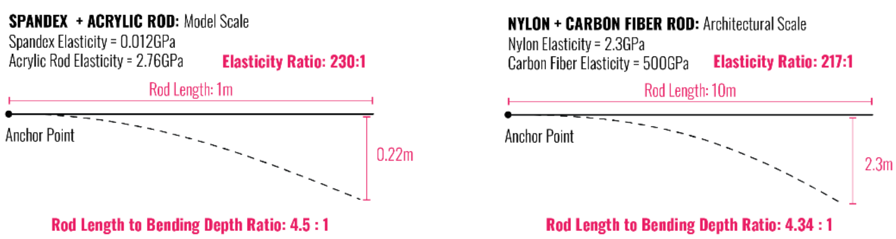

Figure 5. Material Translations (Credit: Authors)

4.4 Digital to Physical Translation

Once the properties of the bi-layer bending system were determined from the physical experiments, it was necessary to accurately translate the bi-layer bending behaviors into a digital system. This enabled the authors to computationally optimize the bending behaviors in the designed shell structure system and accurately analyze their resultant morphologies to determine the best performing candidates. The behavior was modeled in Kangaroo using a rigid rod with a spring attached at both ends to simulate the elastic forces of the fabric in combination with the resistive forces of the stiff rod. The elasticity values and rod to fabric ratios established from the material tests were utilized as inputs to calibrate the digital system.

5 Methodology: Shell Structure Form Creation

5.1 Optimization of the Bi-Layer Bending Shell Structure System

Once the authors gained control over the bi-layer bending system, the behaviors could be leveraged to design a rapidly deployable shell structure system. However, such an architectural artifact required high performance in several complex domains including structural stability, constructability, and material behavior. Thus, it was necessary to use multi-objective optimization to determine an appropriate morphology which satisfied all fitness criteria.
Multi-objective optimization is a process which leverages a set of parameters, or genes, to systematically improve a morphology in reference to several conflicting objectives. Since the fitness criteria are complex and opposing in nature, the result of such a process provides a set of non-dominated high performing individuals, or pareto front members, who are highly tuned and equally fit for the given design problem. As such, multi-objective optimization proved to be an appropriate methodology for solving complex design problems and obtaining unique, yet high-performing shell structures.

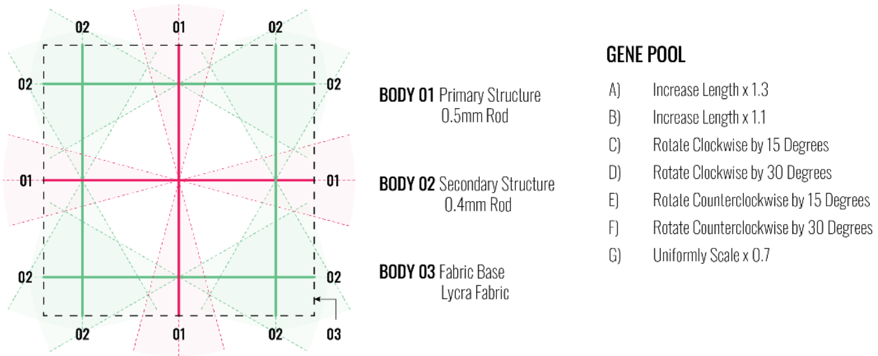

Figure 6. Primitive and Gene Pool (Credit: Authors)

The authors have constructed a streamlined variant of a multi-objective optimization process within the Grasshopper environment, which serves as a visual programming interface for Rhino3D software. This was done to obtain complete control over the crossover and mutation operators throughout the course of the evolutionary simulation. Though this might prolong the time required to execute the optimization problem, it significantly contributes to comprehending the effect of every design decision made during the evolutionary process. As a result, a knowledge base and a functional framework were created to expand this application further using automated processes and pre-existing evolutionary solvers in future studies carried out by the authors.

5.2 Multi-Objective Optimization Experiment

The primitive form for the shell structure consisted of several rigid rods placed on a rectangular fabric base. The controllable genes for this morphology included rod and fabric placement, length, rotation, and size. These parameters allowed for a wide range of achievable shell structures. The morphologies were created by locating the fabric and rods on a flat plane and applying the previously developed bending simulation to achieve a more accurate form. This allowed for a more accurate analysis of the individuals' performances.

Three fitness criteria (FC's) were developed which aimed to produce structurally stable and constructable morphologies. To achieve the former goal, the first objective was to minimize structural deformation (FC 01). This criterion was measured by using a Finite Element Analysis simulator, Karamba 3D, to determine the maximum deformation with gravity and self-weight loads. To achieve the latter goal, two additional criteria were developed. First, a rod to fabric ratio closest to 1.8 (FC 02), which is the practical maximum for fabrication, would ensure the structure had a large degree of curvature, yet was still feasible to build. This was measured by dividing the length of a rod by the length of fabric. The authors also found that minimizing the height difference between the rods (FC 03) allowed the shell structure to remain within the limits of the fabric's elasticity. This was measured by subtracting the heights of the highest and lowest rods. These three fitness criteria increased the probability that the resultant individuals, or phenotypes, would be structural and constructable.

Once the set-up was determined, the multi-objective optimization could be performed. This was done by randomly generating an initial population (generation 00) of ten shell structures using the given genes and systematically breeding them to achieve better performing individuals. This breeding process began with an analysis of each shell structure's fitness criteria performances, followed by a systematic breeding process using the best performing phenotypes to promote more fit individuals over time. Additionally, a mutation was induced randomly to maintain variation in the resultant morphologies throughout the process. This multi-objective optimization method was carried out over ten generations to create a total population size of 100 individuals.

Figure 7 shows a sample of created structures and their performances from the multi-objective optimization. Throughout the process, the authors saw three major trends in the shell structure phenotypes: improved structural stability, improved constructability, and opportunities for openings and segmented volumes. These improvements can be seen in five of the pareto front members. While none of these pareto front members are definitively better than the others, they each have different strengths and weaknesses which afford unique opportunities for each shell structure. The standard deviation graphs continue to support the success of the optimization process as well, where the generated shell structures consistently improved and converged in all fitness criteria as each generation passed (shown as a movement towards 0.0). As such, the final generations of shell structures are highly developed in reference to the given objectives of structural stability and constructability.

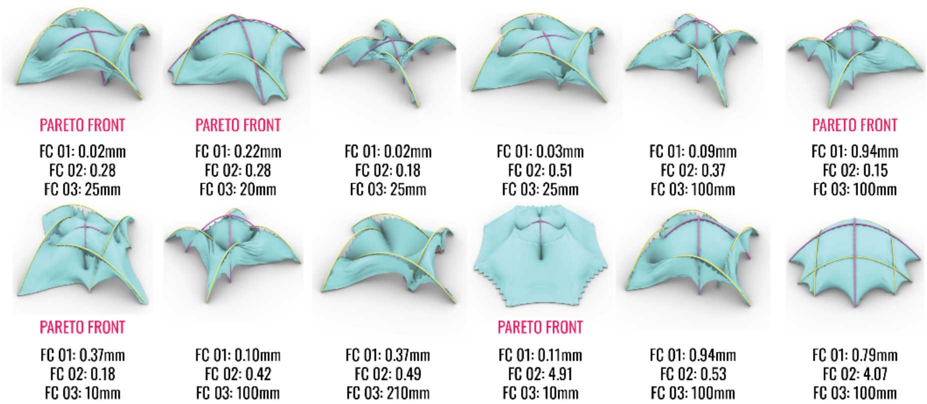

Figure 7. A Selection of Shell Structures (Credit: Authors)

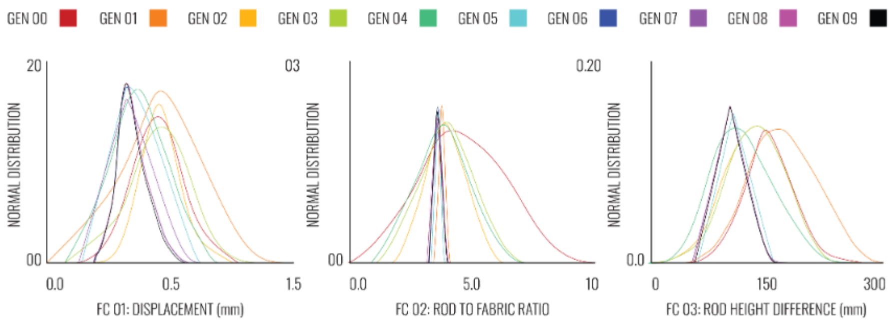

Figure 8. Standard Deviation Graphs (Credit: Authors)

5.3 Architectural Application

The core bi-layer release-based bending mechanism in the developed shell structures were found to be particularly functional as pop-up structures for architectural interventions. These structures could be easily set up and dismantled, providing versatility and unique forms through simple fabrication logic. The design and fabrication strategy aimed to make these rapidly deployable structures user-friendly, with off-site manufacturing and DIY construction using minimal effort and straightforward steps. Potential applications include flea market structures, temporary backyard sheds, exhibitions, refugee camps, and public space events. The inventive use of a simple bi-layer bending mechanism allows for bespoke morphologies to be formed with a few simple elements, creating versatile solutions which are easy to assemble and adapted for various functions and locations.

5.4 Physical Prototype

To test the viability of the resultant shell structures from the multi-objective optimization process, the authors physically constructed a small-scale model using acrylic rods and spandex fabric. This material paring was shown to perform similarly to the architectural-scale materials during the initial material tests. The authors selected the most balanced pareto front member in all three fitness criteria for the small-scale prototype. Such a selection methodology established a shell structure which was the most viable for construction. Additionally, this phenotype had the best spatial quality of all the pareto front members in terms of the openings and interior volumes it created.

The fabrication process began with a deconstruction of the three-dimensional form into a flat pattern. Then, all materials were cut to size and a series of internal pockets were sewn onto the fabric. This ensured the rods remained in place throughout the construction process. Finally, the rods were inserted into the sewn slots and the shell structure was released into its final bent form. Figure 9 shows the final constructed morphology.

Figure 9. Small-Scale Prototype (Credit: Authors)

While the construction of the small-scale prototype was certainly not identical to the construction of the architectural-scale rapid deployable shell structures, the authors found that the fabrication study did bring forth several major insights which can be applied on a larger scale. To achieve a pop-up structure all strings of the fabric needed to be reeled together to achieve the shell-shaped structure. If one end released faster than the other, there was a visible asymmetric stretch on all the rods. This caused the structure to be lopsided, where the structural members were not aligned perpendicular to the ground. As such, a more automated stretch and release system may be required on the architectural scale. Additionally, since this fabrication process was done manually, the materials could not be used to their full potential. The stitched pockets lacked accuracy, causing the fabric to bunch in particular areas. On the architectural scale, these construction issues could be easily resolved if the stitching and fabric creation are done more precisely by accurate machinery.

6 Discussion and Limitations of the Research

While the project showcased a strong integration of the coiling tendril's bi-layer bending mechanism in architecture to design deployable shell structures, there were several improvements which could strengthen the project in the future.

First, a more careful study of the nylon and carbon fiber rods at a large scale would further inform the capabilities of the proposed shell system. While the authors did attempt to create comparisons between the small- and large-scale materials, a lack of resources prohibited more in-depth experimentation on the system's functionality at an architectural scale. Particularly, the elastic and plastic fields of carbon fiber rods should be studied. If the rods are bent beyond their elastic capabilities, they will maintain a bent form and restrict disassembly. As such, future research can focus on analyzing the limitations of architectural-scale materials and integrating their domains as design constraints.

Additionally, future research can focus on the scalability of the proposed shell structure system. The current explorations limited the boundaries of the architectural design to the size of a small pavilion. However, further experimentation can be conducted on how this system may scale up to enable a much larger variety of applications and functions. Such a study can consider how materials may be discretized to achieve much larger structures, and how this segmentation may affect the bending properties of the system.

Finally, additional research can be conducted on the fabrication process at an architectural scale. The small-scale prototype showcased the necessity for an even and consistent release system to mitigate asymmetrical bending and fabric bunching. As such, experimentation may be required to carefully develop an automated stretch and release process which can trigger all rods simultaneously to ensure the shell system functioned as designed.

7 Conclusion

Through this research, the authors investigated the application of a trigger-based, bi-layer bending mechanism in a design setting and explored its potential applications at an architectural scale. Leveraging such a performative biological function for design purposes allowed for the formation of large-scale shell structures with the capability to construct bespoke morphologies by simply integrating a few simple rods within an elastic fabric. As such, this design solution can potentially lower costs, minimize shipping space, and reduce construction times as compared to traditional shell structures.

The presented experiments demonstrate the significance of the application of biological principles across the architecture and structural design disciplines and provides a framework of how the abstracted principles from a natural system can contribute to the design and fabrication of rapid deployable shell structures.

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