U.S. AIR FORCE

USSF

AFRL

Structures Design: Topology Optimization

Dr. James Joo, Tech Advisor

Structures Technology Branch, AFRL/RQV

Outline

- Motivation
- What is Topology Optimization (TO)?
- Suffering of not using it?
- Is TO worth the effort?
- Technical challenges and bottlenecks
- In-house / collaboration research activities
  - TO WiSDM
  - TO in PiCARD (SLA3IR LITE Design)
  - Continuous Fiber Reinforced Composite Structure Design
  - Topology Optimization Post-Processor / Interpreter
  - PISTOL
  - IsoTruss
- Summary

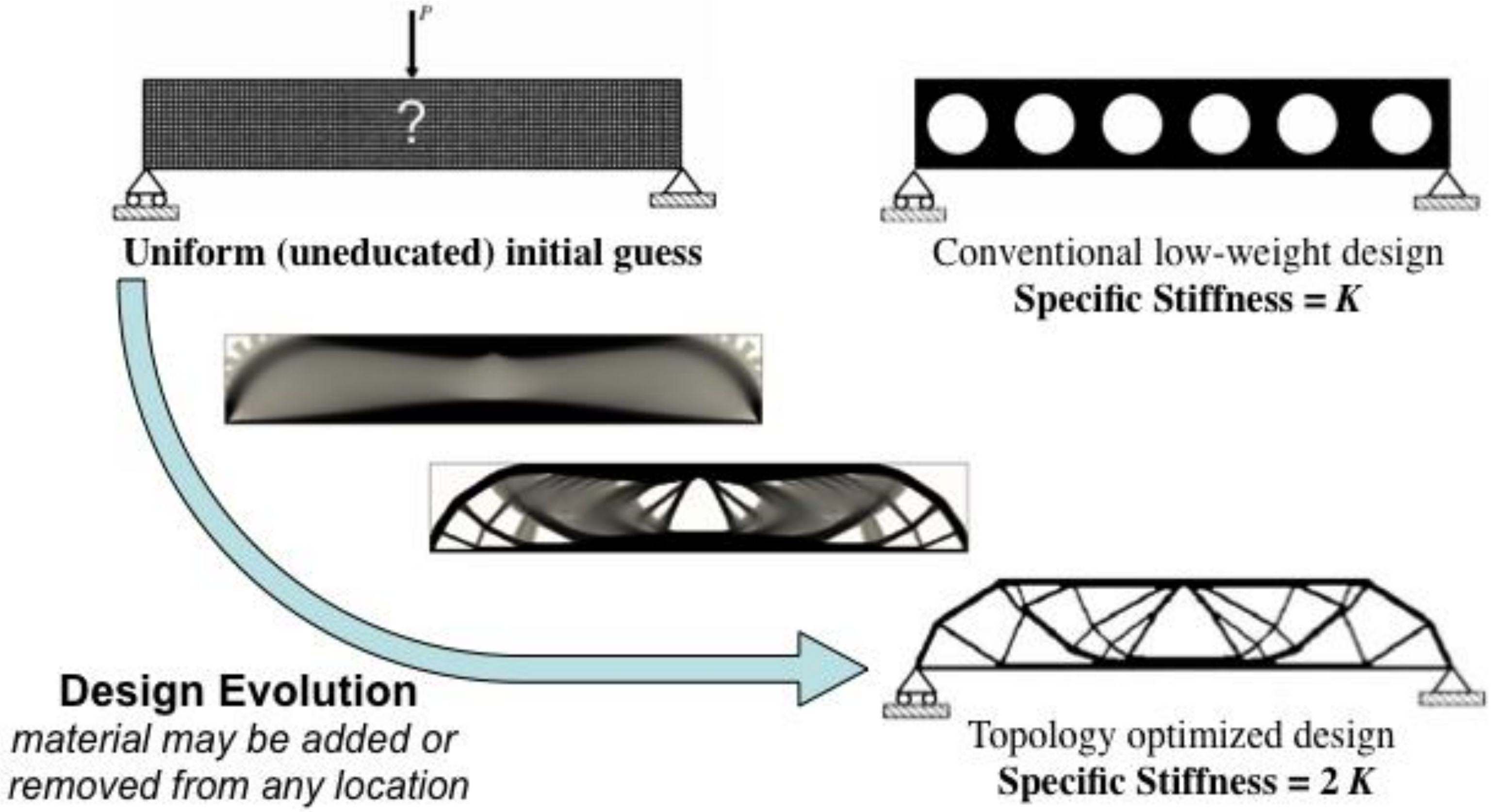
Motivation

- Metal
  - Favorable material for aircraft structures for many decades because it was relatively well understood and favorable to manufacture
  - Orthogonal layout of the aircraft structure is practical but not optimum.
- Topology optimization
  - Developed in the 80s to take advantage of computing power and speed the development of the structures.
  - Viral and disruptive technology in the 90s and 00s, but the interest reduced because people realized there is no easy way to manufacture the TO design
- Metal and polymer 3D printing
  - Meanwhile, metal and polymer printing technologies matured with huge investments, and complicated geometry is no longer an issue.
  - The community has adopted TO as a major design tool
  - People were looking for an optimal design to take advantage of the technology
- Composite
  - Getting popular because it significantly reduces the aircraft's structural weight without no or minimal layout change
  - Expensive and hard to automate the process
- Continuous fiber composite 3D printing
  - Emerging and disruptive technology to remove hand layup process
  - Technology is not mature yet (2.5D), and the material property is 60-70% of the conventional composite
  - Without design change, the printed structure is expected to be 30-40% heavier

Topology Optimization may help to reduce the technology gap

What Is Topology Optimization?

Determination of optimal principal material distribution for a given problem
A powerful tool for concept design stage



Suffering of Not Using TO?

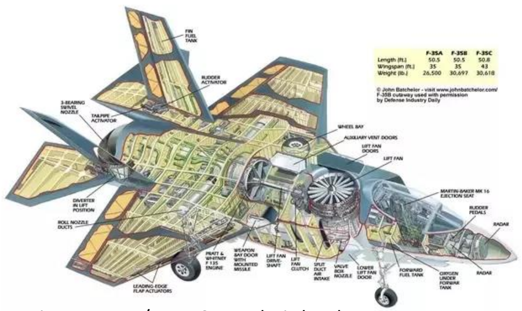
- Orthogonal sub-structure layouts have been used and optimized for many decades. It is hard to expect further weight savings even by replacing them with a lightweight material due to the uncertainty of using new material.
- The orthogonal structure is usually more challenging to print than the non-orthogonal blended structure due to the overhang angle and minimum tow width requirements for composite printing.
- The structure design process is slower than aerodynamic design.
- The material property of printing composite materials is 60-70% of the conventional hand layup composite.

https://airwingmedia.com/downloads/f4-phantom/

F4

https://www.f-16.net/forum/viewtopic.php?t=54123

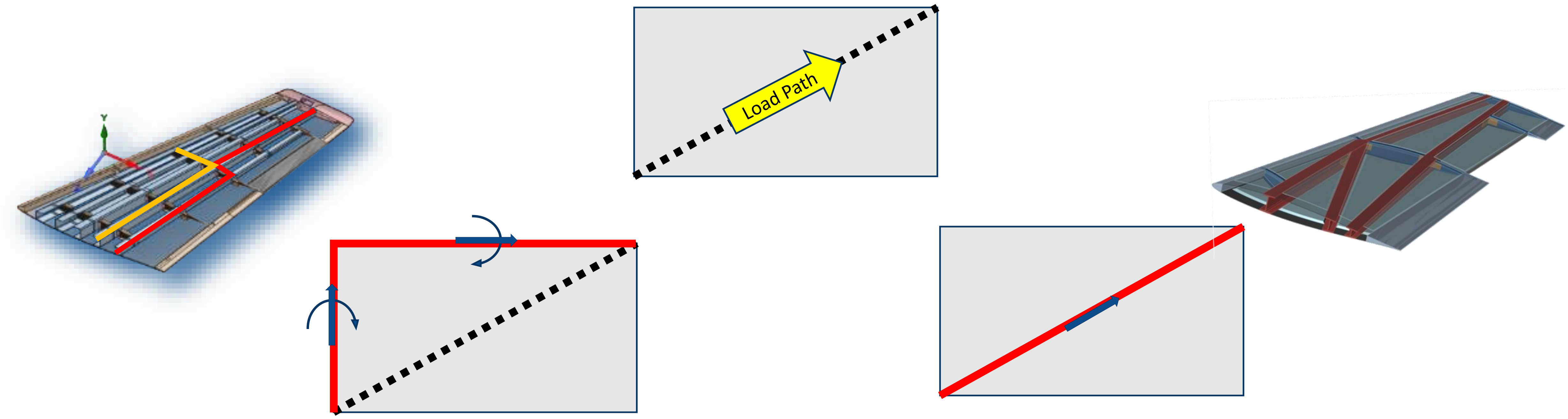
F16



http://www.ausairpower.net/APA-JSF-Analysis.html

F35

Traditional Overdesigned Structure vs Unconventional Lean Structure



<u>Orthogonal Structure</u>

Heavier

Higher stress

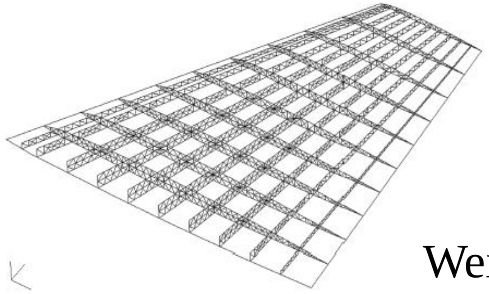
<u>Non-orthogonal Structure</u>

Lighter

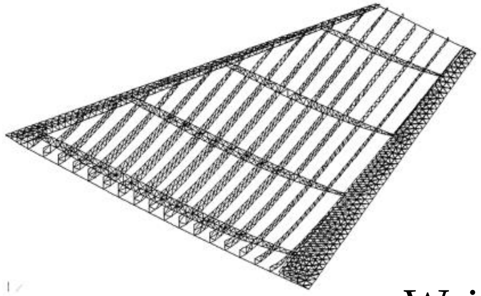
Lower stress

Is TO Worth The Effort?

1000's lb of weight savings
(Not confirmed)



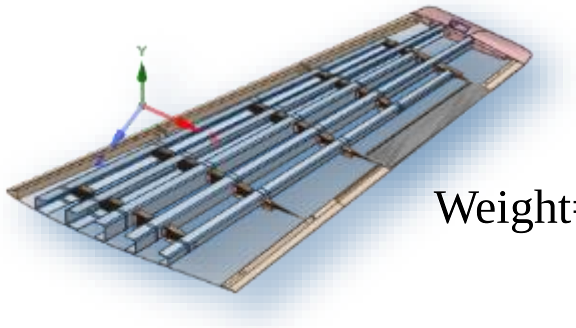
Weight=399 lb



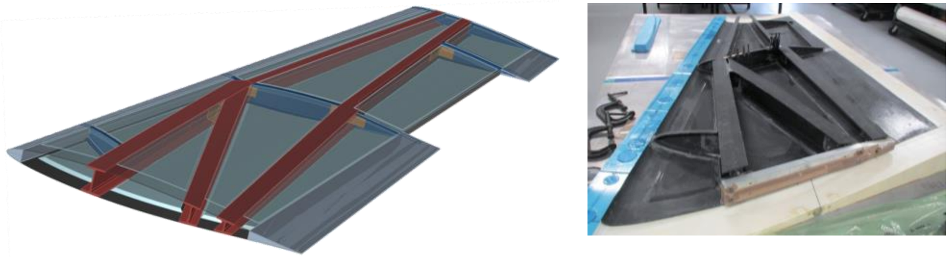
Weight=285 lb

Using curvilinear spars and ribs weight reduction of about 29%.

POC: Prof. Ali Yeilaghi Tamijani, ERU



Weight=57 lb (Aurora)

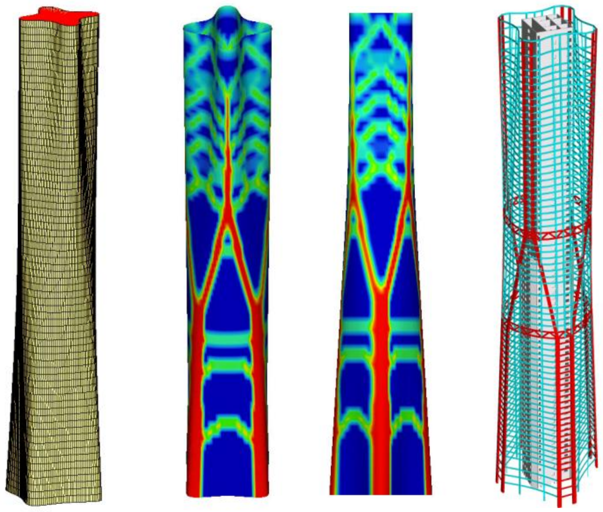


Weight=44 lb

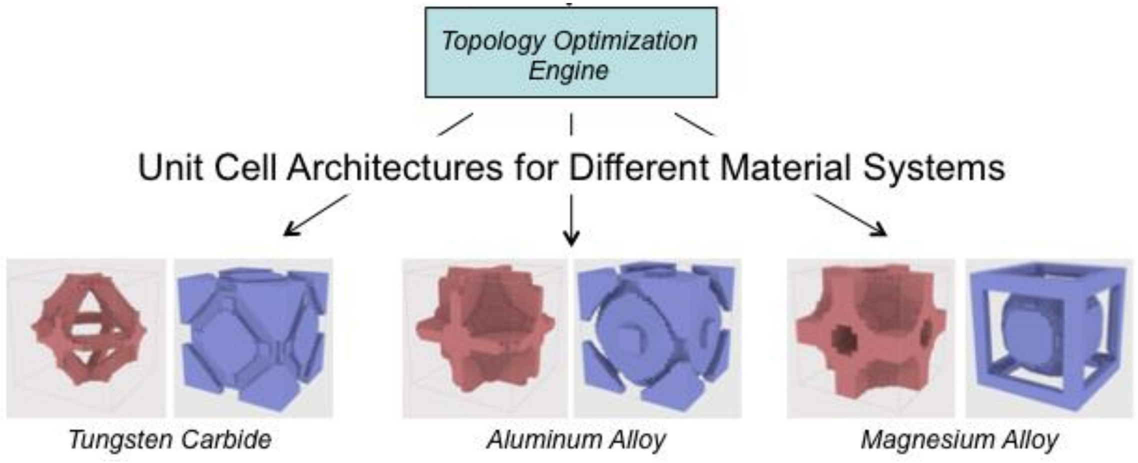
TO based new unorthogonal substructure weight reduction of about 23%.

POC: James Joo, AFRL

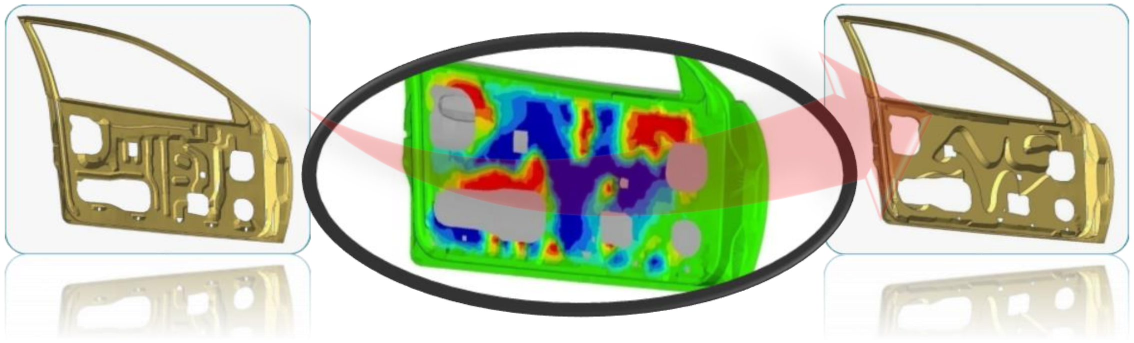
Applications



White Magnolia Plaza Frame design
(Skidmore Owings & Merrill)



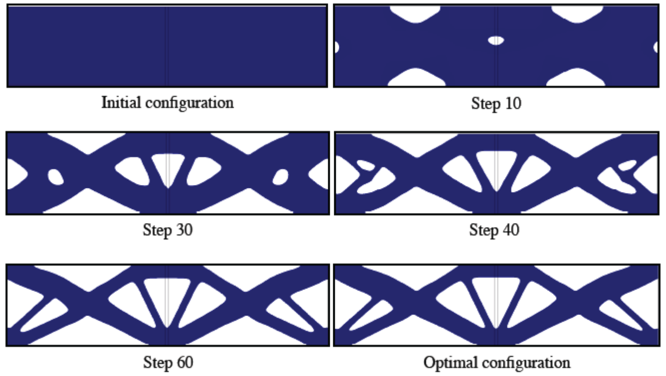
Fixed leading edge
wing ribs designs



https://www.altair.com/optimization/

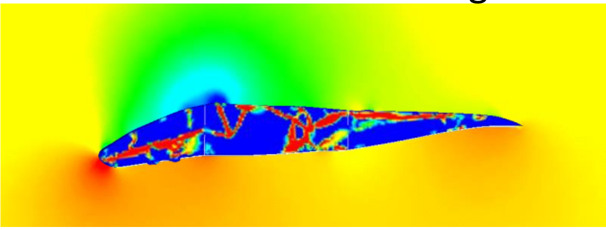
Multi-Physics

Level-set method

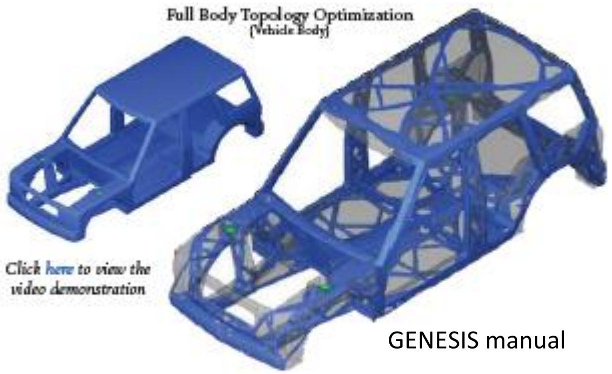


Nishiwaki, S et al (2012)

Aeroelastic design



Maute and Reich (2005) L/D=11.3



GENESIS manual

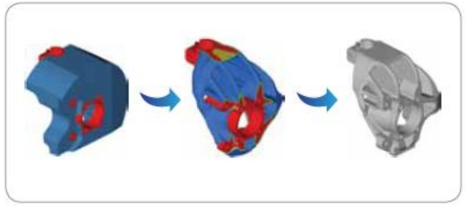
3D structure

Structure
Aeroelasticity
Aerothermal
Packaging & manufacturing
Mechanism
:
Topology optimization is a design methodology we can address these problems all together

Compliant Mechanism

Sigmund (2004)

Component design

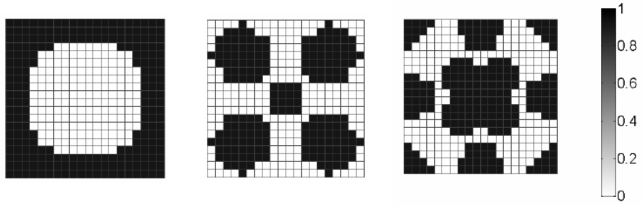


Automobile Knuckle Design Using Manufacturing Constraints

Altair OptiStruct manual

Olhoff, N et al (2011)

Sound barrier

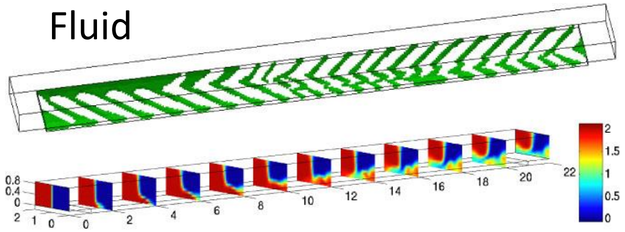


ω=200 ω=1000 ω=2500

Thermal

Sigmund (2001)

Fluid

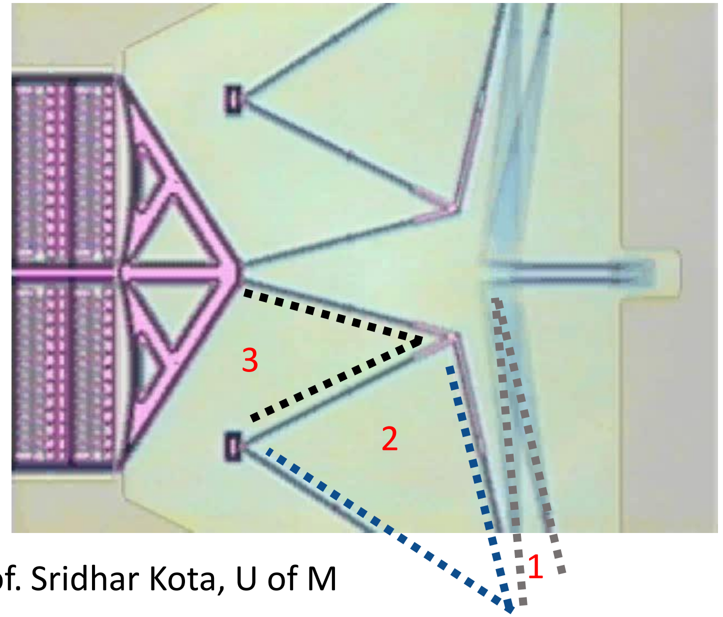


Andreasen et al (2009)

Technical Challenges and Bottlenecks

- Uncertainty and lack of reliability & verification

<u>Building block method (Intuition)</u>

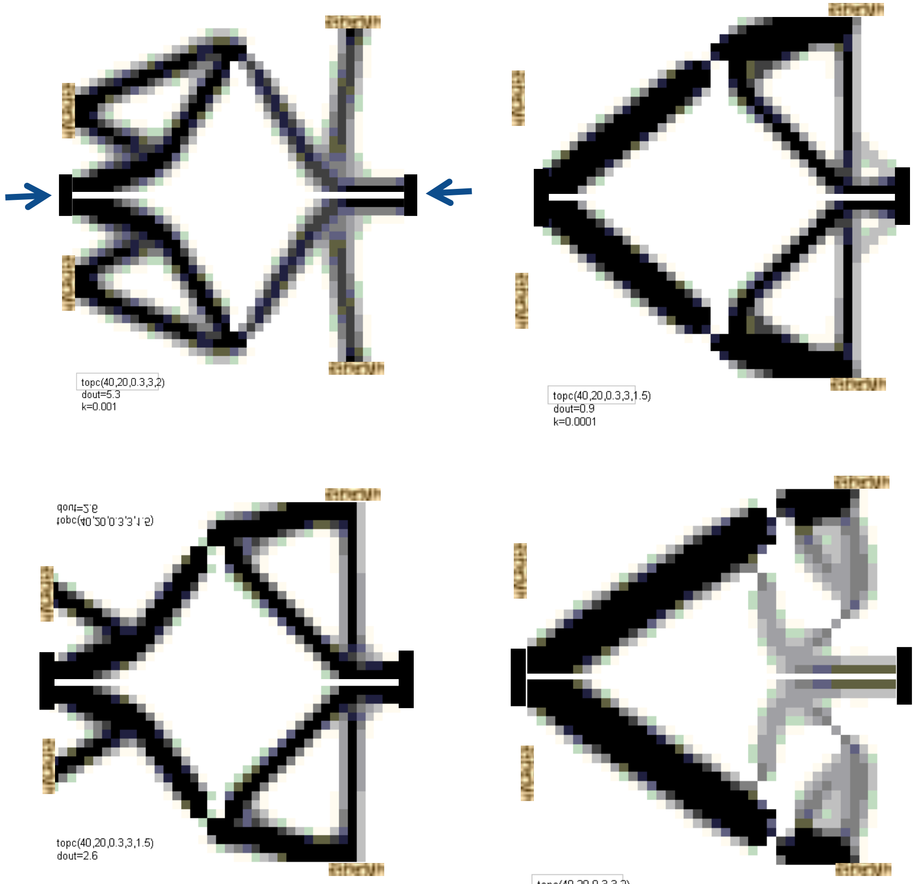


Prof. Sridhar Kota, U of M

Basic building block +
INTUITION (number of building blocks, arrangement, fixed node location, …)

Experience required

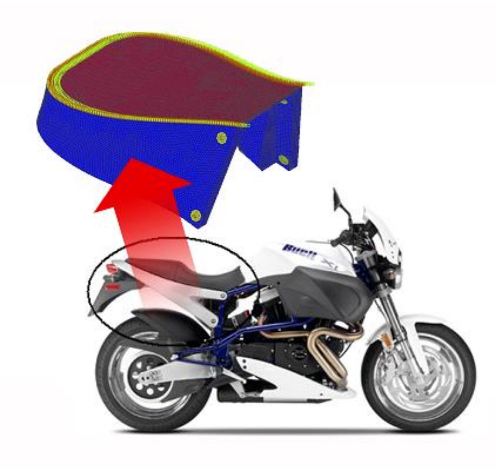
<u>Topology Optimization</u>

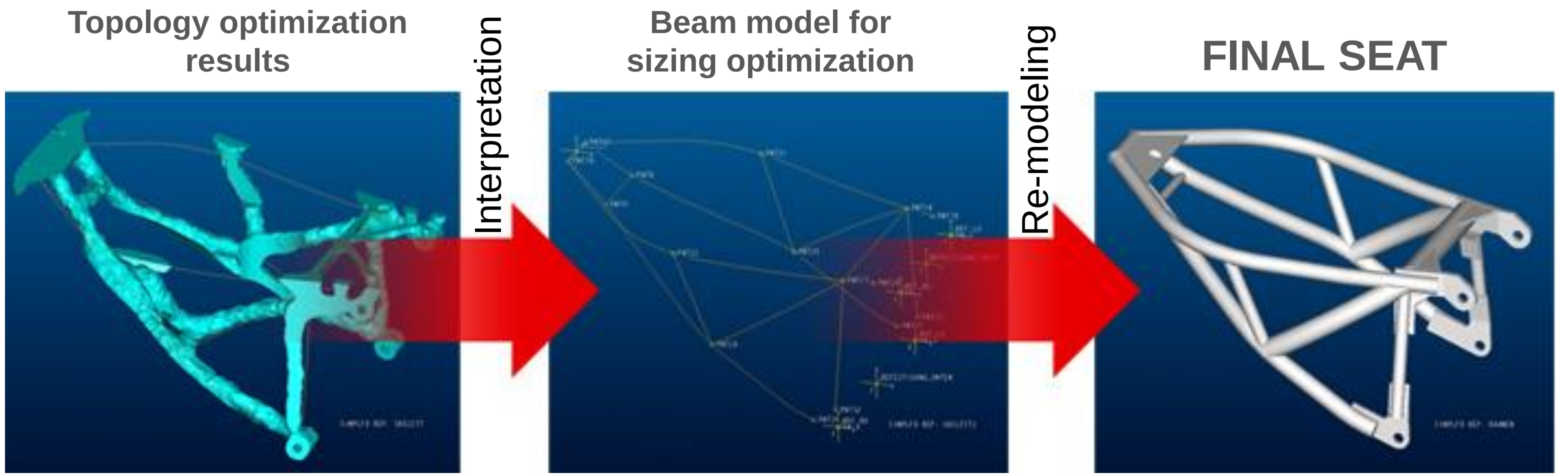


Too sensitive to a small parameter change

Technical Challenges and Bottlenecks

- Topology optimization results $\rightarrow$ CAD model
  - Requires expert's opinion to interpret optimum results (Not an automatic process and need significant interaction with a designer)
  - No systematic translator to CAD model
  - Long modeling time
- Need automatic Iso-surface extraction and remeshing





Technical Challenges and Bottlenecks

- Large Scale Wing Structure Design
  - Still component level result like solution for a system level problem (scale issues?)

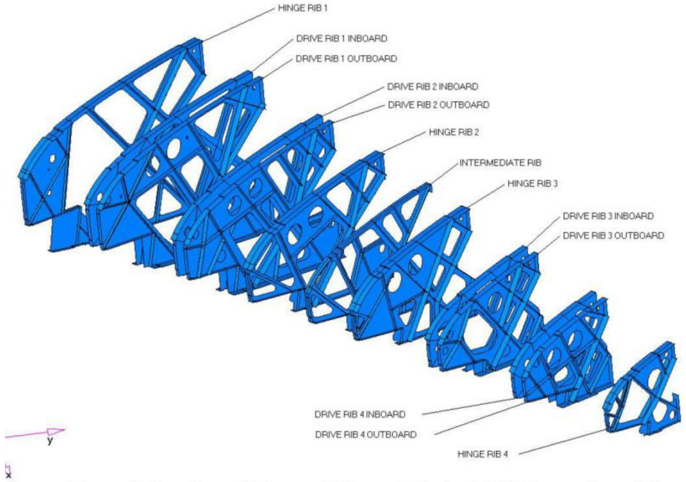
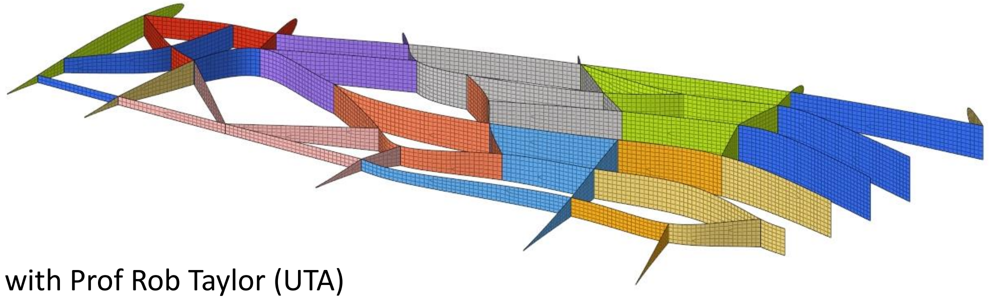
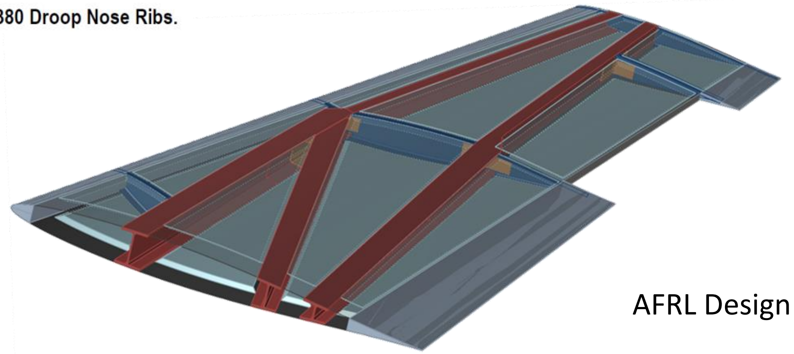


Figure 6: Topology, Sizing and Shape Optimised A380 Droop Nose Ribs.

TO shows load path
Needs shape and size optimization to further develop the design to take advantage of them to further reduce the weight including fiber orientation



Collaboration with Prof Rob Taylor (UTA)



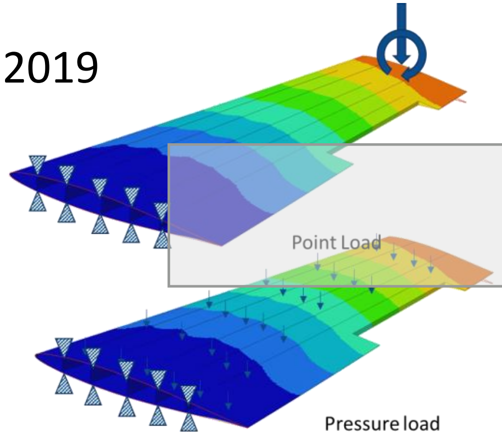
AFRL Design

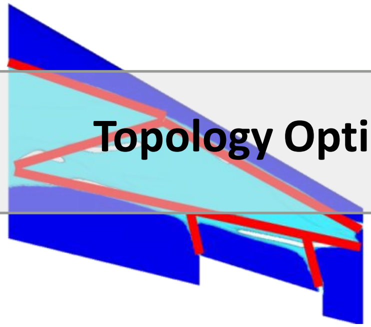
RQVS WiSDM Wing Redesign

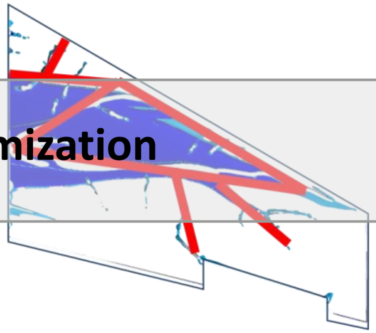
TO WiSDM

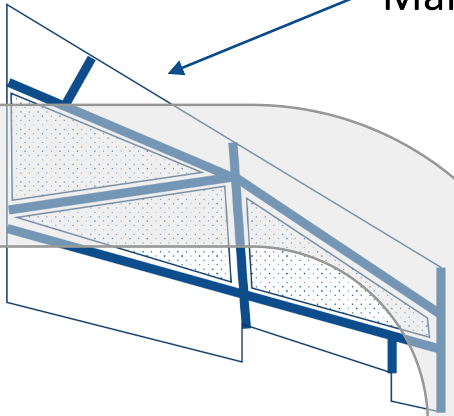
WiSDM Wing Redesign Using TO

Oct 2019





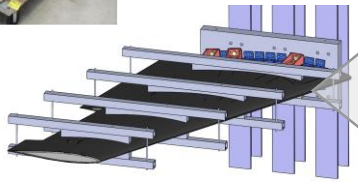




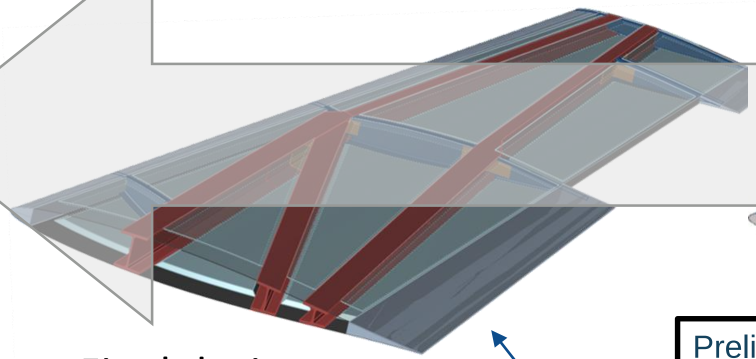
Mar 2020

Topology Optimization

Key Performance Parameter	Req't Threshold	Req't Objective	Value Justification	How Demonstrated/Verified
Weight	90% Baseline	80% Baseline	Weight reduction goal	Measure
Strength (highest stress)	DLL	1.1 x DLL	Structure integrity	Verify by Analysis/Test
Stiffness (tip deflection)	1.1 x Baseline Value	Baseline Value	Deflection measure	Verify by Analysis/Test

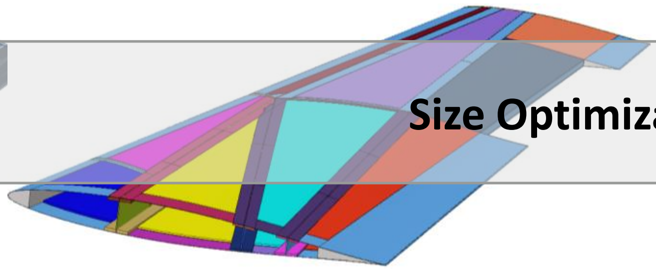


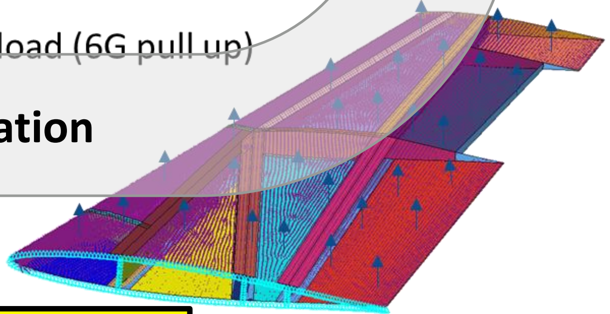
Fab and test by Oct 2020 (13 months)



Final design

Jun 2020

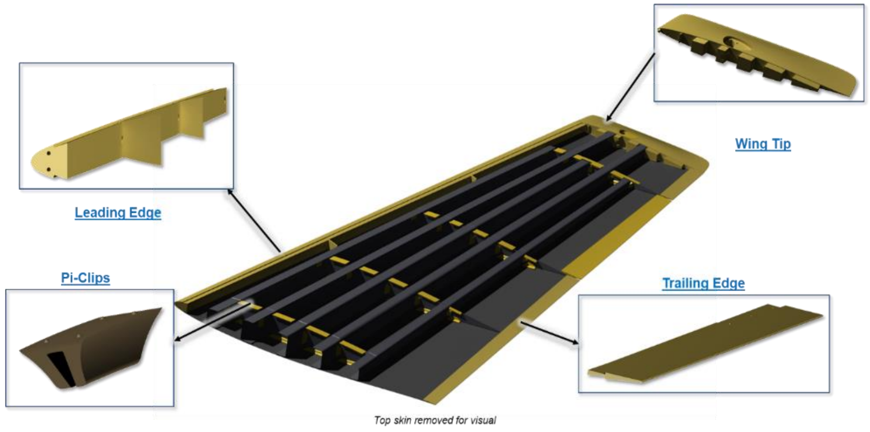


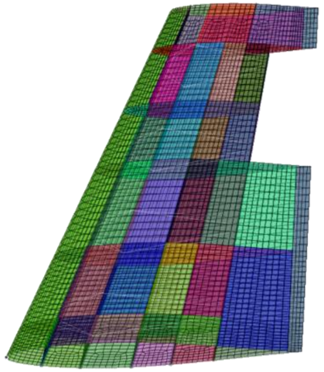


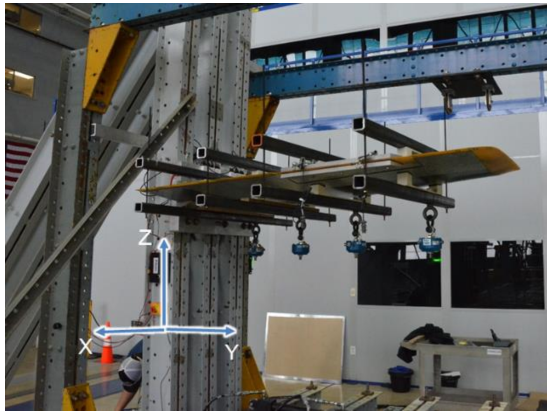
Size Optimization

Preliminary weight estimate was 34 lb
Aurora weight estimate at CDR was 45 lb
} 23% weight savings

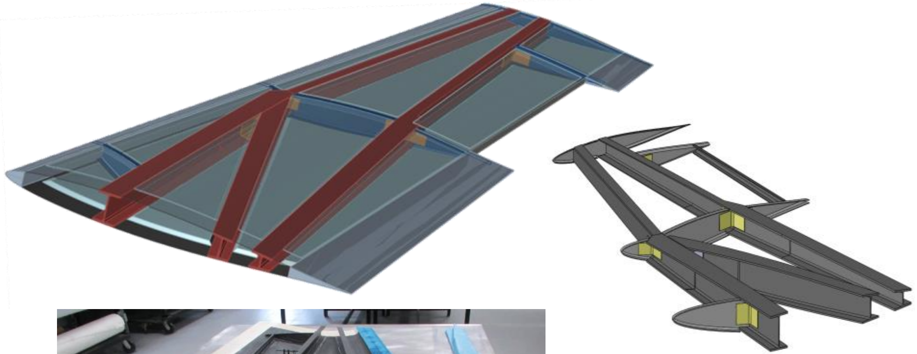
Design Requirements and Ground Test Results

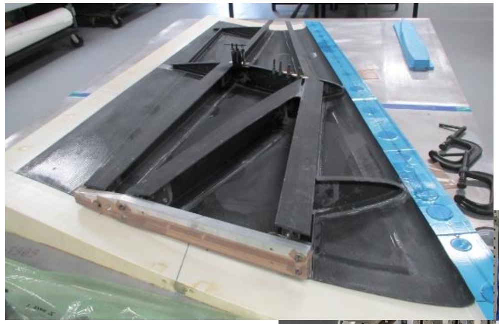






Aurora		AFRL
1.5	Safety Factor	1.5
3	Linear buckling load factor	3
1.1”	Target tip deflection	1.1”
1.17”	Tip deflection @6G	1.23” (+5%)
45 lb	Optimized Weight	34 lb (-24%)
57 lb	Fabricated Wing Weight	44 lb (-23%)
167 % (10.0G)	Failure Load	235 % (14.1G)
Piclip delamination observed	Structure Failure	Skin failure. No substructure failure observed



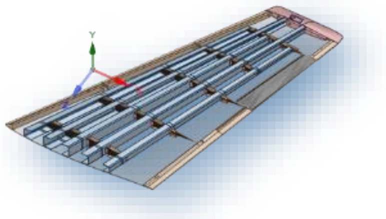


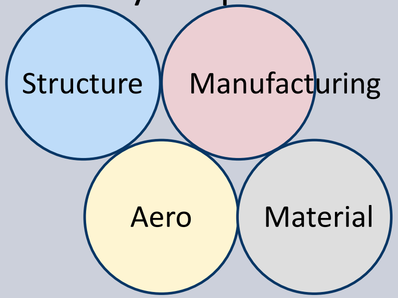
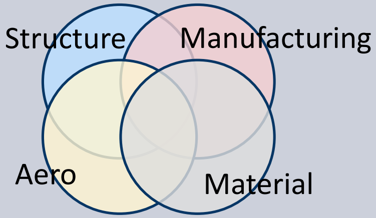
Weight reduction strategy in this project was to redistribute the available material following load path identified by TO. The substructure would take the majority of load and the thin skin would be minimally loaded, which was expected to be the most weight efficient structure.

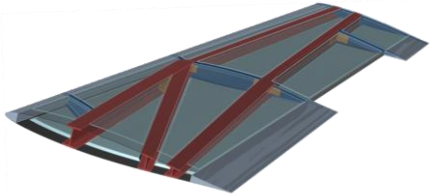
TO in PiCARD Design

New Design Paradigm Shift






State of the Art	Vision
• Traditional overdesigned Structure • Minimally coupled 	• Unconventional Lean Structure • Critically coupled 
• Heavy	• Light
• Expensive	• Cheap
• Hand layup	• 3D printing (Labor free)
• Aerodynamically inefficient	• Aerodynamically efficient
• Slow fabrication	• Fast fabrication (Toolless)


Printed Composites for Attritables and Rapid Deployables (PiCARD)

PiCARD Program

- Topology Optimization
- Risk Based Certification
- Rapid Curing
- Structural Integrated Antenna & Wiring
- Additive Printed Composites
- Low-Cost Manuf. & Assembly

→ Disruptive Technical Capability

SLA³IR LITE: Improved Components

vs.

SLA³IR: Traditional Component Design, M&P, & Cost

→ Significantly Longer Loiter & Lower Cost Structures

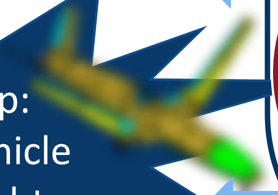
Baseline Vehicle (SLA3IR) Conceptual Design

Mature CONEPS

GIISR Collect Study / Mission & CONEPS

Mission Impact Goals:
- ID mobile targets in A2/AD
- 30% Decreased Mission Cost
- Rapid Insertion of New Tech

Off-ramp: SLA3IR Vehicle Build/Flight

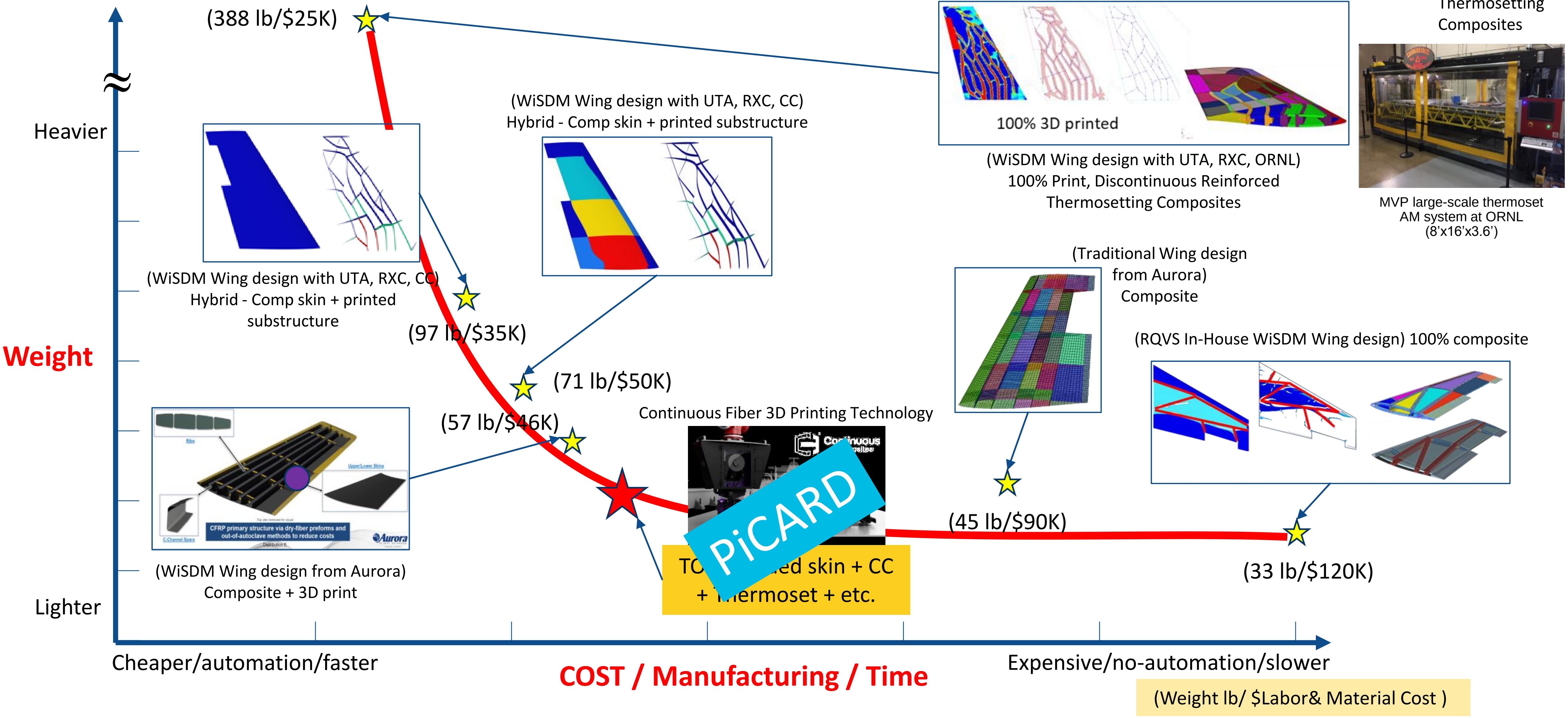


SLA³IR Vehicle

Small
Low-cost
Air-Launched
Attributable
Aircraft for
ISR
Resilience

Seeker

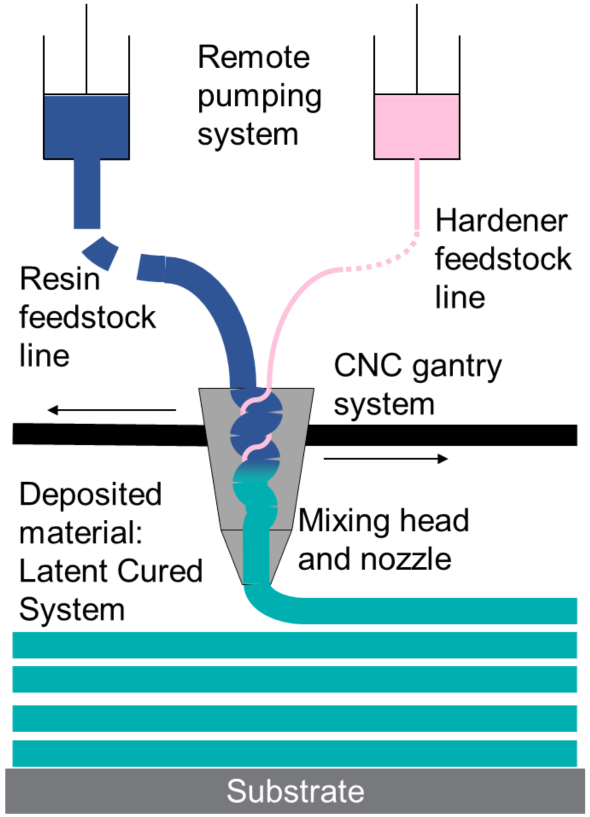
Weight vs Cost / Manufacturing / Time



Scale-up of w/ ORNL MVP Reactive Additive Manufacturing (RAM)

ORNL Scale-up of Epoxy

MVP thermoset AM

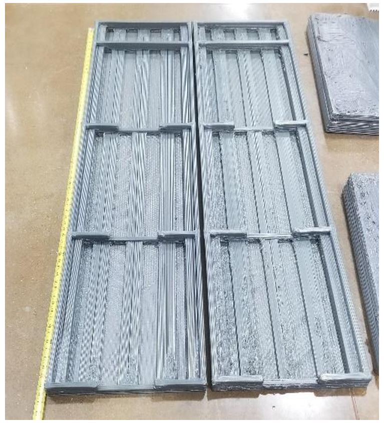


MVP large-scale thermoset AM system

- **Poor Mixing = Brittle**
- **Slumping**

Pivot to Vinyl Ester

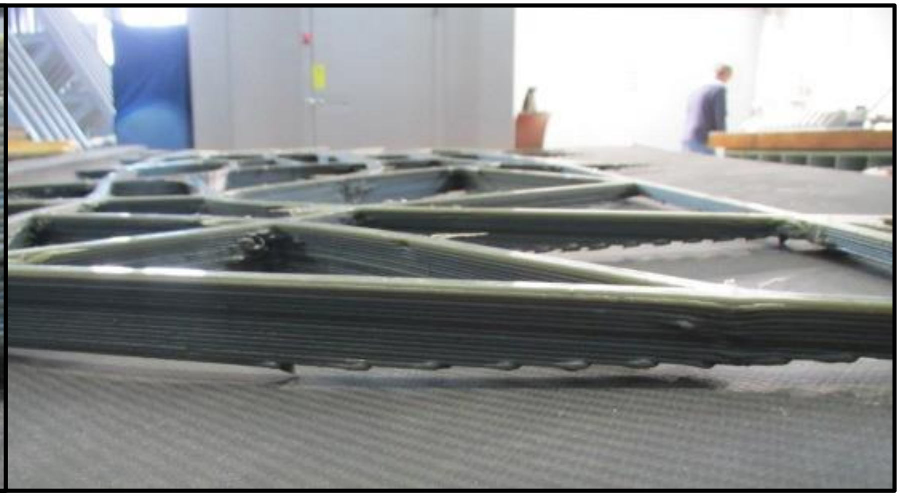
(poorer mechanicals, but more mature)



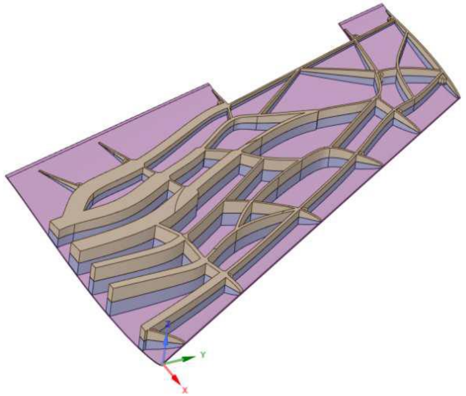
~5.5' USAFA Design Wingbox

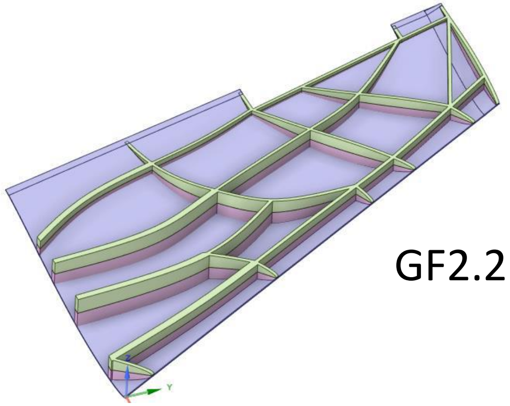
~8' Top Op Wing Frame Halves

Scale-up of w/ ORNL MVP Reactive Additive Manufacturing (RAM)



Chopped Fiber Composite Printing VS Continuous Fiber Printing





GF2.2

New design with improved resign system

How Will Topology Optimization Help?

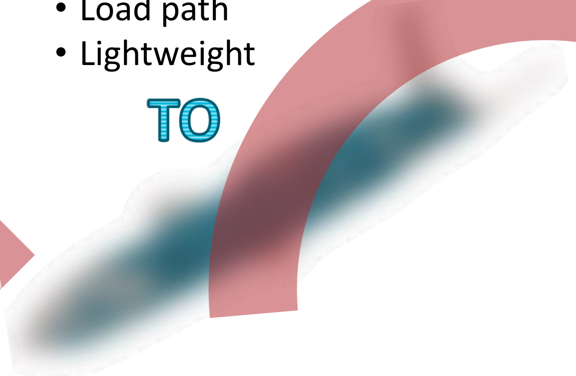
CONCEPT

- Ops analysis
- Performance requirements
- Critical aerodynamic load
- Baseline structure design

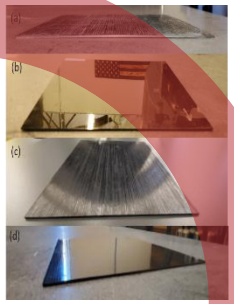
DESIGN

- Load path
- Lightweight

TO



MAT'L

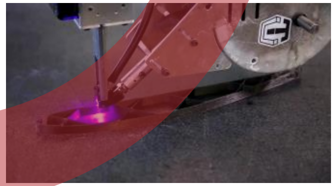


- Material
  - Fiber
  - Resin
- Material property
- Snap cure

SIZE OPT

- Stiffness
- Strength

AM



- Printing Limitation
  - Overhang angle
  - Tow width
  - Printing path
  - Printing direction
  - Printing w/o tools
  - Etc
- Joints
- Risk basis certification

FAB & Test

- Fabrication plan
- Toolless Printing
- Minimum part #

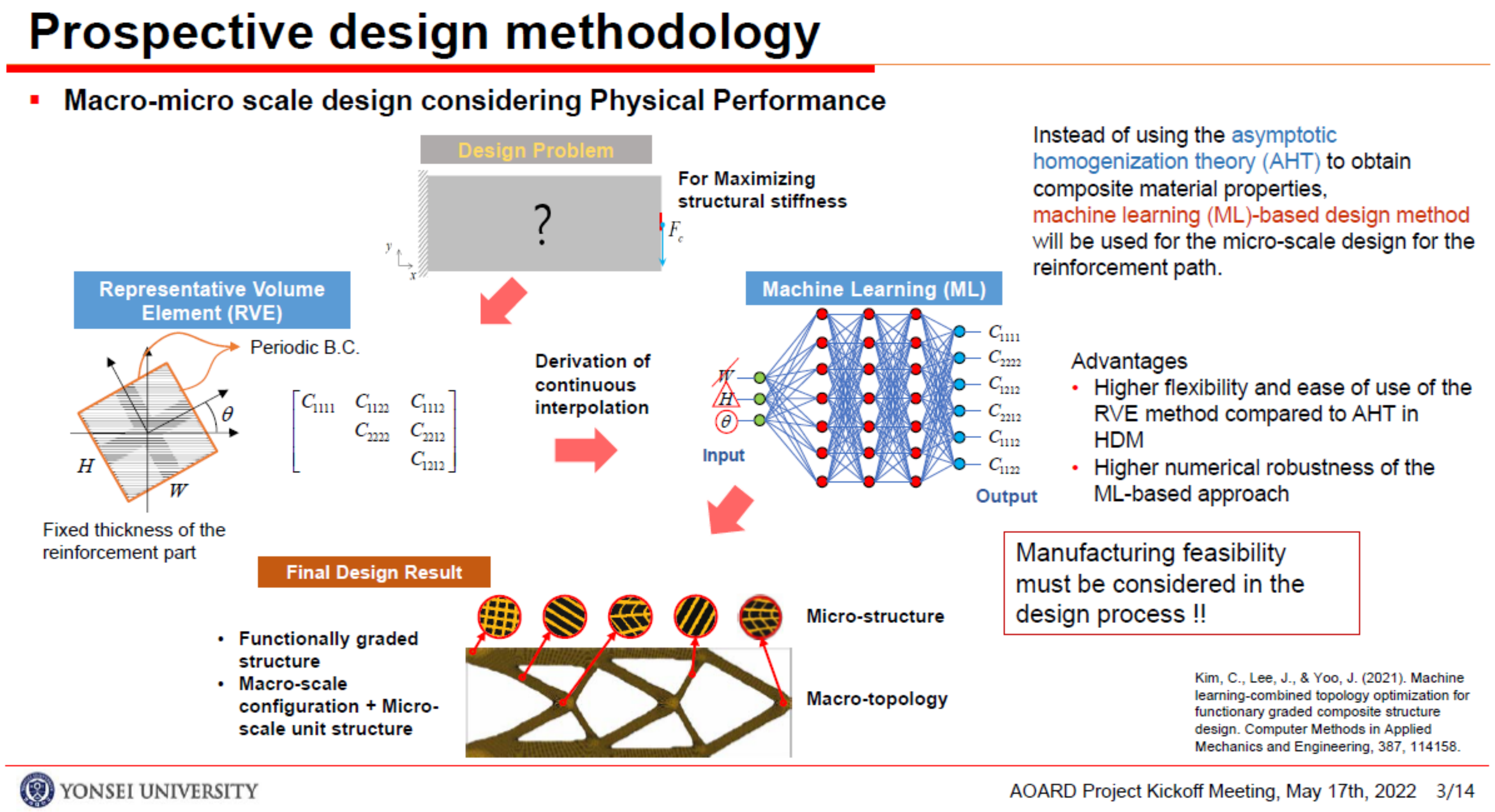
Hand Layup vs 3D printing

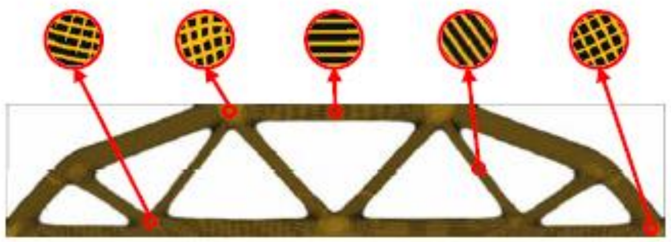
Toolless (True 3D printing)
Fast
Low Cost

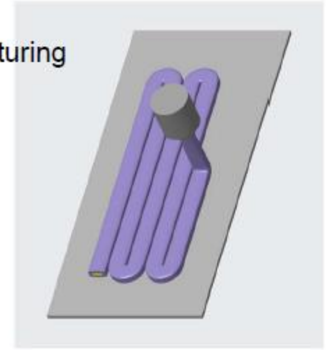
Continuous Fiber Reinforced Composite Structure Design

Continuous Fiber Reinforced Composite Structure Design Using ML Based Homogenization Method

POC: Prof. Junghoon Yoo, Yonsei U, S Korea
Dr. James Joo, RQVS

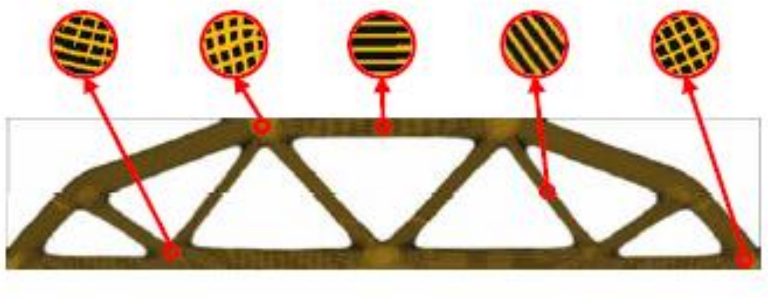


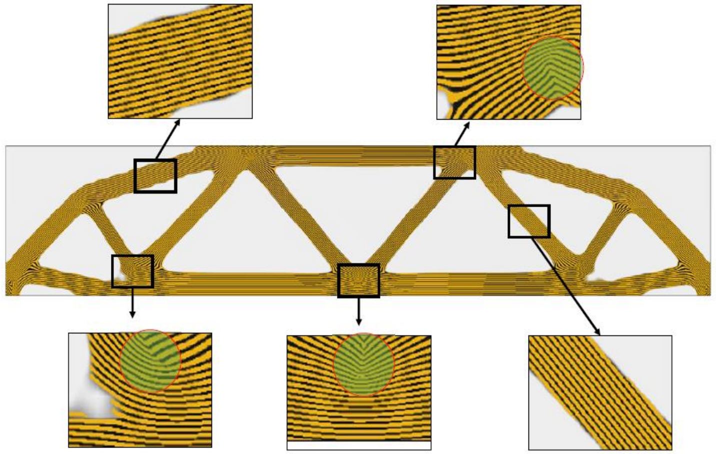


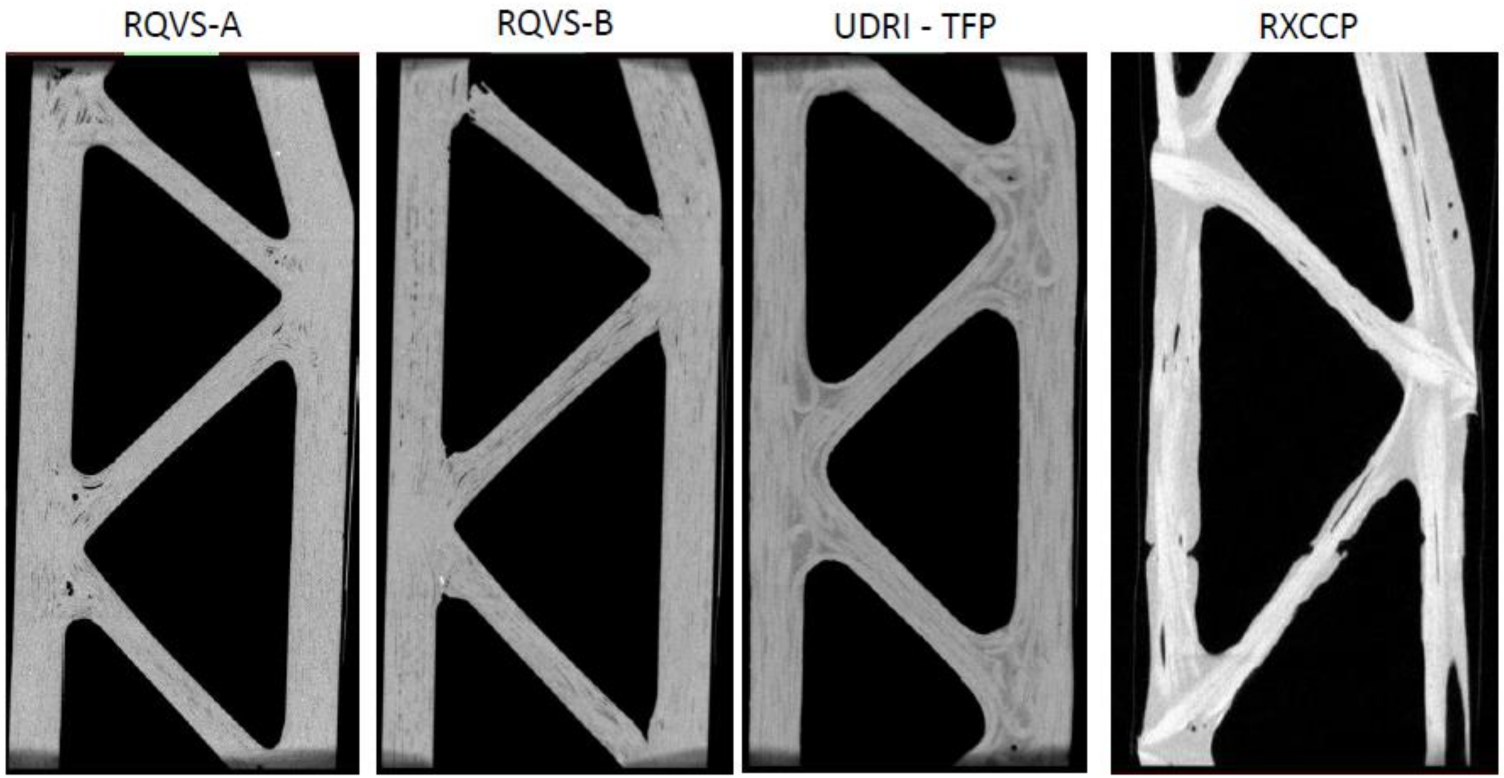


RQ: Joo, Knoth (RQVS), Miller (BAH)
RX: Flores (RXCCP), Koerner (RXCCM)
Industry: Impossible object, ES3, Orbital composites, Raven3D, Ingersoll, Deakin Univ, TFPUDRI, CCI
12 different specimens X 3 will be tested

X-ray uCT Characterization of Truss





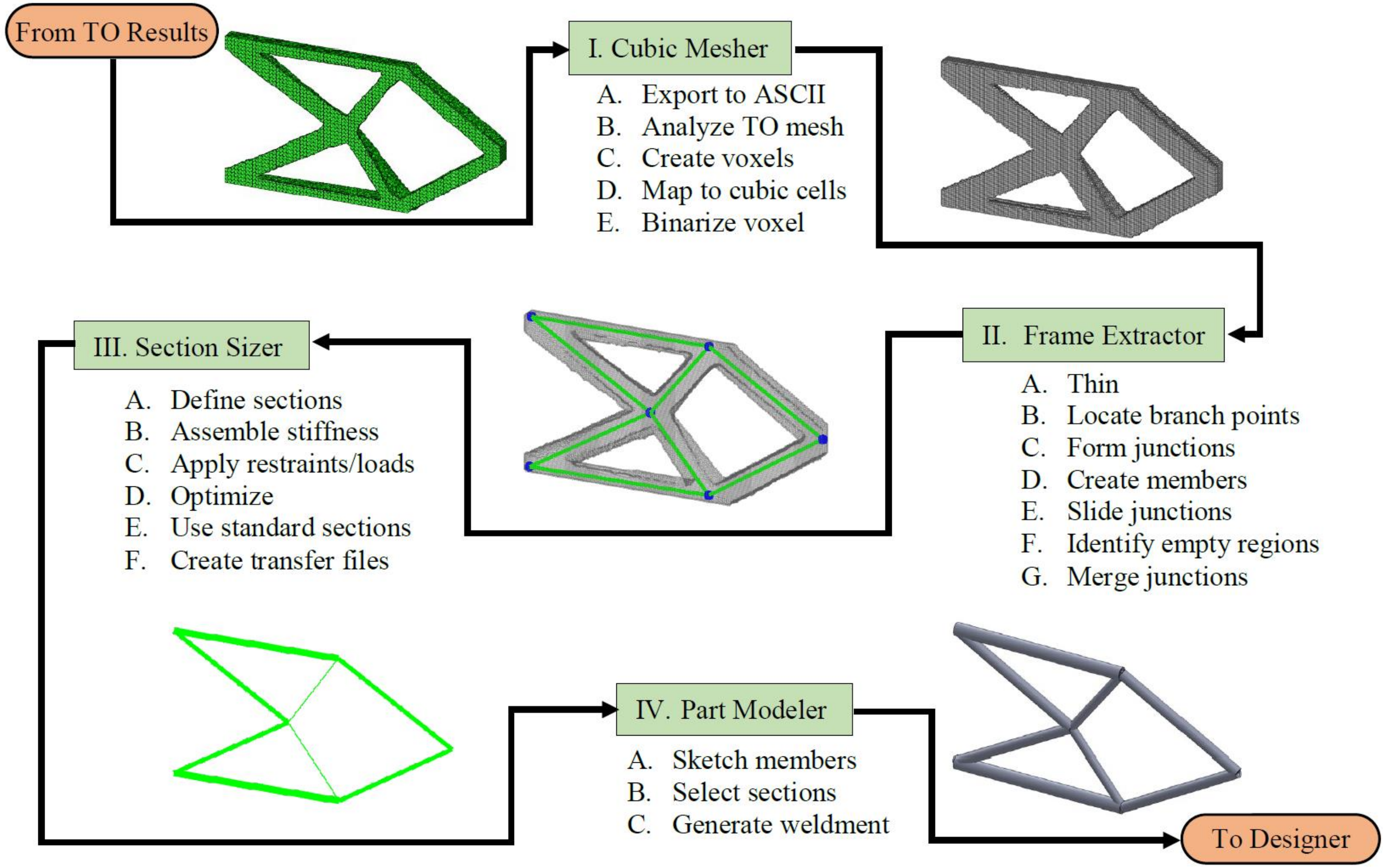


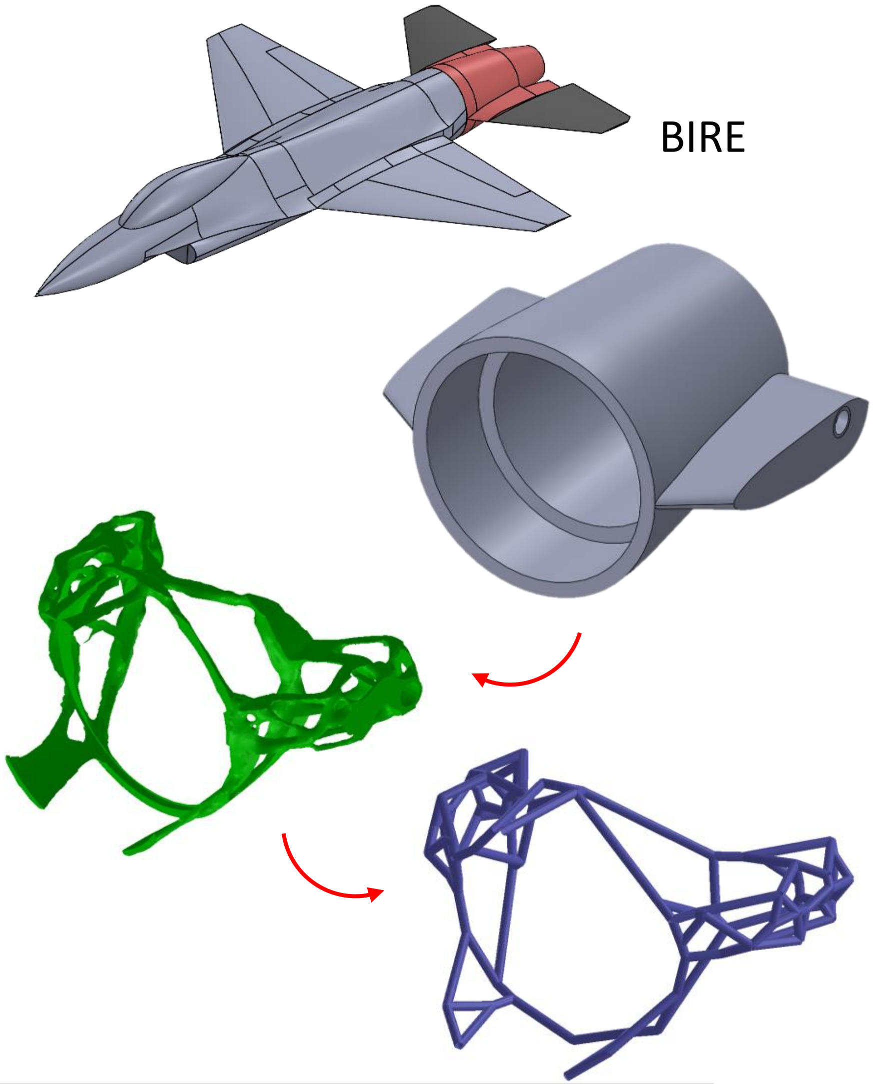
Topology Optimization Post-Processor / Interpreter

Methodology Development

POC: Prof. David Myszka, U of Dayton
Dr. James Joo, RQVS

- Topology Optimization Results Interpreter



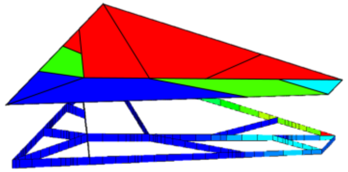


Physics-Informed Structural Topology Optimized Layout (PISTOL)

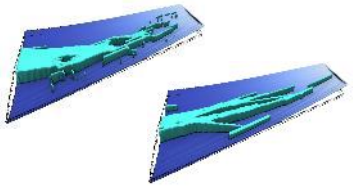
POC: Mr. Matt Leonard, RQVS

Methodology Development

- Physics-Informed Structural Topology Optimized Layout
  - Product: Development next-generation structural layout/topology optimization methods for that incorporate necessary design requirement early in conceptual design
  - Technical Status:
    - Methods Development – Produced preliminary optimized results of the Aurora WiSDM wing for a traditional extruded, density based technique as well as results based on geometric primitive method.
    - Analytical Studies – Completion of initial static sizing studies. Work continues on aero elastic sizing studies.
    - Fabrication Studies – Exploring concept of using a 3D printed shell insert to form a lightweight flyaway tooling core. Composite prototype will be assembled, resin infused and cured in one step.

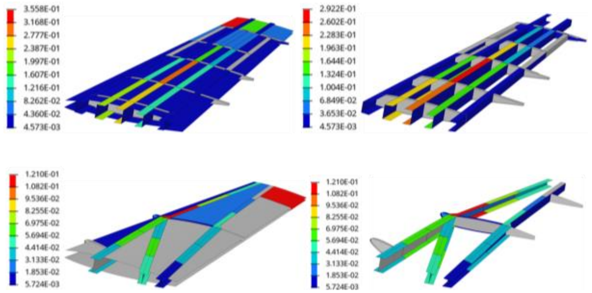


Bio-Inspired Evolutionary Development Method

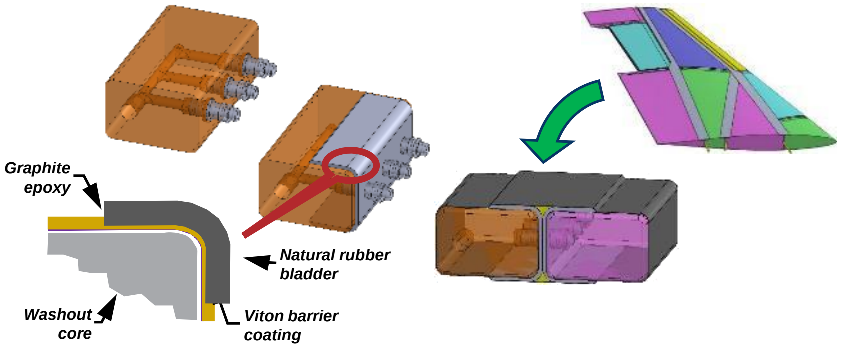


Density-Based TO with Geometric Primitives

Next-generation structural layout/topology optimization methods



High Fidelity Analytical Studies

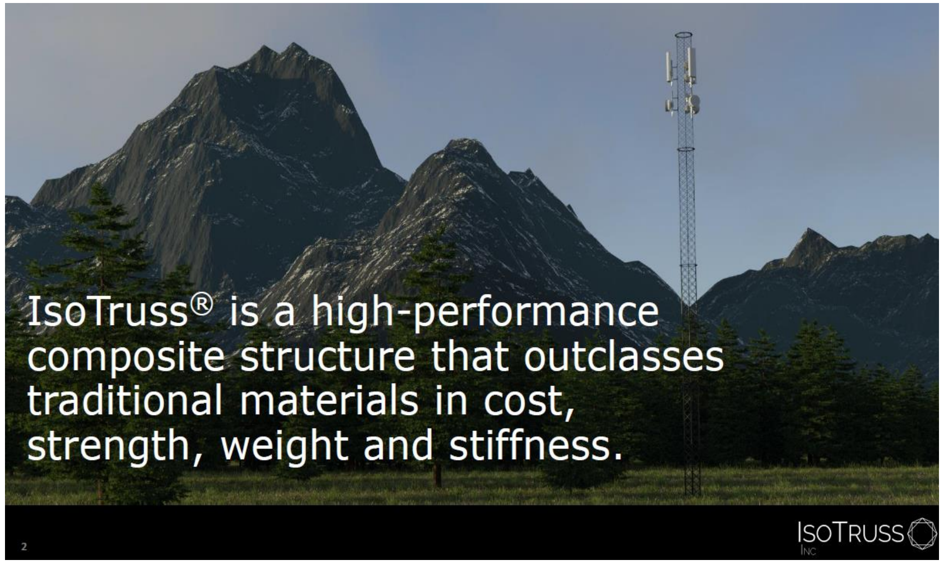


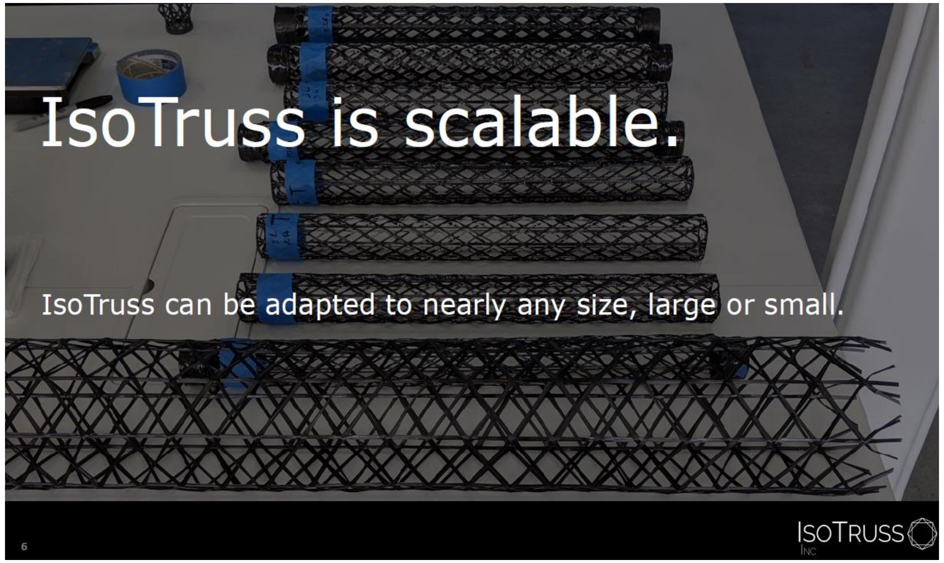
Fabrication/Prototyping Studies

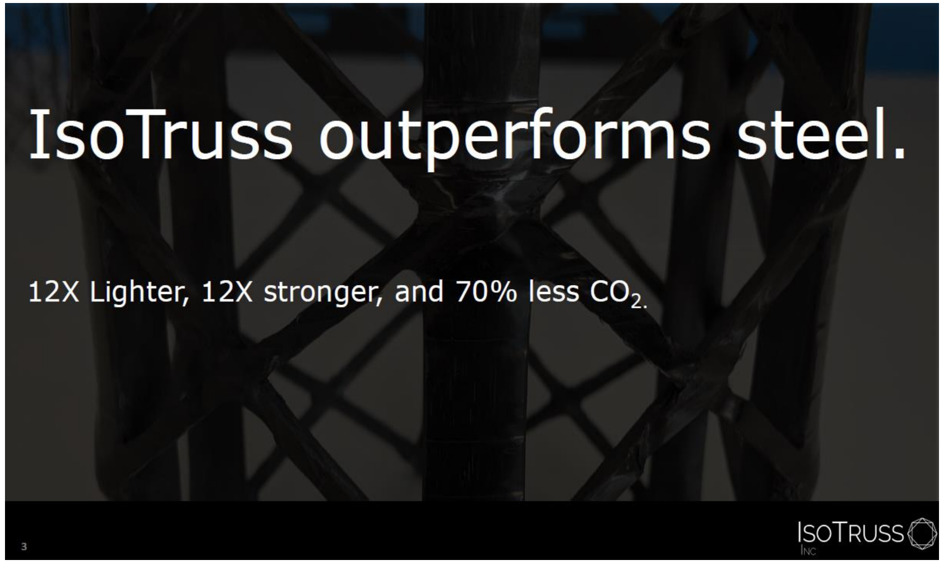
IsoTruss

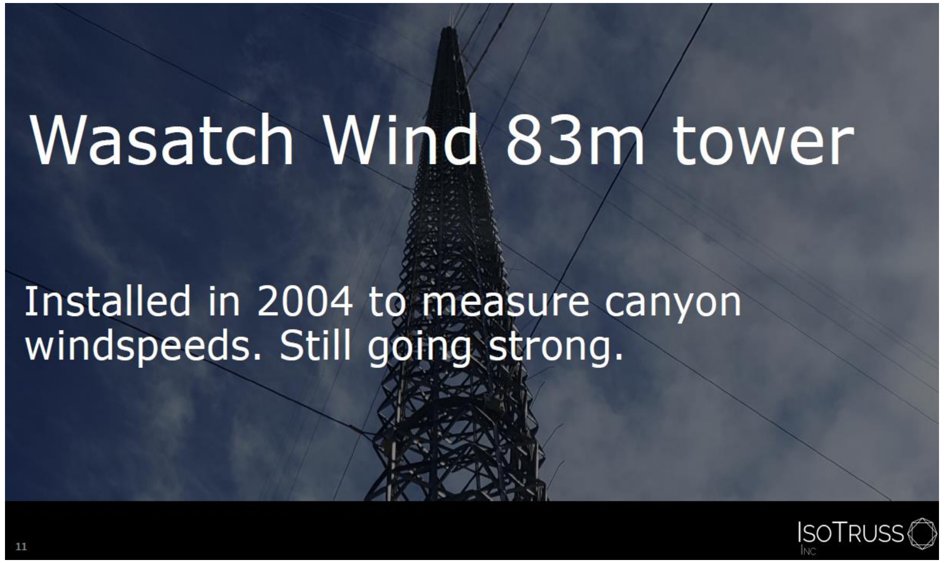
Use IsoTruss as an Alternative of TO Structure?

POC: Mr. Sam Willing, IsoTruss









Summary

- Weight, cost, and speed requirements can't be met using a single best technology alone, including TO. Low-cost vehicle is an excellent platform to integrate high-risk and high-payoff technologies
- Load-path-based design (TO) will offer an unconventional lean structure, and redundancy will be an option.
- Load-path-based design (TO) is not favorable for conventional manufacturing, but new technologies such as composite 3D printing may open the door for non-orthogonal structure fabrication.
- It is important to consider manufacturing at the early design stage as possible to avoid significant design changes later after it is closed.
- A low-cost vehicle is an excellent platform to integrate high-risk and high-payoff technologies

ARE WE READY TO TAKE RISKS?