

## Master thesis – Ivan Immanuel Michael

### Chapter – 3

#### Methodology

##### 1. Paper as a Surrogate Material

###### 1.1 Introduction

This study explores the use of paper as a surrogate material for tensile and buckling tests. Paper's low cost, ease of handling, and orthotropic properties makes it a practical and scalable alternative for preliminary structural testing. This allows researchers to identify failure modes and refine designs before committing to expensive composite materials.

###### 1.2 Advantages of Using Paper in Structural Testing

###### Cost-Effectiveness & Ease of Handling

Paper is an affordable and accessible material that enables extensive testing without significant financial constraints. Its simple fabrication and manipulation allow researchers to rapidly prototype and test multiple design iterations. Unlike composites or metals, paper requires no specialized equipment, reducing setup time and increasing testing efficiency. Engineers can assess different rib configurations on an aircraft tail using paper models, identifying weaknesses before transitioning to advanced materials.

###### Structural & Mechanical Similarities to Composites

Paper and fiber-reinforced composites both exhibit orthotropic properties, meaning their mechanical characteristics differ along three mutually perpendicular axes. This similarity allows paper to serve as an effective stand-in for studying the behavior of composite materials under various loading conditions. Below are typical values for key physical and mechanical properties of both materials:

###### Paper:

- **Tensile Strength:** Varies widely depending on paper type and processing, typically ranging from 20 to 100 MPa.
- **Tensile Modulus (Stiffness):** Generally, between 1 and 4 GPa.
- **Density:** Approximately 0.6 to 1.2 g/cm<sup>3</sup> depending on the paper grade and manufacturing process.

###### Fiber-Reinforced Polymer (FRP) Composites:

- **Tensile Strength:**

- Glass Fiber Reinforced Polymer (GFRP): Approximately 250 to 500 MPa.
- Carbon Fiber Reinforced Polymer (CFRP): Typically ranges from 300 to 1500 MPa.
- **Tensile Modulus:**
  - GFRP: Around 20 to 50 GPa.
  - CFRP: Typically, between 70 and 200 GPa.
- **Density:**
  - GFRP: Approximately 1.8 g/cm<sup>3</sup>.
  - CFRP: Around 1.6 g/cm<sup>3</sup>.

These values illustrate that while paper has lower tensile strength and stiffness compared to fiber-reinforced composites, its orthotropic nature and mechanical behavior under varying conditions make it a valuable material for simulating and studying the structural responses of composites.

### **Scalability & Controlled Testing**

Unlike composites and metals, which often have inconsistencies due to fabrication complexities, paper provides a uniform and predictable testing environment. It enables precise scaling of structural models, allowing engineers to simulate large-scale aerospace components at a fraction of the cost.

#### **1.3 Integration with HSB (Handbuch Struktur Berechnung) Method**

The HSB method, a material-independent structural analysis approach, enables comparative evaluation of different materials, including orthotropic ones like paper and aerospace composites.

- **Experimental validation:** Paper specimens can be tested under controlled conditions and compared with HSB predictions.
- **Performance assessment:** Researchers can estimate how advanced materials will behave under similar loads before investing in full-scale prototypes.
- **Model refinement:** Insights gained from paper-based testing contribute to the enhancement of analytical models, leading to more accurate predictions of structural behavior and improved design optimizations.

For instance, engineers can use HSB to compare computational predictions with observed paper model results, refining their analysis before applying it to composite materials.

### **2. Design Approach**

This study employed a mixed-methods design to comprehensively investigate the tensile and buckling behavior of vertical tail planes in the aircraft, utilizing paper as a surrogate material. The research paradigm adopted is pragmatism, emphasizing practical solutions and integrating both qualitative and quantitative data to enhance the robustness of the findings.

A quasi-experimental design was implemented, incorporating both descriptive and correlational analyses to evaluate mechanical behavior. The use of convenience sampling was justified by the accessibility, affordability, and ease of manipulation of paper specimens. The methodology ensured consistency in experimental conditions to improve the reliability and validity of results.

Ethical considerations included ensuring the safety of the experimental setup, maintaining data transparency, and adhering to scientific integrity in the reporting of results. The study acknowledges limitations, particularly the use of paper as a surrogate material, which may not fully capture the complex mechanical properties of advanced composite materials typically used in aerospace applications.

## 2.1 Tensile Testing

To determine the Young's modulus of paper, serving as the surrogate material, a tensile test was conducted. The test specimens were prepared from a reinforced paper sheet, which was fabricated by laminating multiple fiber-aligned strips in 0/90-degree and  $\pm 45$ -degree orientations. This reinforcement method aimed to simulate the anisotropic characteristics of composite materials, which exhibit direction-dependent strength and stiffness properties.

### Sample Preparation

- The entire reinforced paper sheet and all test specimens were cut using an **oscillating multi-tool**, ensuring precision and consistency.
- Test Coupons were prepared in two distinct fiber alignments: **0/90-degree and  $\pm 45$  - degree** orientations.
- Each tensile test coupon measured **15 cm in length and 3 cm in width**. These dimensions were chosen to ensure uniformity across the tests and selected for their practicality and consistency.
- To maintain uniformity across test specimens, the tensile test samples were extracted from the excess material left over from the buckling test specimens, ensuring consistency in material composition.
- The paper strips were **conditioned under controlled environmental conditions** to minimize variability due to external factors. The room temperature was maintained at approximately  $23^{\circ}\text{C}$  ( $73.4^{\circ}\text{F}$ ), with a relative humidity of  $50 \pm 5\%$ , following typical testing standards.

### Testing Procedure

- Each strip was subjected to tensile testing using a Universal Testing Machine (UTM) mentioned below and shown in **Figure: 1**, equipped with a precision load cell for accurate force measurements.
- The specimens were clamped with minimal slippage using pneumatic grips, ensuring an even distribution of load.

## 2.2 Tensile Testing Machine: Universal Testing Machine (UTM)

### Equipment and Instruments Used

The **Galdabini Quasar 100 Universal Testing Machine (UTM)** is a high-precision mechanical testing system designed to evaluate tensile, compression, bending, and shear properties of materials. This state-of-the-art instrument ensures compliance with international standards and is widely used in material science, engineering research, and quality control applications.

#### Specifications:

- **Model:** Galdabini Quasar 100 UTM
- **Load Capacity:** Up to 100 kN (kilonewtons)
- **Crosshead Speed Range:** 0.001 to 1000 mm/min
- **Accuracy:**  $\pm 0.5\%$  of the indicated load
- **Control System:** Digital interface with advanced software for real-time monitoring, data acquisition, and analysis
- **Testing Space:** Adjustable to accommodate a variety of specimen sizes and geometries
- **Compliance:** Conforms to ASTM, ISO, and EN standards

#### Key Features:

- **High-Precision Load Cells:** Ensures accurate force measurements with minimal error.
- **Advanced Software Integration:** Facilitates precise test control, automated report generation, and real-time data analysis.
- **Interchangeable Grips and Fixtures:** Enables versatile testing configurations for different material types and specimen dimensions.
- **Safety Mechanisms:** Equipped with overload protection, emergency stop functions, and real-time monitoring to enhance operational safety.

## 2.3 Critical Components

**Grips & Fixtures** Grips and fixtures secure the specimen during testing, ensuring consistent force application and minimizing slippage. Available configurations include wedge grips for high-strength materials, pneumatic grips for delicate specimens, and specialized fixtures for compression and bending tests.

**Load Cell** The load cell is a fundamental sensor that measures the applied force during testing, converting mechanical load into an electrical signal. This data is essential for determining mechanical properties such as yield strength, ultimate tensile strength, and modulus of elasticity.

**Extensometer** An extensometer precisely measures strain (elongation) during tensile testing. It provides real-time data on material deformation under load, crucial for evaluating mechanical behavior, ductility, and failure characteristics.



**Figure: 1**

### 3. Buckling Analysis

The buckling analysis was conducted using a picture frame fixture, designed to apply uniaxial tension and generate shear stress within the specimen. This method effectively simulates the loading conditions experienced by the ribs of an aircraft's vertical tail plane, which are predominantly subjected to shear forces during operation.

#### Sample Preparation

- A base sheet of paper was reinforced by laminating multiple layers of fiber-aligned strips in 0/90-degree and  $\pm 45$ -degree orientations.
- A controlled curing period of approximately two days was maintained at a temperature of 23°C (73.4°F) and a relative humidity of 50  $\pm$  5% to ensure full adhesion and stabilization of the layered structure while minimizing variability caused by external factors.
- Post-curing, the sheet was precisely cut to its final dimensions of 210 mm  $\times$  210 mm with a thickness of approximately 20 mm using an oscillating multi-tool, ensuring accuracy and consistency
- The remaining material from the reinforced sheet was allocated for tensile testing to ensure uniformity across specimens.

## Testing Procedure

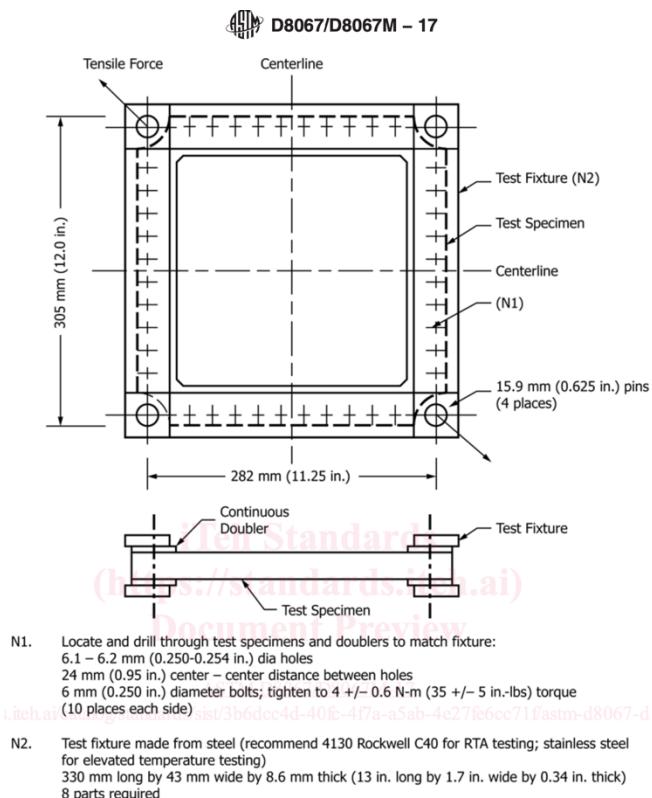
- The specimen was secured within the picture frame fixture to induce shear stress under uniaxial tensile loading.
- The applied uniaxial tension created tensile forces oriented at a 45-degree angle effectively generating and distributing shear stress.
- Multiple metal strings were used to monitor displacement, with the small end attached to the test specimen and the longer end extending outward. The setup was aligned to a straight line to visually detect any deflection.

### 3.1 Fabrication of an Aluminum Picture Frame Fixture for Buckling Analysis

To analyze buckling behavior in reinforced paper specimens, a metallic picture frame test fixture was designed and fabricated. The fixture provides uniform boundary conditions and ensures accurate load distribution. Modifications were made based on ASTM D8067/D8067M-17 as shown below in **Figure: 2** to tailor the design for this study's specific requirements.

### 3.2 Design and Fabrication

The test fixture is a square aluminum frame with external dimensions of 252 mm × 252 mm, designed to enclose the paper specimen while ensuring controlled loading conditions. The fixture and specimen were marked along their lengths, featuring 10 drilled holes fastened with bolts and self-locking nuts for precise alignment.



**Figure: 2**

**Material Selection** Aluminum was selected due to its lightweight properties, corrosion resistance, and ease of machining. As the primary focus of the study was on paper specimens, the frame's structural influence remained minimal yet sufficient for accurate testing.

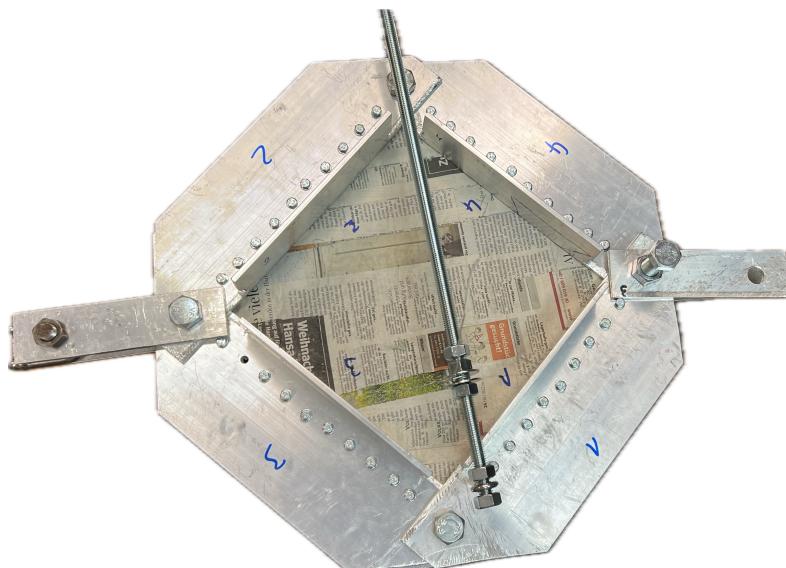
**Test Specimen Preparation** Paper specimens were reinforced and arranged in two configurations:

- **0°/90° Orientation:** Perpendicular paper strip layers.
- **±45° Orientation:** Strips arranged at an angular offset to assess the influence of fiber orientation on buckling behavior.

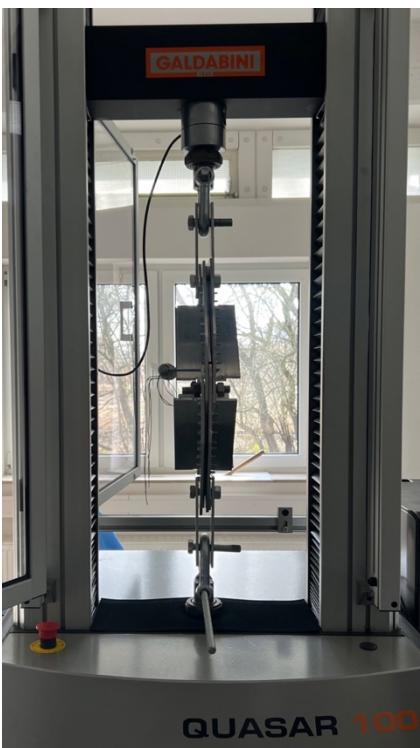
Layers were alternately bonded using high-strength adhesive to maintain structural consistency, simulating real-world applications.

### 3.3 Assembly and Testing Procedure

1. The aluminum frame was machined using a chop saw and a table saw to achieve the required dimensions. Subsequently, precisely positioned bolt holes were drilled using a drilling machine to ensure alignment with the specimen attachment points.
2. Reinforced paper specimens were precisely cut using an oscillating multi-tool to fit within the frame, ensuring uniform edge distribution.
3. The frame was assembled to secure the test specimen between two aluminum sections, with load distribution plates incorporated to ensure even force application and minimize stress concentrations as shown in **Figure 3**.
4. The setup was integrated into a Universal Testing Machine (UTM) by replacing pre-existing fixtures and clamps, directly attaching the frame to the machine for load application as shown below in **Figure: 4 and Figure: 5**.
5. Gradual force was applied while recording deformation and buckling onset through strain measurement.



**Figure: 3**



**Figure: 4**



**Figure: 5**

#### 4. Conclusion

This study highlights the efficacy of using paper as a surrogate material for preliminary tensile and buckling tests in aerospace structural analysis. The application of paper allows for cost-effective, scalable, and insightful investigations into mechanical behavior, offering a viable alternative before transitioning to expensive composite materials. The integration of the Universal Testing Machine (UTM) and an aluminum picture frame fixture ensured precise force application and accurate data collection. By leveraging paper-based testing alongside analytical and experimental models, engineers can streamline research, reduce costs, and enhance the predictive accuracy of aerospace structural evaluations.