Structural Sizing of a Tow-Steered Truss-Braced Wing Box Test Article

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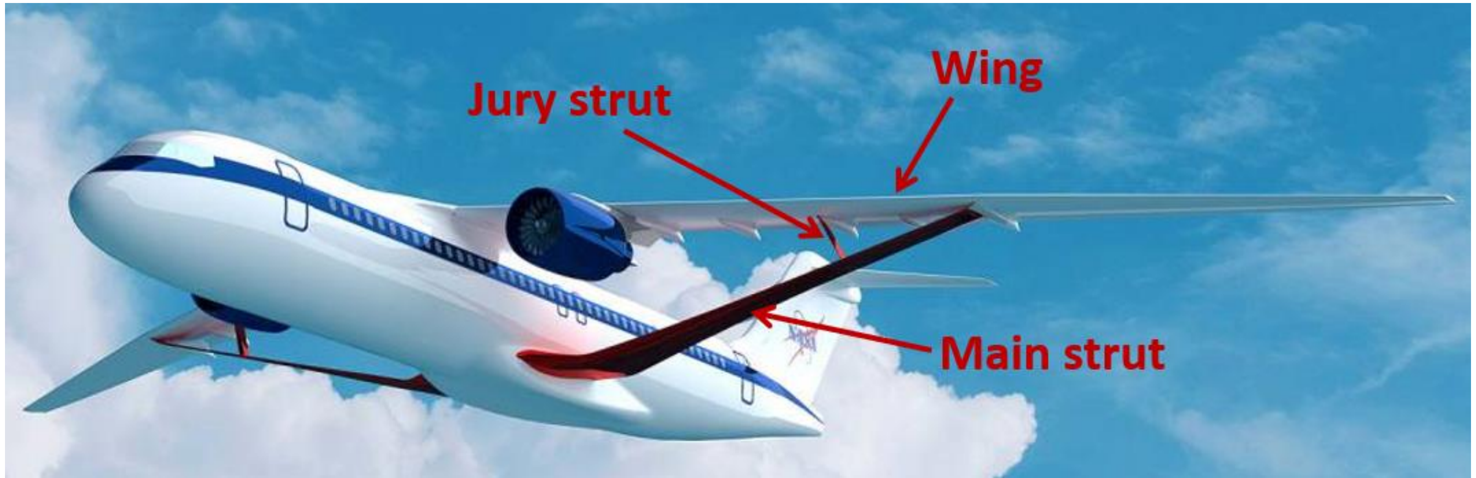
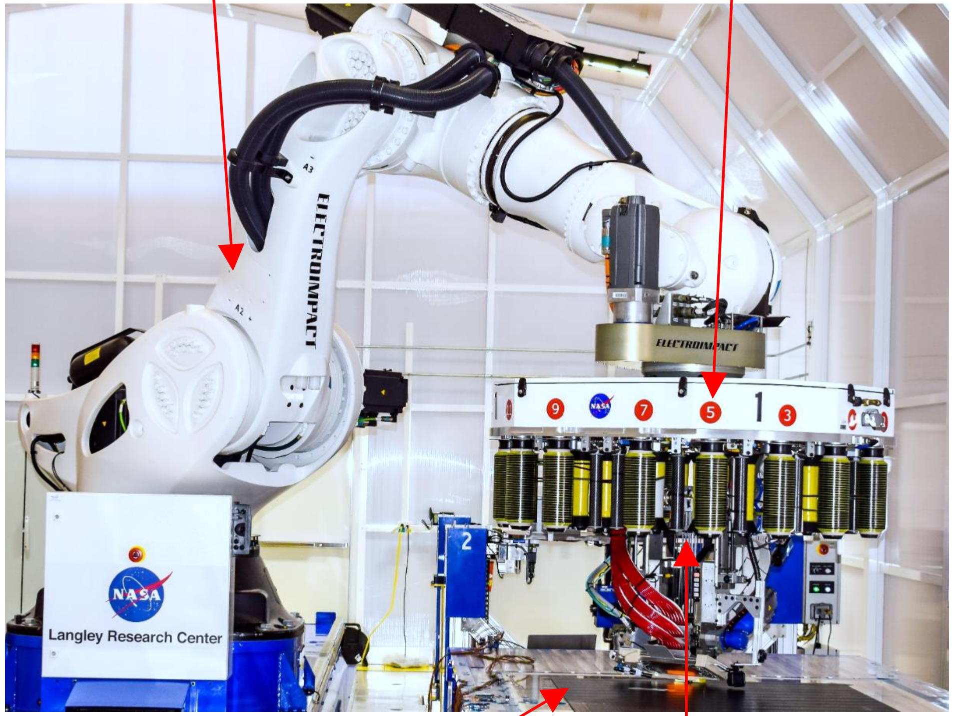
Motivation and Background

- Background
  - Transonic truss-braced wing (TTBW) concepts have been explored by NASA and industry for years due to reductions in fuel consumption, noise, and emissions
  - Significant effort has been spent on aerodynamic modeling and wind tunnel testing
  - **Thoroughly defined structural designs not completed**
- Motivation
  - Advanced Air Transport Technology (AATT) project tasked to develop technology for next generation of commercial aircraft
  - Armstrong Flight Research Center (AFRC) wanted a test article to explore behavior anticipated in the X-66 TTBW demonstrator supported by the Flight Demonstration Capabilities (FDC) program



Overview

- Structural Wing Experiment Evaluating Truss-bracing 15-ft (SWEET-15) article
  - Develop a structural test article with truss-braced wing characteristics
  - Evaluate wing-strut joint
  - Evaluate advanced design and manufacturing concepts
- Automated fiber placement (AFP)
  - Tow-steering (wing upper cover panels)
  - Integral stiffening (wing lower cover panels)
- Stitching (main strut)
- Integrated Structural Assembly of Advanced Composites (ISAAC) facility at NASA Langley Research Center (LaRC)



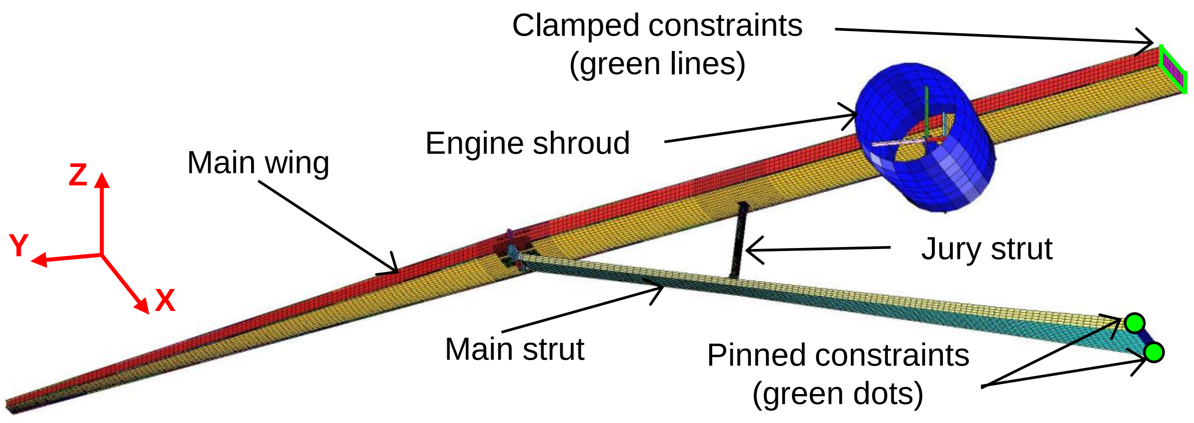
Outline

- LaRC vision vehicle
- Test article geometry and applied loads
- Tow-steered sizing
- Refined finite element model (FEM)
- Concluding remarks

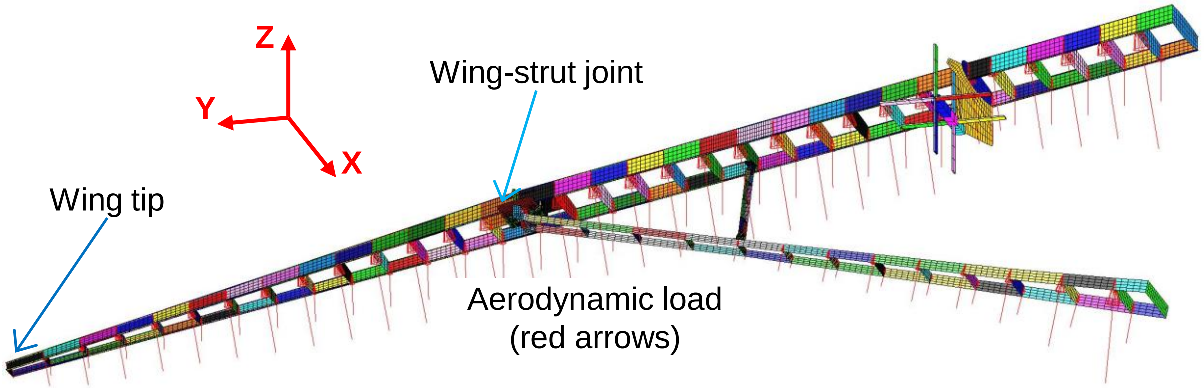
LaRC TTBW Vision Vehicle

- LaRC TTBW publicly-available vision vehicle used
- Presented in Jutte, “Simplified Applied Loads of a Transonic Truss-Braced Wing Derived from Computational Fluid Dynamics,” SciTech 2024, AIAA 2024-2811
- Used to define baseline geometry of SWEET-15
- Developed at NASA LaRC using Conceptual Design Shop (CDS)
- Model developed in MSC/NASTRAN
- Vision vehicle loads and dimensions scaled down to 15-ft length of SWEET-15
- Structural displacements from FEM of vision vehicle also scaled as targets for design of SWEET-15

FEM of wing, main strut, jury strut and engine



FEM with covers removed for visibility



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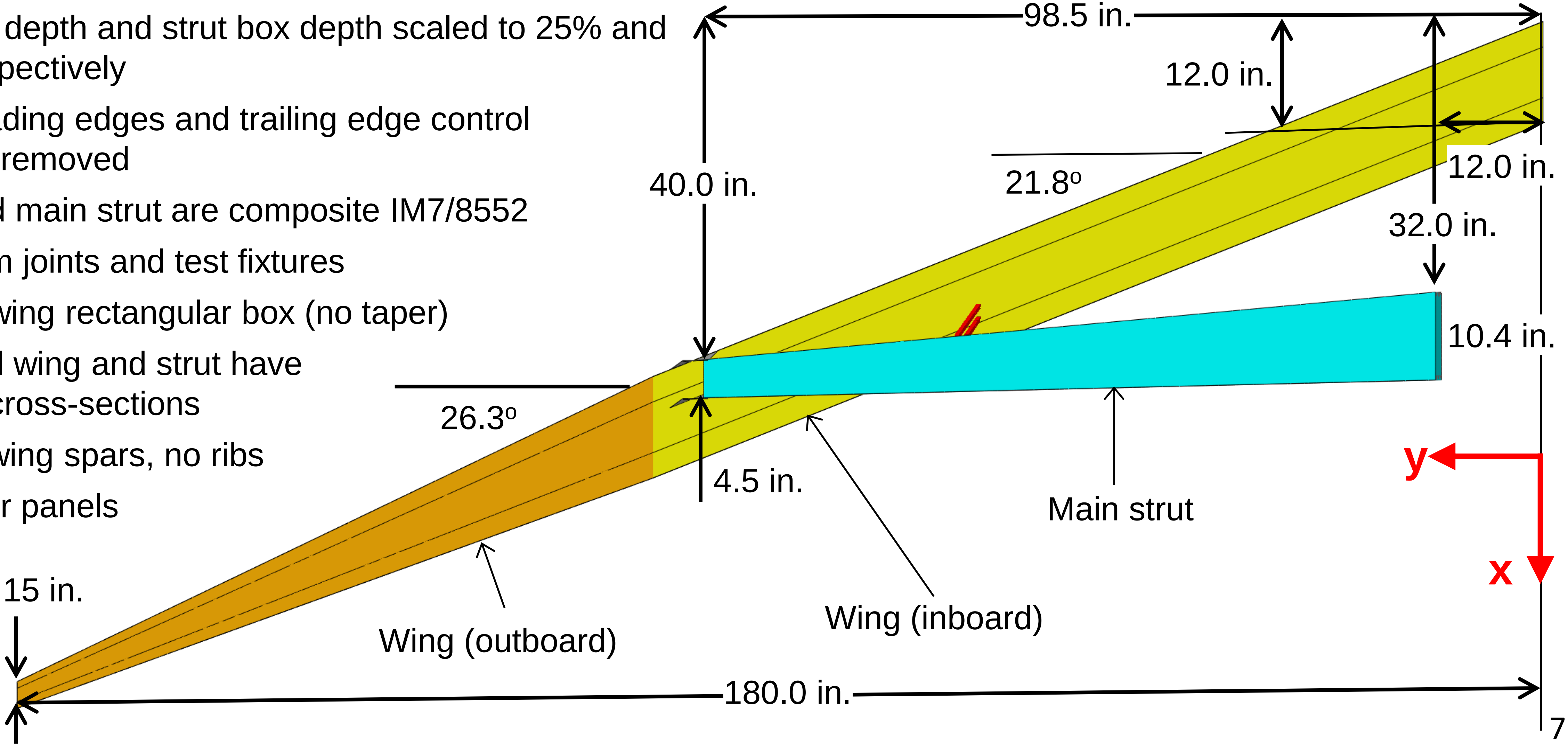
SWEET-15 Geometry

- TTBW vision vehicle geometry scaled to 18.6% in x- and y-dimensions for SWEET-15 test article
- Wingbox depth and strut box depth scaled to 25% and 33%, respectively
- Airfoil leading edges and trailing edge control surfaces removed
- Wing and main strut are composite IM7/8552
- Aluminum joints and test fixtures
- Inboard wing rectangular box (no taper)
- Outboard wing and strut have tapered cross-sections
- Tubular wing spars, no ribs
- Flat cover panels

Bottom View of SWEET-15

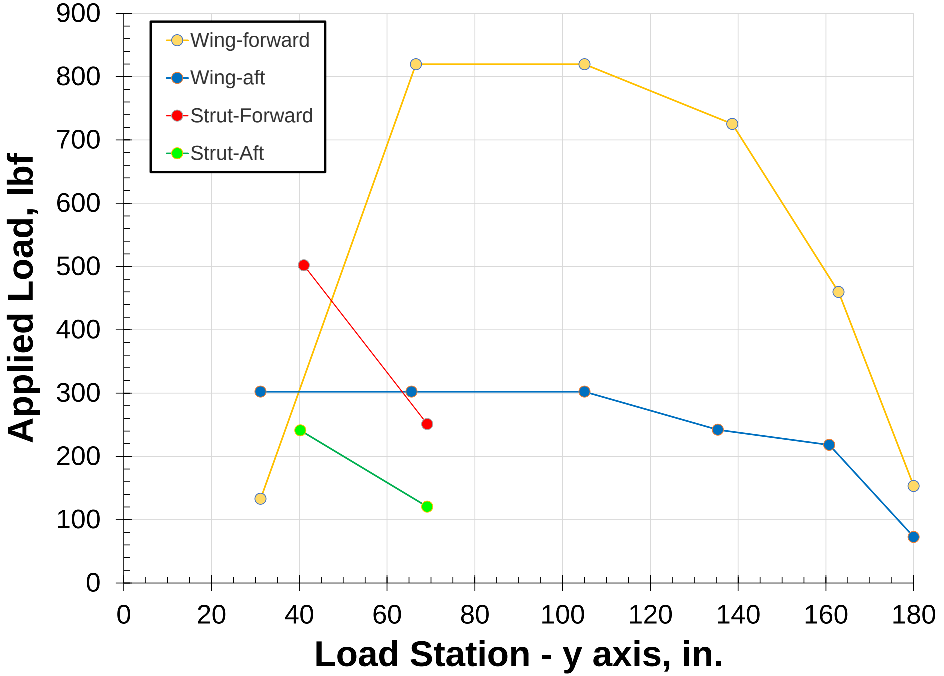


Applied Loads

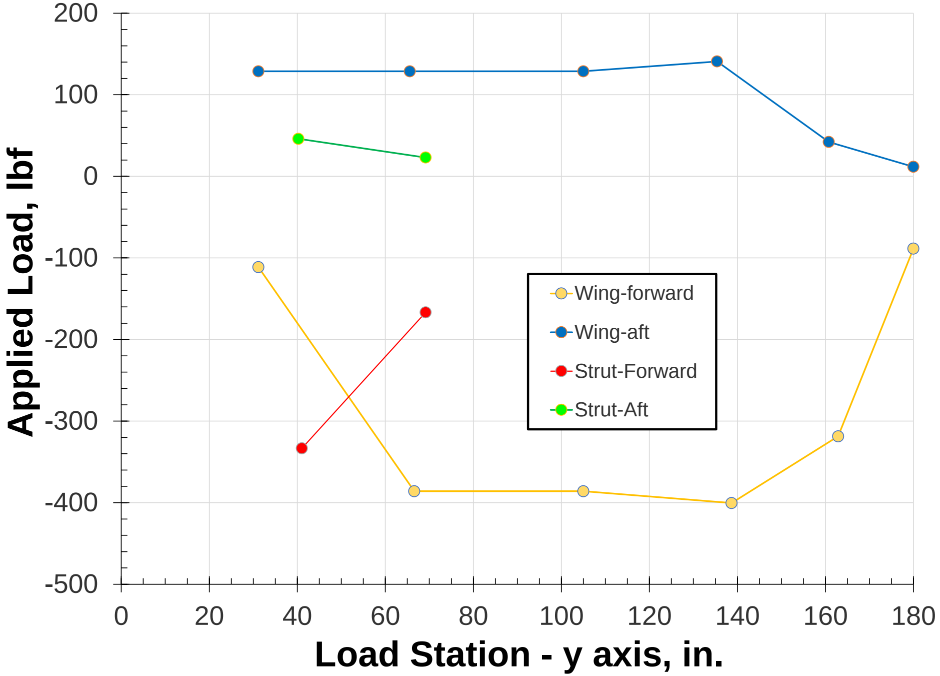
- Two load cases
  - +2.5-g (positive limit) maneuvering load case
  - -1.0-g (negative limit) maneuvering load case
- Engine inertial relief included before scaling
- Ratio of tip over joint displacement
  - Ideal value 5.47 (3.84% / 0.70%)
  - Acceptable range 5.27 to 5.67
- Loads scaled 4.1% from full-scale to preserve tip displacement

Case (limit load)	Displacement at joint	Displacement at tip
Full-scale vision vehicle	6.81 in.	37.28 in.
Percentage of wing length	0.70%	3.84%
SWEET-15	1.26 in.	6.92 in.

+2.5-g (Positive Limit) Maneuvering Load



-1.0-g (Negative Limit) Maneuvering Load



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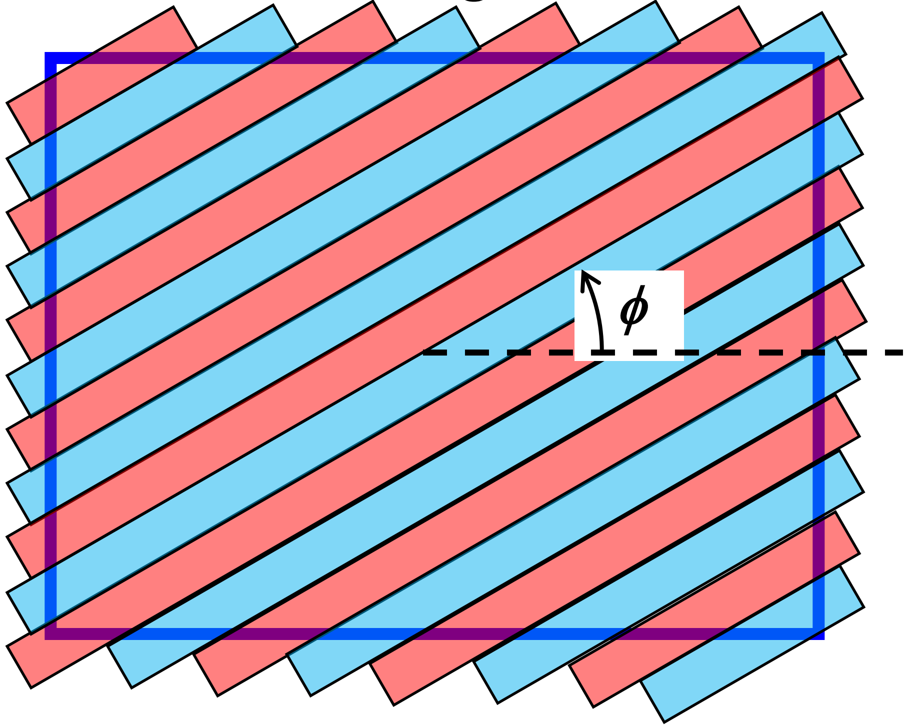
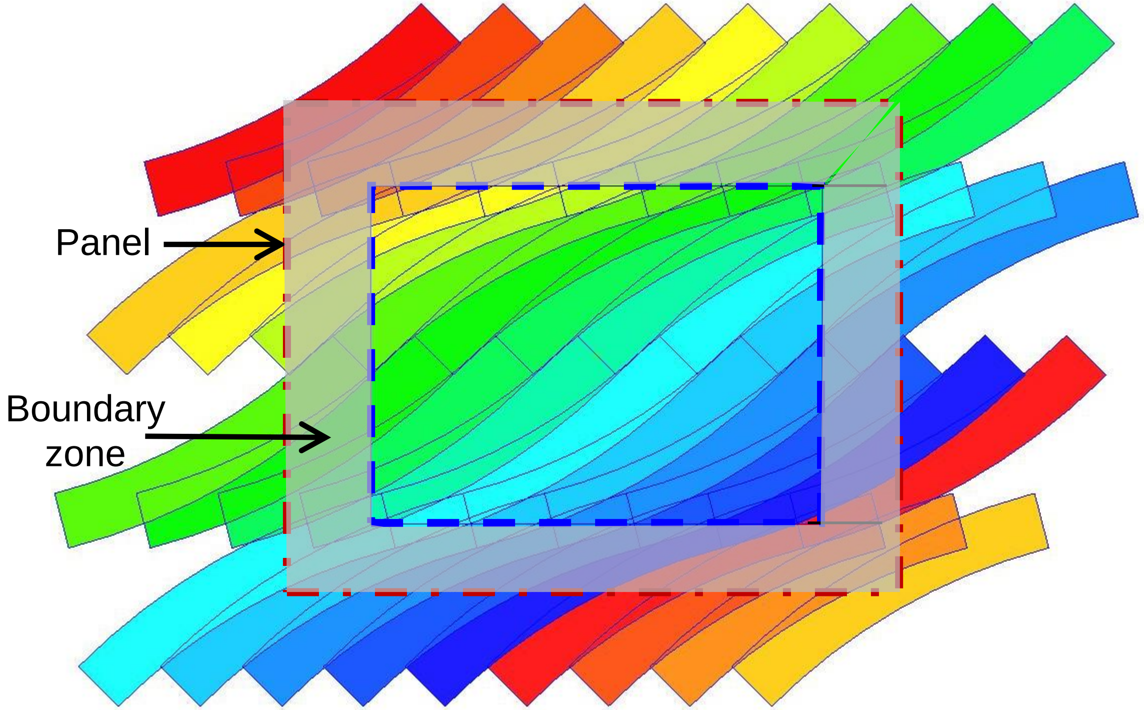
Comparison of Straight and Tow-Steered Fibers

Straight



- Straight fiber ply
  - Bundles of fibers called "tows"
  - Sets of tows placed simultaneously called "course"
  - Courses are typically laid next to each other with minimal overlaps or gaps
  - Ply is defined by a single ply angle variable
  - Standard approach in AFP

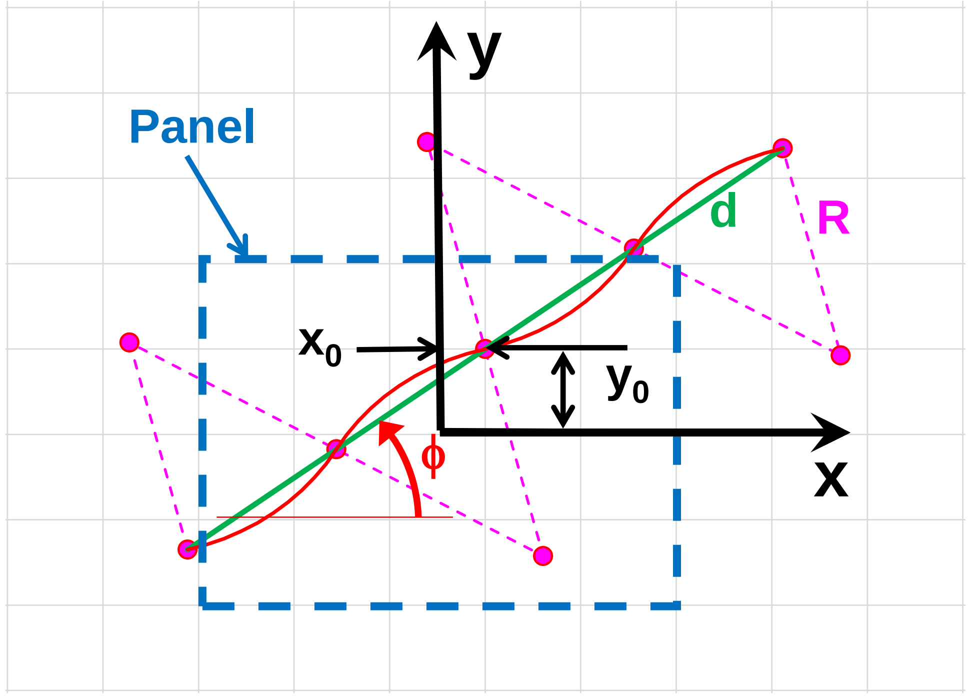
Tow-steered



- Ply with non-straight fibers
  - Courses have overlaps and/or gaps because of different inner and outer radii of courses
  - Many variables needed to define shape and placement of courses
  - Using mirrored circular arc pattern (MCAP)

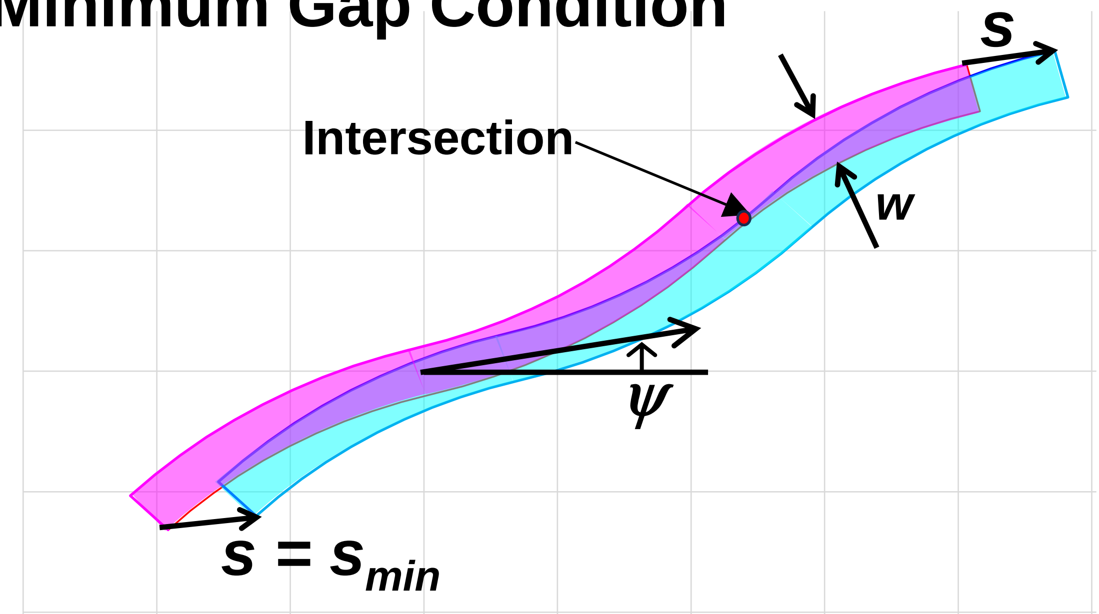
Tow-Steering Variables for MCAP Approach

- Course geometry represented as chain of arcs
- Three variables define base arc
  - Radius of curvature (R)
  - Orientation (ϕ)
  - Half-wavelength (d)
- Two variables define starting location (x_0, y_0)



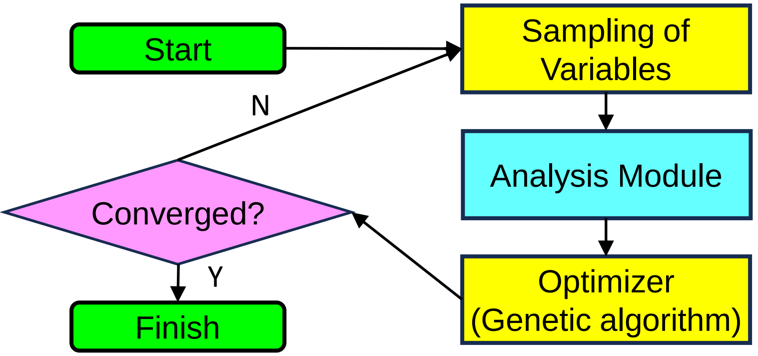
- Ply contains multiple courses with identical shapes
- Course are placed based on three variables:
  - Course width (w)
  - Shift angle (ψ)
  - Shift distance (s, dependent variable)
- Overlap condition
  - Inner edges touch at a repeated point
  - Minimum distance (s_{min}) must be computed
  - Independent variable: gap ($g = s - s_{min}$)

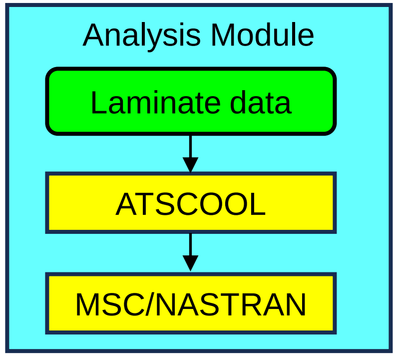
Minimum Gap Condition



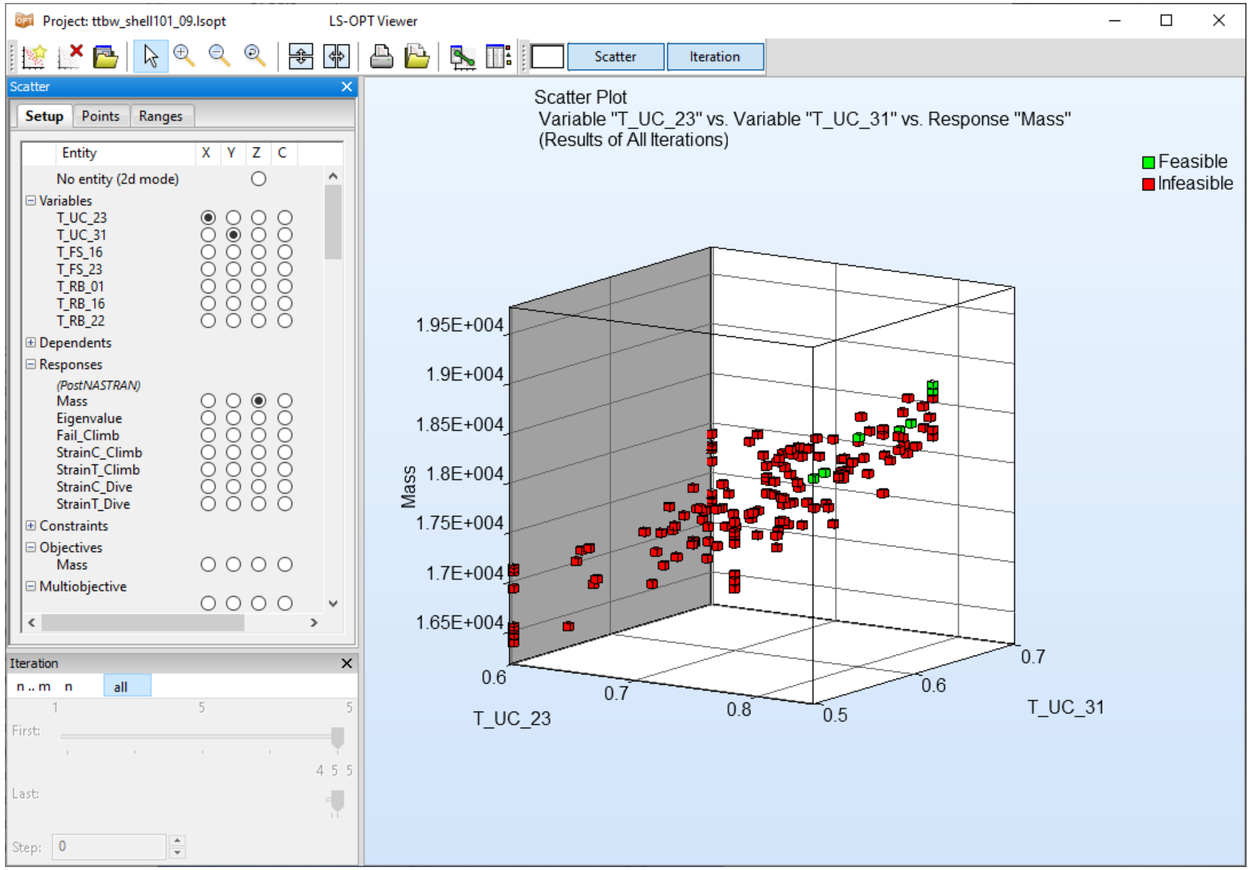
Tow-Steering Design Tools

- Tow-steering software
  - Automated Tool for Steered Composite Optimizable Laminates (ATSCOOL)
  - Developed at NASA LaRC
  - Supports MSC/NASTRAN and Abaqus
- Design problem statement
  - Minimize structural weight
  - Subject to design constraints
    - Buckling
    - Tsai-Hill first-ply failure criterion (strength)
    - Ratio of tip over joint displacement 5.27 to 5.67
  - Target factor of safety (FOS) = 1.5
  - Design variables based on MCAP





- Used LSDYNA optimization software package (LS-OPT)
  - Includes several tools to explore the design space
  - Feasible designs shown in green in scatter plots



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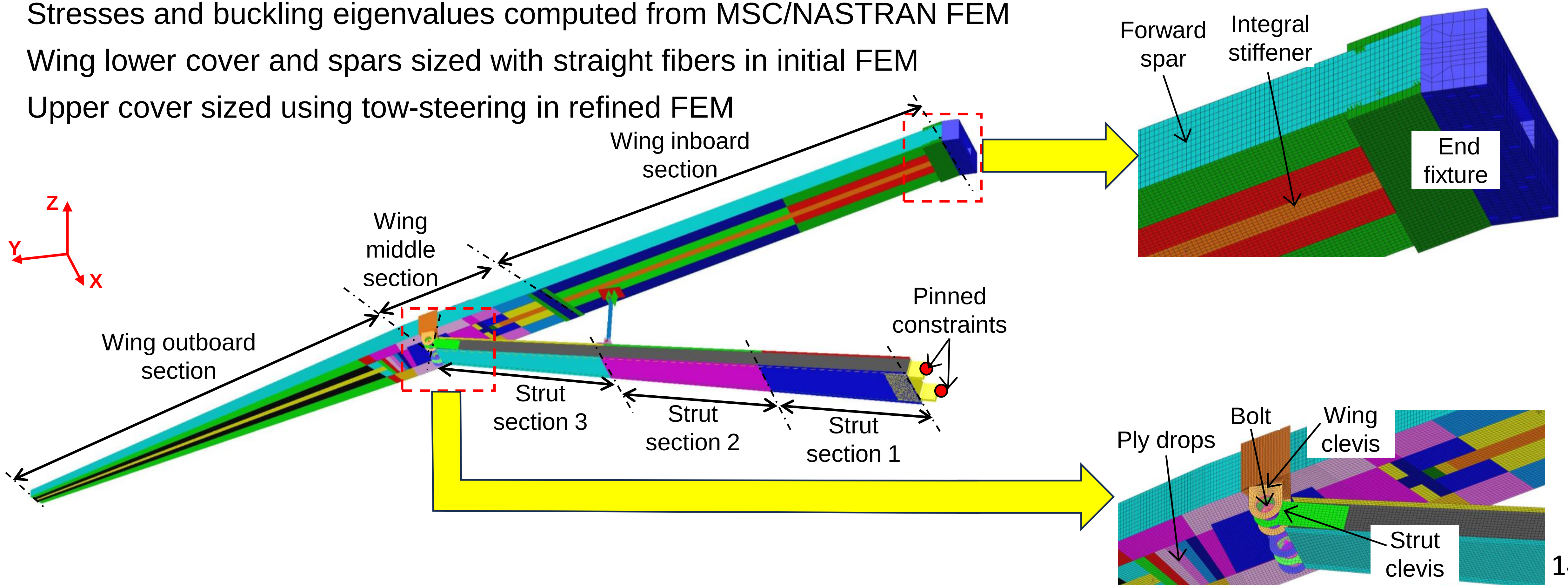
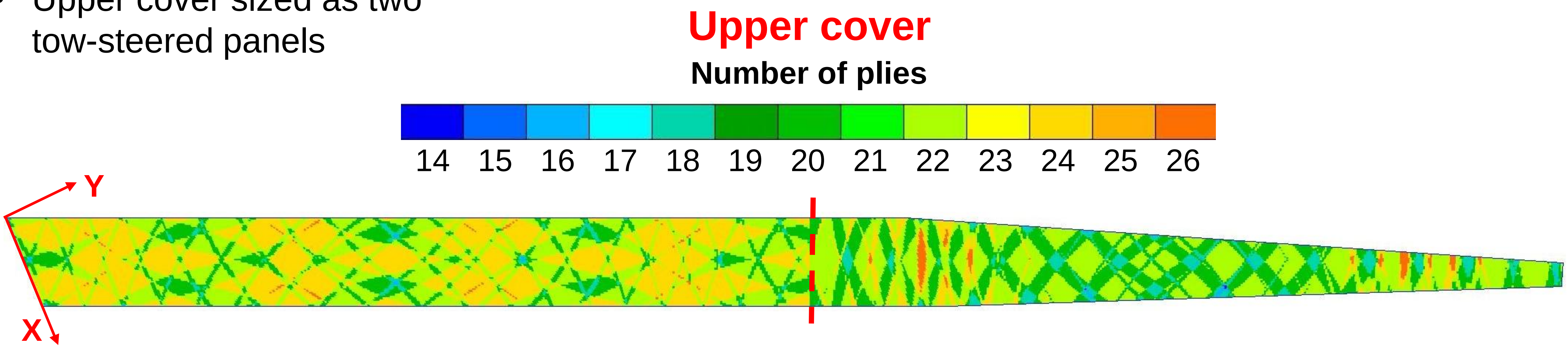
Refined FEM of SWEET-15 Article

- Model consists of:
  - 204,910 quadrilateral shell elements
  - 10,800 hexahedral solid elements
  - 12 beam elements (bolts)
  - 219,844 nodes
- Stresses and buckling eigenvalues computed from MSC/NASTRAN FEM
- Wing lower cover and spars sized with straight fibers in initial FEM
- Upper cover sized using tow-steering in refined FEM



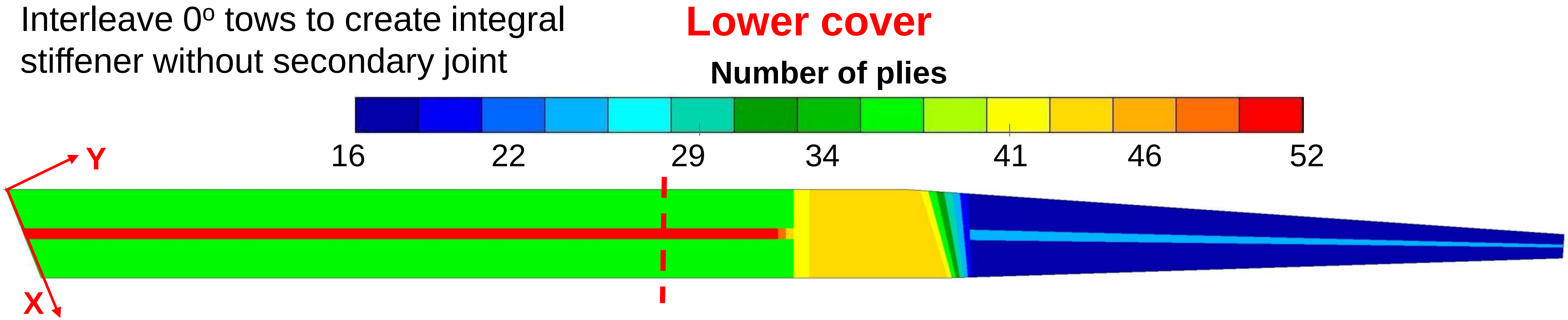
Results of LSOPT/ATSCOOL Sizing

- Upper cover sized as two tow-steered panels



24 plies [±45/0/90/±25$^{R36d18g4.0}$/0$_2$/±55$^{R40d24g0.5}$/90/0]$_S$ 22 plies [±45/90/0/±60$^{R37d30g1.5}$/90$_2$/±65$^{R37d29g0.5}$/90]$_S$

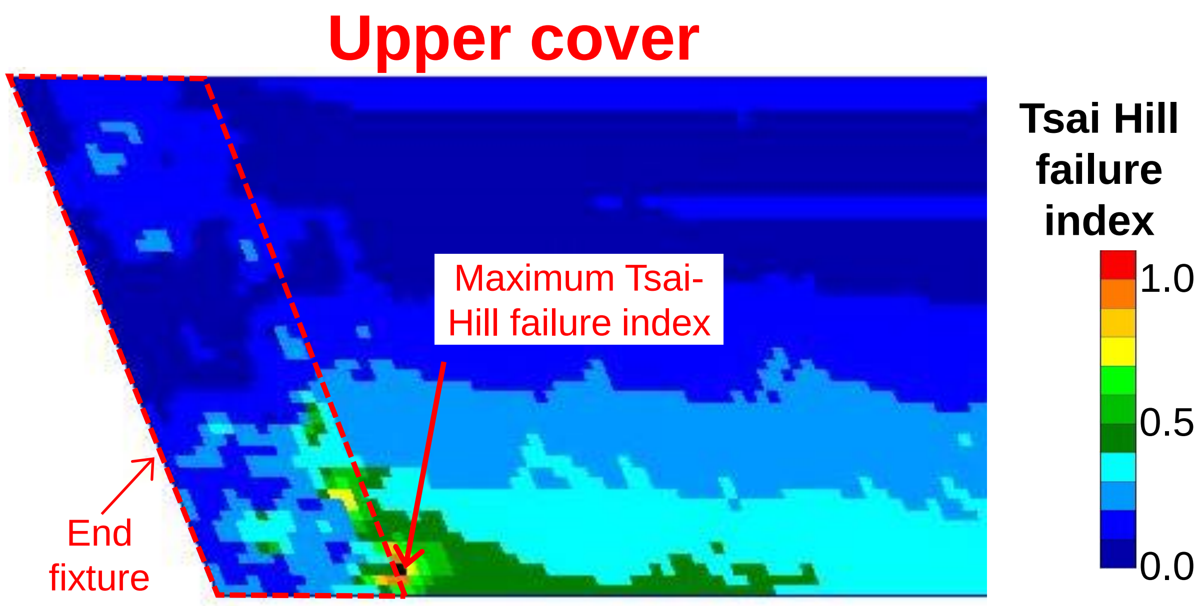
- Interleave 0º tows to create integral stiffener without secondary joint

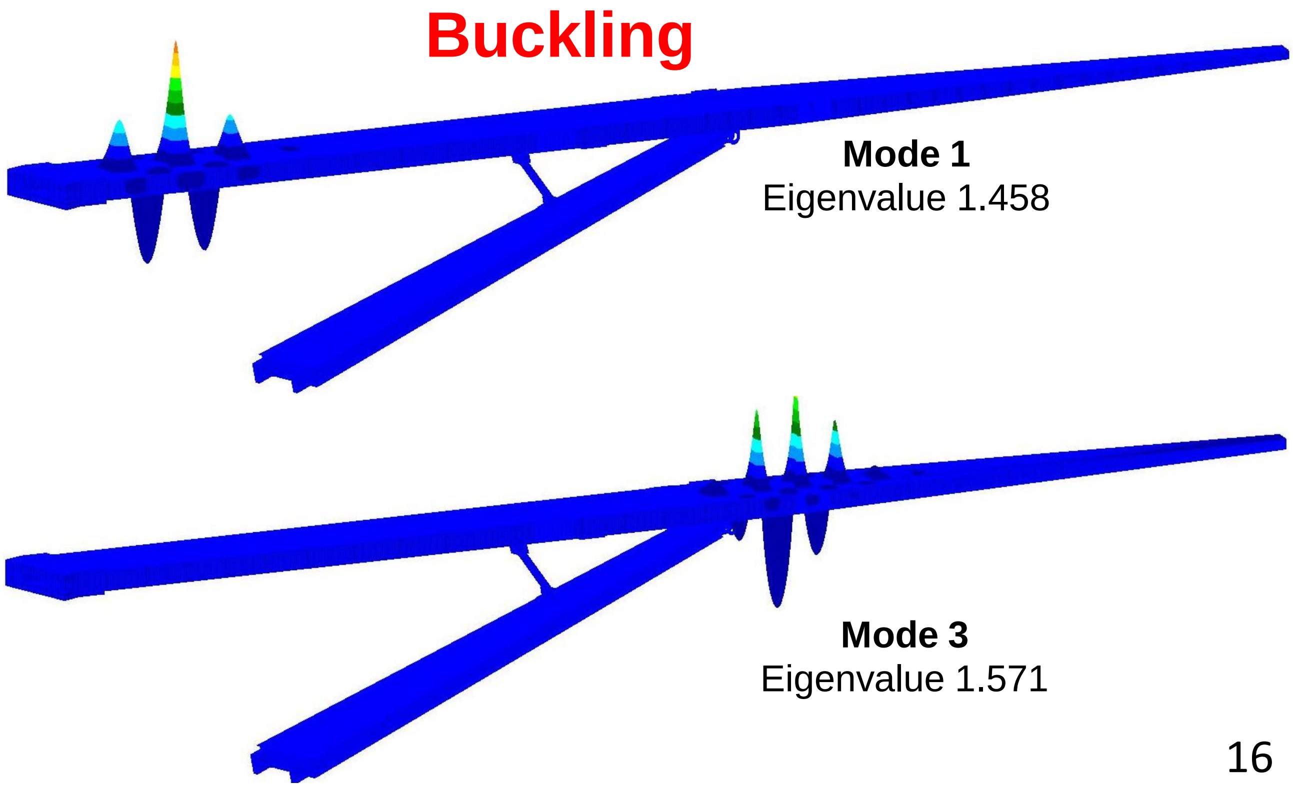


Structural Response and Weight

- Tow-steered upper cover panels 6.4% lighter than straight-fiber panels in initial model
- Upper cover panels
  - Strength dominated design at bolted joints in inboard section
  - Buckling more critical in than strength in outboard section
- Straight-fiber design in upper cover not evaluated in refined model

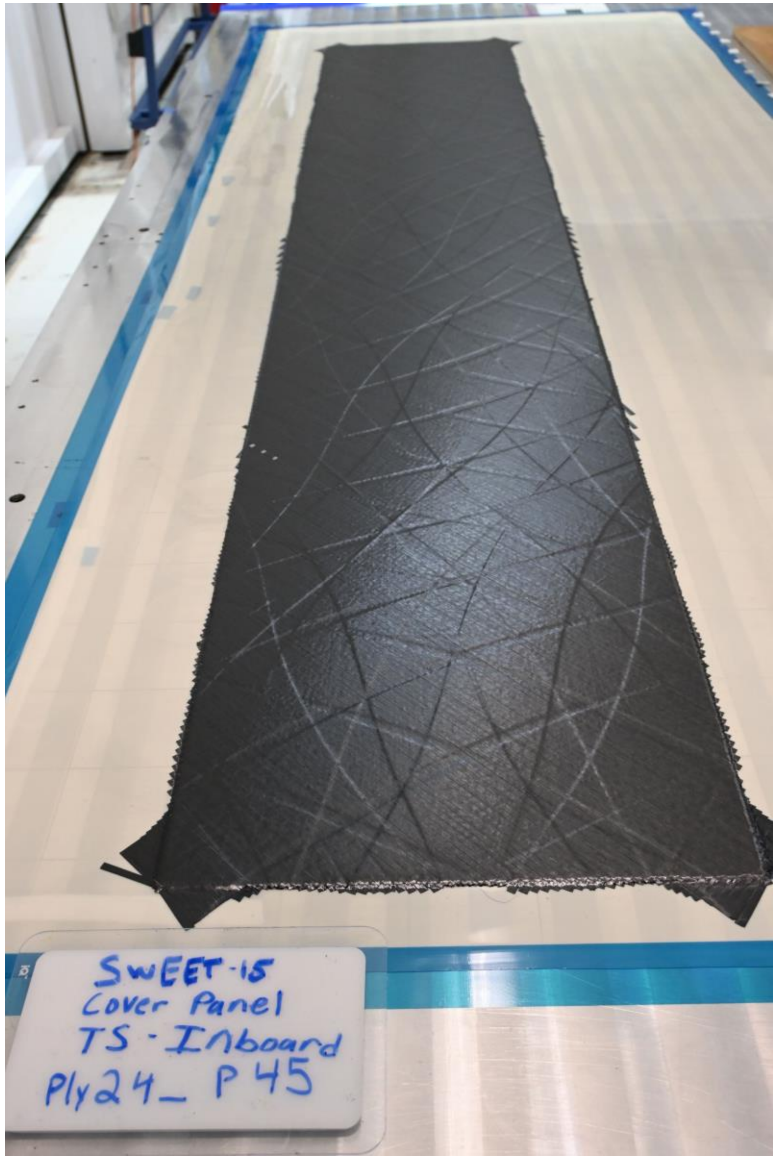
Location	Panel weight, lbf
Inboard upper, initial, straight	8.04
Inboard upper, initial, tow-steered	7.42
Inboard upper, refined, tow-steered	7.79
Outboard upper, initial, straight	4.48
Outboard upper, initial, tow-steered	4.30
Outboard upper, refined, tow-steered	4.81

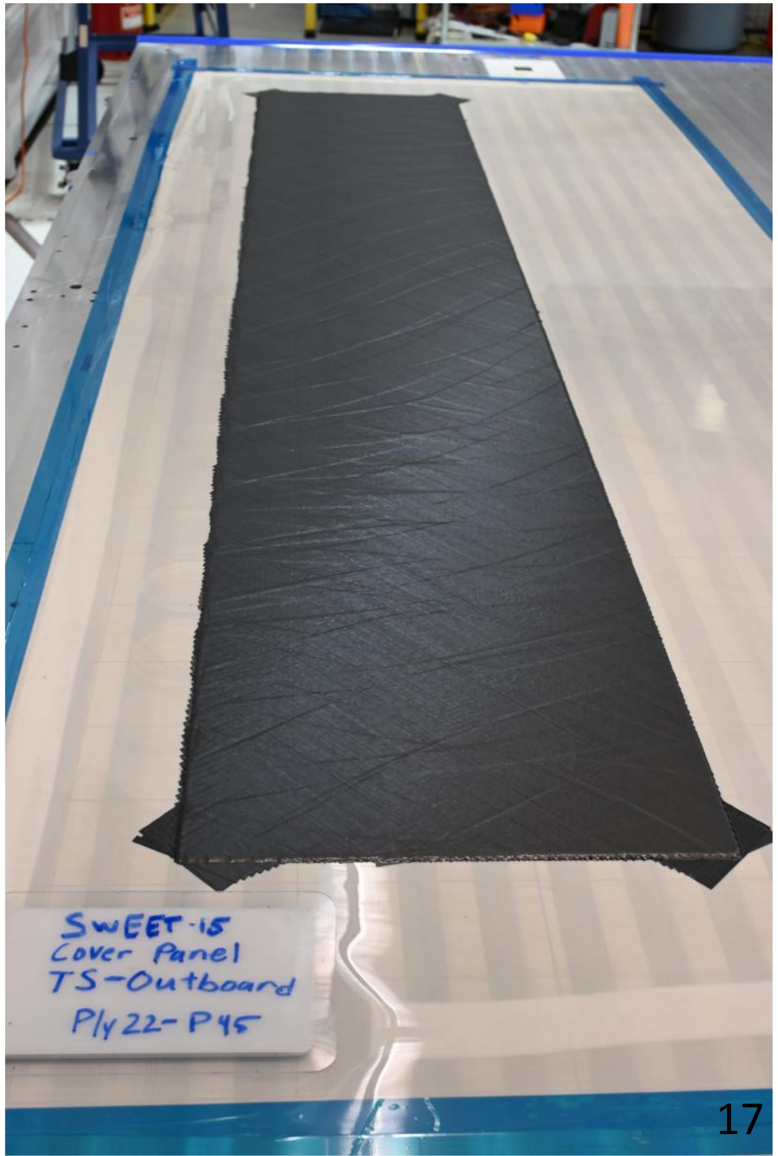




As-built Upper Cover Panels

- Curve geometry generated by the ATSCOOL tool
- Curves imported to the Vericut Composite Programming (VCP) software to program tow paths for ISAAC
- Cover panels have been manufactured at ISAAC with AFP





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Concluding Remarks

- SWEET-15 test article designed to match structural response of LaRC TTBW vision vehicle
  - Wingspan scaled to 18.6% of vision vehicle
  - Loads scaled to 4.1% of vision vehicle to have displacement profile
- Tow-steering of upper cover panels included in design process
  - Uses 8 variables per ply instead of 1 used in straight-fiber design
  - LaRC ATSCOOL tool used to define tow-steered properties in FEM and for ISAAC AFP process
  - LSOPT software linked to ATSCOOL in design process to optimize design
- Refined MSC/NASTRAN FEM developed to represent detailed joints and test fixtures
  - Strength critical at joint and wing root fixture bolt locations
  - Buckling critical in outboard section
  - Tow-steered upper cover panel design 6.4% lighter than straight-fiber design in initial FEM
- Cover panels successfully manufactured at ISAAC facility