Tow Steered Wing Structure Design

Mike Henson
University of Texas at Arlington, Arlington, TX
Bo Wang
University of Texas at Arlington, Arlington, TX

Outline

- Motivation and Research Goals
- Background
- Analytical Approach
- Numerical Implementation
- Current Challenges
- Summary and Future Work

Motivation and Research Objectives

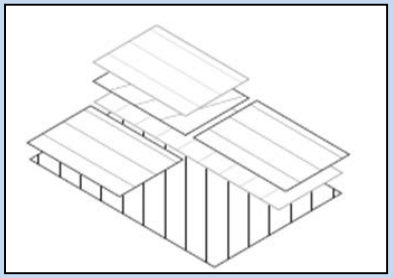
- Motivation
  - Enable airframe definition to keep pace with rapidly evolving configurations
  - Identify efficient structural concepts during conceptual design
  - Access to computational geometry and coupled analyses

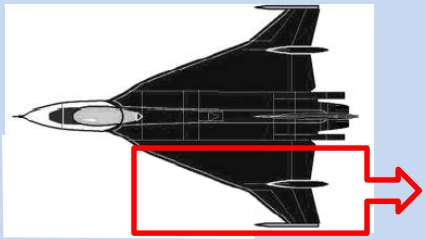
- Objectives
  - Develop analysis method for variable stiffness wing box structures
    - Static, Vibration, Buckling
    - Aeroelastic response
  - Demonstrate an efficient sizing framework
    - Ability to trade off speed, fidelity and level of detail

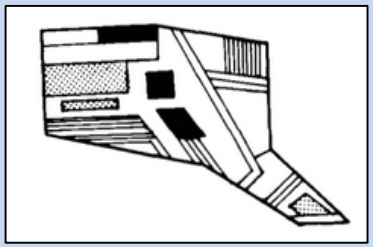
Conventional and Steered Laminates

Conventional Multi-Zone Laminates

- Discrete zones of constant properties
- 0/+45/-45/90 ply angles throughout
- Tailored by ply percentages and stack
- Zones are typically sized for worst case point condition -> conservative
- Well established design and analysis

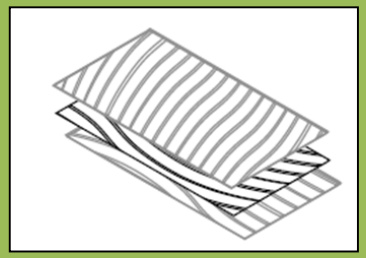


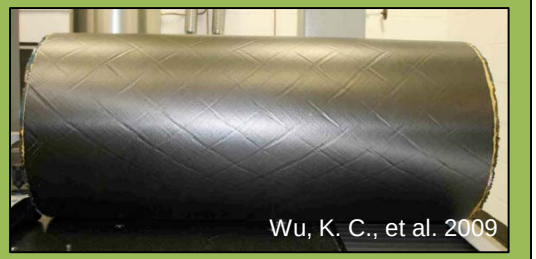




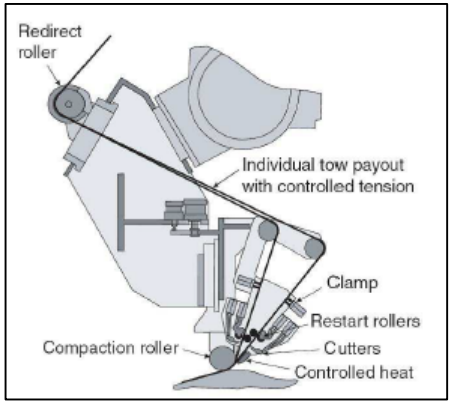
Fiber Steered Laminates

- Stiffness and strength tailored by varying both fiber angle and ply stack
- Fiber paths are in-plane curvilinear
- Design and analysis is more complex
- Offers potential for significant performance improvements

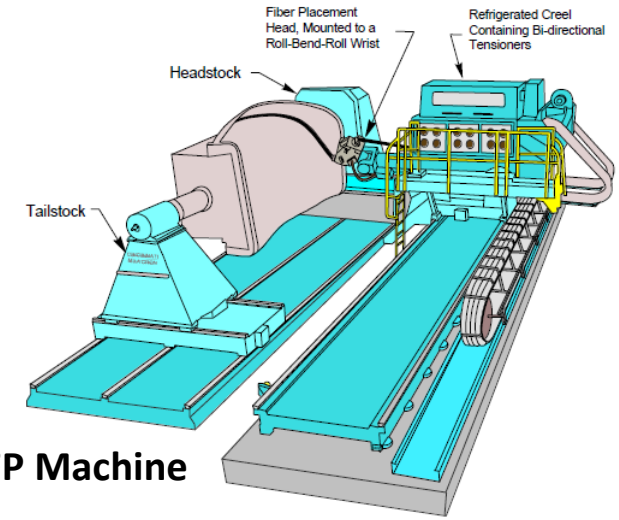




AFP Manufacturing Flexibility & Challenges



Fiber placement head

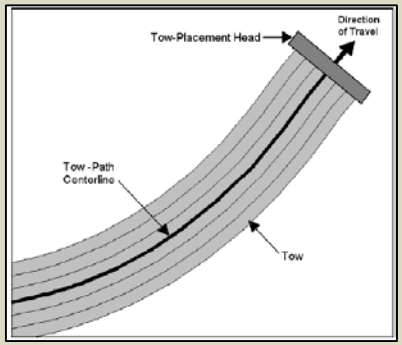


AFP Machine

Tow and slit tape

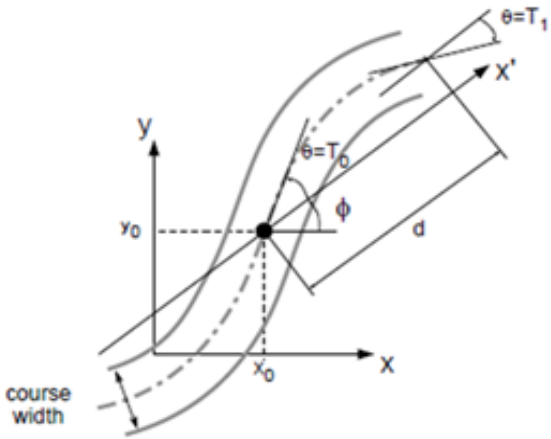
Tow Steering: Challenges & Concerns

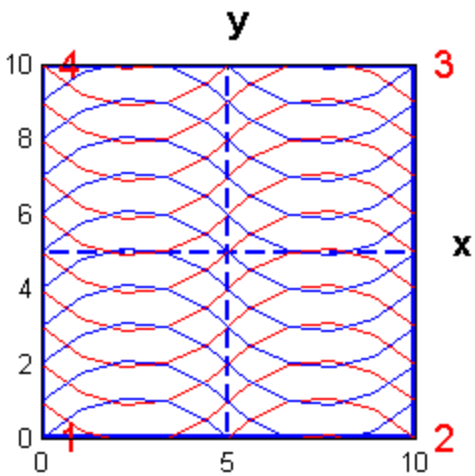
- Current AFP design approach uses traditional methods
- Tow steering exceeds engineering design practice - the concept of fiber steering is not addressed and potential weight and performance advantages are unrealized
- Design/Analysis concerns: fiber path modeling, variable stiffness/strength and certification
- Fabrication concerns: steering limits, gaps/overlaps & quality

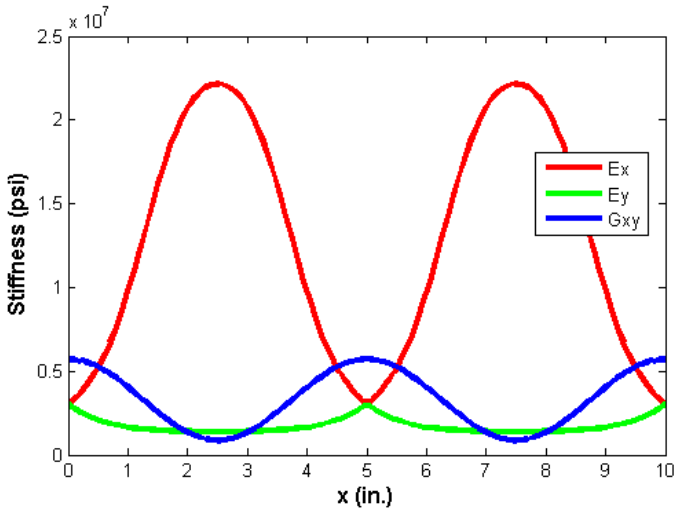


AFP steered material course

Curvilinear Fiber Path Definition





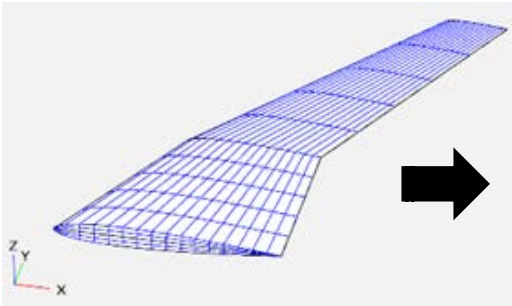


- Linear Fiber Path Model: $\theta(x') = \emptyset + (T_1 - T_0)\,\frac{|x'|}{d} + T_0$
- Ply angle $\boldsymbol{\theta}$ varies linearly over distance $\boldsymbol{d}$ from $\boldsymbol{T_0}$ to $\boldsymbol{T_1}$ along $\boldsymbol{x'}$
- Laminate designation: $\emptyset \pm < T_0 | T_1 >$ e.g. [±<45|45>]

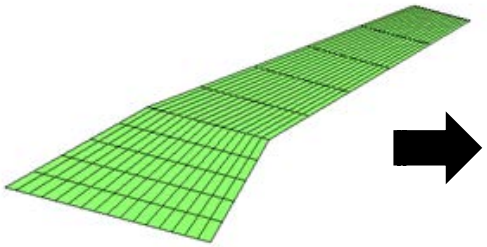
(Gurdal and Olmedo 1993)
(Tatting and Gurdal 2002)

Wing Geometry and Construction

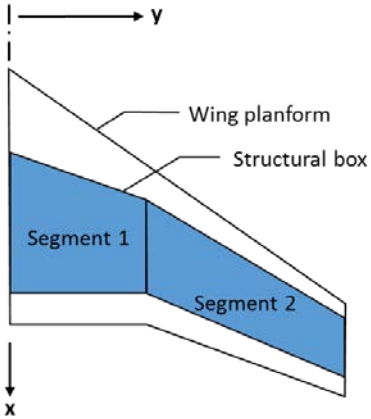
- VSP wing geometry exported to DegenGeom format
- Wing planform modeled as an assembly of quadrilateral segments



VSP 3D Geometry

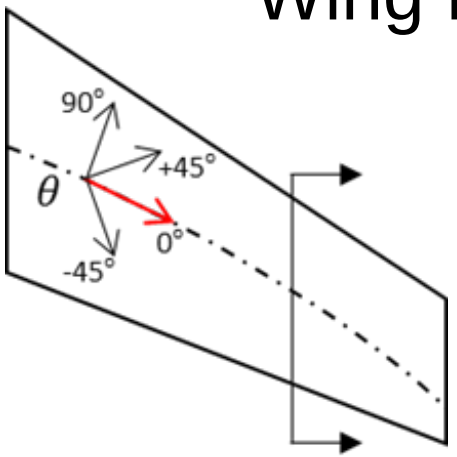


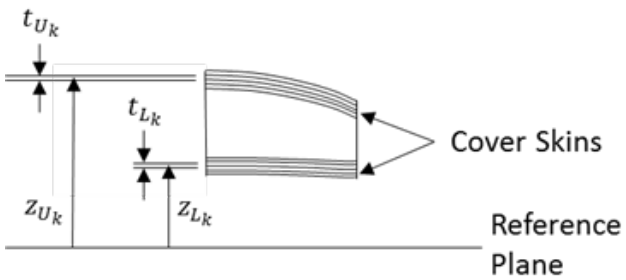
3D Degenerative Plate



2D Segmented Planform

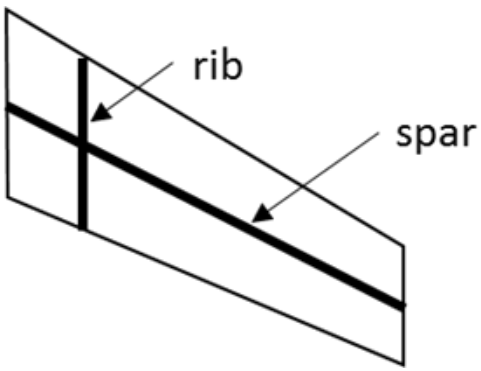
Wing Laminate Cross Section

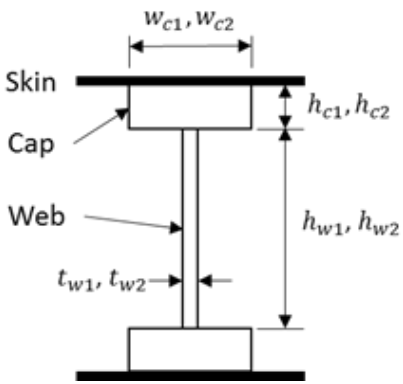




- Reference plane: represents the equivalent plate surface
- Wing skin covers: orthotropic laminate or single isotropic layer
- Linearly varying 0° reference fiber path: $\theta(y') = \emptyset + (T_1 - T_0)\,\frac{y'}{s} + T_0$
- Constrained ply orientations: [0/+45/-45/90] relative to reference fiber path
- Variable laminate stiffness: $Q = Q(x, y)$

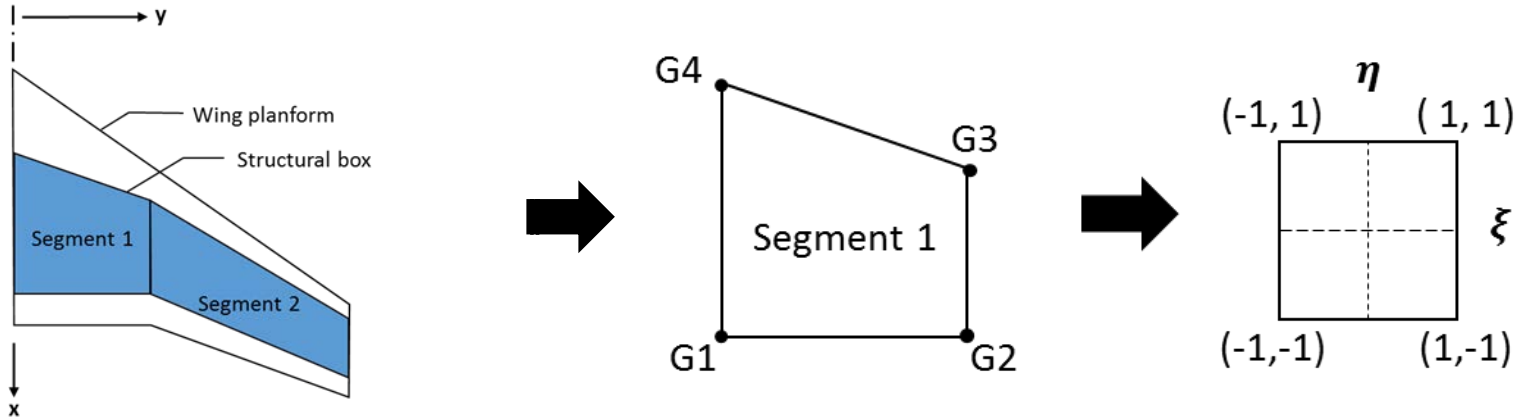
Wing Substructure Cross Section





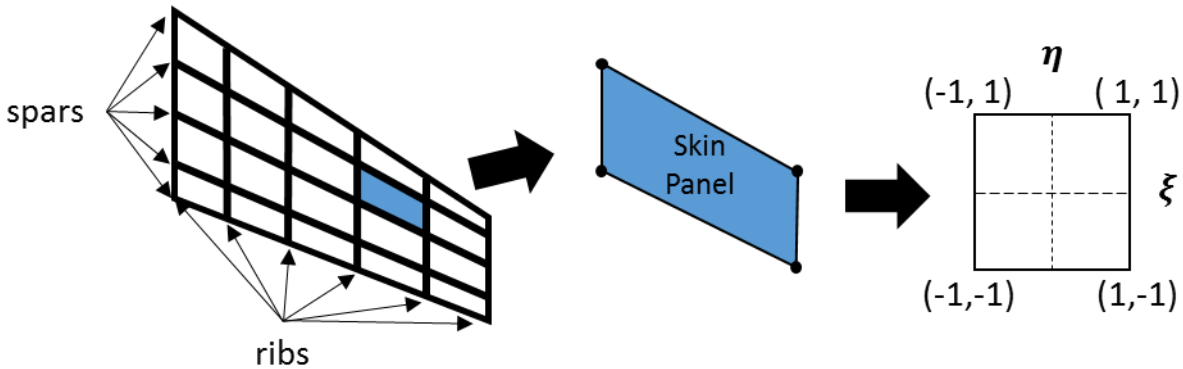
- Substructure: Ribs and spars or solid material
- Section variables

Analytical Approach

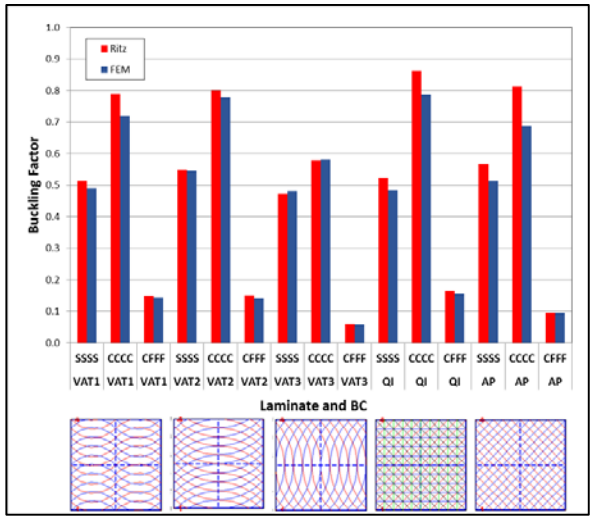


- FSDT: Reissner-Mindlin and Legendre basis functions
- Ritz numerical solution

Buckling Panel Definitions



- Panels derived from rib-spar intersections
- Ritz buckling analysis:
  - Reference: AIAA 2016-1975
  - Good correlation with Nastran FEM



Overview of Analytical Approach

- Mindlin plate theory: $[u, v, w, \phi_x, \phi_y]$
- Linear fiber path model: $\theta = \theta(x, y)$
- Lamination theory: $\bar{Q}_{ij} = \bar{Q}_{ij}(x, y)$
- Ritz and Legendre polynomials
- Energy transformation: $\Pi = \Pi(\xi, \eta)$
- Numerically integrate energy equations
- MATLAB implementation
- Optional NASTRAN solution

$$u(x, y, z, t) = u_0(x, y, t) + z\phi_x$$
$$v(x, y, z, t) = v_0(x, y, t) + z\phi_y$$
$$w(x, y, z, t) = w_0(x, y, t)$$
$$\phi_x = \frac{\partial u}{\partial z}, \quad \phi_y = \frac{\partial v}{\partial z}$$

$$\theta(x') = \phi + (T_1 - T_0)\frac{x'}{d} + T_0$$

$$[K_c] \cong \sum_{i=1}^{M_g} \sum_{j=1}^{N_g} g_i\, g_j K_{mn}(\xi_i, \eta_j)$$

$$K_{mn} = \left[[C]^T [T_e]^T [D][T_e][C]|J|\right]_{(\xi_i, \eta_j)}$$

$$g_i, g_j = Gauss\ weights$$

Inputs
- Geometry
- Fiber Paths
- Loads, BCs
- Parameters

→

Matrix Equations
- $[K]\{q\} = \{F\}$
- $[K - \lambda M]\{q\} = 0$
- $[K - \lambda G]\{q\} = 0$

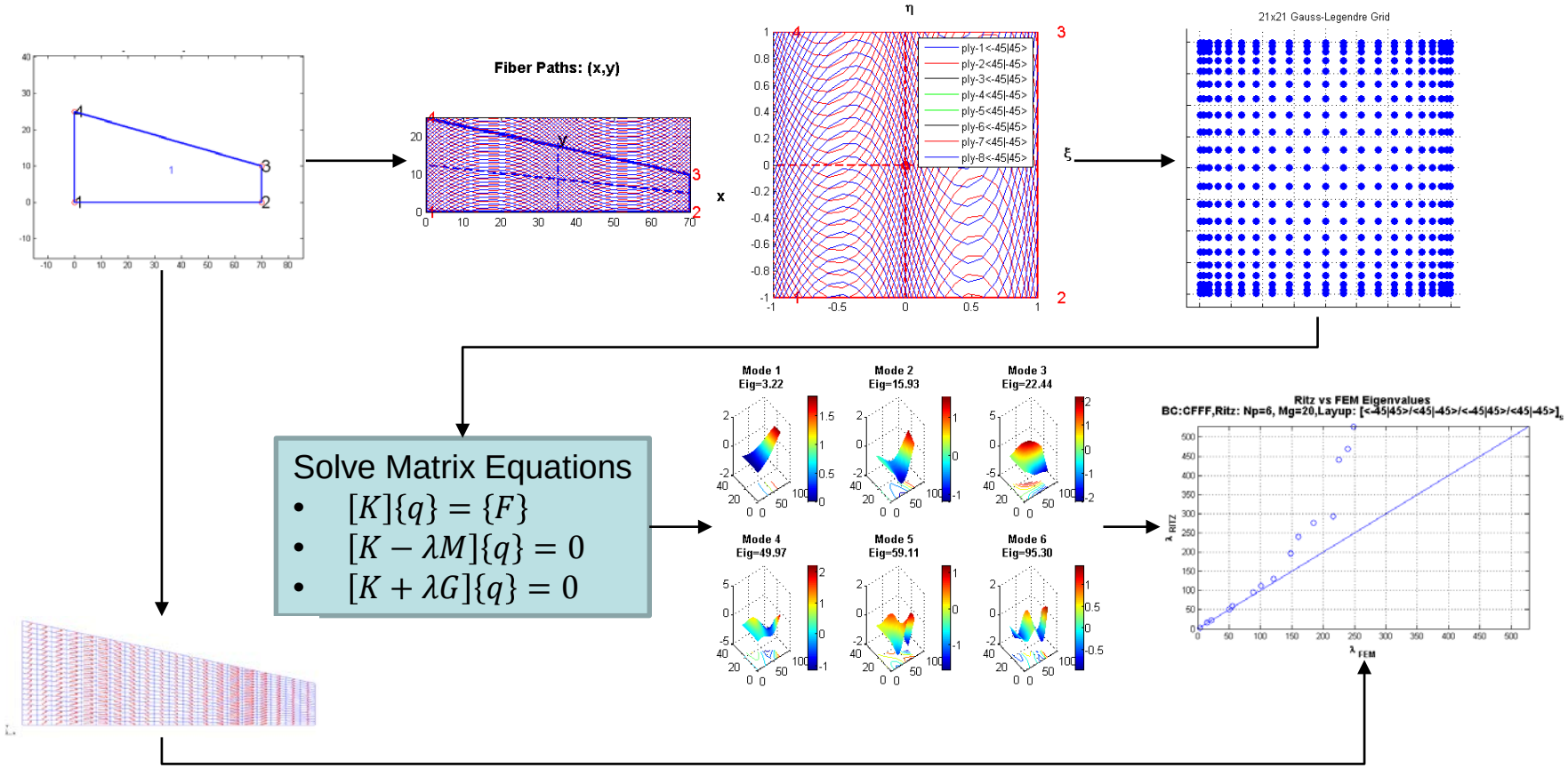
→

Solve and Post-processing
- Eigenvalues/vectors
- Displacement vector
- Strain recovery

→ **Verification**

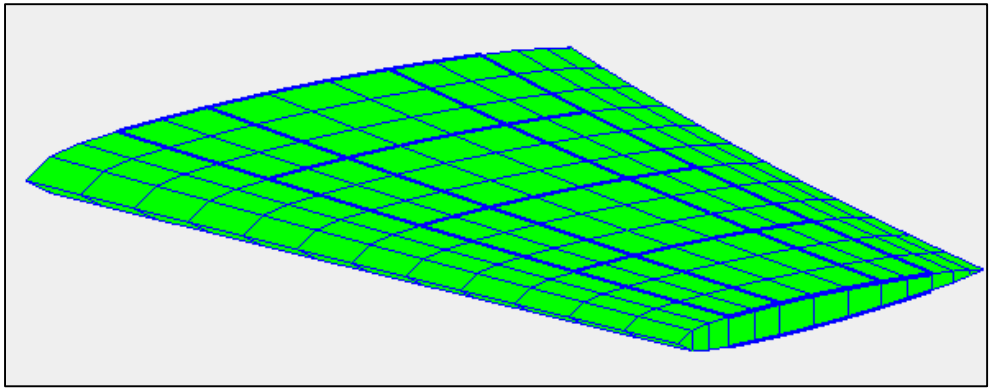
NASTRAN
- SOL 101
- SOL 103
- SOL 105

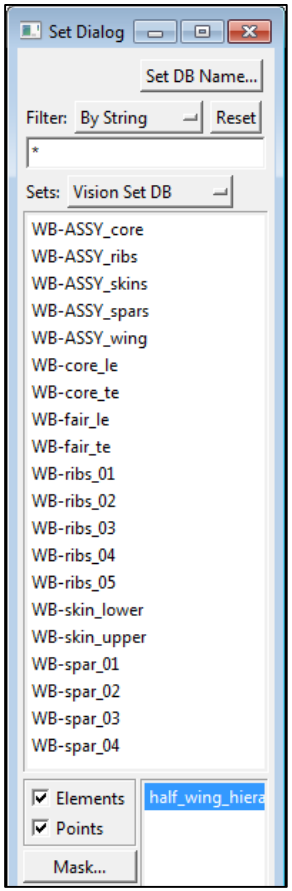
Numerical Implementation



- MATLAB single Ritz element of order N_p and $M_g x M_g$ integration points
- NASTRAN finite element model QUAD4 mesh density = $M_g x M_g$

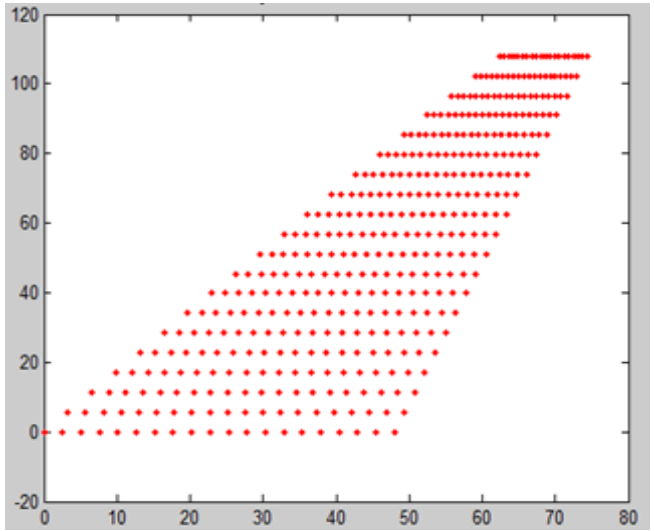
Finite Element Solution

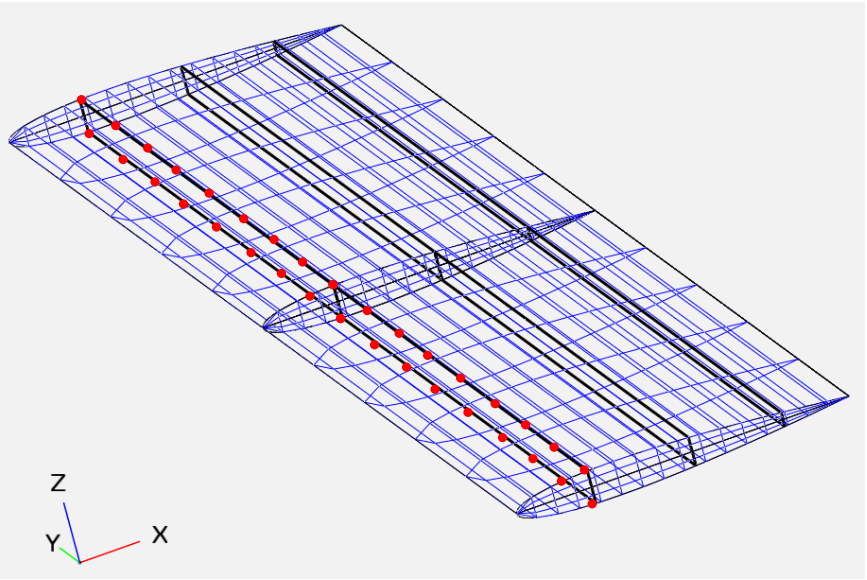




- Desired: Ability to create in VSP
- Nastran FEM created automatically and solved in parallel
- Provide calibration of Ritz solutions
- Higher fidelity + ability to increase level of detail
- Managing product structure (TMP/Vision-Viewsets)
- Managing results (TMP/Slim DB)

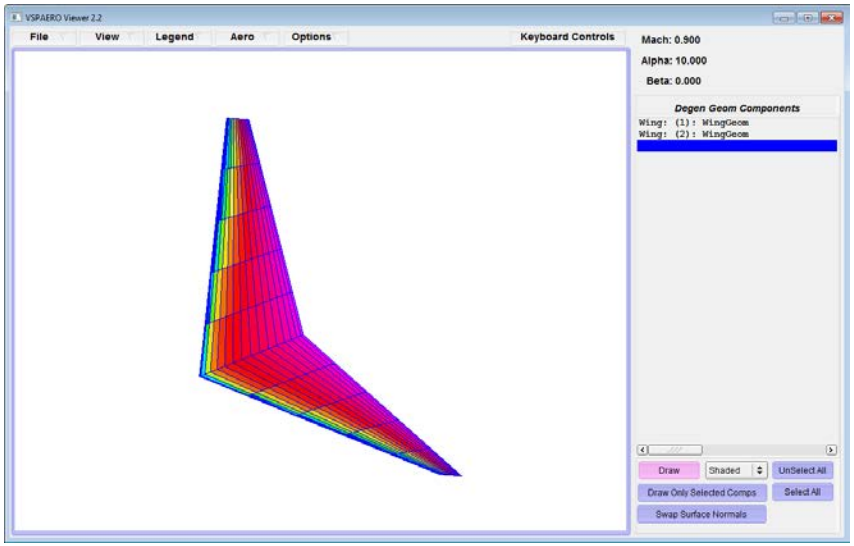
Current Challenges: VSP Geometry to Analysis





- Interpolating integration points on VSP wing surfaces
- Modeling and extracting rib and spar geometry

Current Challenges: VSPAero Loads Interface



- How to acquire pressure distributions
- Mapping/interpolating pressures from aero to structural mesh (Ritz or FEM)
- Some desired capabilities
  - Recovering results programmatically (pressure distribution, …)
  - Capability to configure and access massive numbers of runs
  - Ability to submit deformed geometry for analysis

Summary & Future Work

- A high order Ritz solution using Legendre polynomials developed to model quadrilateral VAT plates for static, vibration and buckling analyses
- Methodology is being extended to model tow-steered wing structures
- Ritz and FEM solutions have demonstrated good agreement
- Future plans
  - Demonstrate a sizing framework
  - Explore parallelized solution strategies

Thank You and Questions