ME-438: Final Project Report

Strength-to-Weight Ratio Optimization of Spider-Web Structures

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1 Introduction

Lightweight, high-performance structures are essential in a wide range of fields, including aerospace and automotive engineering, as well as biomedical implants [3][5]. However, exploring the vast design space of bio-inspired geometries, such as spider-web–style lattices with dozens of interacting parameters, via traditional trial-and-error methods or exhaustive parametric sweeps are prohibitively time-consuming and costly.
The integration of SolidWorks and ANSYS simulations with a Bayesian optimisation loop in MATLAB facilitates the construction of a probabilistic surrogate model of strength-to-weight performance. This model serves as a guide, directing each new design choice towards regions of both high promise and high uncertainty. Consequently, the necessity for conducting a high number of costly real-world experiments to ascertain the optimum is significantly reduced. The result of the process is a web structure that is minimal in mass and maximally stiff, with a wide range of possible applications.

2 Design Problem

The objective of this project is to optimize the strength-to-weight ratio of bioinspired artificial spider webs, maximizing the load-bearing capacity while minimizing material use. Inspired by the structural efficiency of natural webs, we aim to design web structures that are both lightweight and mechanically robust. The following objective function was selected to guide the optimization:

$$\max_{\mathbf{x}} \frac{F_{max}(\mathbf{x})}{m(\mathbf{x})} \tag{1}$$

where F_{max} is the maximum load capacity from ANSYS FEA and m is the total mass of the web structure $\mathbf{x}$.
The design problem is subject to four discrete design variables (the number and radii of radial and spiral threads), the overall web radius, and several material properties of thermoplastic polyurethane (TPU).
The four design variables were hypothesized to be the most geometrically relevant to describe the load bearing capacity of the web structures. Together, they encoded the geometry of the designs, whose overall size was constrained by r_{web}.

Number of radial threads	n_{radial}	$\in [5,\ 6,\ \cdots,\ 15]$
Number of spiral threads	n_{spiral}	$\in [5,\ 6,\ \cdots,\ 15]$
Radius of radial threads	r_{radial}	$\in [2.5,\ 3,\ 3.5,\ 4]\,\text{mm}$
Radius of spiral threads	r_{spiral}	$\in [0.5,\ 1,\ 1.5,\ 2]\,\text{mm}$
Radius of the web	r_{web}	$= 400\,\text{mm}$

In previous publications, polylactic acid (PLA) [1][2], was utilised to model artificial spider web structures. Consequently, this was the approach adopted in the present study. In order to maintain the capacity to print the web structures with the components supplied in class, the simulation was adapted to TPU, whose properties [4] are given here and used in **section 3**:

Density	ρ_{thread}	$=$	$1240\,\text{kg/m}^3$
Poisson number	ν_{thread}	$=$	0.35
Young's modulus	E_{thread}	$=$	$2000\,\text{MPa}$
Shear modulus	G_{thread}	$=$	$740.74\,\text{MPa}$
Bulk modulus	K_{thread}	$=$	$2222.2\,\text{MPa}$
Yield stress	σ_{yield}	$=$	$42\,\text{MPa}$
Tangent modulus	$E_{\tan}$	$=$	$960\,\text{MPa}$

It was determined that no further reduction of dimensionality was necessary, given that the four variables were both low-dimensional and discrete. The resulting search space contains $11 \times 11 \times 4 \times 4 = 1936$ unique designs.

The initialization of the Bayesian optimizer was achieved through the generation of four seed designs using a Latin Hypercube Sampling (LHS) over the four-dimensional domain. These seeds guarantee adequate coverage across the extremes and midpoints of each parameter's range, thereby ensuring a robust surrogate fit from the outset. Subsequent iterations then balance exploration of under-sampled regions with exploitation around high strength-to-weight candidates. These formed the basis for further data-driven optimization, as explored in **section 4**.

3 Experimental Setup

Experimental Pipeline

We implemented a closed-loop pipeline as shown in **Figure 1** that begins in MATLAB, where four initial designs are drawn from our four-dimensional parameter space via Latin Hypercube Sampling. A Python script then automates SolidWorks to generate the corresponding 2D sketches, which are exported as STEP files and imported into ANSYS. In SpaceClaim, we assign the correct cross-sectional areas to all web members and share their intersecting nodes to create a single contiguous part. Within ANSYS Mechanical, all exterior nodes are fixed and a load is applied perpendicular to the web face at its central node; we then employ the Direct Optimization block—using TPU with a 42 MPa yield strength as objective—to determine the maximum load capacity. The resulting strength-to-weight ratios are returned to MATLAB's Bayesian optimization routine to propose the next design. This process is repeated until convergence is achieved or a cap of twenty computationally expensive FEA evaluations is reached.

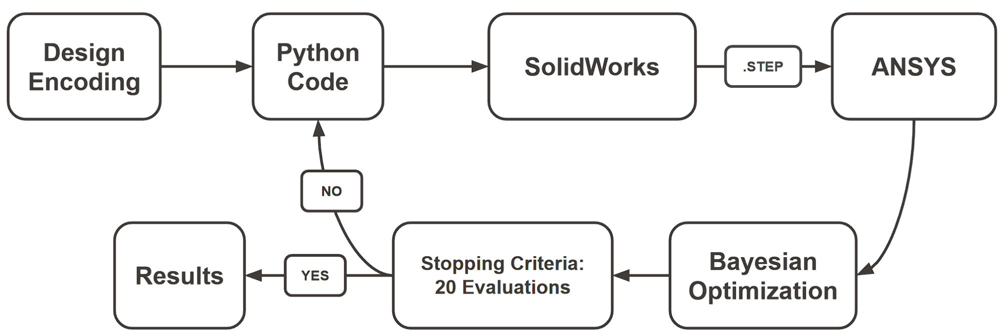


Figure 1: Experimental Pipeline for Strength-to-Weight Ratio Optimization of Spider-Web Structures

Data Quality and Computational Trade-offs

The ANSYS Direct Optimization block ensures high precision in determining the maximum load capacity, consistently converging to a yield strength of 42 MPa with a tight tolerance of ± 0.1 MPa. This narrow margin reflects the robustness of our FEA setup and the reliability of the optimization process. However, due to the computationally expensive nature of the workflow—including pre-processing in

SolidWorks, cross-sectional area assignments in SpaceClaim, and lengthy ANSYS simulation runs—we imposed a strict cap of 20 evaluations in the Bayesian optimization loop. While this limits the breadth of design exploration, it balances computational feasibility with sufficient data quality for meaningful convergence. The trade-off ensures practical runtime without compromising the precision of individual evaluations, though future work could explore surrogate modeling or parallelization to improve efficiency.

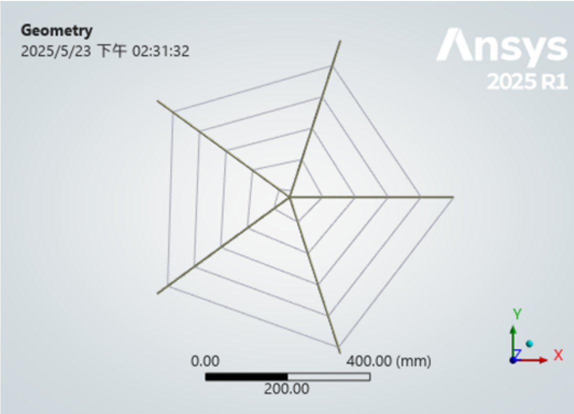
4 Data-Driven Method

For the optimization problem at hand, Bayesian optimization was identified as suitable given the design problem. Due to the costliness of the data, an optimization method requiring a few data points was favored given the experimental setup. The time required for pre-processing and design generation was the main reason for the cost of the data. Implementing Bayesian optimization would also allow for maximal improvement feedback per design evaluation, ensuring high data efficiency. The high data efficiency of Bayesian optimization diminishes with higher dimensionality, which supports the suitability of Bayesian optimization for the four-dimensional design problem at hand. Data efficiency is also achieved by modifying the exploration ratio, allowing the shift from exploring the design space to exploiting good solutions.
The Bayesian optimization code was implemented in MATLAB, with the acquisition function Expected improvement Plus, using a Gaussian Process. A segmented optimization was realized through a decay function that progressively reduced the exploration ratio in four Stages from 0.9, 0.64, 0.38, to 0.2. The discrete variable space was processed by integer variable handling which maps the variable spaces to integer indices. Simulation results were input manually, after having been evaluated, as previously mentioned in **section 3**.
Expected Improvement Plus (EI+) was selected as an acquisition function, because it strategically balances exploration and exploitation while mitigating the risk of over-committing to deceptive local optima- a limitation of standard Expected Improvement (EI). Unlike EI, which targets the best observed value directly, EI+ uses a conservative baseline (the lower confidence bound, L(x+)) to guide the search towards statistically robust regions that show promise. This approach is particularly advantageous in low-dimensional problems that are expensive to evaluate, where sample efficiency is critical.
The stopping criterion was based on the number of evaluations that could be performed within the time frame, but can be adjusted in future implementations. No further tuning of the objective problem was deemed necessary as a result of the design space simplicity.

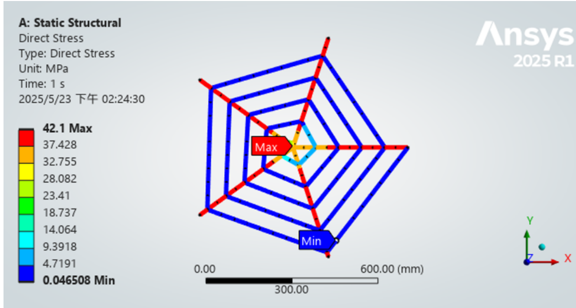
5 Results

As a result, the Bayesian search converged on the smallest-possible web geometry as the optimum: 5 radial threads, 5 spiral threads, a radial-thread radius of 2.5 mm, and a spiral-thread radius of 0.5 mm (**Figure 2a**). Despite its minimal material usage (0.054 kg), this design can handle a 720N force at the center node (**Figure 2b**), which delivered the highest S/W ratio (13225.79) of all 1,936 candidates—demonstrating that, for TPU under our load and boundary conditions, concentrating material in a few thicker filaments rather than proliferating many thin ones yields the most efficient structure.
The pair-wise scatter and marginal histograms in **Figure 3** reveal that the S/W ratio decreases nearly monotonically as each design parameter increases. In particular:

- **Number of radial threads, n_r:** We can see that extreme values of n_r has the best S/W ratio.
- **Number of spiral turns, n_s:** As n_s grows from 5 to 15, the S/W ratio falls by about 1×10^3, reflecting diminishing returns in strength for added spiral mass.



(a) Optimal Web Geometry from our Optimization



(b) Simulation Results of the Optimal Web Structure

Figure 2

- **Radial thread radius r_r and spiral thread radius r_s:** As radii increase, S/W ratio decreases, since mass increases with radius squared, so thicker threads penalize weight a lot.

Overall, the highest S/W ratios cluster at the minimum values of all four parameters, which explains why the Bayesian optimizer converged on the smallest web geometry.

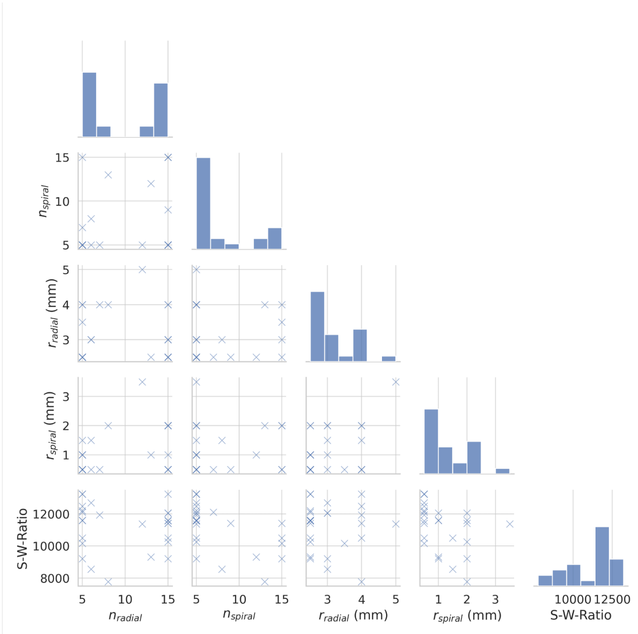


Figure 3: The Pair-wise Scatter and Marginal Histograms of Different Parameters

6 Discussion and Conclusion

In this study, our ultimate goal was to replicate the ultra–fine geometry of natural spider webs by designing and simulating filament radii on the order of micrometers. However, when we attempted to run ANSYS simulations at this scale, the extremely small element sizes led to numerical instabilities and frequent solver failures. To work around these issues, we elected to upscale all dimensions into the millimeter range, which preserved the qualitative trends in strength-to-weight performance while restoring robust convergence in the finite-element analyses.

Another issue we faced with the ANSYS simulations was accurately defining the material properties. Initially, in order to accurately reflect the non-linear elasticity of TPU, we opted to use

Mooney-Rivlin constants. Due to the methodology of the ANSYS solver, these constants could not be applied to beam elements, which meant that a linear model had to be used, skewing the results.

One aspect which influenced costliness of the data, were the parameter definitions. The parameters describing the number of radial threads and spiral threads, define the quantity of elements within the design, rather than their dimensional properties. While this approach ensured that a range of geometries could be distinctly described and structural relationships between components were preserved, it had significant impacts on the design pipeline. When individual designs were evaluated, each test configuration had to be fully regenerated as opposed to rescaled, adding pre-processing time to each evaluation.

In order to accelerate this stage, the program for the design of the web geometries was implemented, which in turn meant that the structures were composed of beam elements as opposed to volumes. This became a problem when defining the material properties in the simulation. Initially, in order to accurately reflect the non-linear elasticity of TPU, we opted to use Mooney-Rivlin constants. Due to the methodology of the ANSYS solver, these constants could not be applied to beam elements, which meant that a linear model had to be used, skewing the results

Performance of the Data-Driven Pipeline

Our closed-loop SolidWorks–ANSYS–MATLAB workflow reliably converged within 20 expensive FEA evaluations, identifying a spider-web geometry that maximizes strength-to-weight ratio with minimal material usage. The Bayesian optimizer consistently balanced exploration and exploitation, automatically reducing the 1,936-point candidate space to the optimum design in under a day of compute time, despite the upscaling needed to ensure solver stability.

Constraint Handling and Application-Driven Objectives

While maximizing pure strength-to-weight favors the smallest feasible geometry, this yields less practically interesting results for load-critical applications. To address this, future formulations should include explicit load-bearing constraints or multi-objective criteria. For example, one may require

$$F_{\max}(\mathbf{x}) \geq 1000\,\mathrm{N} \quad \text{and then optimize} \quad \max_{\mathbf{x}} \frac{F_{\max}(\mathbf{x})}{m(\mathbf{x})},$$

which biases the search toward configurations that meet both a minimum capacity and exhibit high mass efficiency. This approach prevents the optimizer from defaulting to the smallest trivial design and ensures relevance to specific engineering requirements.

Practical Definition of Strength

While establishing the objective function and design space of the problem, strength was identified as the force required to achieve a direct stress of 42 MPa in the web, the stress value for the TPU yield strength. This poses two significant influences on the interpretation of the results: as the web is not tested to failure, the measurement of the force serves as a proxy for stiffness, which reflects mechanical resistance. This would convert the strength-to-weight ratio into a stiffness-to-weight ratio, more similar in nature to stiffness efficiency. Furthermore, using the yield strength of TPU, displays the relationship of applied force to the material properties of the thread material as opposed to the geometric properties of the web. These aspects make it difficult to trace the result back to the structural aspects of the web.

Another way in which the use of yield strength as the tested stress value has had an influence on the results of this design problem is the effect on the simulations. The yield strength being the point where material transitions from elastic to plastic transformation is also the boundary between linear and non-linear material behavior. Coupled with the fact this definition of strength is tied to material properties, the objective space remains flat, because the web structure does not experience non-linear deformation behavior, such as buckling or cracking that would occur as the structure approaches failure. In this way the definition of strength proposed, neglects some of the relevant geometric trade offs that would produce a more topographically pronounced objective space.

Improvements and Extensions

Looking ahead, we aim to fully automate the end-to-end pipeline —from parameter sampling and CAD generation through meshing, solving, and post-processing—to eliminate the substantial manual effort currently required. One key challenge is that our design parameters govern the number of threads (i.e., discrete elements) rather than simply their dimensions, so each candidate geometry must be rebuilt from scratch rather than rescaled. Future work will therefore focus on developing scriptable CAD-to-FEA workflows (e.g., via SolidWorks and SpaceClaim API scripting) and investigating mesh-independent surrogate models or physics-informed reduced-order methods to further accelerate the optimization process and enable true micro-scale investigations without solver breakdowns.

Insights into the Design Problem

Our results reveal that, for a uniform TPU material under central-load bending, minimizing both the count and cross-sectional area of filaments yields the highest mass efficiency—contrary to the intuition that denser webs always perform better. By incorporating load constraints into the objective, future studies can uncover non-trivial trade-offs between capacity and efficiency that better inform application-specific designs.

In summary, despite numerical challenges at micro-scale, our data-driven framework proved effective for rapid topology discovery in spider-web–inspired lattices. By advancing automation, constraint handling, and surrogate model fidelity, we anticipate unlocking truly bio-realistic micro-structured designs for aerospace, automotive, and biomedical applications.

References

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