Investigating Wing Properties through Bio-Inspired Construction

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ABSTRACT

Across various fields, design possibilities are often limited by material properties and manufacturing methods. However, novel manufacturing methods have exponentially increased the possibility for property optimization. Our research objective is to analyze biological structures for material construction and to build and subsequently test these structures for property optimization. Utilizing CAD modeling software on Solidworks, physical 3D prints, and stress tests conducted by an Instron, we designed, tested, and attempted to optimize properties in a typical dragonfly wing.

Our approach began with designing typical dragonfly wings with inbuilt Voronoi structures, printing such structures, then physically testing them for equivalent and principal stress. Then the iteration process began, where areas of high stress were adjusted to increase overall stress test efficacy. Future work includes possible machine learning algorithms used on training data to automatically increase strength. This basis of this research involves customization of materials and bio-inspired structures, a field that allows us to manufacture and tailor materials for specific applications in any area.

INTRODUCTION

Background Overview

The main focus of this research has two underlying foundations. The first goal was to explore the possible advantages to biological structures and bio-inspired rules of material construction. The second objective was to explore these natural rules with respect to aerospace, more specifically analyzing the stress properties of dragonfly wings.

First exploring bio-inspired rules of nature, our goal was to research natural systems to create structures that take a high amount of energy to fail. Construction in nature relies on reacting to the environment and adapting to it rather than following a sequential, systemic method of construction. After researching different bio-inspired construction techniques already in play, we found that typical wings follow traditional honeycomb structures *(as seen in Figure 1)*.

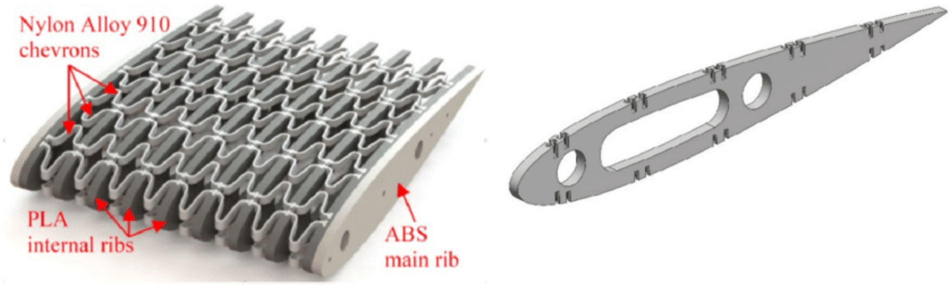

Figure 1: Traditional internal honeycomb airplane substructure (www.researchgate.net)

Airfoils are used as the basic form of a wing, a horizontal stabilizer inside airplane wings whose curved structures allow for favorable lift and drag throughout a flight. Our hope was to combine these traditional construction methods with stochastic structures and test the strength of these potential structures.

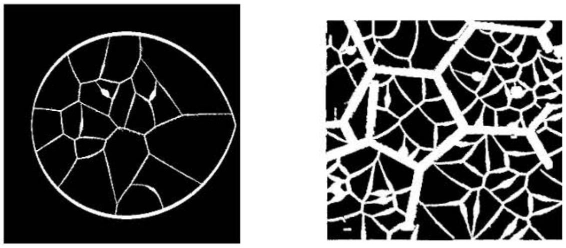

Figure 2: Example structures with stochasticity generated by bio-inspired rules

Exploring the second concrete goal of this project, we aimed to utilize iteration and the design processes to build and test prototypes resembling dragonfly wings. This involved initially analyzing the vein patterns evident in dragonfly wings. The structure of the wing is formed by a Voronoi diagram, which allows for lightweight use of the wing with a limited use of material. Apart from the basic large vein patterns that seemed to be mirrored on each wing across different dragonflies, the individual smaller vein patterns displayed an apparent facet of randomness.

Research Goals

Thus the main objective of the research is to first understand the properties of wings in nature, then research dragonfly wings and the method that the structure stayed lightweight. Finally the goal is to investigate how stress is distributed across the vein patterns. The goal is also to train prototyping skills (CAD modeling, manufacturing, stress tests), utilize effective experimental skills through iterative work, and build a strong foundation in solid mechanics.

PURPOSE

Broadly approaching the objective, our purpose is to utilize bio-inspired designs for material construction, and to build and subsequently test these structures for property optimization. Our motivation is to generate lightweight, strong structures for different applications. We will run simulations testing different properties to create parts that in the future are envisioned for aerospace, prioritizing lightweight, resilient structures.

More specifically, the purpose that the project began with was to identify the favorable properties that a bio-inspired stochastic wing presented in comparison to traditional wings. Taking this further, we hoped to analyze how those specific properties could be optimized in a specific structure. Design optimization is a key advantage with respect to building prototypes through 3D printers and Computer Aided Design modeling. Therefore, iterative building of different models after conducting tests for stress would allow property optimization on an initial small scale.

Our design implementation will follow patterns such as Voronoi designs and cell structures. After researching different bio-inspired construction techniques, we will implement them to design prototypes. Such designs open up possibilities for customizing both outer shapes and internal structure.

The specific question we address is how stress is distributed across the veins of a dragonfly wing, and how such structures can be optimized.

METHODS

The following details the brief procedure:

1. Research advantages to bio-inspired designs and design specific used in aircrafts
2. Create two dimensional CAD drawings resembling a chosen structure (dragonfly wings)
3. Employ CAD features such as offset entities to render a three dimensional dragonfly wing
4. 3D print prototypes of the dragonfly wing and identify properties to test
5. Using an Instron, conduct necessary stress tests
6. Analyze stress distribution results across the dragonfly wing
7. Review and edit the model based on these results, and continue the iterative design process by redesigning, reprining, and retesting the new models

The first step in this research involved reading and analyzing the advantages of bio inspired designs as a whole. The aforementioned advantage to bio-inspired designs deals with the way that nature employs a level of randomness in design. When the method of disruption to a given object is known, such as stress applied to one specific area in a controlled testing environment, building a known structure with limited variability can be far more advantageous. However, when the disruption to the material is variable and dependent on the environmental properties surrounding the object, the inbuilt random designs of nature allow for stronger resilience when faced with contingent possibilities. Further, the advantage to bio-inspired designs or biometrics is the awareness that such biological systems have been naturally advanced and progressed depending on natural circumstances over a multitude of years. Therefore commonly known biomimetic technology such as whale inspired wind turbines, velcro, and spider-web glass take advantage of the natural testing done over years of pressure from the environment.

Following this investigation, the second goal was to look into specifics of airplanes and therefore common properties that were seen throughout different parts of the wing. This would allow us to choose a property to later optimize in the dragonfly wing. The first research went into air foils and the various different versions of such airfoils. After sketching different possibilities, I compared the basic airfoil design to that of the dragonfly wing (as seen in Figure 3).

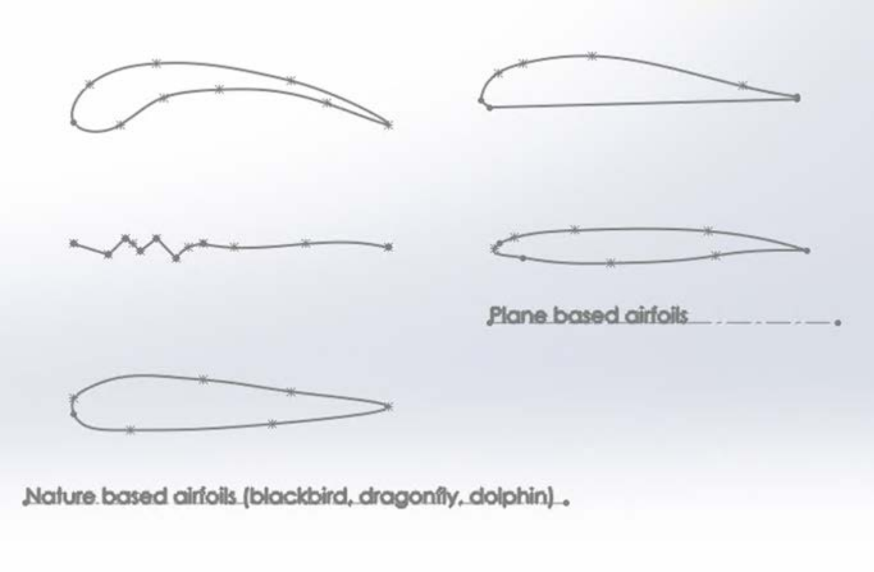

Figure 3: Sketches of various airfoil designs

Then, I identified the main features seen in common aerospace airfoils. This included the basic design specifics such as the leading edge radius, the airfoil contour, and the chord length. It also included the camber line and chord line. The camber line displays the curvature of the airfoil, laying halfway between the upper and lower sides of the airfoil and intersecting the chord line. The chord line is seen as a connector between the leading and trailing edges of an airfoil. Both of these imaginary lines are visualized in the sketch that I drew through CAD software (as seen in Figure 4).

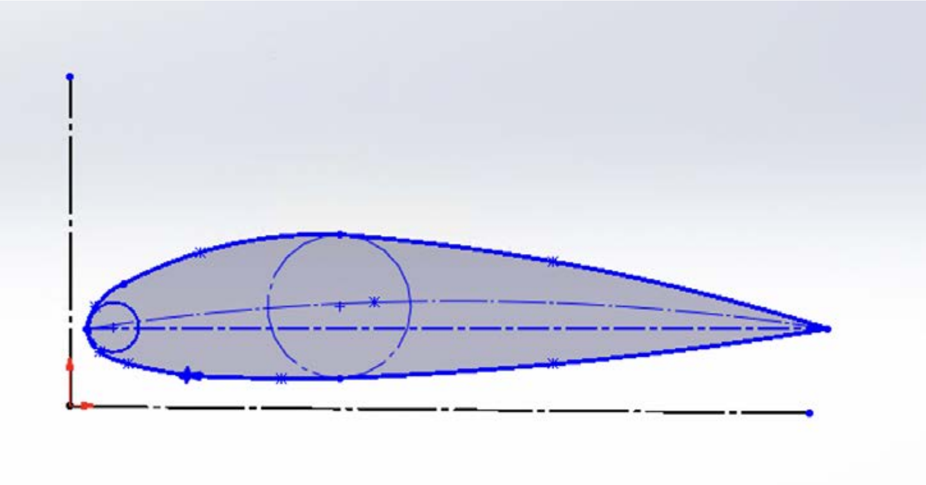

Figure 4: Typical airfoil design specifications

I then took an existing dragonfly wing and created a two dimensional sketch that mirrored the vein patterns of the wing. I mirrored this basic structure of the right wing onto the left wing to view the basic similarities between each wing. I then included contours in the right wing with specific intentional voronoi designs displayed. This allowed a visualization of the dragonfly wing that could be manually manipulated for optimization in later steps. While several sketched vein patterns were near exact replicas of the initial dragonfly wing pictured, others had variability from manual creation. This mirrored some of the randomness seen across different dragonfly wings.

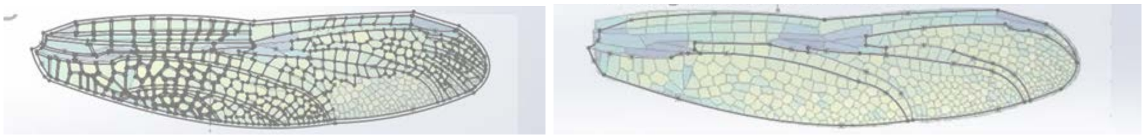

Figure 5: Dragonfly left wing vein patterns mirrored onto right wing

I then took this two dimensional sketch and began to offset each entity to create a three dimensional dragonfly wing. To ensure consistency, each large vein that separated the sections and remained constant across different wings had a thickness of .1 cm, while each individual smaller wing had half the thickness, reaching only .05 cm. Before completing the full drawing, I also created a honeycomb structure inside the basic dragonfly wing structure to view visual differences.

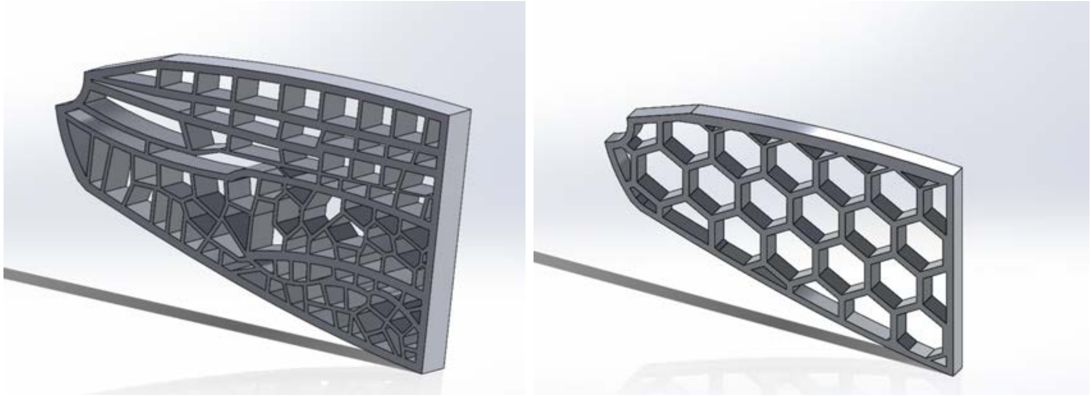

Figure 6: Initial comparison between dragonfly vien pattern and honeycomb structure

Then I completed the 3D creation of the initial wing manually. Having a 3D wing built specifically on computer aided design software allowed for manal optimization wherever necessary. Beams could be included both horizontally and vertically, entities could be fileted for softer edges, thickness of such beams could be increased for strength.

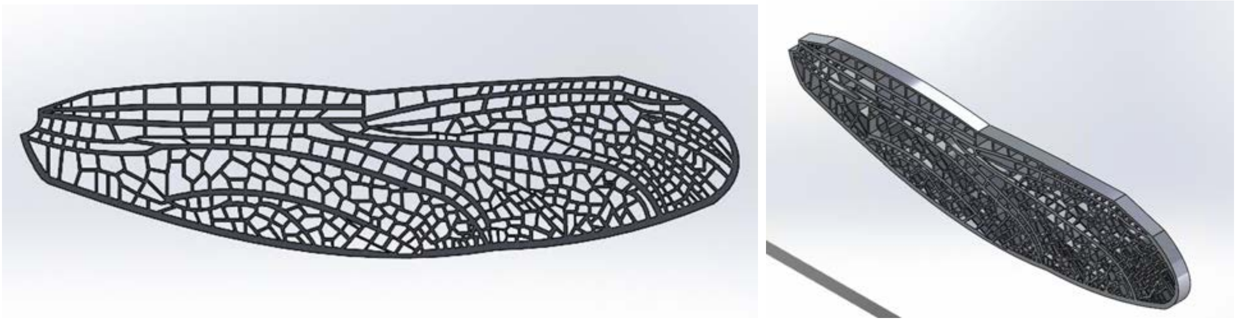

Figure 7: Three dimensional CAD visualization of dragonfly wing prototype

After the first three dimensional CAD model was built, we 3D printed the model to be able to physically conduct stress tests on the object. This step allowed me to physically learn the specifics behind 3D modeling as I was able to inspect the set up, loading, and manual building involved in the 3D printing process.

Figure 8: Physical 3D printing of dragonfly wings in action

Once the object was 3D printed, stress tests were conducted with an Instron. Here, I was also able to learn to use such state of the art technology. The instron machines allow for an array of testing possibilities including tensile, compression, impact, structural, fatigue, and far more. For this specific project, the goal was to use a three point bend test. Through this test, we were able to analyze the stress distribution across the object, both looking into equivalent and principal stress. Images of the stress distribution can be seen in the results section of the report.

After such diagrams were produced, I was able to investigate which areas were clearly of higher stress, thus weakening the structure. Therefore I made a variety of edits for each iteration. I included supporting vertical beams in areas of high stress. I added several larger spanning horizontal beams for overall strength. I included filets throughout various regions of the wing, varying and increasing filet thickness depending on the stress in the given area.

This process showed me the distinct importance of the iterative design process. This unique and effective process involves brainstorming and eventually building a prototype, only to continually improve the product after analyzing initial results. Implementing various prototypes of the same model allowed me to see differences caused by such iterations and detailed inclusions, rather than only looking at the efficacy of the structure as a whole.

RESULTS

After conducting several 3D prints and running stress tests on the model, we created stress distribution drawings of the dragonfly wing focusing on two different facets of stress. The first was equivalent stress and the second was principal stress.

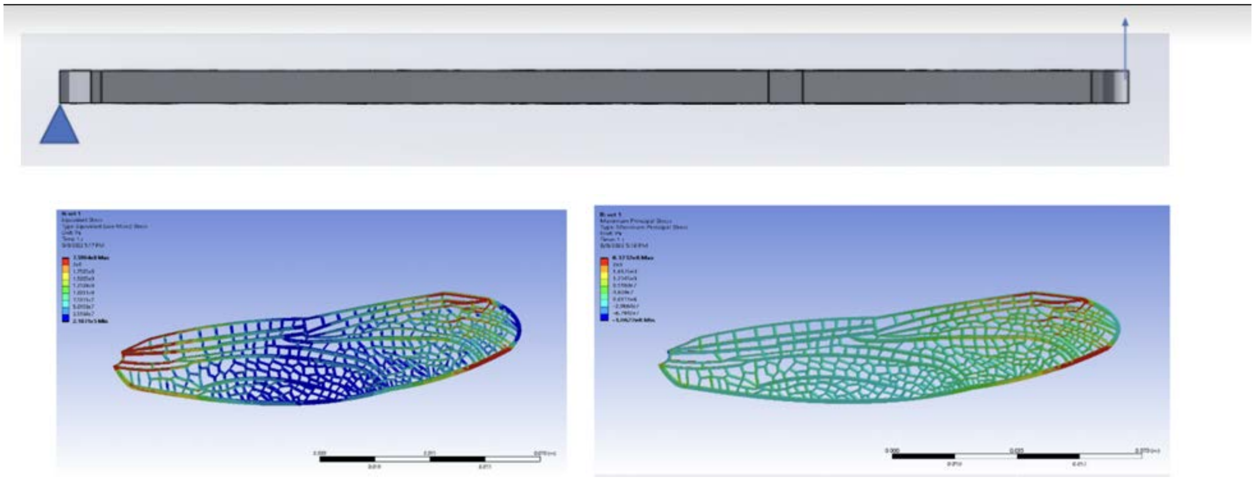

Figure 9: Bending test (pictured above) followed by equivalent stress distribution (pictured left) and principal stress distribution (pictured right)

Multiple iterations were made off of the stress diagrams, each iteration allowing us to focus on a singular property rather than the wing as a whole. Comparisons between different sets can also be visualized.

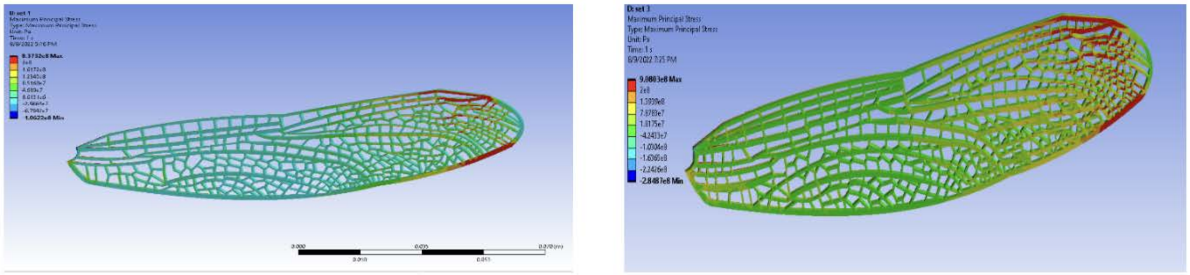

Figure 10: Comparisons between iterations with principal stress test distributions

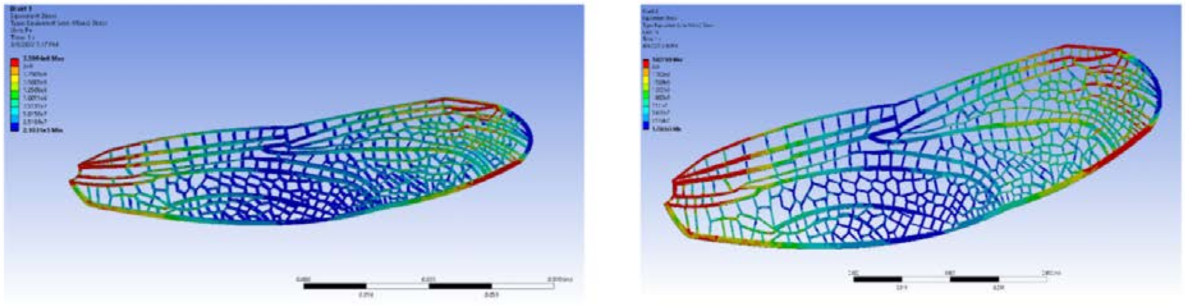

Figure 11: Comparisons between iterations with equivalent stress test distributions

Equivalent stress is represented by just a value and no associated directions. It represents the material's ductility. Equivalent stress is seen through the following formula:

EQUIVALENT STRESS:

$$\sigma_v^2 = \frac{1}{2}[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{23}^2 + \sigma_{31}^2 + \sigma_{12}^2)] = \frac{3}{2}s_{ij}s_{ij}$$

Principal stress is a tensile stress with associated directions. There is no shearing component associated with principal stress. The following formulas dictate principal stress:

PRINCIPAL STRESS

$$\sigma' = Q \cdot \sigma \cdot Q^T$$

$$\sigma'_{xx} = \sigma_{xx}cos^2\theta + \sigma_{yy}sin^2\theta + 2\tau_{xy}sin\theta cos\theta$$

$$\sigma'_{yy} = \sigma_{xx}sin^2\theta + \sigma_{yy}cos^2\theta - 2\tau_{xy}sin\theta cos\theta$$

$$\tau'_{xy} = (\sigma_{yy} - \sigma_{xx})sin\theta cos\theta + \tau_{xy}(cos^2\theta - sin^2\theta)$$

$$\sigma_{max,}\sigma_{min} = \frac{\sigma_{xx}+\sigma_{yy}}{2} \pm \sqrt{(\frac{\sigma_{xx}-\sigma_{yy}}{2})^2 + \tau_{xy}^2}$$

CONCLUSION

Throughout this research process, I was able to investigate the nuances of bioinspired material construction, facets of the aerospace manufacturing process, dragonfly stress distribution and associated property optimization, and the importance of the design process through iterative design. For future progress, the goal is to algorithmically generate structures that are optimized for the aerospace environment. From here, we will continue to test for structural optimization of our designs. Isolating a variety of different variables, we will be able to optimize properties such as toughness, strength, stability, and weight and conduct tests to generate further data. In fields where design possibilities are limited by material properties and manufacturing methods, this research can have a heavy impact.