Boeing Thermoplastic Composite Wing Design

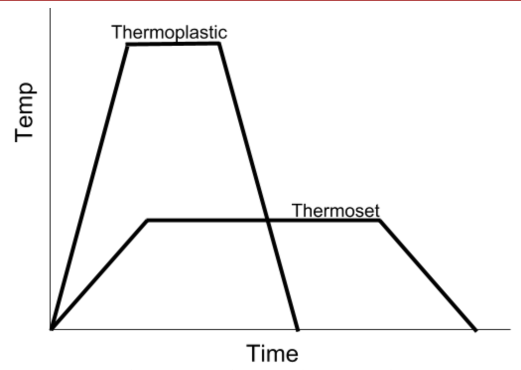
Roger Cheng, Mitchell Frimodt, Gary Lam, Tianqi Liu

Advisor: Susan Murphy | Mentors: Matthew Bozzonetti & James Dobberfuhl

William E. Boeing Department of Aeronautics & Astronautics

University of Washington, Seattle, WA 98195-2400 (Spring 2019)

INTRODUCTION



Problem & Motivation: The impact of composites has greatly improved fuel efficiency by reducing the weight of aircraft, but the long processing time of thermoset composites limits the overall production. While thermosets require a lower temperature with a longer curing time, thermoplastics require a higher temp. but a much shorter processing time → Reduce cost and production time

Goal & Requirement: To design, build, and test an aerodynamic wing body composed of thermoplastics composite for the purpose of exploring innovative manufacturing methods and helping industrial implementation of thermoplastics.

ORGANIZATION

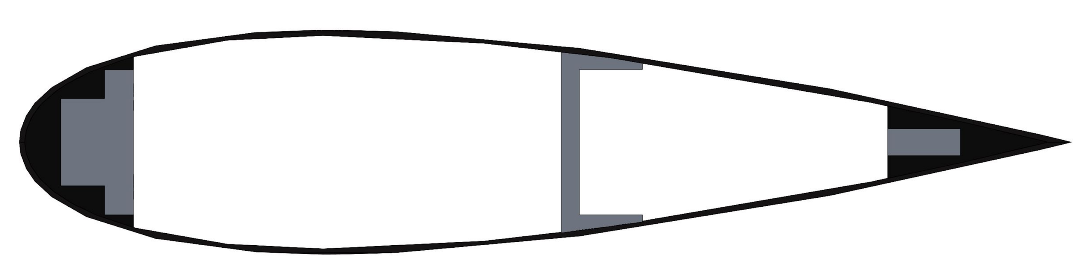
Facilities & Scheduling: Throughout the project, many facilities were used including the low-speed wind tunnel, 3D printer, water-jet machine, Instron tensile machine, machine shop, CNC machine, and the Boeing autoclave. As for the scheduling, constant adjustments were made to accomodate budget & time.

Budget & Cost: The team set up the budget independently since no restrictions were given and the total cost was **$2,615** with approx. **520+ hrs** of working time.

DESIGN

Design Overview

Because of the unique project objective, the design was driven by external constraints such as the wind tunnel and manufacturing costs. The span of the wing is 35.5", approximating an infinite wing inside the 3'x3' wind tunnel. The cross-section profile of the wing is constant along the entire span and is a NACA 0021 airfoil with a chord length of 7.26", which was thick enough to accomodate an internal mounting configuration and required the manufacturing of only a single tool. The composite skin of the wing consists of two similar halves made out of thermoplastic composite material consisting of carbon fiber and a PEEK matrix. Each skin is constructed of three, twill-weave plies with a layup orientation of [(0°,90°)/(45°,-45°),/(0°,90°)], providing a balance of strength and manufacturability. The internal structure of the wing consists of three aluminum spar structures which add flexural rigidity and aid in the joining of the two skin halves. The load cell mount, a 3D-printed ABS part, transfers the aerodynamic loads from the skin and the spars to the load cell of the wind tunnel.



Aerodynamic Analysis

The aerodynamic loading on the wing was driven by the capability of the wind tunnel, which operates at wind speeds of 15m/s to 60m/s, yielding an achievable Reynold's number range of 186,000 to 746,000. Based on two mathematical models (Eppler and Xfoil) for two-dimensional subsonic flows, the max aerodynamic load was calculated to be 504 N [1][2].

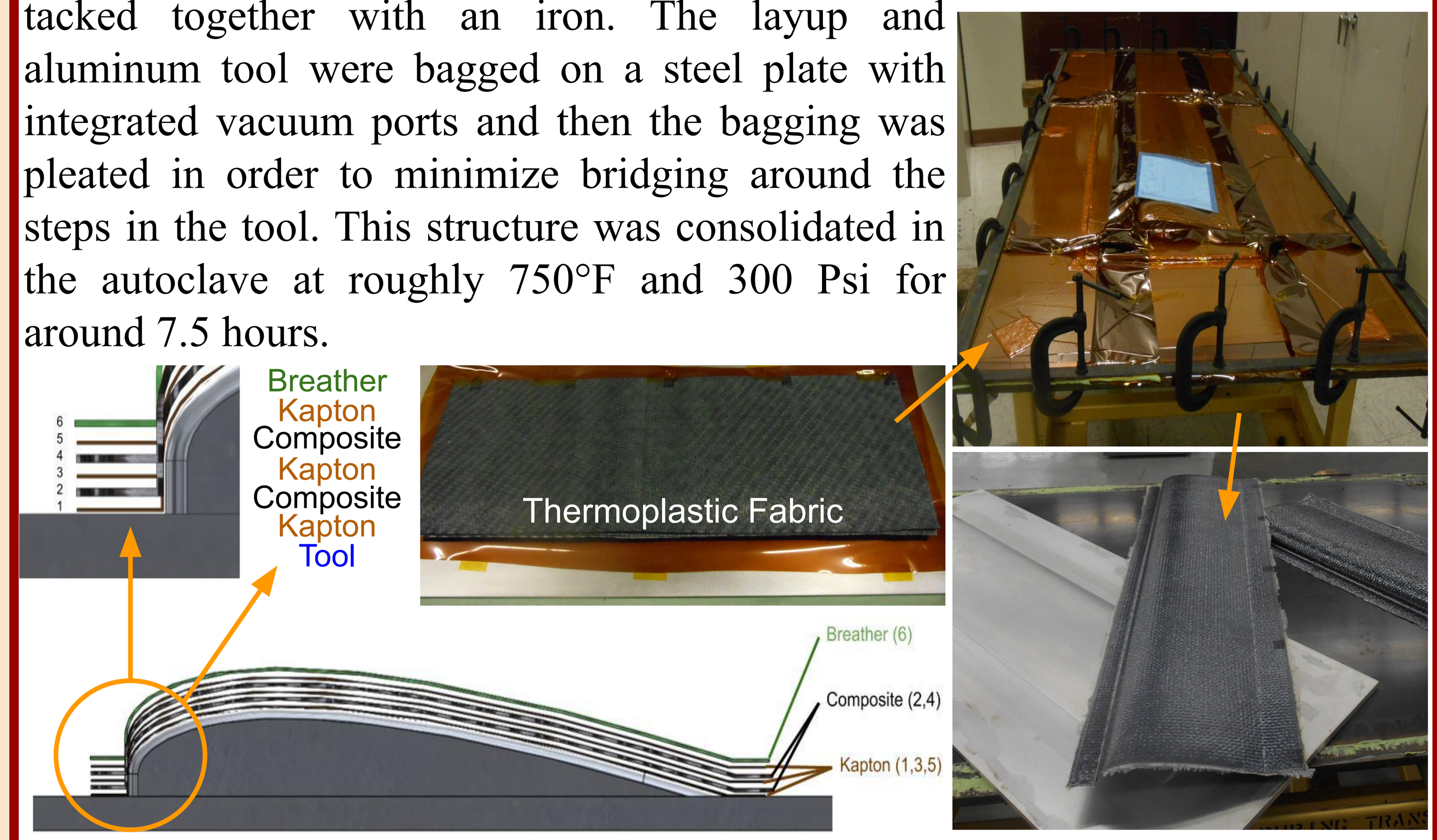
Structural Analysis

Using classical laminate theory (CLT) and modeling the three ply weave layup as a six ply layup of unidirectional tape the structural properties of the laminate were estimated and are displayed in **Table 1** [3]. Using beam bending equations for the main components and FEA for the load cell mount, the max stress of each component was calculated and yielded large margins of safety (MOS).

Table 1	
E_x	8.49msi
E_y	8.49msi
G_{xy}	.202msi
ν_{xy}	0.208
t	.0375 in

MANUFACTURING

The composite layup consisted of 6 different layers of Kapton film, thermoplastic composite pre-preg fabric, and woven fiberglass that were secured onto the tool with Kapton tape. Two composite panels were produced at the same time on the tool and each was comprised of 3 plies of fabric that were tacked together with an iron. The layup and aluminum tool were bagged on a steel plate with integrated vacuum ports and then the bagging was pleated in order to minimize bridging around the steps in the tool. This structure was consolidated in the autoclave at roughly 750°F and 300 Psi for around 7.5 hours.



3D printing and milling were used to fabricate the internal components out of aluminum and ABS, then the composite panels were trimmed using a dremel and sanded to size. With all the parts finished, the assembly began by fastening the spars to the load cell mount. Next, the ABS and aluminum parts of the spars were joined with an epoxy (1). Mounting holes were drilled in the composite skins and the surfaces that would be in contact were sanded to improve adhesion. The combined load cell mount, C-channel, and leading edge spar were adhered to the each composite skin, using clamps and weights to apply pressure (2,3,4). After the epoxy cured, the trailing edge spar was adhered in a similar fashion. Once all of the components were joined, additional epoxy was used to fill in the gap in the leading edge, which was then sanded smooth (5,6).

ACKNOWLEDGEMENT

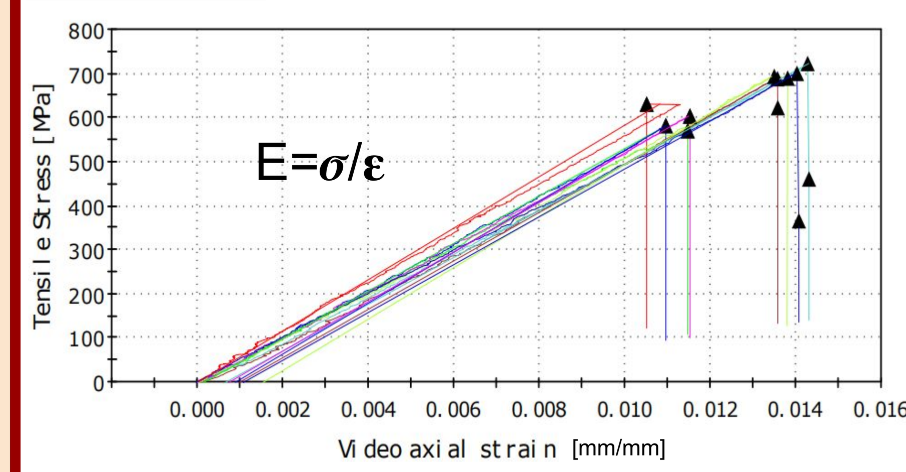
- Boeing Industrial Mentors: Jim P Dobberfuhl and Matthew T Bozzonetti; and other Boeing employees such as Nicolas Zayas, Alvaro Zambrana Acosta, Tony Gliane, Julie Murphy, and everyone who helped us at Boeing
- UWAA Capstone Project Director: Susan Murphy, TA John Berg, Bob Scott, Prof. Owen Williams, Eliot George, and Fiscal Specialist Nancy-Lou at UW
- A&A Department, ME Department, MSE Department, and UW Hyperloop

References:

1. Sandia National Laboratories, *Aerodynamic Characteristics of Seven Symmetrical Airfoil Sections Through 180-Degree Angle of Attack for Use in Aerodynamic Analysis of Vertical Axis Wind Turbines*, Albuquerque, New Mexico: Sandia National Laboratories, 1981.
2. "NACA 0021 (naca0021-il) Xfoil prediction polar at RE=1,000,000 Ncrit=9", *Airfoiltools.com* Available: http://airfoiltools.com/polar/details?polar=xf-naca0021-il-1000000.
3. Tuttle, M., *Structural analysis of polymeric composite materials*, Boca Raton, FL: CRC Press, 2013.

TESTING & RESULTS

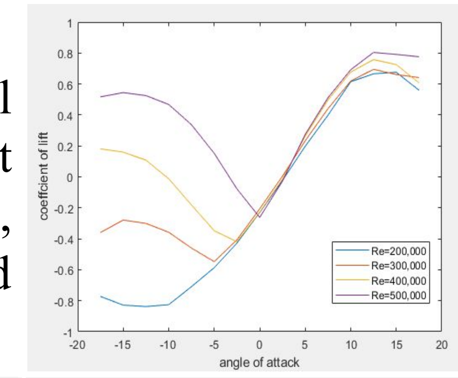
Tensile Test

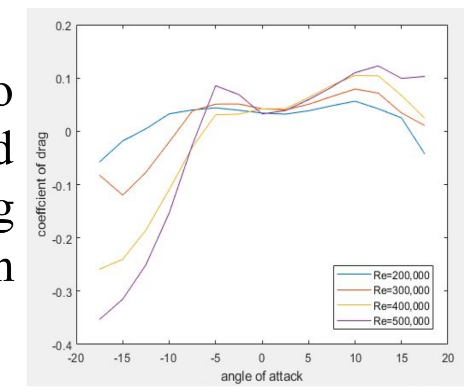


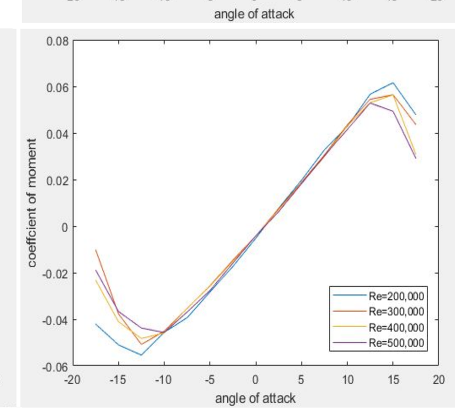
Total of eight dog-bone specimens trimmed from top and bottom panels were tested with "Instron 5585H 250 kN electromechanical test frame" to find the physical properties of the thermoplastic composite, utilizing measurements of axial stress and strain. The bottom panel specimens broke earlier than the top panel specimens. The maximum load applied to bottom specimens was about 1 kN less than that on top specimens, but the average Young's modulus of bottom panels was a little bit higher. That meant the displacement of bottom panel was shorter under the same stress. The average Young's modulus was 51.83 GPa with standard deviation of 1.806. Although the estimated Young's modulus using CLT was 58.6 GPa, the average experimental results yielded an 11.55% difference.

Wind Tunnel Test

In the wind tunnel test, lift force, drag force and pitching moment were tested in 3'x3' low speed wind tunnel with angles of attack ranging from -17.5° to 17.5°. By controlling the indicated pressure, Q_{in}, the air flow speed could be adjusted to correspond to Reynolds number of 200,000\300,000\400,000\500,000. Then, coefficients of lift, drag force and pitching moment were calculated and adjusted by relative equations and calibration. As shown in the plots, the results for positive angle of attack followed with expected results, however, the negative angle of attack results were somewhat incorrect. This occurred during the testing process for negative angle of attack because the edge of panel touched the load cell support structure. In order to get better data, the second test was done with wing flipped, and similar plots were constructed. Thus, the top and bottom panels were symmetric in general, but not exactly identical because of the different roughnesses of the two surfaces and the large linear and angular deflections of the wing under high air flow speed with large angle of attack.







CONCLUSION

Key Lessons & Contributions: The final product and all deliverables including the wing, testing results, manufacturing procedures, joining methods, and the engineering report were delivered to the Boeing Company. The key findings will help Boeing gain a better understanding of thermoplastic composite materials and manufacturing, and impact future composite development in aerospace industries.

- Aerodynamic surfaces should consolidate against a solid or tooling surface
- Under 300 psi in the autoclave, the weave form still created surface waviness
- When cutting the thermoplastics composites, use coolant and proper abrasive tools to prevent the polymer from melting/coating onto the tooling surface
- Aluminum tool performed well inside the autoclave at high temp. and pressure

Ethical/Environmental Impact: It is important to understand the performance of a material before applying it in situations where there might be potential injuries or death if failure occurs. The recyclability and reformability of thermoplastic composites reduces material waste, which improves environmental impact.