Optimum patterns of lattice structure for bending test

Introduction to Innovative Aerospace Design

Seoul National University, Fall 2024

Group 3

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1. Introduction

The pursuit of efficiency and performance in the aviation industry has led to a constant drive for innovation in aircraft designs. Developing a lightweight yet strong structure for airplane wings is therefore an important area of focus since it can minimize weight to improve fuel efficiency and overall aircraft performance.

Traditional aircraft wing structures have often relied on solid, heavy materials. However, with material and manufacturing technology advancements, new possibilities for creating lightweight designs have opened. By leveraging the principles of tensile strength and optimization of structures, engineers can now design and manufacture wings that are lighter and stronger than before.

1.1 Purpose and Goal

This project aims to explore the potential of 3D-printed tensile structures that have high mechanical properties and weight constraints. The goal is to design specimens with unique lattice structures using the computer-aided design (CAD) program SolidWorks to optimize structural performance and thereafter execute tensile testing to measure performance.

1.2 Constraints

There are two main constraints while constructing the structures. The first is a volume constraint whereas the design part should be less than 50% of the part without lattice. In other words, 50 % of the volume in the design area should be removed. The second is a section constraint that is added for simplicity and printability of the specimen since a 3D-printer will be used. The section views along the z-axis must be identical. The specimen should be extruded along the z-axis from a sketch on x-y plane.

2. Data and Methodology

In this study, three rounds of designing, producing and testing the specimen took place. The design was made in Solidworks and the production through 3D-printing using the Sindoh 3DWOX.

2.1 Specimen 1A

The first design, Specimen 1A, was a specimen with four larger rectangular holes on the design part. It was designed to minimize the weight in a simple way and to examine how this structure would perform in the tensile test in comparison to the circular patterned Specimen 1B.

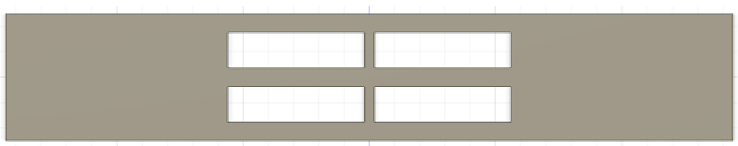


Figure 1: Specimen 1A – first design with rectangular pattern

Before the first test, we have done the simulation on two types of rectangular structure, one with fillet and another without the fillet. (The radius of fillet is 1mm)

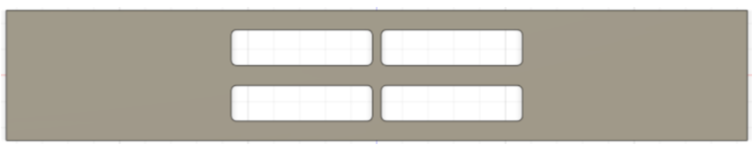


Figure 2: rectangle structure with fillet

For the simulation, we give both side a 100N force, the results are shown below:

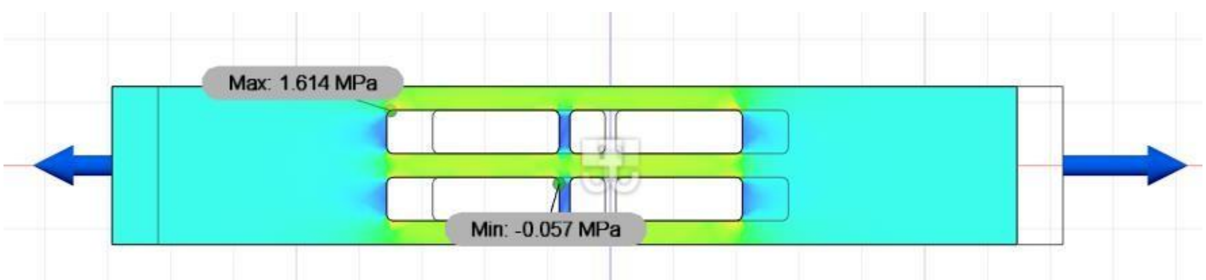


Figure 3: force simulation of rectangle structure with fillet

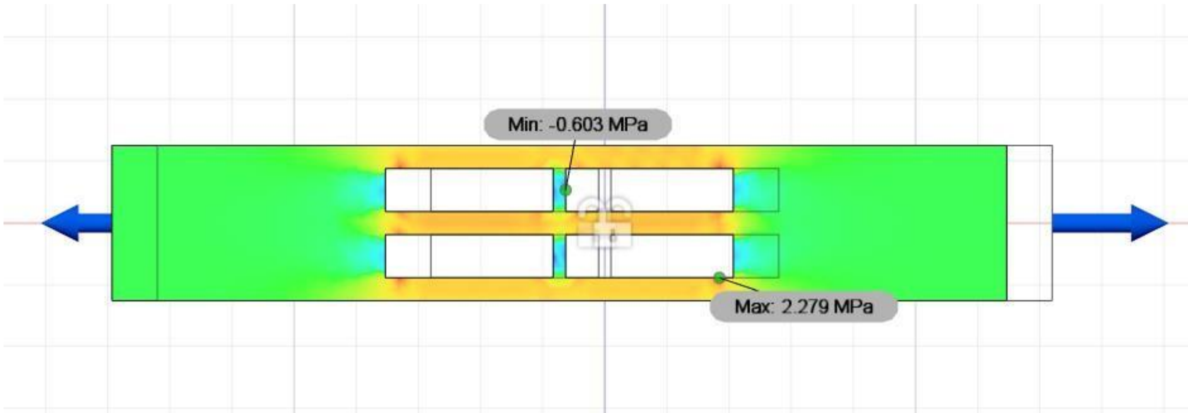


Figure 4: force simulation of rectangle structure without fillet

We can tell from the result that adding fillets on the corner can actually decrease the maximum X-direction stress, it is because it distributes the force to other areas, avoiding the concentration of stress.

(Algarni, 2021)2.2 Specimen 1B

A lattice circular pattern was implemented on the second design, Specimen 1B (**Error! Reference source not found.**). A circular shape is used with the idea of minimizing stress concentrations occurring in edges. The radius of the circles is chosen to maximize the solid volume without exceeding the maximum allowed volume. Around edges, stress accumulations occur resulting in high stress factors and possible failure at the edges, as illustrated in **Figure** 6 and Figure 7. The radial symmetry of the circular holes allows for a more even stress propagation and reduces localized stress concentrations. The symmetry of the pattern also provides consistent material properties across all directions of the designed part (CHONG & PINTW, 1983).

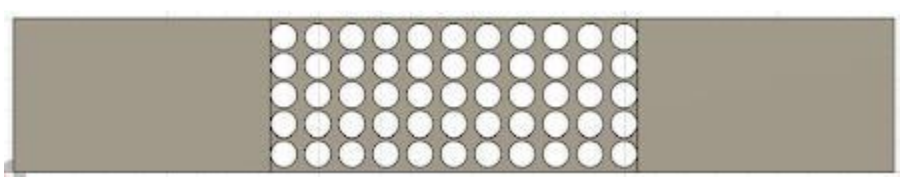


Figure 5: Specimen 1B – second design with circular pattern

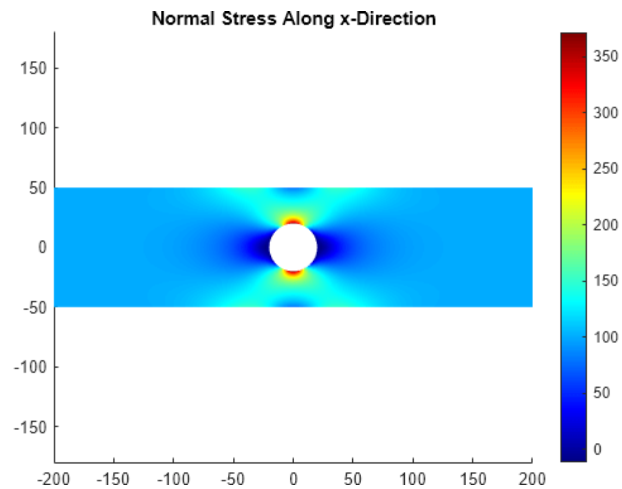


***Figure** 6. Normal stress along x-Direction in a lattice structure with a circular hole (MATLAB, 2024).*

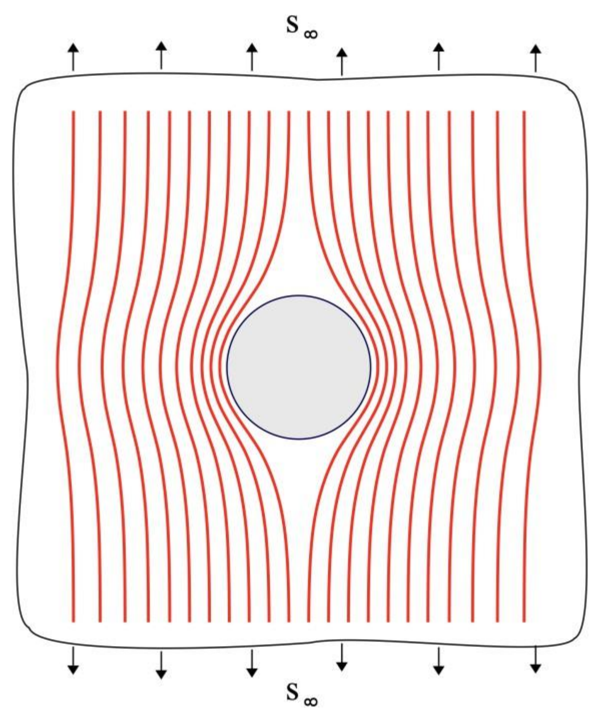
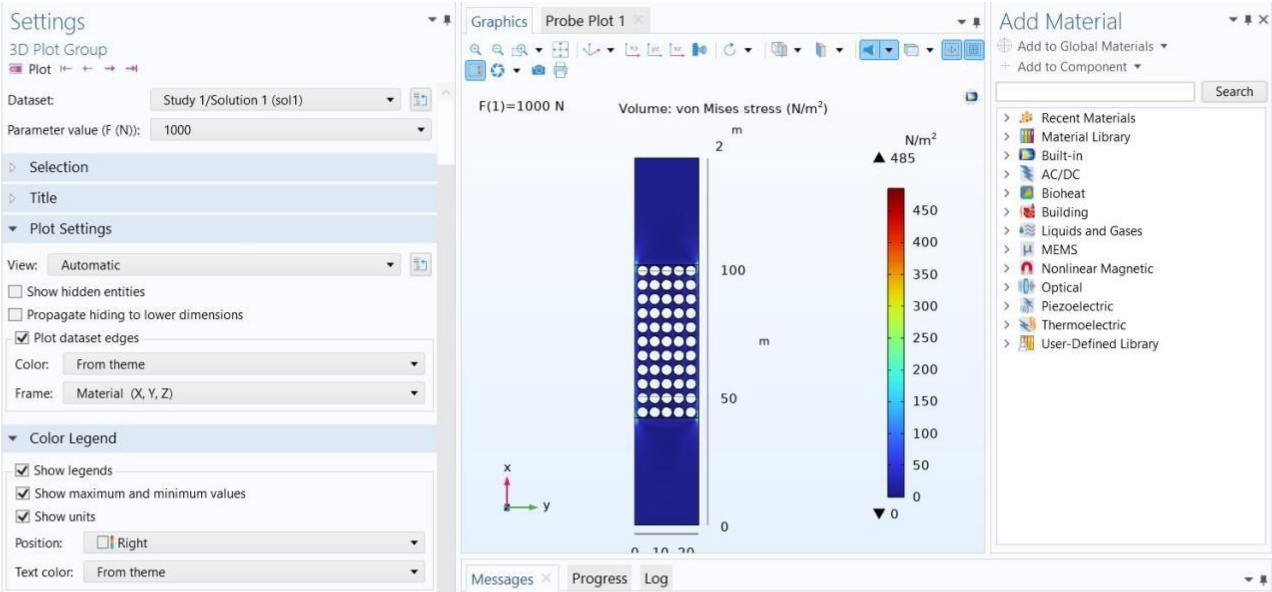


Figure 7. Stress concentrations around a circular shape illustrated by the flow field of forces (Todd, 2023).



2.3 Specimen 2A

In the second round, two new designs were constructed – Specimen 2A and 2B. The third design, Specimen 2A, is an iteration of Specimen 1B from the first round, however, this time using hexagons instead of circles in a linear pattern.

Figure 8. Specimen 2A – third design[1] with hexagonal (HEX30) pattern

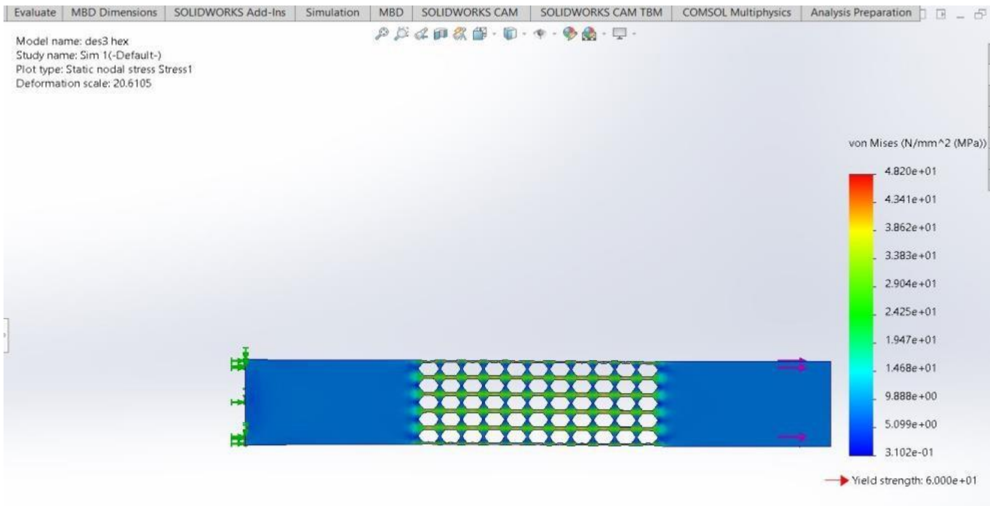


Figure 9: STRESS SIMULATION OF HEX30 design

Boundary Conditions and Setup

1. **Fixtures**:
    a. Fixed constraints applied at the left-hand side of the structure to restrict displacement.
2. **External Load**:
    a. Force of -1,000 N applied uniformly at the right-hand edge of the lattice structure.
3. **Mesh Details**:
    a. **Type**: Standard mesh. With max element size 2mm
    b. **Quality**: High-quality mesh for enhanced accuracy in stress evaluation.

Simulation Results

Stress Distribution

- The **von Mises Stress** plot displays stress variation across the hexagonal lattice structure.
- The maximum von Mises stress values are concentrated near the hexagonal edges and force application zones, where stress concentrations are most significant.

Maximum Stress (MPa)	Yield Strength (MPa)
48.20	60.0

- **Observation**:
    - The maximum von Mises stress remains **below the yield strength** (60 MPa).
    - This indicates that under the current load conditions, the structure remains within the elastic region, avoiding plastic deformation.

Displacement and Strain

1. **Displacement**:
    a. Displacement is primarily localized near the force application region with minimal deflection elsewhere.
2. **Strain**:
    a. The equivalent strain distribution follows the stress patterns, with noticeable values at sharp hexagonal edges.

Comparative Analysis and References

- Similar studies have demonstrated that **hexagonal lattice structures** provide high strength-to-weight ratios and excellent mechanical efficiency.
    - A study by **Fleck and Deshpande (2001)** demonstrated that hexagonal honeycomb structures exhibit superior energy absorption properties under uniform loading conditions.
    - **Lu et al. (2013)** analyzed the stress distribution in lightweight lattice structures, concluding that hexagonal configurations minimize stress concentrations under uniform static loads.
- **Relevance to Current Study**:
    - The simulation results align with previous findings, showing that hexagonal lattice structures exhibit reduced stress levels under lighter loads, effectively distributing forces through the network of edges.

Key Findings

1. **Stress Analysis**:
    a. Maximum von Mises stress (48.20 MPa) is well below the material's yield strength (60 MPa).
2. **Structural Efficiency**:
    a. The hexagonal lattice structure efficiently distributes stress, minimizing peak values and avoiding material failure under the applied load.
3. **Validation with Literature**:
    a. Results confirm the robustness of hexagonal geometries as supported by previous studies, emphasizing their suitability for lightweight design applications.

As we progressed with the project, we sought optimization of results and often compared the patterns to see which one performed better as this would guide us on the next steps to take. We made a comparison between circular and hexagonal geometry which was supported by already existing studies.

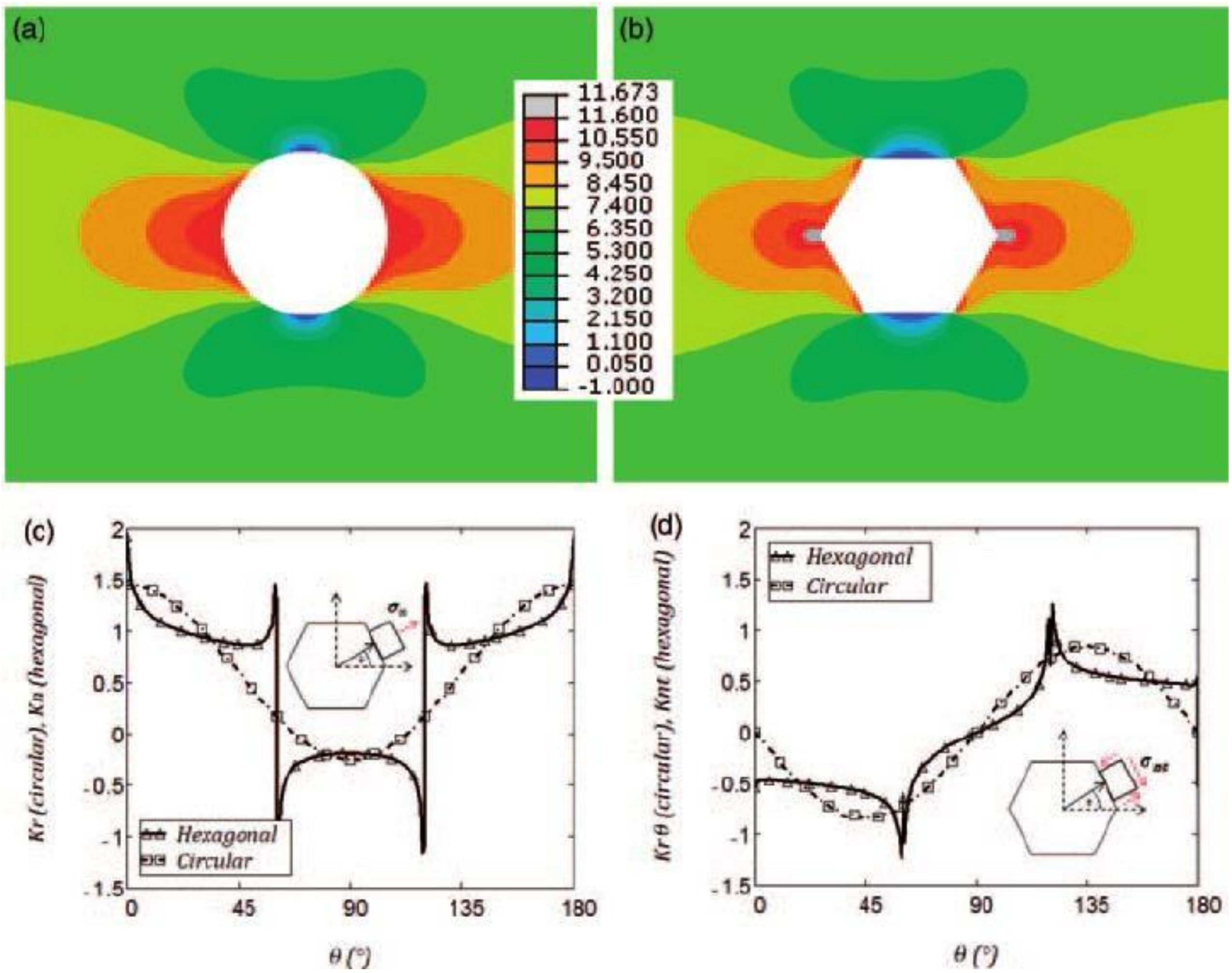


Figure 11; Maximum principal stress distribution in the models with (a) circular and (b) hexagonal lattice patterns (MPa) (stresses in the modeled fibers are not shown). Variation of (c) radial and (d) shear stress concentrations along the fiber–matrix interface for fibers with hexagonal and circular cross-sections. (Sabuncuoglu, 2014)

2.4 Specimen 2B

The fourth design, Specimen 2B is an entirely new design using triangles. After doing research on geometries, triangles are concluded to be one of the most strong and stable geometric structures.

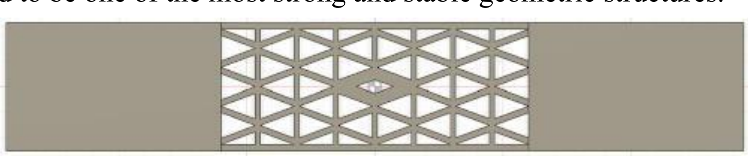


Figure 10. Specimen 2B – fourth design with triangular pattern

For this specimen, we had different goals in mind. Indeed, according to the literature, an effective stress distribution is an important factor to enhance mechanical properties. Besides, a triangle pattern can offer a better resistance to deformation and interrupt crack propagation.

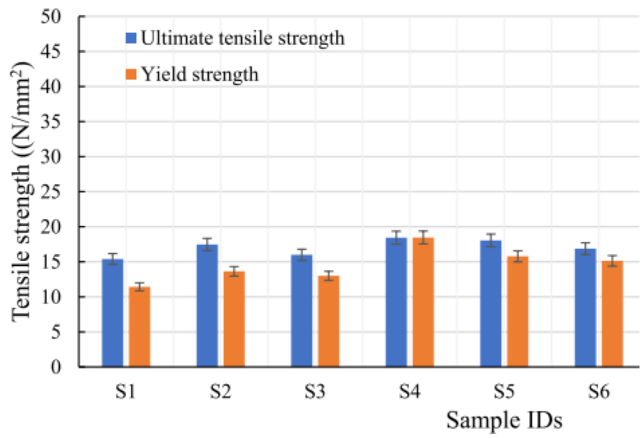


Figure 11: Influence of process parameter on tensile strength (Agrawal)

In the figure above, the samples S1 to S3 represent a line pattern as shown in the figure below and S4 to S6 a triangle pattern with different parameters. Those pattern as shown in previous studies good mechanical properties (Sabuncuoglu, B., 2014) and the figure show a higher ultimate tensile strength and yield strength for the triangle pattern.

For this reason, we tried to make our own triangle pattern with a different configuration and by reinforcing the center of the specimen, as shown in figure 10, where the fracture usually occurs.

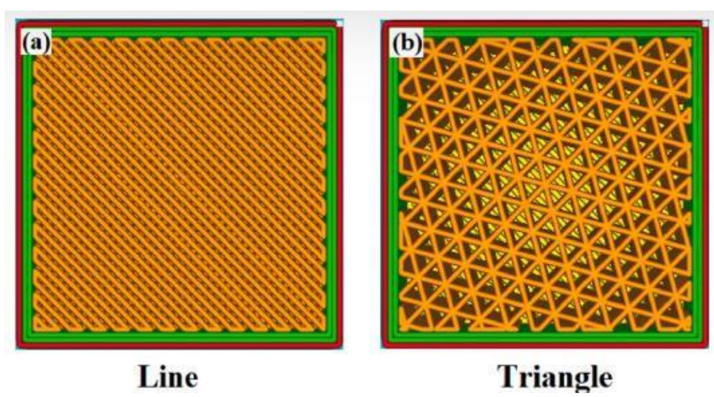
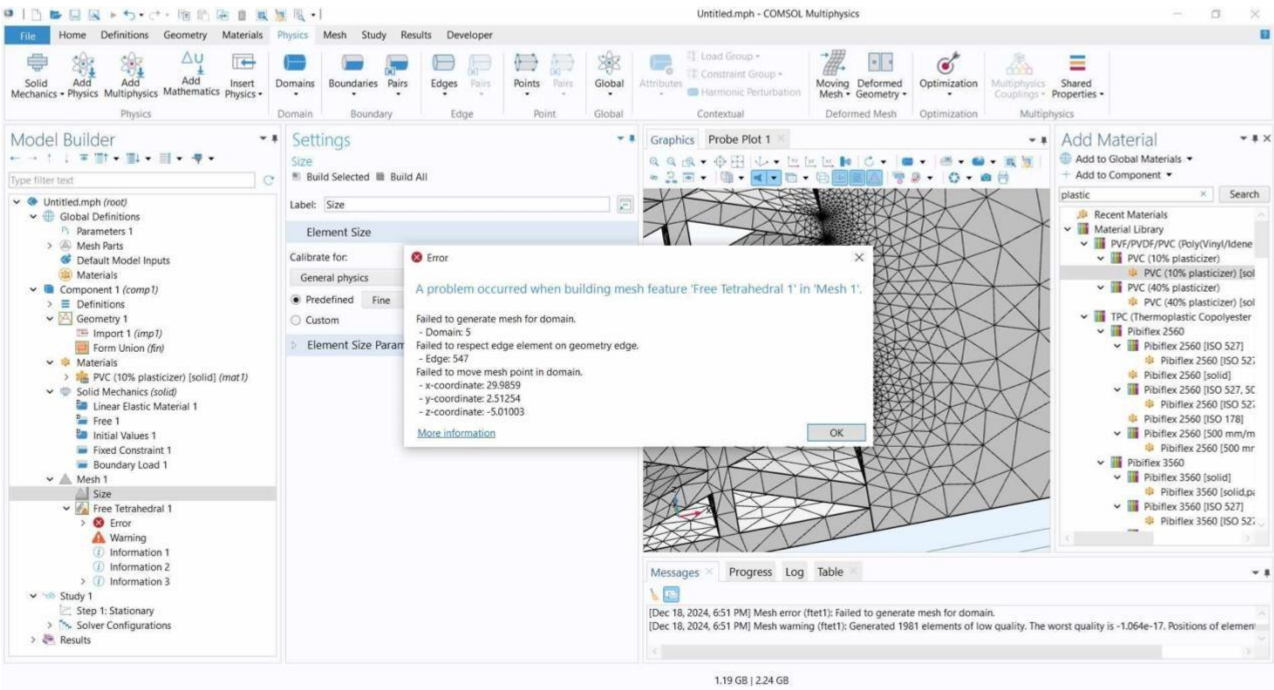


Figure 12: Geometrical arrangement of infill patterns (a) Line; (b) Triangle (Agrawal)

Simulation



The simulation for Specimen 2B proved particularly challenging due to persistent issues associated with the complex mesh and boundary constraints inherent to its geometric design. Despite multiple attempts to refine the mesh and calibrate the simulation parameters, the process consistently resulted in errors, such as failure to generate the mesh or respect edge elements, as seen in the provided error log. These complications highlight the limitations of the simulation software in accommodating intricate lattice structures under the given modeling conditions. However, while the numerical simulations were unsuccessful, the physical testing of Specimen 2B yielded highly positive results, confirming its superior mechanical performance and validating the geometric optimization. This discrepancy emphasizes the need for advanced computational tools capable of handling complex designs and further underscores the promising potential of Specimen 2B as a viable solution for lightweight structural applications.

2.5 Specimen 3

In the third and final round, we chose specimen 1B as the fifth design to test the specimen again. However, this time the results did not correspond with the results from the previous test which might have occurred because of improper calibration of the tensile test machine.

2.6: Simulation Software Disparity and Material Property

In this study, simulations for the lattice structures were conducted using two distinct software tools, **SolidWorks** and **COMSOL Multiphysics**. It is important to highlight that **Specimen 2A** was the only design successfully simulated in SolidWorks, this explains the more detailed description on its simulation, whereas the remaining specimens were analyzed using COMSOL Multiphysics. This disparity arose due to several challenges encountered during the study.

The primary challenge was the **incompatibility of SolidWorks with macOS operating systems**, which presented a significant constraint for the design and simulation process. While SolidWorks is a robust tool for CAD modeling and simulation, the software's native limitations in cross-platform accessibility hindered its full utilization for this project. Additionally, the lattice structures for the remaining specimens were modeled using alternative CAD software, and these designs could not be successfully imported or simulated within the SolidWorks environment.

To overcome this limitation, COMSOL Multiphysics was employed as an alternative simulation platform. COMSOL provided the flexibility to import complex geometries and perform detailed simulations, particularly for the advanced lattice structures that could not be processed in SolidWorks. Despite the initial constraints, this approach ensured the successful completion of the simulation process for all specimens, allowing for a comprehensive analysis of stress distributions, deformation patterns, and structural performance.

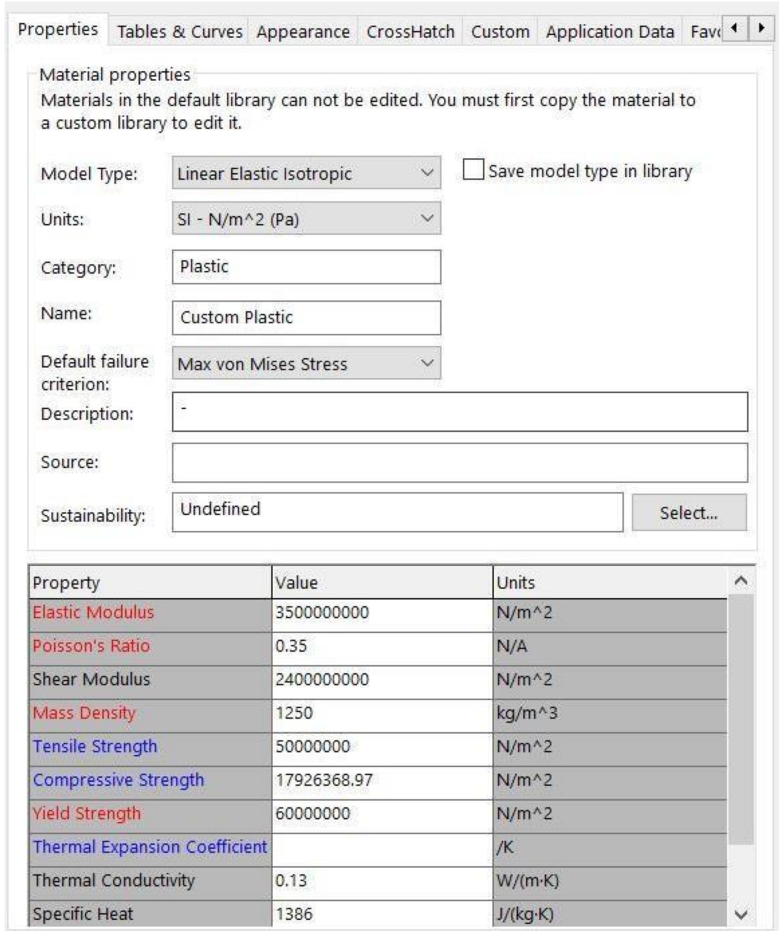


Figure 13: Material Properties for PVC

To provide clarity on the material properties used in the simulations, the figure above illustrates the mechanical characteristics of the **PVC material** utilized for all specimens. This material was chosen due to its widespread application in structural and industrial components, offering a balance of flexibility and strength. The figure highlights key properties such as **Young's modulus, Poisson's ratio, and density**, which were critical inputs for ensuring accurate simulation results. These parameters were consistently applied across all analyses to maintain uniformity and enable a reliable comparison of the specimens' structural responses under loading conditions

3. Results

In this chapter, results from the three rounds of the tensile tests will be summarized.

3.1 Tensile Test Round 1

Specimen 1A weighed 15.85 g while Specimen 1B weighed 15.74 g. The first-round tensile results are stated below in **Table** 1, **Figure** 14 and Figure 15.

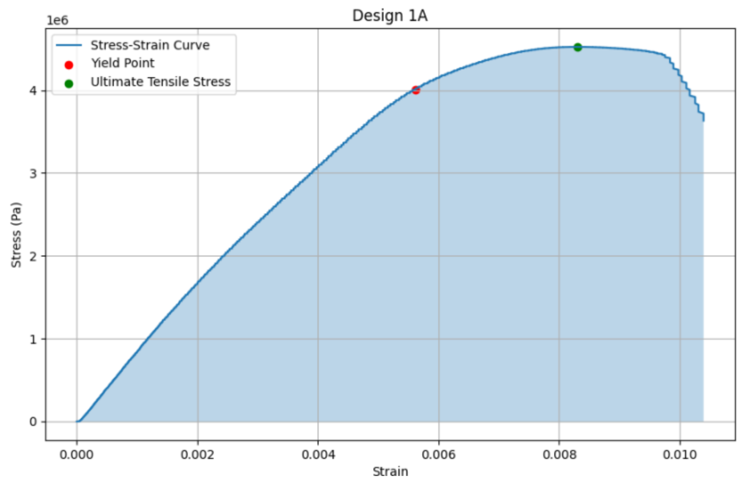


***Figure** 14. Stress strain curve of design 1A*

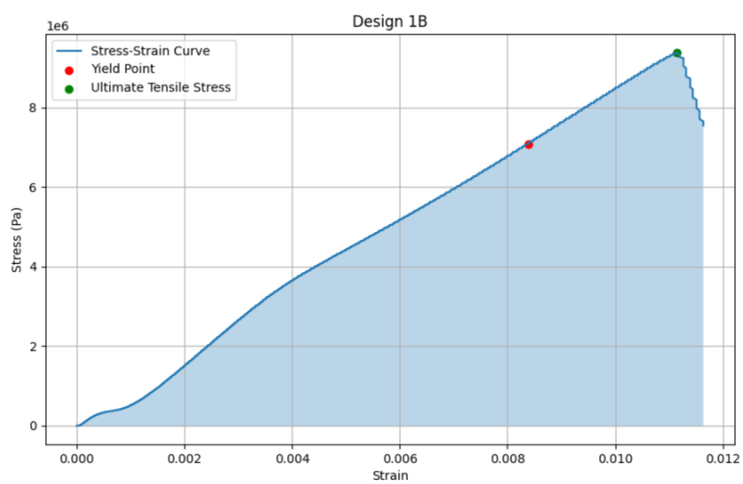


Figure 15. Stress strain curve of design 1B.

The stress strain curve of Specimen 1A and 1B are given in the above figures**Figure** 14. The numerical results of the test are the following:

__Table__ 1. Results of the first-round tensile test.

	Specimen 1A	Specimen 1B
Yield Strength [MPa]	4.30	7.08
Ultimate Tensile Stress [MPa]	4.53	9.37
Total Strain at Failure	0.0105	0.0116
Fracture Energy [kJ/m^3]	33.3	57.0

For the calculating of the yield strength, an offset curve of the elastic region with 0.1% has been used.

3.1.1 Comparison of specimen 1A and 1B.

From Figure 16 can be concluded that specimen 1B has superior tensile properties over specimen 1A. Furthermore, the values for UTS and fracture energy are higher for specimen 1B whilst it is also slightly lighter than specimen 1A, making it a superior design overall.

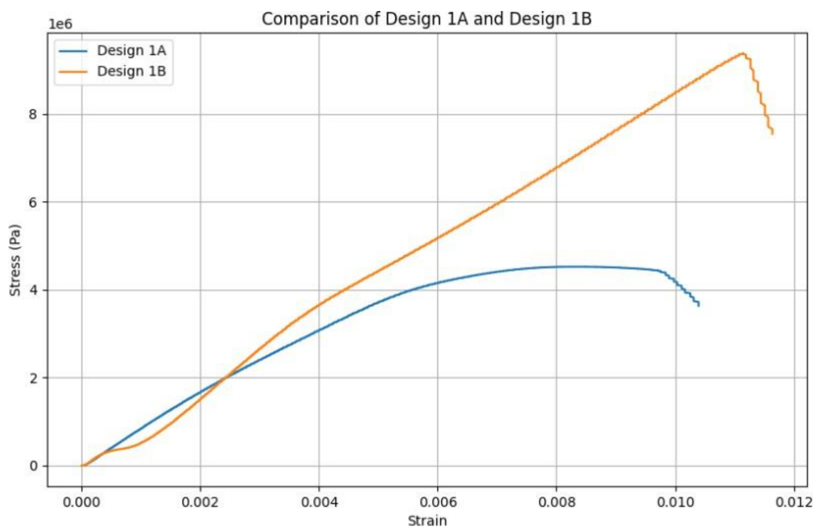


Figure 16. Comparison of specimen 1A and 1B.

3.2 Tensile Test Round 2

The weight of Specimen 2A was 13.91g and 14.84g for Specimen 2B.

Table 2. Results of second round tensile test.

	Specimen 2A	Specimen 2B
Yield Strength [MPa]	4.17	3.85
Ultimate Tensile Stress [MPa]	4.46	13.2
Total Strain at Failure	0.0202	0.0195
Fracture Energy [kJ/m^3]	71.0	157

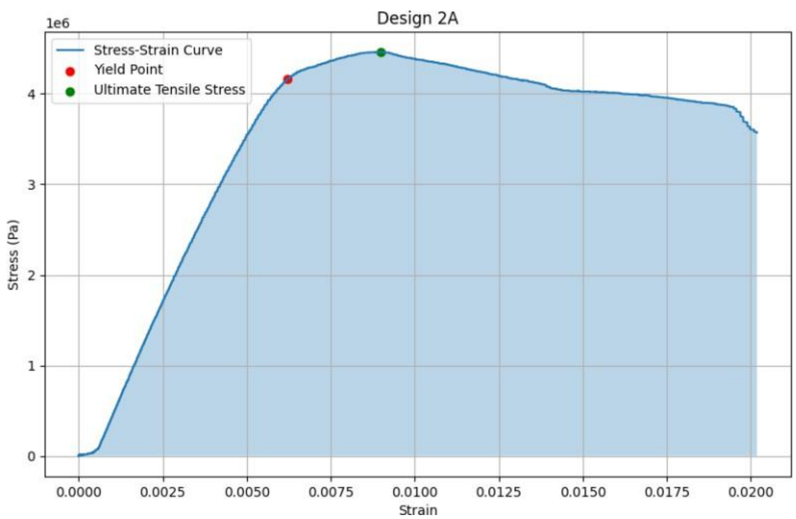


Figure 17. Stress strain curve of design 2A

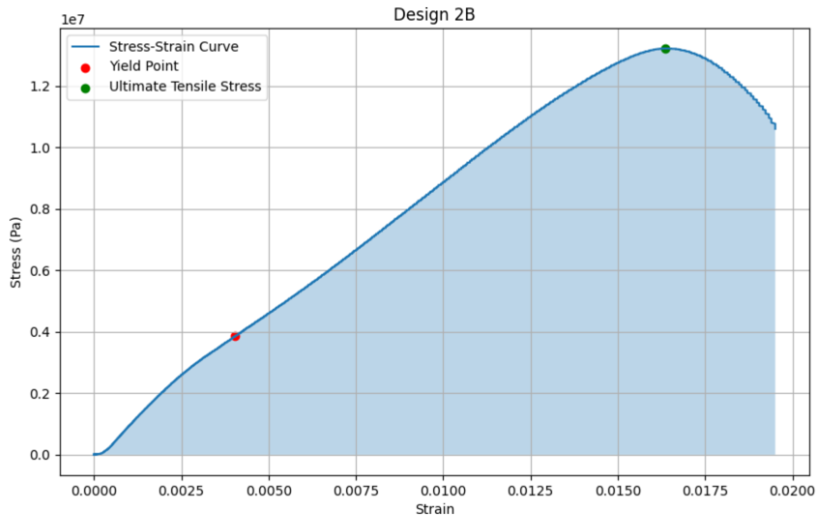


Figure 18: Stress strain curve of design 2B

3.2.1 Comparison of specimen 2A and 2B.

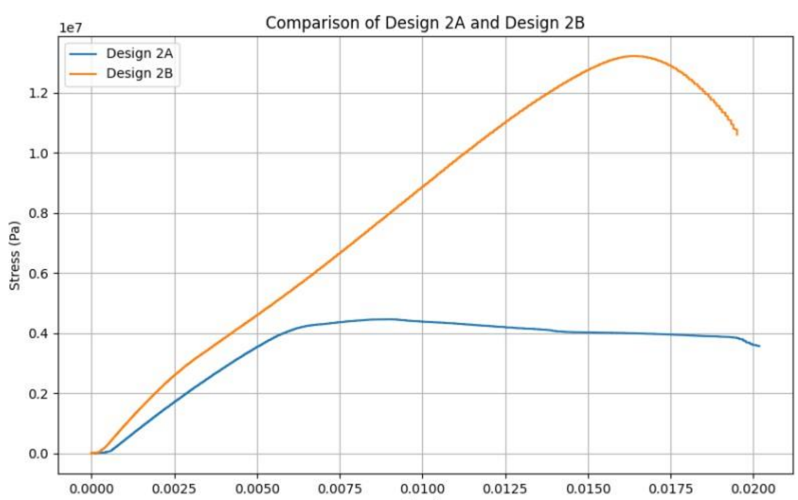


Figure 19: Comparison of specimen 2A and 2B.

Specimen 2B clearly has better results than 2A, mainly due to the triangular geometry.

3.3 Tensile Test Round 3

The fifth specimen weighs 16.55g which is 0.7g more than 1A even though the same design was used.

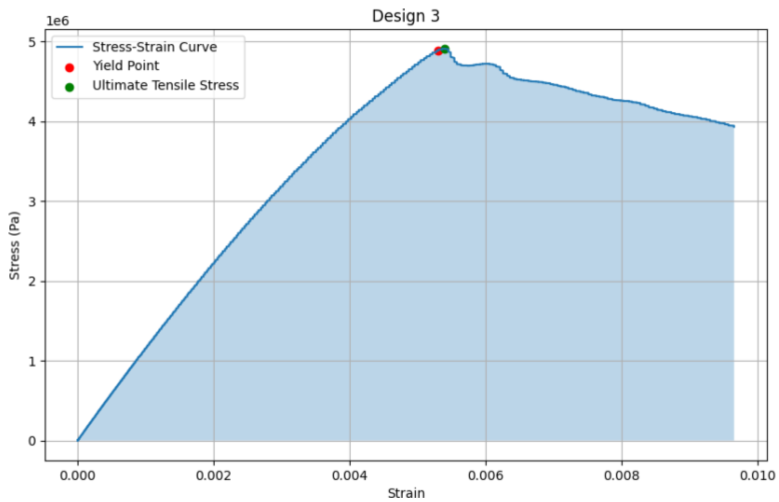


Figure 20. Stress strain curve of design 5 (same pattern as specimen 1B)

Table 3: Results of third (final) round tensile test.

	Specimen 3
Yield Strength [MPa]	4.89
Ultimate Tensile Stress [MPa]	4.91
Total Strain at Failure	0.0097
Fracture Energy [kJ/m^3]	33.5

3.4 Comparison of all tests

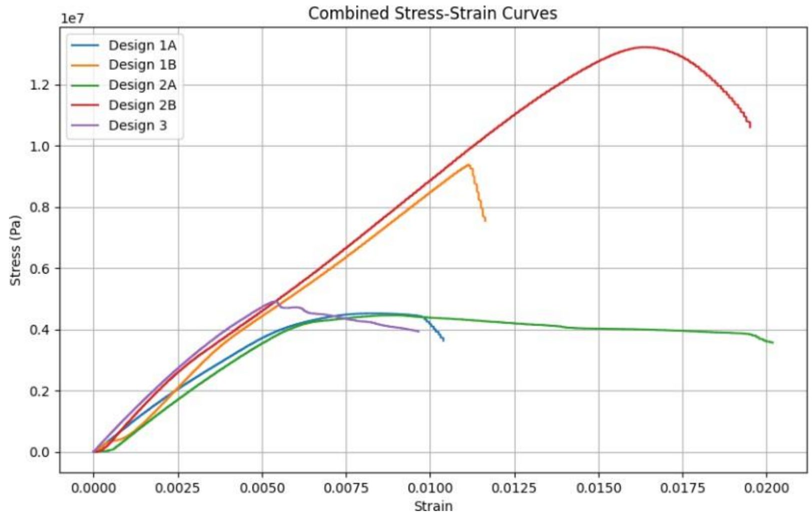


Figure 21: Stress strain curve of all designs.

4. Discussion

Table 4. Non normalized test results

design	Mass (g)	Yield Strength (Pa)	UTS (Pa)	Total Strain	Fracture Energy (J/m³)
Design 1A	15.74	4008160	4523280	0.010395833	33074.00028
Design 1B	15.85	7077040	9374720	0.011638889	56978.92944
Design 2A	13.91	4166000	4462160	0.020180556	70972.2925
Design 2B	14.84	3851360	13215040	0.019506944	156860.4856
Design 3	16.55	4886720	4912000	0.009656875	33503.86014

Table 5. Normalized test results (by weight):

design	Normalized Yield Strength (Pa/g)	Normalized UTS (Pa/g)	Normalized Fracture Energy ((J/m³)/g)
Design 1A	254648.0305	287374.8412	2101.270666
Design 1B	446500.9464	591464.9842	3594.885138
Design 2A	299496.7649	320787.9224	5102.249641
Design 2B	259525.6065	890501.3477	10570.11358
Design 3	295270.0906	296797.5831	2024.402425

Design 2B scores the best on the normalized as the non-normalized results. The triangular design proves to offer the best overall properties for a tensile test over the other geometries used in our tests and still maintain the lowest mass.

5. Conclusion

The project successfully explored the potential of 3D-printed lattice structures for lightweight and high-performance aircraft wing designs, demonstrating the impact of geometric optimization on tensile properties. Among the tested geometries, the triangular lattice design (Specimen 2B) outperformed others, exhibiting superior strength-to-weight ratios and energy absorption capabilities. The findings highlight the triangular geometry’s effectiveness in minimizing stress concentrations and maximizing structural efficiency under load.

Simulation and tensile testing confirmed that strategic geometric patterns, such as triangular, hexagonal, and circular designs, can significantly enhance mechanical properties while maintaining weight constraints. Despite challenges with software compatibility, the combined use of SolidWorks and Fusion ensured comprehensive analysis.
Despite achieving substantial insights, the study faced limitations, including software compatibility issues and variations in experimental conditions. Addressing these challenges in future research could lead to more definitive conclusions. Additionally, the observed disparities between simulation and experimental results underscore the need for improved calibration of testing equipment and standardized methodologies.

This study reinforces the viability of lattice structures for lightweight design applications and provides a foundation for future advancements in aerospace structural optimization, particularly through additive manufacturing and computational modeling.

6. Further studies

Upon findings presented in this report, potential avenues for further research will be addressed in this chapter. The current study provides valuable insight into the behavior of lightweight structures with different patterns. However, it also has its limitations, and further studies are needed for more definite conclusions.

A challenge during this research was the inconsistency in design parameters across different samples which made it difficult to draw definitive conclusions on optimal lightweight structure. To address this in future studies, a standardized approach should be adopted. This standardization will involve selecting a consistent base geometry and establishing a set of standard hole patterns that then will be systematically varied in terms of shape, size, spacing and orientation. This variation will allow for more comprehensive understanding of the relationship between geometric parameters, stress distribution and stress concentration.

Relevant studies are:

1. Comparision of elliptical and circular holes. This study is for comparing stress distributions in structures with elliptical and circular holes of equivalent area. Different ratios will be applied for the ellipses in order to analyze their influence on stress concentrations compared to circular holes.
2. Effect of hole size, spacing and pattern on stress distribution and stress concentration. This study is to understand the relationship between hole sizes and stress concentration as well as exploring the impact of different hole spacing and pattern in relation to stress concentration.
3. Analysis of hole orientation and pattern. This study is for understanding the effects of rotating the hole pattern relative to the applied load to analyze the results of stress distribution.

With a more systematic approach, further studies on this topic will establish more definitive relationships between geometric parameters, stress distribution, stress concentration, and therefore overall performance of lightweight structures. It will provide a more stable dataset for analysis which allows for statistically significant conclusions and development of predictive models. This will also contribute to the development of optimized designs for various engineering applications other than in the aviation industry. Lastly, a standardized methodology allows easier comparison and validation of results across different studies.

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8. Appendix

```python
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt


def process_data(file_name, width=25e-3, thickness=5e-3, gauge_length=144e-3):
    """Process raw data from excel file and return processed dataframe"""
    cross_sectional_area = width * thickness

    data = pd.read_excel(file_name)
    # Subtract initial load value from all load measurements
    initial_load = data["Load N"].iloc[0]
    data["Load N"] = data["Load N"] - initial_load

    if "test5" in file_name:
        data["Deformation m"] = data["Deformation 1 microm"] * 1e-3

    else:
        data["Deformation m"] = data["Deformation 1 microm"] * 1e-6

    if "test4" in file_name:
        print(data["Load N"].idxmax())

    data["Strain"] = data["Deformation m"] / gauge_length
    data["Stress (Pa)"] = data["Load N"] / cross_sectional_area

    # Trim data to 80% of max stress
    max_stress = data["Stress (Pa)"].max()
    threshold = 0.8 * max_stress
    max_valid_idx = data[data["Stress (Pa)"] >= threshold].index[-1]
    data = data.iloc[:max_valid_idx + 1]

    return data

def find_linear_region(strain, stress, window_size=200, filename=None):
    """Find the most linear region using sliding window and R² criterion"""
    max_r2 = 0
    best_start = 0

    # Use 20% cutoff for test5, 50% for others
    if filename and "test5" in filename:
        max_idx = int(len(strain) * 0.1)
    else:
```

```python
        max_idx = int(len(strain) * 0.5)

    for start in range(0, max_idx - window_size):
        end = start + window_size
        strain_window = strain[start:end]
        stress_window = stress[start:end]

        try:
            # Reshape data for polyfit
            X = strain_window.values.reshape(-1, 1)
            y = stress_window.values

            # Calculate R² score
            coeffs = np.polyfit(strain_window, stress_window, 1)
            y_pred = np.polyval(coeffs, strain_window)
            r2 = 1 - np.sum((stress_window - y_pred) ** 2) / np.sum((stress_window - np.mean(stress_window)) ** 2)

            if r2 > max_r2:
                max_r2 = r2
                best_start = start

        except np.linalg.LinAlgError:
            continue

    return best_start, best_start + window_size

def calculate_yield_strength(data, offset_strain=0.001, filename=None):
    """Calculate yield strength using 0.1% offset method"""
    # Find most linear region
    start_idx, end_idx = find_linear_region(data["Strain"], data["Stress (Pa)"], filename=filename)

    # Use identified linear region
    strain_elastic = data["Strain"].iloc[start_idx:end_idx]
    stress_elastic = data["Stress (Pa)"].iloc[start_idx:end_idx]

    elastic_modulus = np.polyfit(strain_elastic, stress_elastic, 1)[0]
    offset_line = elastic_modulus * (data["Strain"] - offset_strain)

    difference = abs(data["Stress (Pa)"] - offset_line)
    idx_yield = difference.idxmin()

    return data["Stress (Pa)"].iloc[idx_yield], idx_yield, offset_line

def calculate_uts(data):
    """Calculate Ultimate Tensile Stress"""
    return data["Stress (Pa)"].max()
```

```python
def calculate_total_strain(data):
    """Calculate total strain at failure"""
    return data["Strain"].iloc[-1]

def calculate_fracture_energy(data):
    """Calculate fracture energy using trapezoidal integration"""
    return np.trapz(data["Stress (Pa)"], data["Strain"])

def plot_single_curve(data, yield_strength, idx_yield, offset_line, uts, ax=None):
    """Plot stress-strain curve with key points for a single dataset"""
    if ax is None:
        fig, ax = plt.subplots(figsize=(10, 6))

    ax.plot(data["Strain"], data["Stress (Pa)"], label="Stress-Strain Curve")
    ax.fill_between(data["Strain"], data["Stress (Pa)"], alpha=0.3)
    #ax.plot(data["Strain"], offset_line, "--", label="0.1% Offset Line", color='gray')
    ax.scatter(data["Strain"].iloc[idx_yield], yield_strength, color="red", label="Yield Point")
    ax.scatter(data["Strain"][data["Stress (Pa)"].idxmax()], uts,
            color="green", label="Ultimate Tensile Stress")

    ax.set_xlabel("Strain")
    ax.set_ylabel("Stress (Pa)")
    ax.grid(True)

    return ax

def analyze_multiple_files(file_names):
    """Analyze multiple files and create plots"""
    fig_combined, ax_combined = plt.subplots(figsize=(10, 6))

    # Create additional figures for comparing specific tests
    fig_test1, ax_test1 = plt.subplots(figsize=(10, 6))
    fig_test2, ax_test2 = plt.subplots(figsize=(10, 6))

    results = []

    design_names = {
        0: "Design 1A",
        1: "Design 1B",
        2: "Design 2A",
        3: "Design 2B",
        4: "Design 3"
    }

    masses = {
        0: 15.74,  # Design 1A
        1: 15.85,  # Design 1B
```

```
    2: 13.91,  # Design 2A
    3: 14.84,  # Design 2B
    4: 16.55   # Design 3
}

for i, file_name in enumerate(file_names):
    data = process_data(file_name)
    yield_strength, idx_yield, offset_line = calculate_yield_strength(data, filename=file_name)
    uts = calculate_uts(data)
    total_strain = calculate_total_strain(data)
    fracture_energy = calculate_fracture_energy(data)

    # Calculate normalized values
    mass = masses[i]
    yield_strength_norm = yield_strength / mass
    uts_norm = uts / mass
    fracture_energy_norm = fracture_energy / mass

    # Store results
    results.append({
        'design': design_names[i],
        'mass': mass,
        'yield_strength': yield_strength,
        'yield_strength_norm': yield_strength_norm,
        'uts': uts,
        'uts_norm': uts_norm,
        'total_strain': total_strain,
        'fracture_energy': fracture_energy,
        'fracture_energy_norm': fracture_energy_norm
    })

    # Individual plot in separate window
    fig_individual = plt.figure(figsize=(10, 6))
    ax = fig_individual.add_subplot(111)
    ax = plot_single_curve(data, yield_strength, idx_yield, offset_line, uts, ax=ax)
    ax.set_title(design_names[i])
    ax.legend()

    # Add to combined plot
    ax_combined.plot(data["Strain"], data["Stress (Pa)"], label=design_names[i])

    # Add to comparison plots
    if i == 0 or i == 1:  # Design 1A and 1B
        ax_test1.plot(data["Strain"], data["Stress (Pa)"],
                      label=design_names[i])
    elif i == 2 or i == 3:  # Design 2A and 2B
        ax_test2.plot(data["Strain"], data["Stress (Pa)"],
```

```python
                 label=design_names[i])

    # Format combined plot
    ax_combined.set_xlabel("Strain")
    ax_combined.set_ylabel("Stress (Pa)")
    ax_combined.set_title("Combined Stress-Strain Curves")
    ax_combined.legend()
    ax_combined.grid(True)

    # Format test1 comparison plot
    ax_test1.set_xlabel("Strain")
    ax_test1.set_ylabel("Stress (Pa)")
    ax_test1.set_title("Comparison of Design 1A and Design 1B")
    ax_test1.legend()
    ax_test1.grid(True)

    # Format test2 comparison plot
    ax_test2.set_xlabel("Strain")
    ax_test2.set_ylabel("Stress (Pa)")
    ax_test2.set_title("Comparison of Design 2A and Design 2B")
    ax_test2.legend()
    ax_test2.grid(True)

    plt.show()

    return results


# write here the path to the tests folder on your own computer!!
TEST_DIR = "tests"

file_names = [
    f"{TEST_DIR}/test1.xlsx", # test 1_1 , specimen from Rafael
    f"{TEST_DIR}/test2.xlsx", # test 1_2 , specimen from Wao
    f"{TEST_DIR}/test3.xlsx", # test 2_1 , specimen from Ian
    f"{TEST_DIR}/test4.xlsx", # test 2_2 , specimen from Ian
    f"{TEST_DIR}/test5.xlsx", # final test, specimen from Rafael again
]

results = analyze_multiple_files(file_names)

# Create DataFrames for results
df_all = pd.DataFrame(results)
df_all.set_index('design', inplace=True)

# Create non-normalized results DataFrame
df_non_norm = df_all[['mass', 'yield_strength', 'uts', 'total_strain', 'fracture_energy']]
```

```python
df_non_norm.columns = ['Mass (g)', 'Yield Strength (Pa)', 'UTS (Pa)', 'Total Strain', 'Fracture Energy (J/m³)']

# Create normalized results DataFrame
df_norm = df_all[['yield_strength_norm', 'uts_norm', 'fracture_energy_norm']]
df_norm.columns = ['Normalized Yield Strength (Pa/g)', 'Normalized UTS (Pa/g)', 'Normalized Fracture Energy ((J/m³)/g)']

# Export to Excel with multiple sheets
with pd.ExcelWriter('tensile_test_results.xlsx') as writer:
    df_all.to_excel(writer, sheet_name='All Results')
    df_non_norm.to_excel(writer, sheet_name='Non-normalized Results')
    df_norm.to_excel(writer, sheet_name='Normalized Results')

print("Results exported to tensile_test_results.xlsx")
```