Overview of Georgia Tech ASDL Research with HyperSizer

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Background & Motivation

- Conceptual Design of Aerospace Vehicles
  - ***Design space exploration*** for performance trends → converge toward an optimal or robust feasible design region
  - Translate requirements into a physical description of a vehicle
  - Traditionally executed with empirical models of historical design data

- Advanced Configurations in the Conceptual Design Phase




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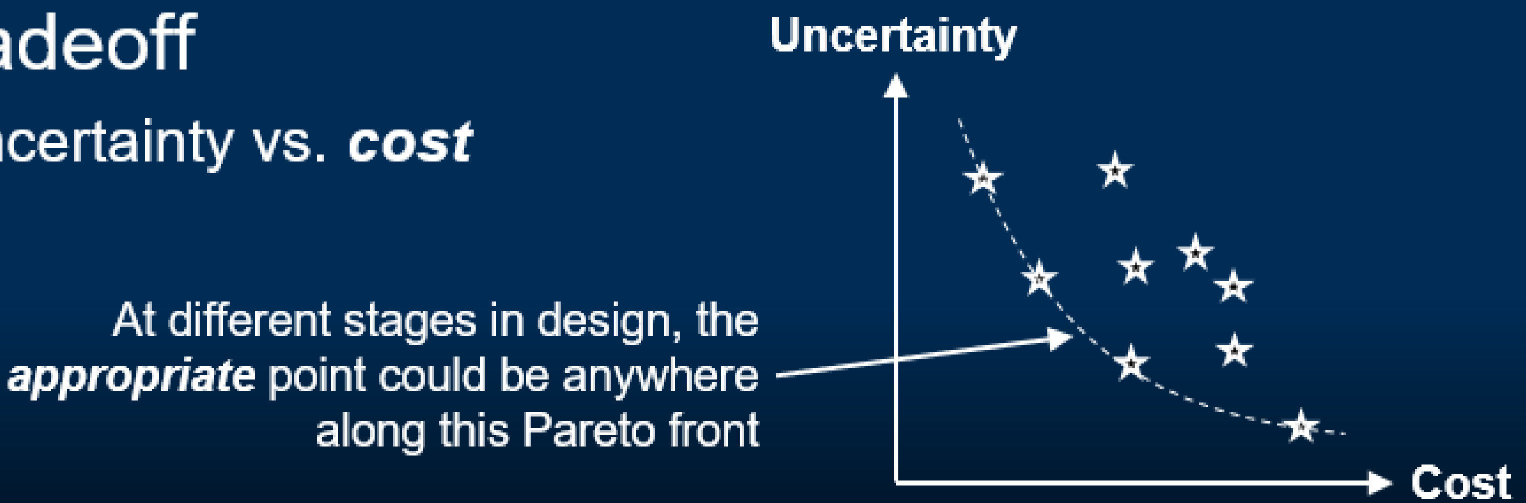
- Potential options for overcoming a lack of historical data in traditional conceptual design
  - Technology and configuration dials for empirical models
  - First principles
  - Physics-based computational modeling
- Important tradeoff
  - Accuracy/uncertainty vs. ***cost***



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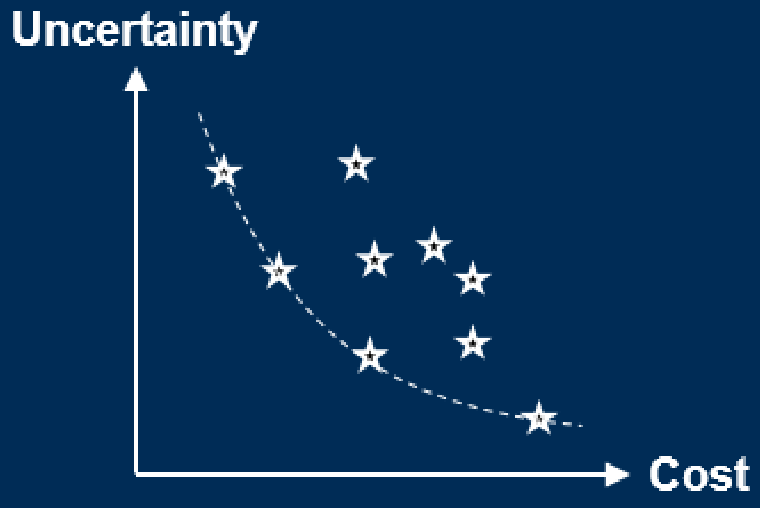
Design Challenges for Advanced Configurations

- Why causes the uncertainty/cost tradeoff in design metrics for advanced configurations?
  - Undefined detailed features and characteristics
  - Geometry and feature complexity
  - Order of physics-based equations
  - Execution time of computational code
  - Pre-processing time for model generation
  - Potential number of required disciplines
  - Dimensionality of the overall design space



Multiple levels of the design space

Design Challenges for Advanced Configurations

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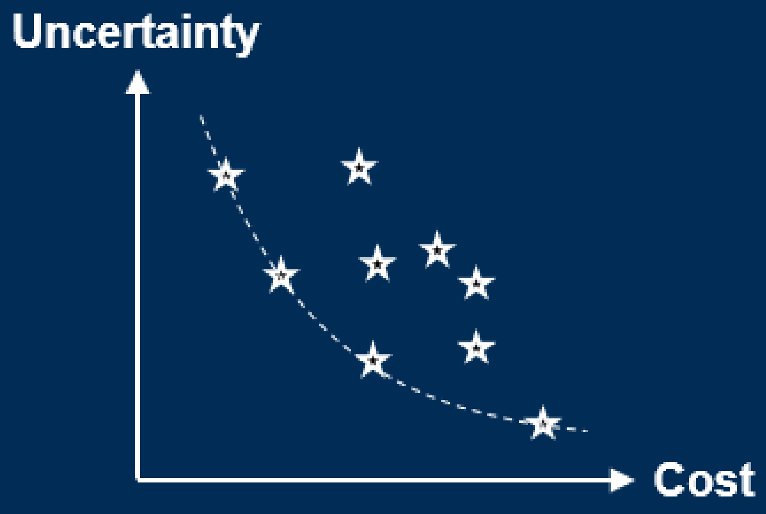

Multiple levels of fidelity

Design Challenges for Advanced Configurations

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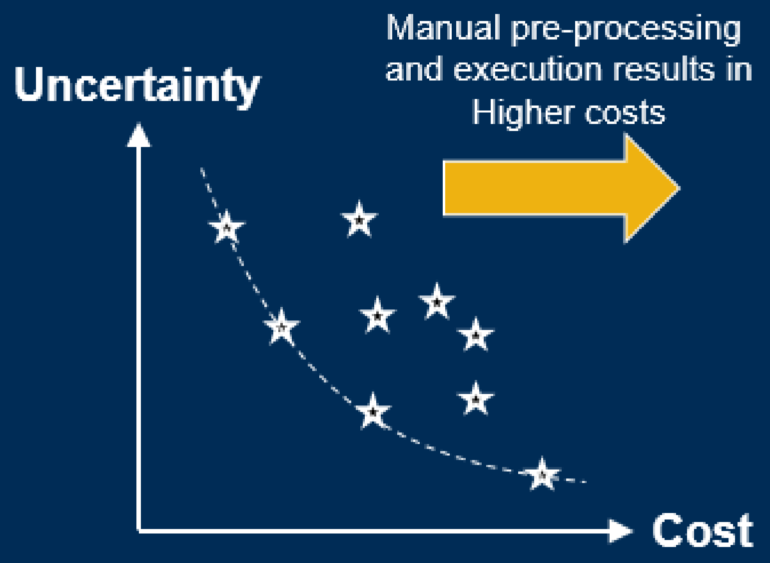
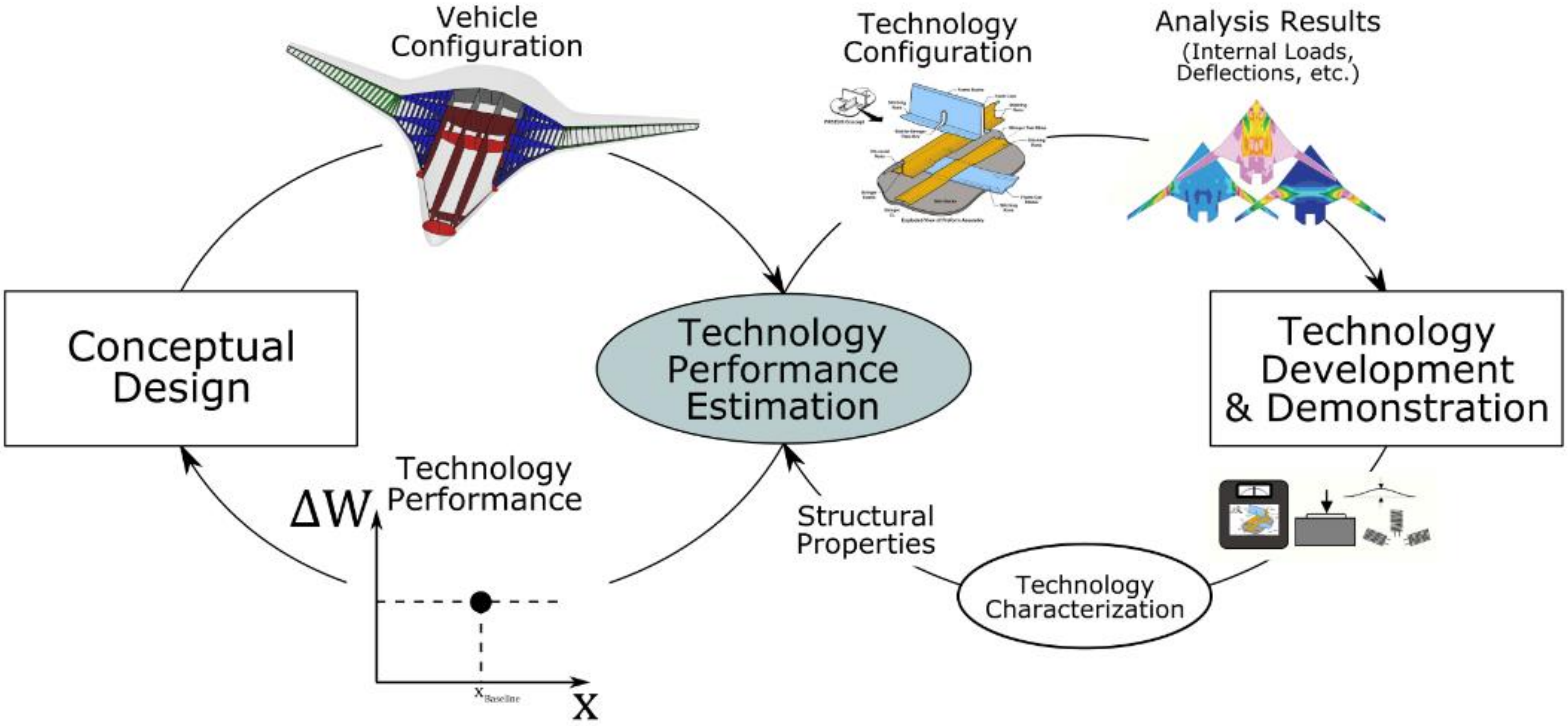


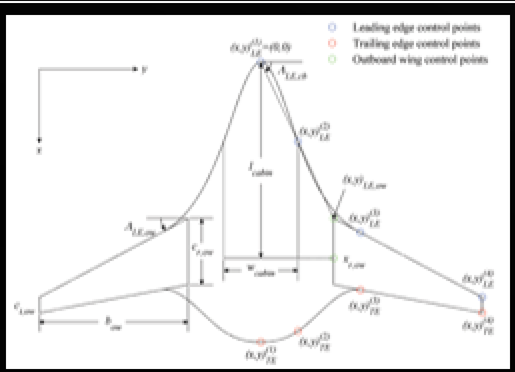
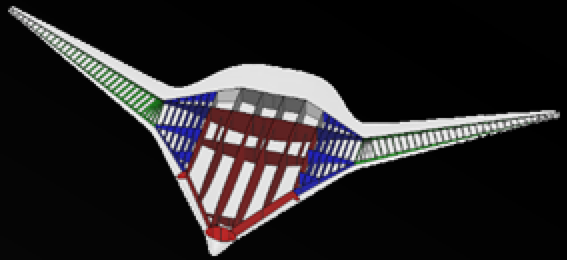
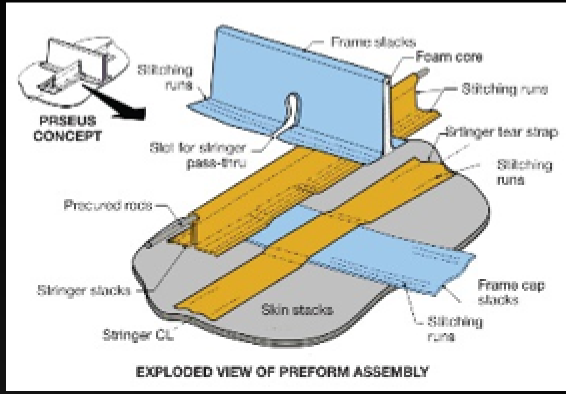
Large degree of automation

Structural Technology Performance Estimation

Benchmark Technology Performance Estimation Process



Structural Design Space

Outer Mold Line *(Conceptual Design)*		**Wing** • Area • AR • TR • Sweep **Center Section** • Cabin Length • Cabin Width • RCB % Chord • Sweep	GAP 1 Structural Model
Structural Layout *(Conceptual/Prelim Design)*		**Outboard Wing** • FS % Chord • RS % Chord • Rib Pitch **Centerbody** • # Bays • RS % Chord • FS % Chord	GAP 2 Structural Model
Technology *(Prelim/Detail Design)*		**Skin** • Thickness • Material **Stringer** • Height • Thickness • Material • Rod Diam. • Spacing **Frame** • Height • Thickness • Material • Foam Width • Spacing	Structural Sizing

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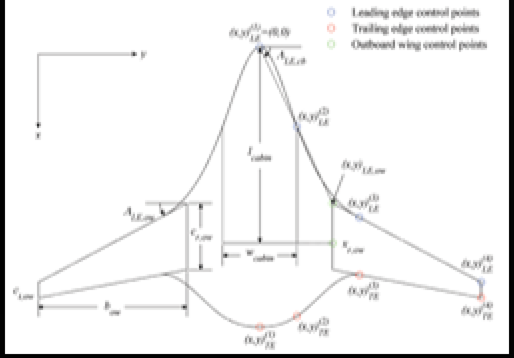
Structural Design Space

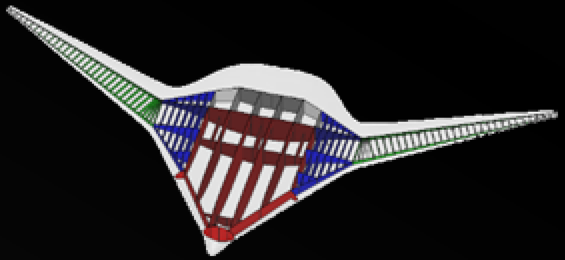
Outer Mold Line
(Conceptual Design)



Wing
- Area
- AR
- TR
- Sweep

Center Section
- Cabin Length
- Cabin Width
- RCB % Chord
- Sweep

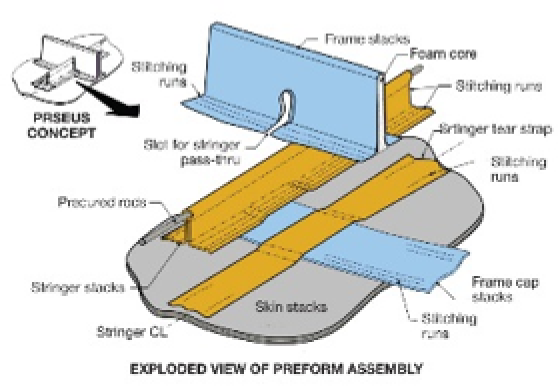
Structural Layout
(Conceptual/Prelim Design)



Outboard Wing
- FS % Chord
- RS % Chord
- Rib Pitch

Centerbody
- # Bays
- RS % Chord
- FS % Chord

Technology
(Prelim/Detail Design)



Skin
- Thickness
- Material

Stringer
- Height
- Thickness
- Material
- Rod Diam.
- Spacing

Frame
- Height
- Thickness
- Material
- Foam Width
- Spacing

GAP

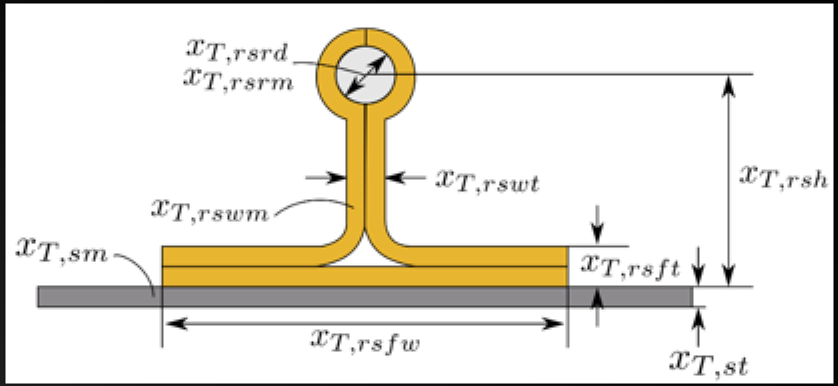
G

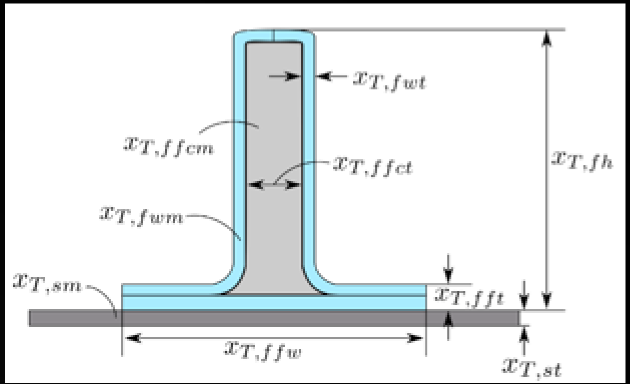
Increasing Modeling, Design, & Analysis Effort

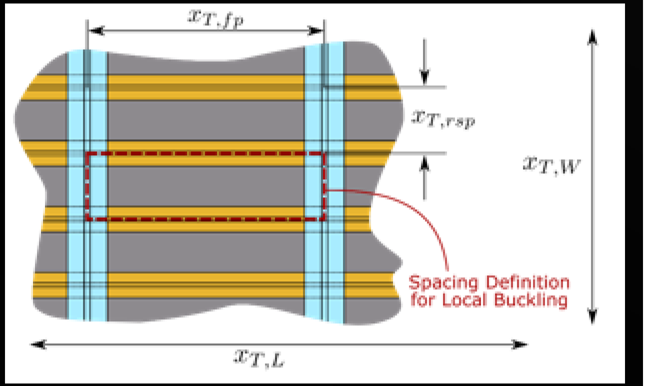
Technology Design Space

- Technology Level (PRSEUS)
  - 18 design variables
  - Bounds and # of permutations defined for grid search optimization in Hypersizer

General		Centerbody		Wing	
Variable	Nominal	Limits	Perm	Limits	Perm
$x_{T,st}$	0.052	[0.052, 0.408]	4	[0.052, 0.408]	4
$x_{T,sm}$	AS-4 EL	AS-4 EL (r)	-	AS-4 EL	-
$x_{T,rsh}$	1.25	[1.25, 3.75]	4	[0.75, 3.25]	6
$x_{T,rsp}$	6.0	[6.0, 6.0]	1	[6.0, 6.0]	1
$x_{T,rswt}$	0.104	[0.104, 0.208]	3	[0.104, 0.208]	3
$x_{T,rswm}$	AS-4 EL	AS-4 EL	-	AS-4 EL	-
$x_{T,rsft}$	0.104	[0.104, 0.208]	2	[0.104, 0.208]	2
$x_{T,rsfw}$	3.37	[3.37, 3.37]	1	[3.37, 3.37]	1
$x_{T,rsrd}$	0.375	[0.375, 1.0]	3	[0.375, 1.0]	3
$x_{T,rsrm}$	AS-4 EL (0)	AS-4 EL (0)	-	AS-4 EL (0)	-
$x_{T,fh}$	6.0	[4.0, 10.0]	4	[4.0, 8.0]	3
$x_{T,fp}$	20.0	[24.0, 24.0]	1	[36.0, 36.0]	1
$x_{T,fwt}$	0.104	[0.104, 0.312]	4	[0.104, 0.312]	4
$x_{T,fwm}$	AS-4 EL	AS4 EL	-	AS-4 EL	-
$x_{T,fft}$	0.156	[0.156, 0.312]	3	[0.156, 0.312]	3
$x_{T,ffw}$	3.93	[3.93, 3.93]	1	[3.93, 3.93]	1
$x_{T,ffct}$	0.5	[0.5, 0.5]	1	[0.001, 0.001]	1
$x_{T,ffcm}$	R 110 WF	110 WF	-	R 110 WF	-







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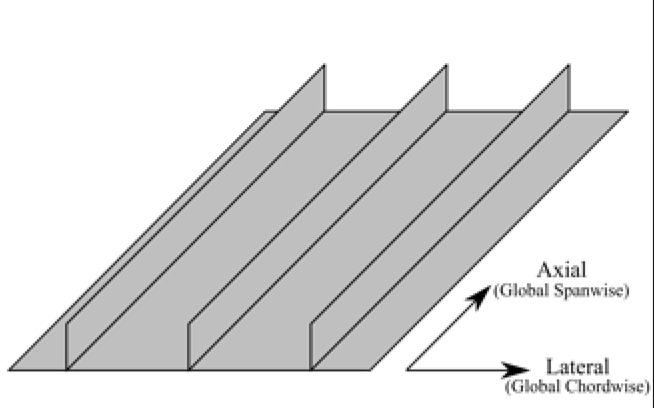
Technology Design Space

Baseline Structure Concept (Wing)

Blade Stiffened Composites (Same material as PRSEUS – different knockdowns, etc.)

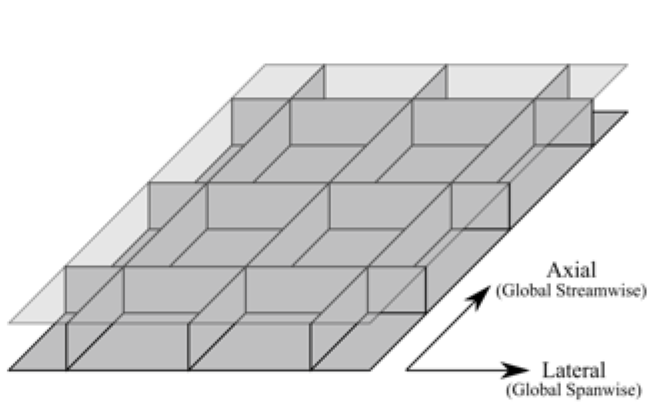


Variable	LB	UB	Perm
$x_{B,w,st}$	0.05	0.8	10
$x_{B,w,sm}$		– AS-4 EL –	
$x_{B,w,ash}$	1	6	8
$x_{B,w,asp}$	6.0	8.0	2
$x_{B,w,aswt}$	0.05	0.80	10
$x_{B,w,aswm}$		– AS-4 EL –	

Confirmed baselines with Boeing technology development team

Baseline Structure Concept (Centerbody)

Orthogrid Stiffened Sandwich Composites (Same material as PRSEUS – different knockdowns, etc.)



Variable	LB	UB	Perm
$x_{B,cb,stt}$	0.05	0.50	7
$x_{B,cb,smt}$		– AS-4 EL –	
$x_{B,cb,stb}$	0.05	0.25	7
$x_{B,cb,smb}$		– AS-4 EL –	
$x_{B,cb,ash}$	1	4	4
$x_{B,cb,asp}$	6.0	12.0	4
$x_{B,cb,aswt}$	0.10	0.50	6
$x_{B,cb,aswm}$		– AS-4 EL –	
$x_{B,cb,lsa}$	30°	30°	1
$x_{B,cb,lsh}$	2	8	4
$x_{B,cb,lswt}$	0.10	0.65	6
$x_{B,cb,lswm}$		– AS-4 EL –	

Development of Rapid Airframe Design Environment

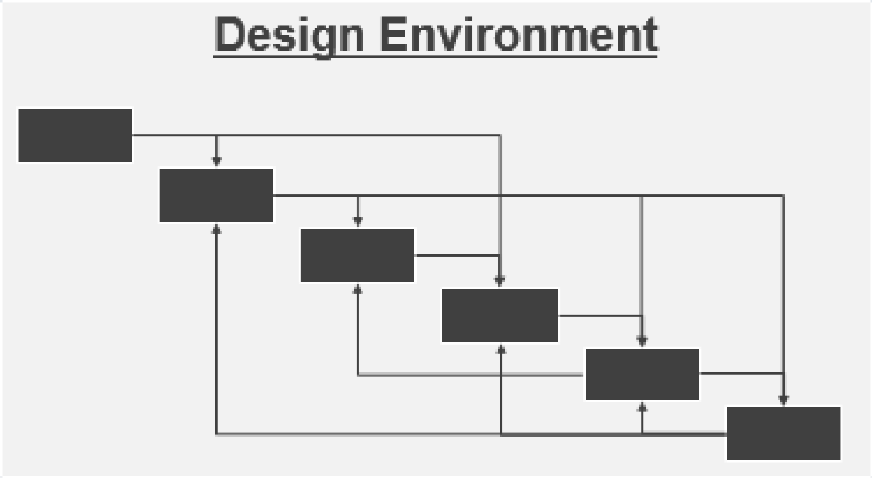
NASA Transformational Tools & Technologies Program

What is a "Design Environment"

- A representative description and implementation of design events
  - Results in a testbed to generate data to examine trades in design metrics, explore design spaces, optimize configurations, etc.

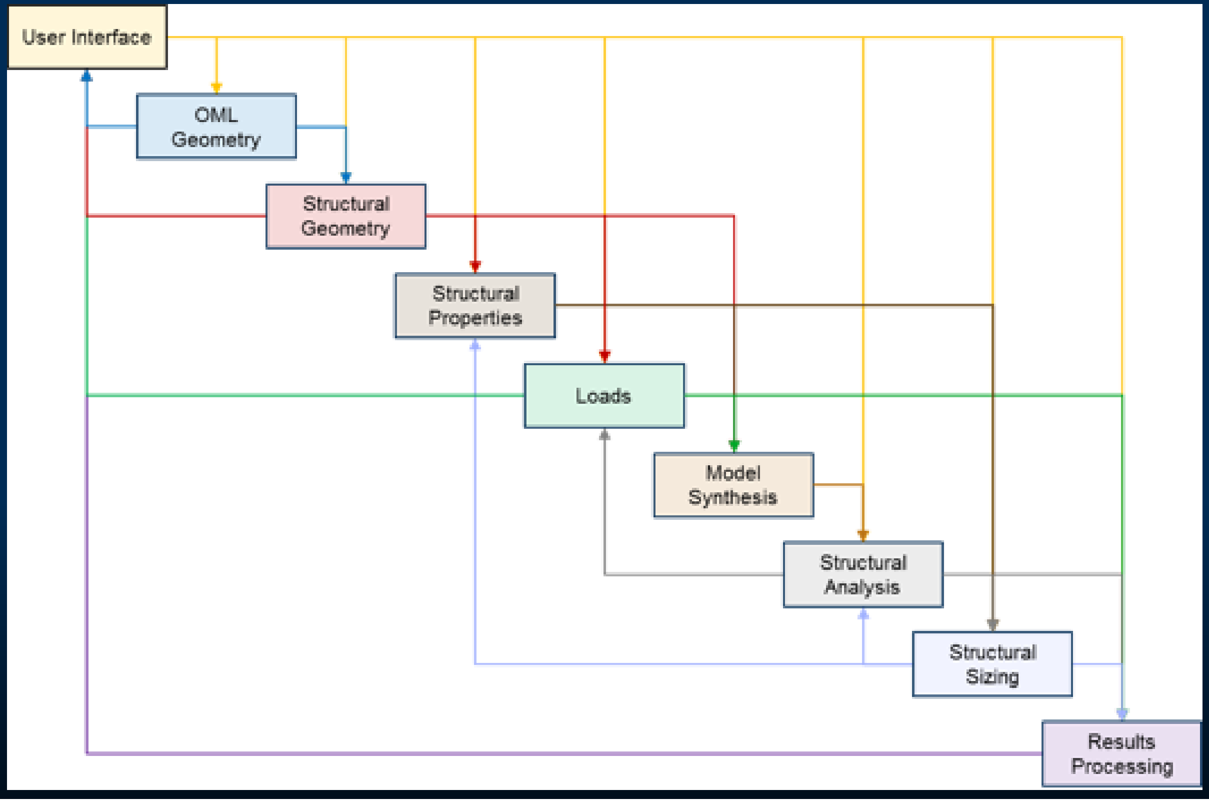
- Graphical vs. scripting implementation

- Enabling integration software:
  - Phoenix Integration ModelCenter
  - OpenMDAO
  - Siemens PLM/NX
  - Dassault Systemes 3DEXPERIENCE
  - GEMS
  - Many more…



Evolution of Toolkit Implementation

- Project with NASA Transformational Tools & Technologies (T^3)
  - **Objective:** Bring higher fidelity structural modeling earlier in the design process
  - Resulted in development of the Rapid Airframe Design Environment (RADE)
  - Initial development focused on enabling a monolithic workflow similar to FEM pre-processing



Most Important Characteristics For Successful Implementation

Robust Parametric Execution

Robust Automation

Flexibility

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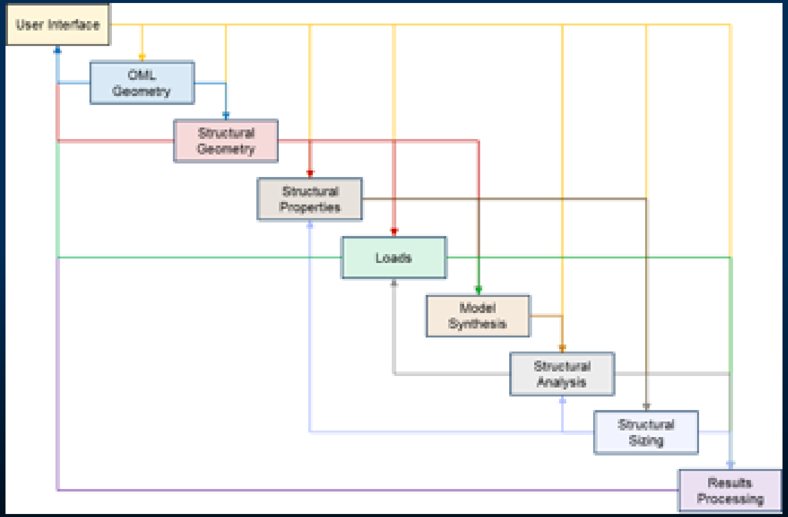
Evolution of Toolkit Implementation

Robust Parametric Execution	Robust Automation	Flexibility

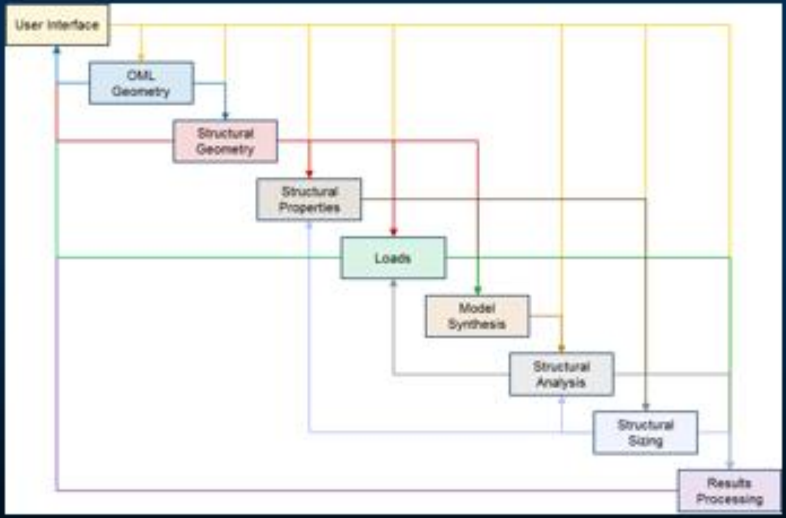
Conceptual Phase
Structural Weight Estimation



Evolution of Toolkit Implementation

Robust Parametric Execution | Robust Automation | **Flexibility**

Conceptual Phase Structural Weight Estimation → **Comprehensive Multidisciplinary Design Optimization and Analysis**



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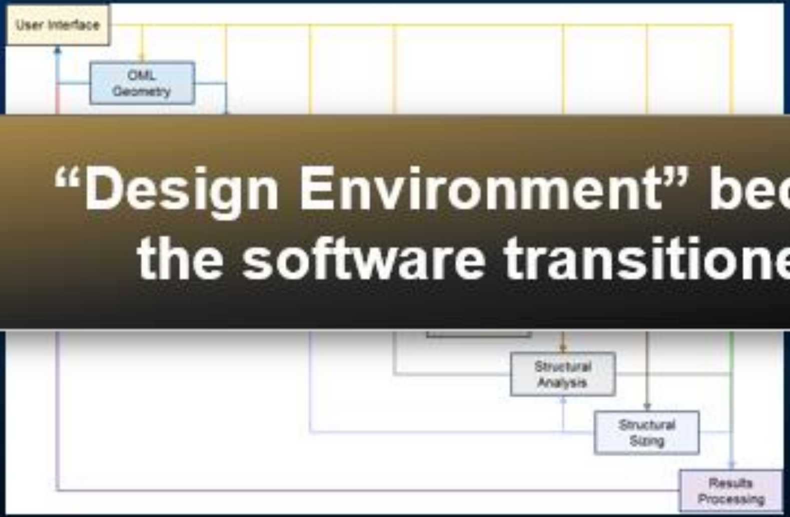
Evolution of Toolkit Implementation

Robust Parametric Execution | **Robust Automation** | **Flexibility**

Conceptual Phase Structural Weight Estimation → **Comprehensive Multidisciplinary Design Optimization and Analysis**



"Design Environment" became a misnomer in RADE as the software transitioned toward an MDAO toolkit

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Aeroelastic Design Space Exploration

Wingtip Propulsion Configuration

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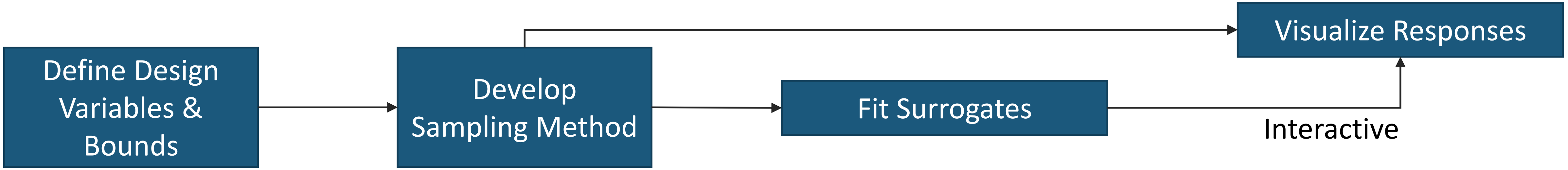
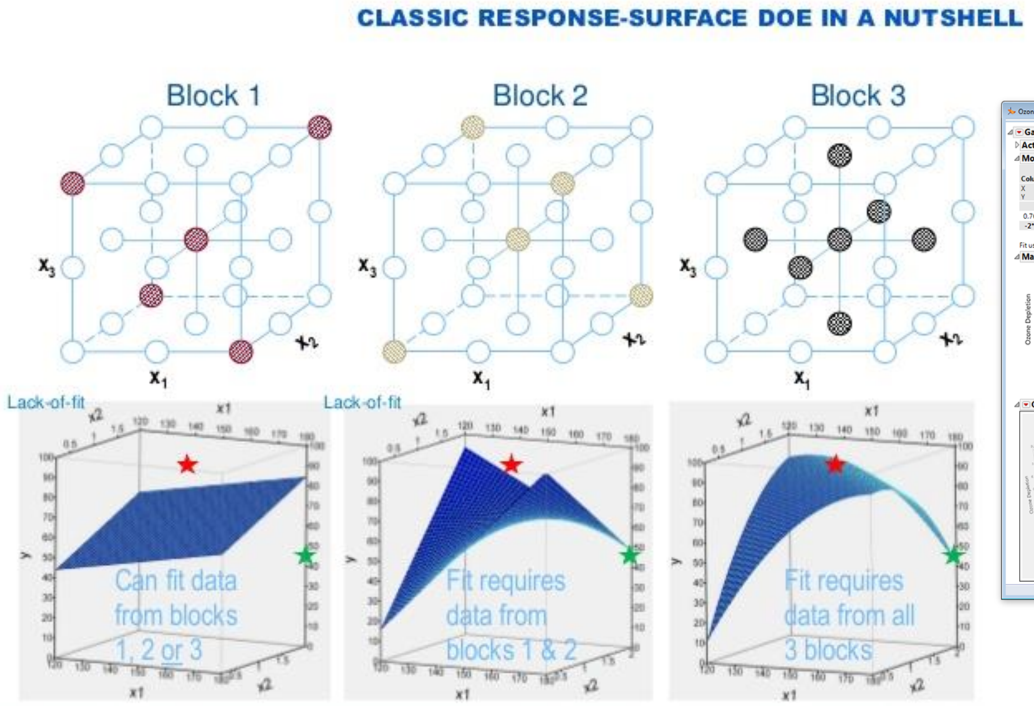
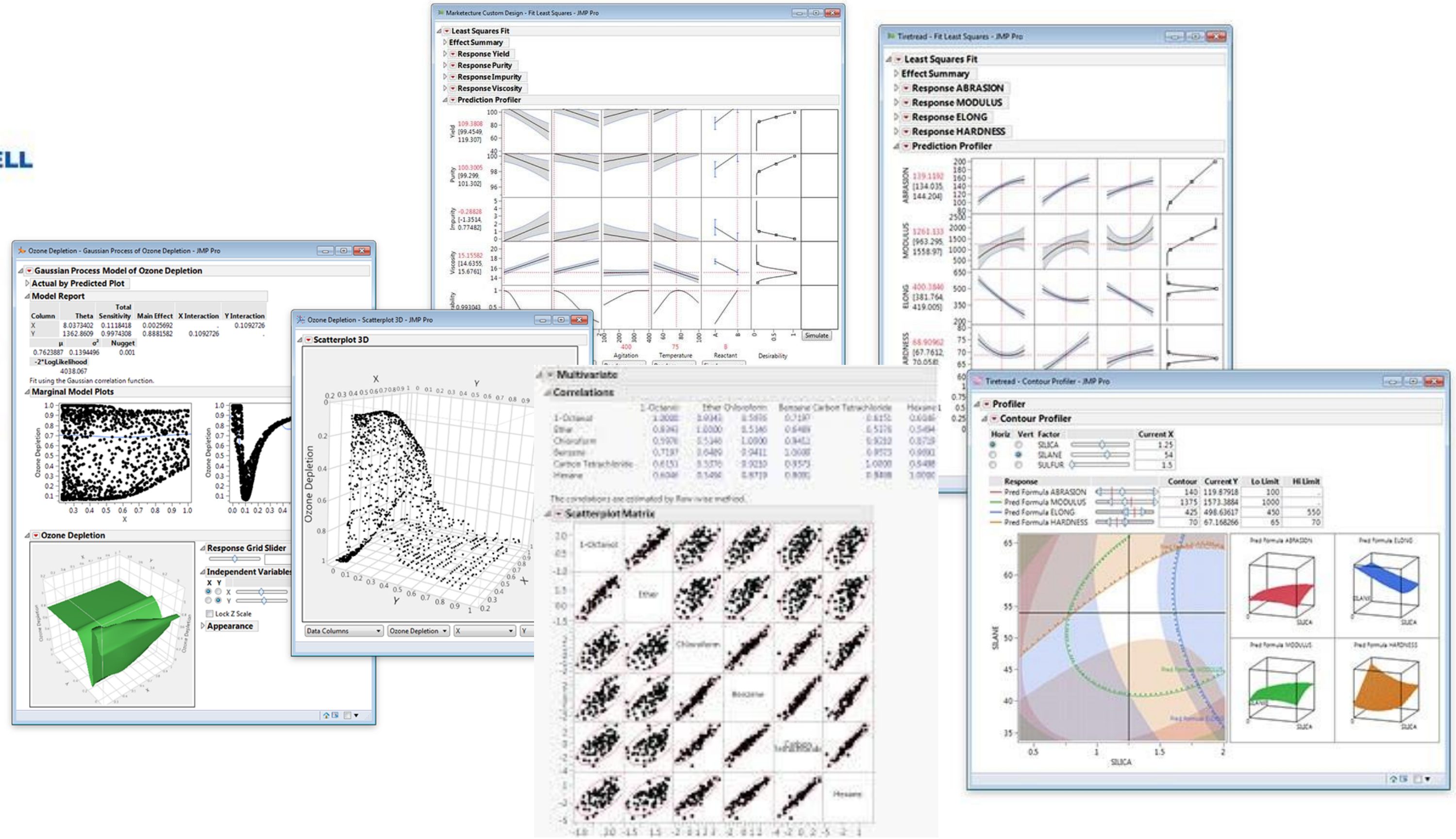




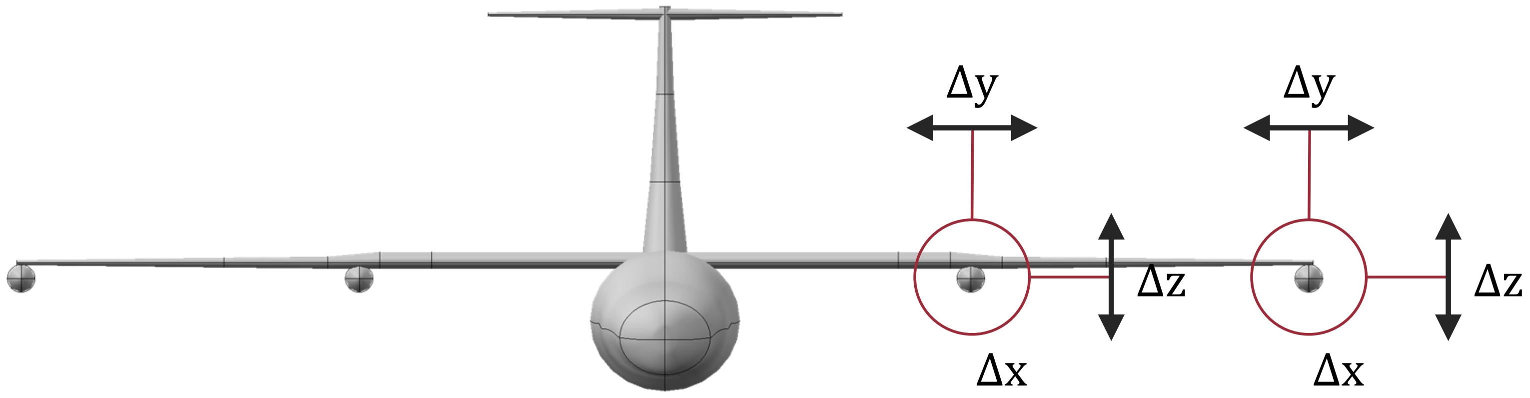


JMP Tutorials: https://www.jmp.com/en_us/applications/design-of-experiments.html

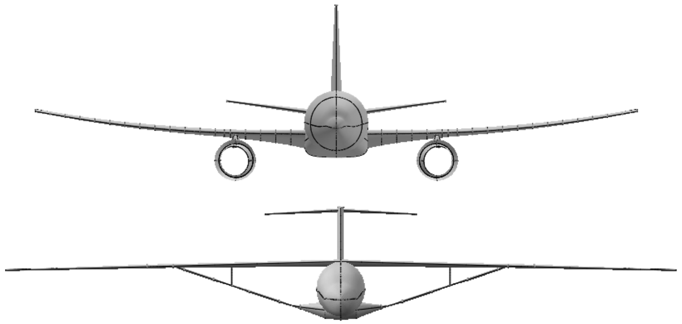
Research Problem Definition

Overall Objective:

Explore the design space of a wing with engines located in the outboard region



- Important Considerations:
  - Time Frame – 6 to 7 months for completion of work
  - Aeroelasticity considered for responses, constraints, and objectives



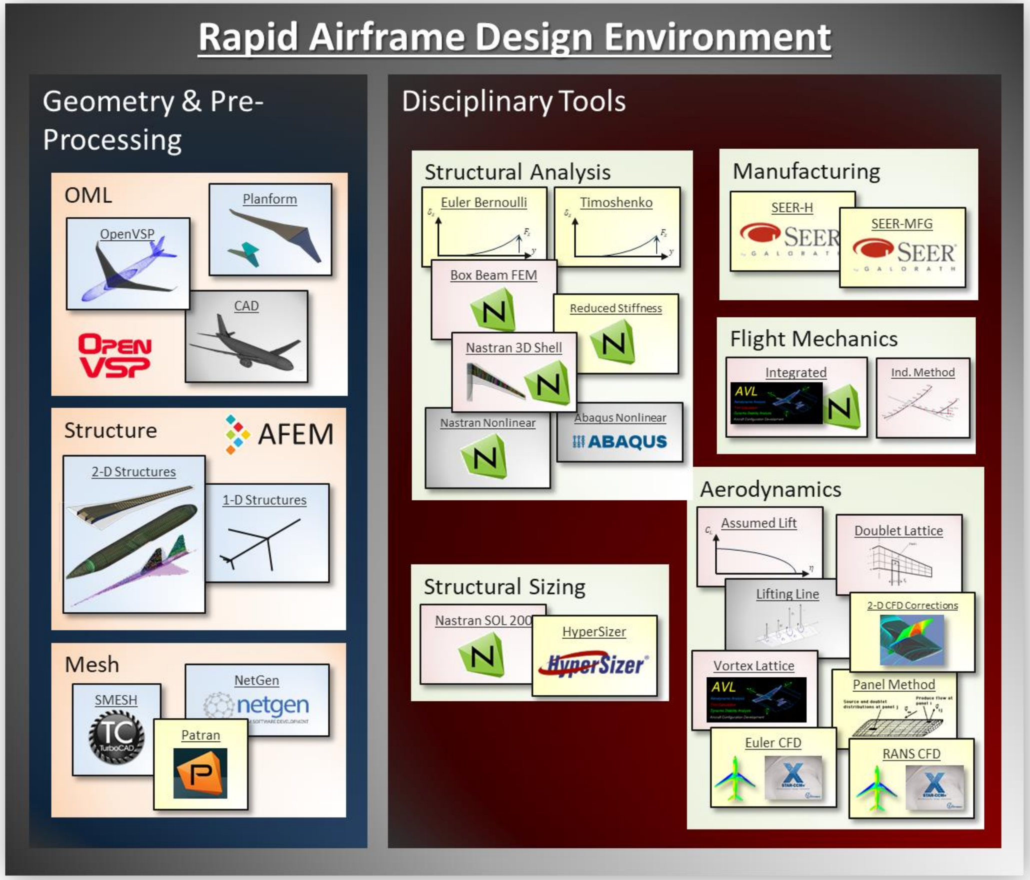
- Assumptions
  - Iteratively converged and developed through project timeline

Enabling Capabilities

- Rapid Airframe Design Environment (RADE)
  - Early phase multidisciplinary design toolkit
  - Developed through NASA TTT Program under contract
  - NASA Tech Lead: Erik Olson

- Environmental Design Space (EDS)
  - Vehicle level performance modeling with environmental response focus

- NASA AATT Dashboard



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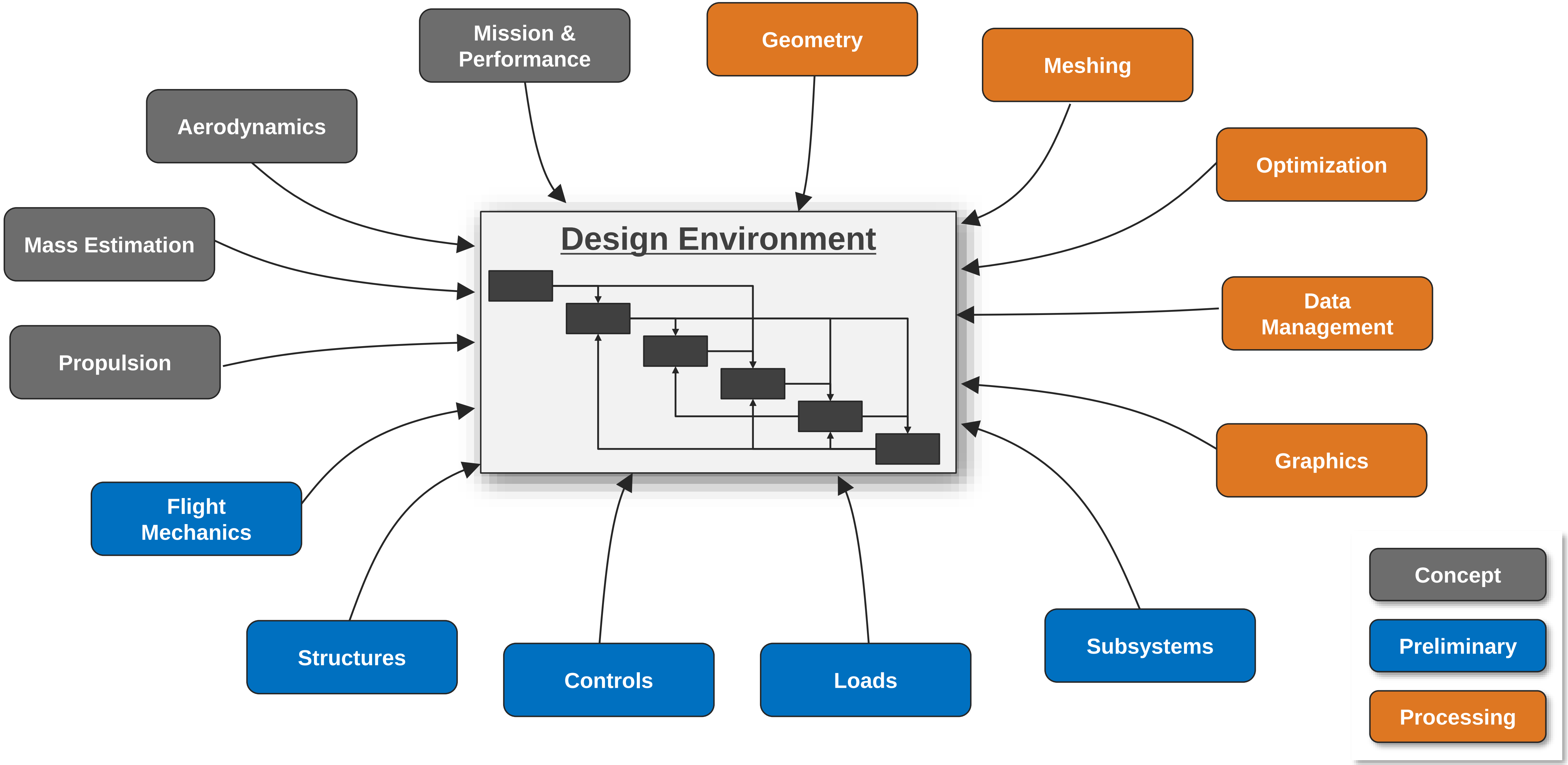
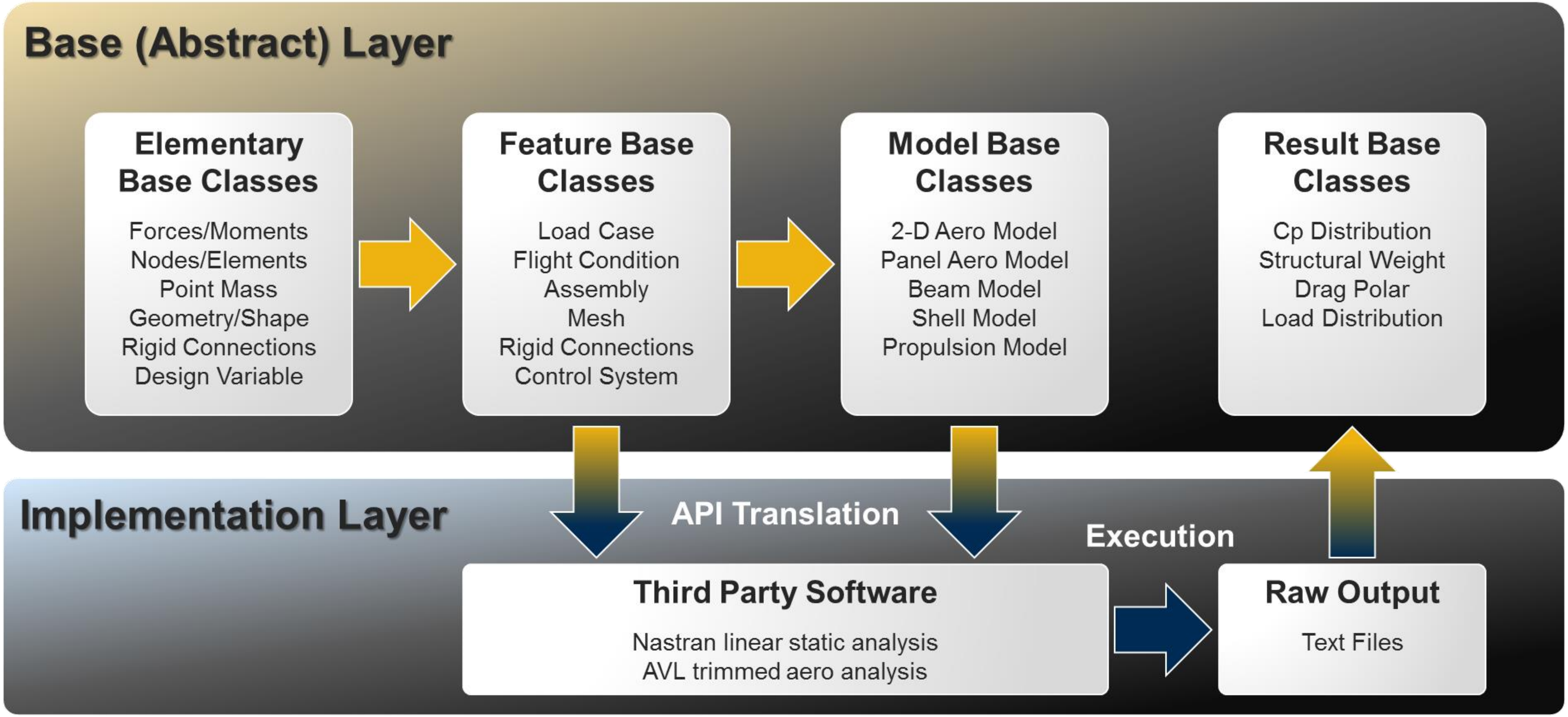
Creating a Environment for Wingtip Propulsion Aeroelastic Design



Modeling in RADE

Robust Parametric Execution | Robust Automation | Flexibility



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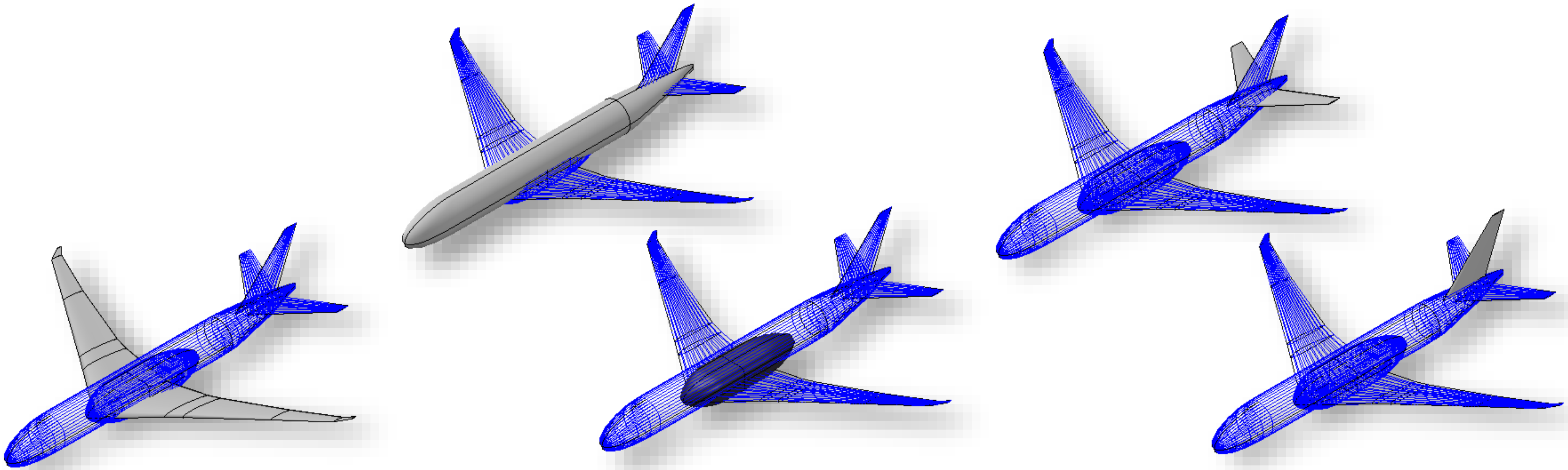
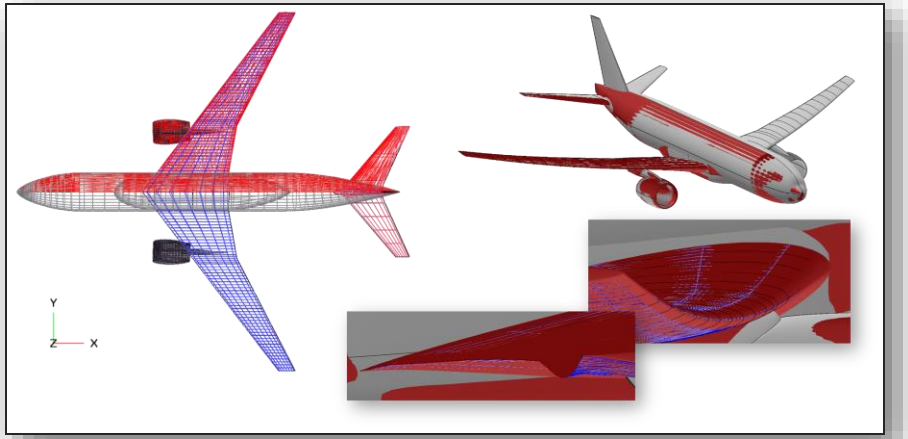
Modeling in RADE: Outer Mold Line

- All vehicle designs start with representation of OML
- Baseline models are created with OpenVSP with fundamental regions:
  - Wing
  - Fuselage
- Parametric changes enabled through OpenVSP python API
- OuterMoldLine object is a container of named regions with reference geometries



Modeling in RADE: Aerodynamics



Feature Base Classes

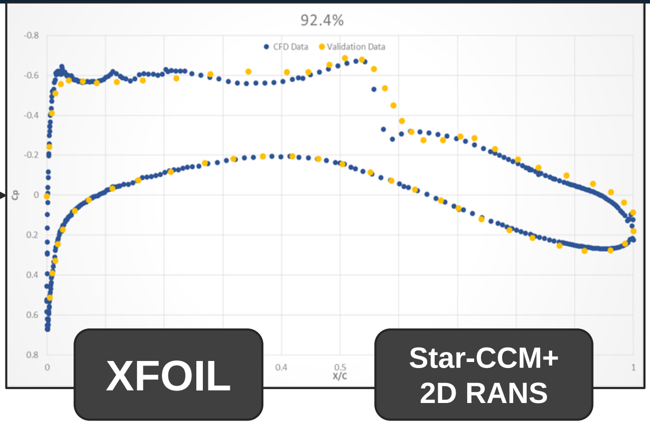
- Flow Conditions
- Vehicle State
- Controls States

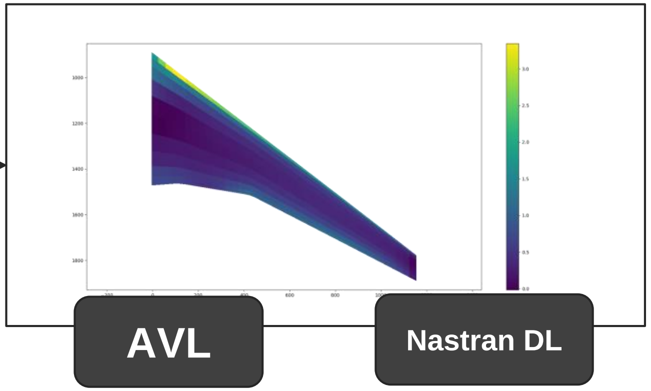
Elementary Base Classes

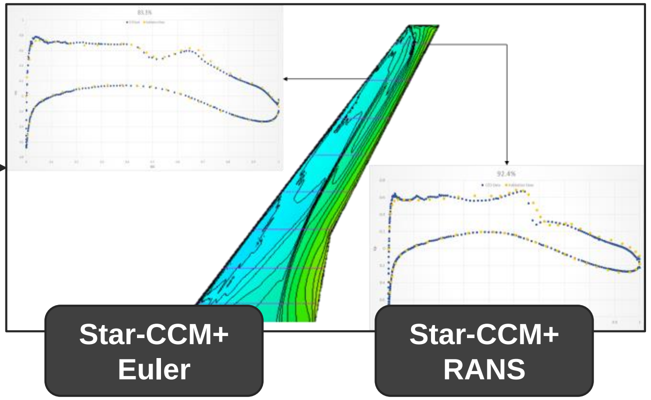
- Geometry
- Mesh

Model Base Classes

- 2-D Airfoil
- Panel Model
- 3-D CFD

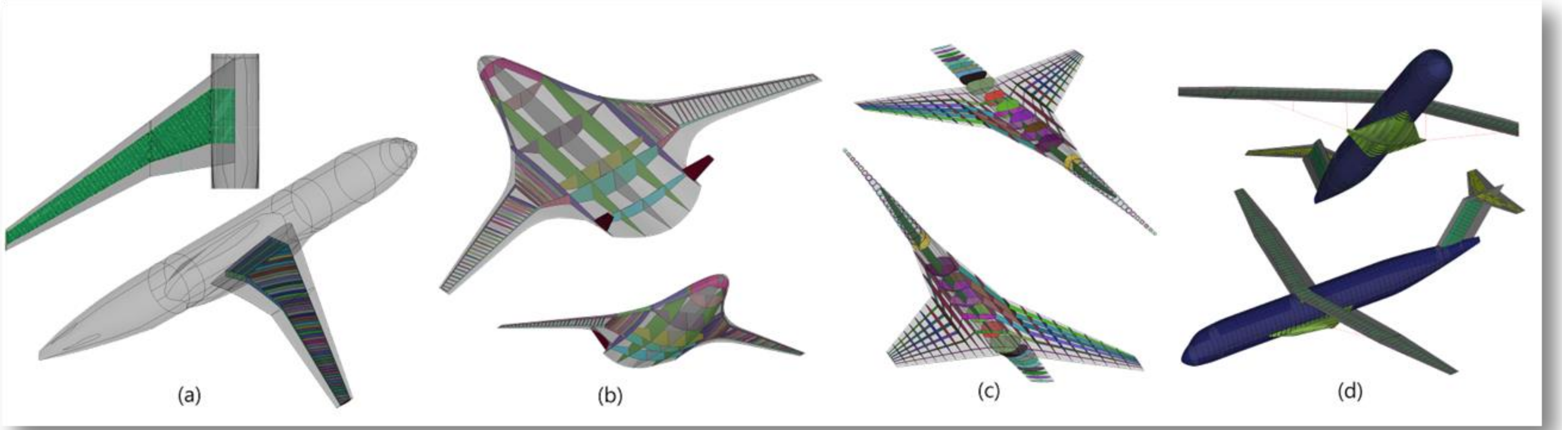




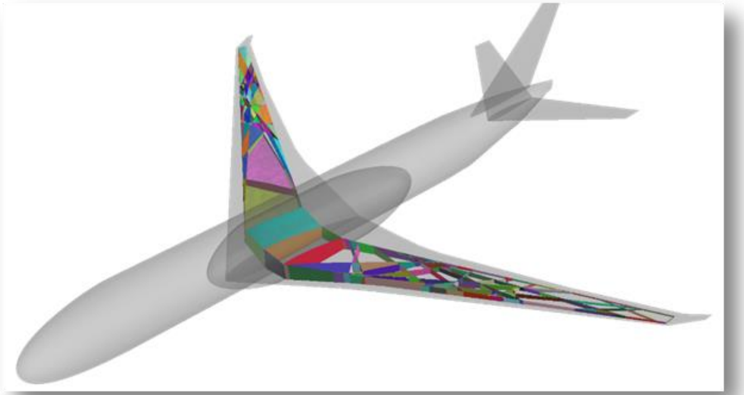


Modeling in RADE: Structural Geometry & Meshing

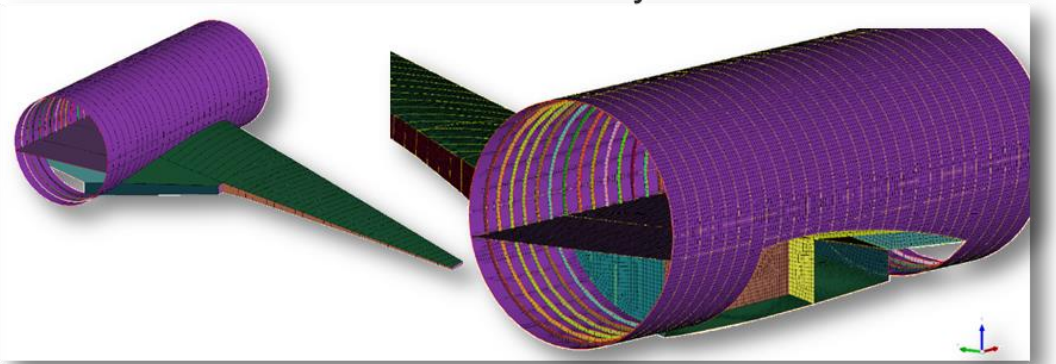
Flexible definition of OML (OpenVSP) and Structural Geometry (AFEM)



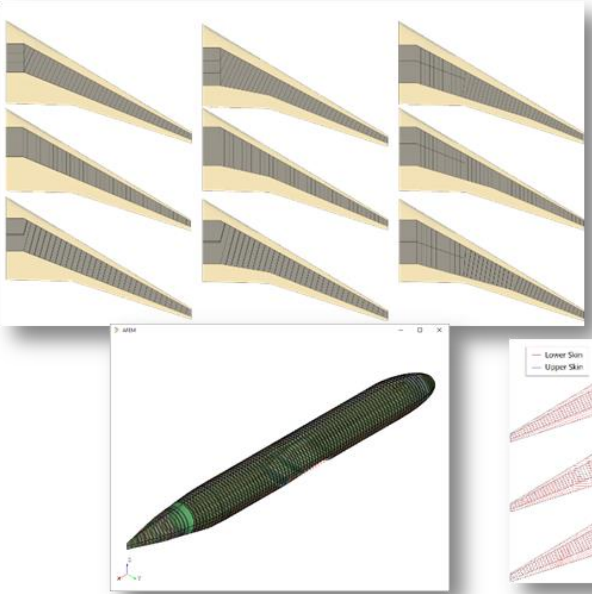
Robust skin panel identification



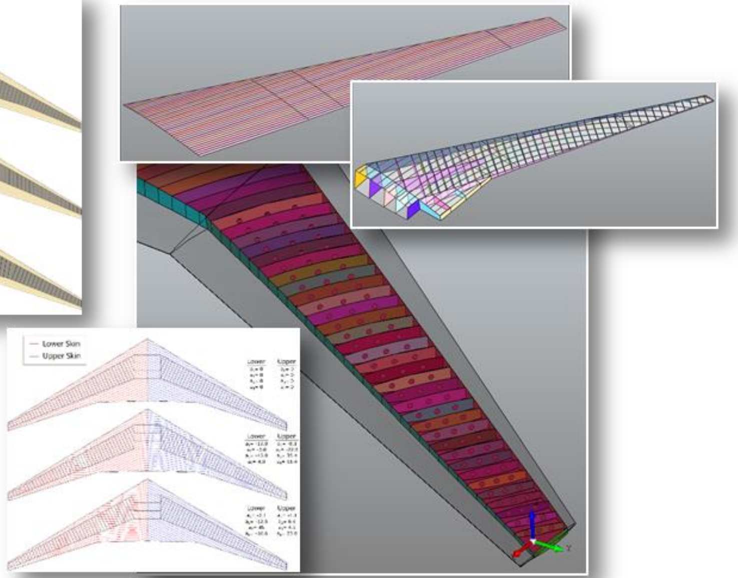
Robust join methods for congruency and mesh continuity



Default topologies for ease of use



Detailed feature definitions



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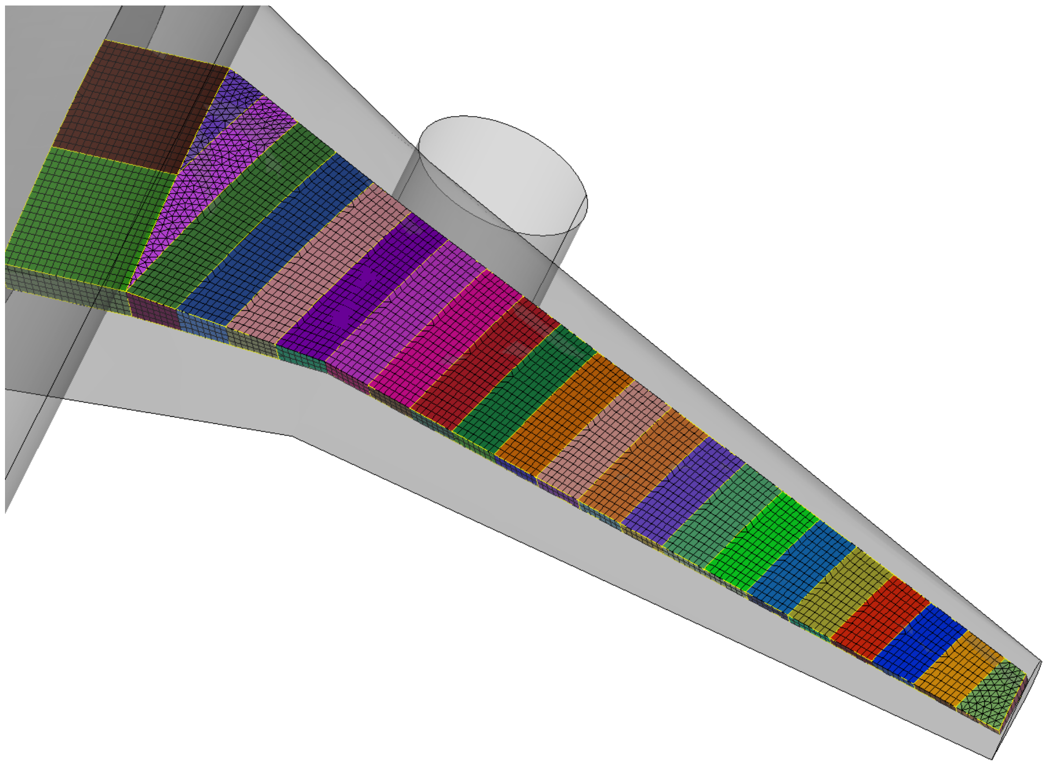


Model Representation Options

Complexity, Order, & Dimensionality (Fidelity)

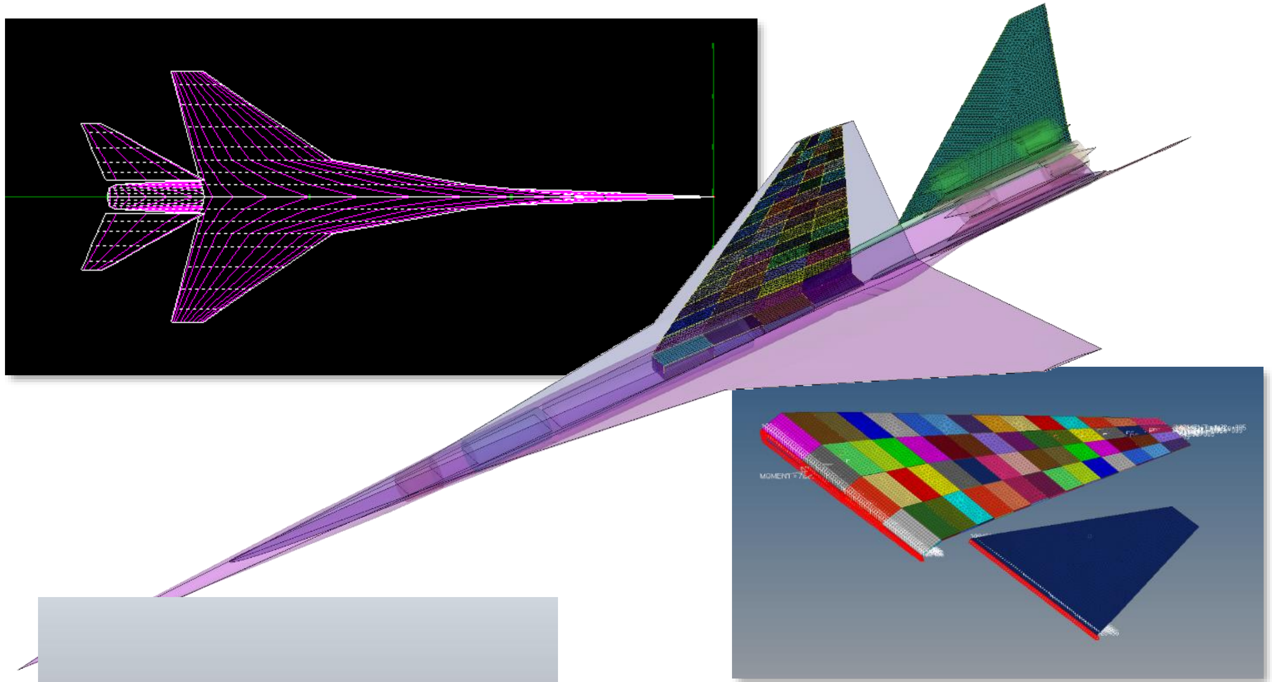
Increasing Fidelity

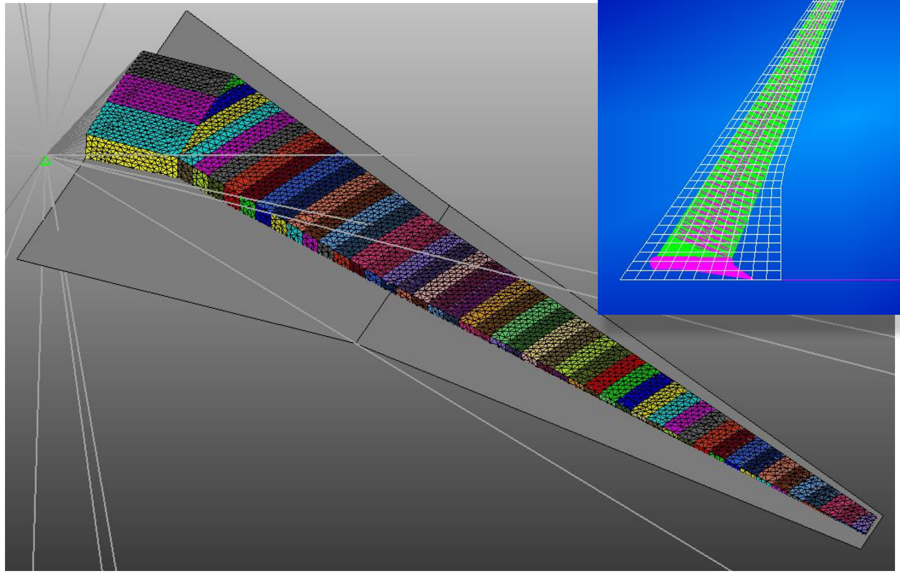
- Shell of spanwise variant sectional parameters
- Shell of constant spanwise variant thickness
- Shell of constant component thickness
- Guyan Reduced Stiffness Matrix
- Beam of spanwise variant EI, GJ
- Beam of constant EI, GJ

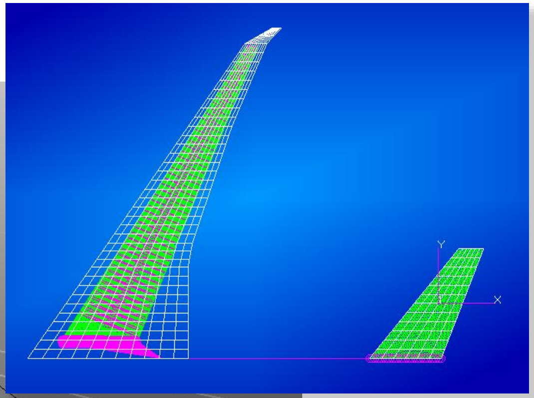
Discretizations

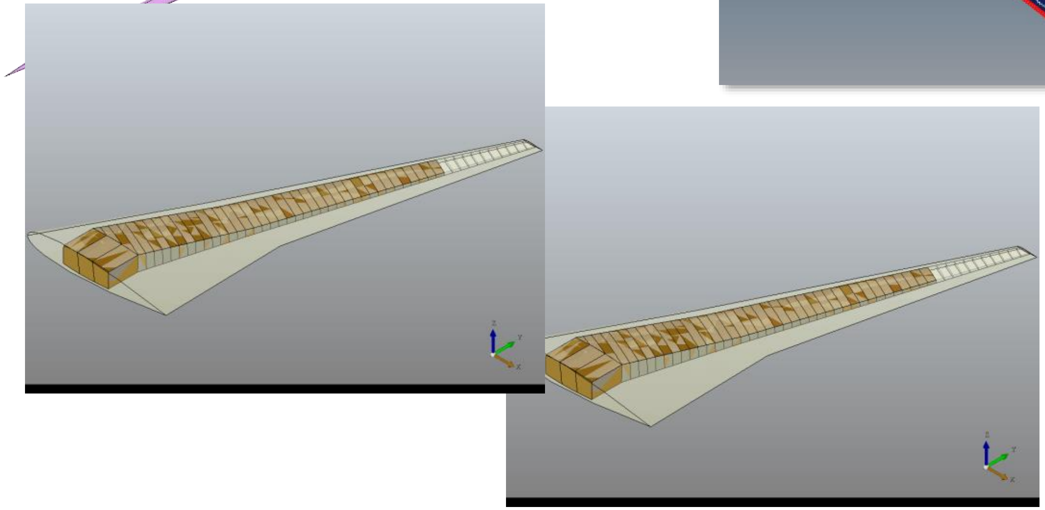
Modeling in RADE: Mass & Loads

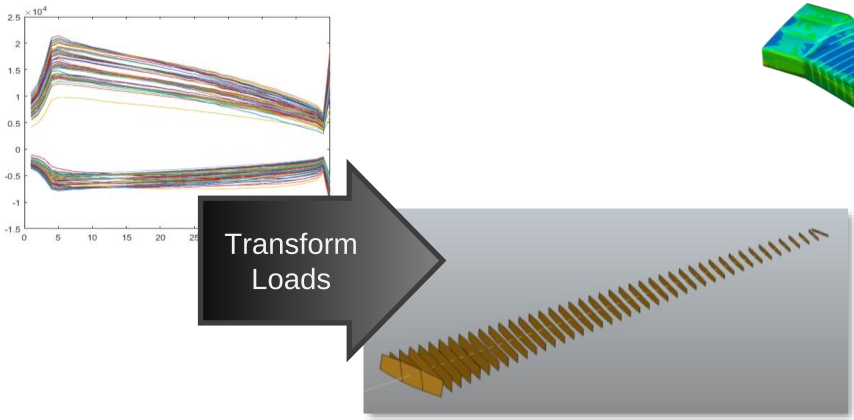
Seamless, geometry-centric integration of disciplinary toolsets

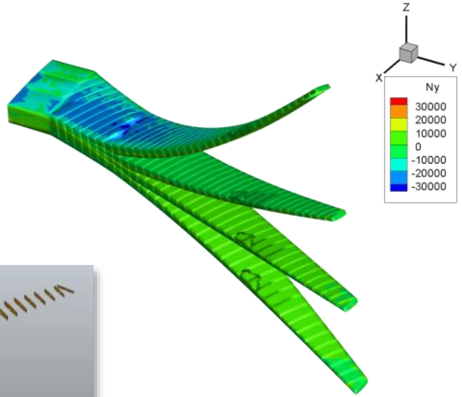












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- Some of the latest work in RADE (and most relevant to this project) is with dynamic loads and their effect on structural sizing
- A paper was published for AIAA SciTech 2020
- Goal:
  - Quantify the increment of structural mass added to the wing by considering dynamic gust cases in addition to typical early-phase static maneuver loads

Structural Sizing of Unconventional Aircraft under Static and Dynamic Aeroelastic Loading

David Solano*, Darshan Sarojini†, Jason Corman‡, and Dimitri Mavris§
Georgia Institute of Technology, Atlanta, GA, 30363 Code

A framework was created to size an airframe structure of interest with both static and dynamic loading conditions, allowing the designer to take into account dynamics early in the design process. For that, two important tools, the Rapid Airframe Design Environment (RADE), and NASRAN are used. The framework allows the sizing of conventional aircraft, like the NASA Common Research Model Aircraft, and unconventional, such as a thruss-braced wing, put forward by Boeing and NASA. In the paper, static aeroelastic loads such as 2.5 and -1 G maneuvers and dynamic aeroelastic loads, such as sharp or One-Minus cosine gust are tested and contrasted. Finally, sizing of the wing is performed using HyperSizer.

I. Introduction

A. Next generation aircraft targets

Modern and future aircraft are continuously becoming lighter and more efficient. Metrics such as decreased fuel burn, noise, NOx emissions, and takeoff field length are priority for the aircraft of the future. Thus, to push the envelope, aircraft designers are attempting new designs, such as the new N+3 concepts NASA is creating, which involve blended wing body configurations and double-bubble configurations [1]. Other designs include the Boeing's Transonic Truss-Braced Wing (TBW) [2], composite very high aspect ratio wings, box wings, and other innovative designs that will be possible thanks to advances in material technologies. On the lower speed side, designs such as the sailplane SB 13 from Akaflieg Braunshweig [3] and the AK-X prototype from Akaflieg Karlsruhe [4] are also plausible design alternatives. These new designs, however, experience dynamic loading conditions that are large enough to be relevant during sizing, and tools are needed to correctly assess such loads. These tools, however, are normally used at later stages of the design process, and by then critical decisions in terms of configuration and size may have been made, which translates in correcting efforts that are costly and time-consuming. On the other hand, through the use of the appropriate structural model, it is possible for the engineer to make detailed load and aerodynamic analysis such as the ones encountered during maneuvers, gusts, and flutter [5].

B. Structural Airworthiness

The Federal Aviation Administration (FAA) sets Federal Aviation Regulations (FARs) to place requirements on aircraft design, including structural design, to achieve a desired level of safety and reliability for all certified aircraft. These regulations are intended to account for the worst-case loads to occur in flight [6, 7].

Dynamic load conditions, in particular, often result in the most critical or constraining loads being developed on the structure, and may lead to catastrophic structural failures if unforeseen. A case in point is the loss of American Airlines Flight 587 (an Airbus A300B4 aircraft) due to structural failure of the vertical tail, when the first officer's rapid, and aggressive rudder inputs in response to a wake turbulence encounter resulted in dynamic loads that exceeded the ultimate loads that the tail had been designed for. Thus dynamic load conditions must be thoroughly accounted for during structural design and tested for during the certification process [8–10]. Given the monetary cost and time requirements associated with certification programs, a capability that allows dynamic loads arising from constraining maneuver scenarios to be better predicted earlier in the design process is a definite advantage for the aircraft manufacturer. Such a simulation framework would provide a tool for determining the loads that develop during these maneuvers for a given design, thus enabling better decisions in the design of safe and reliable structures in the aircraft design process.

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§Professor, Aerospace Systems Design Lab, Dept. of Aerospace Engineering, AIAA Fellow

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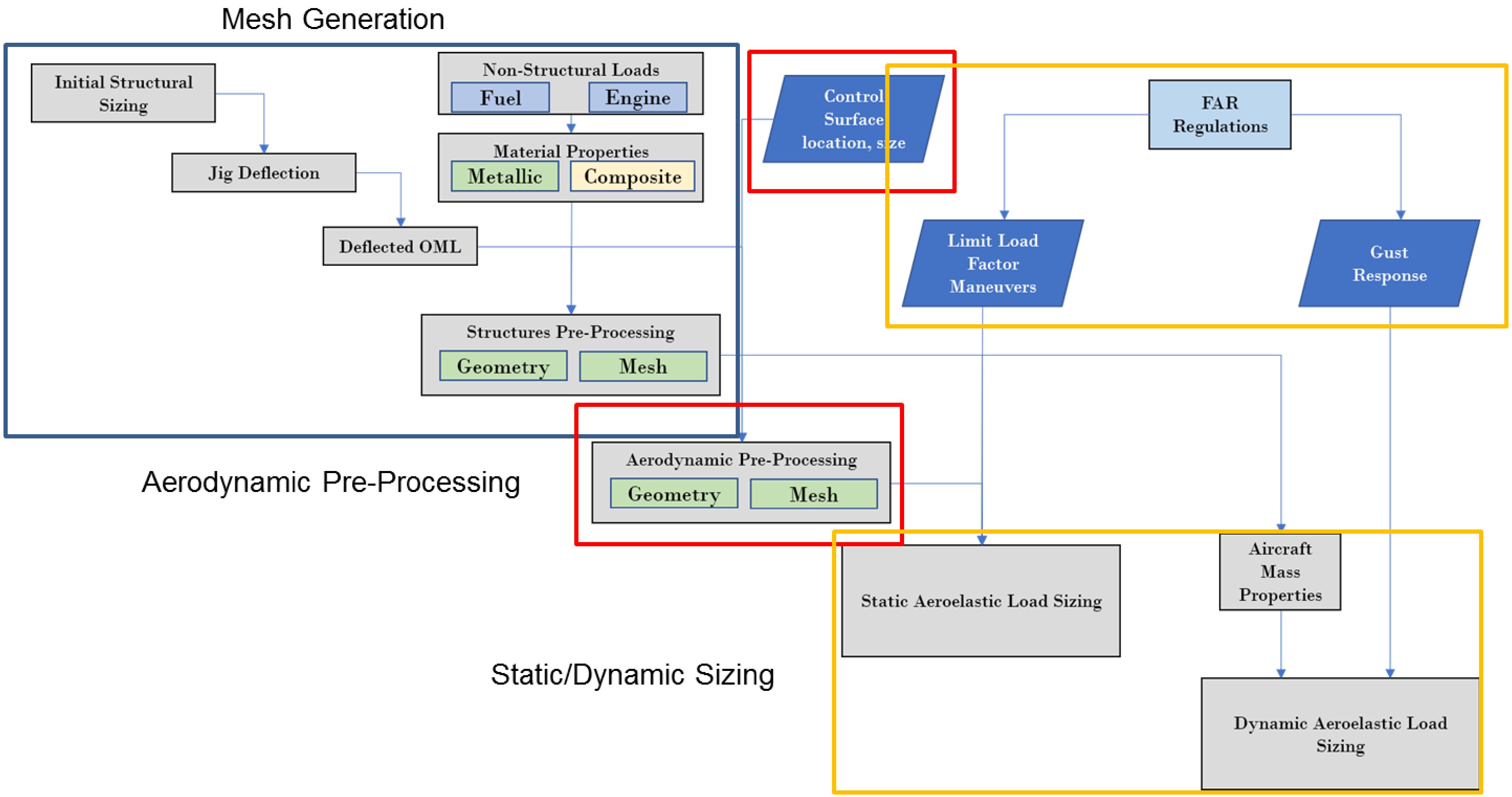
Modeling in RADE: Mass & Loads



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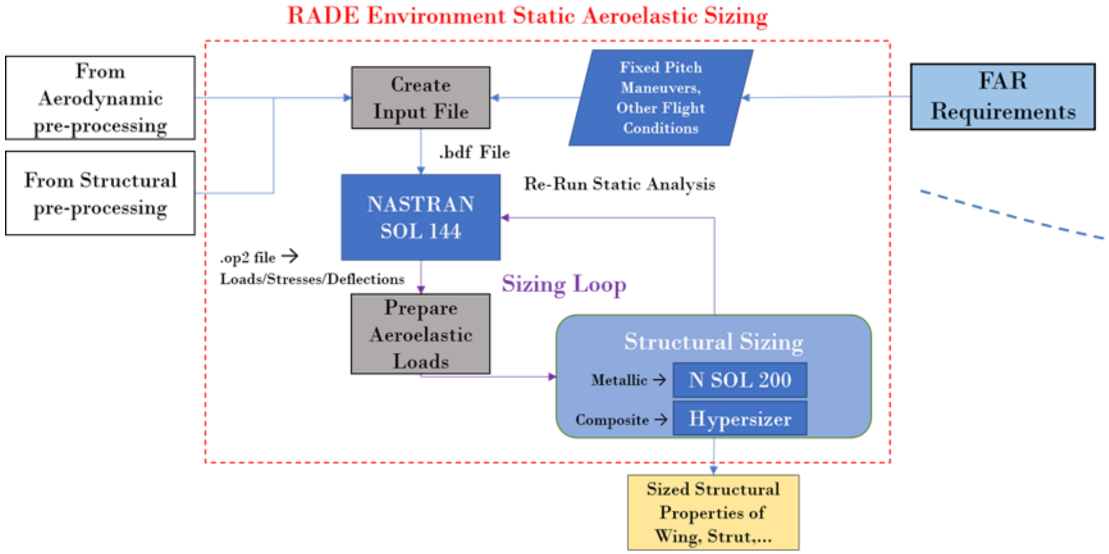
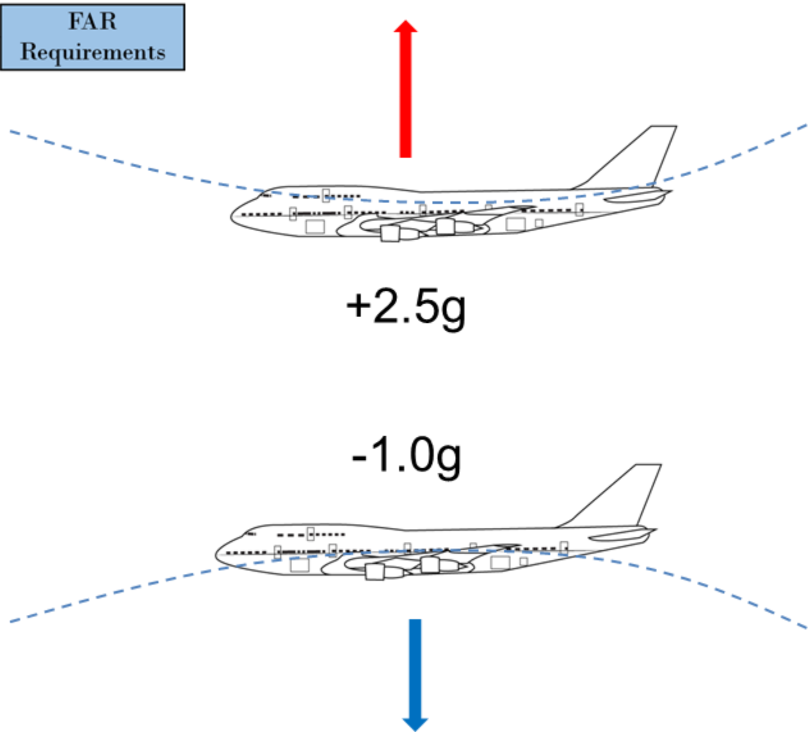
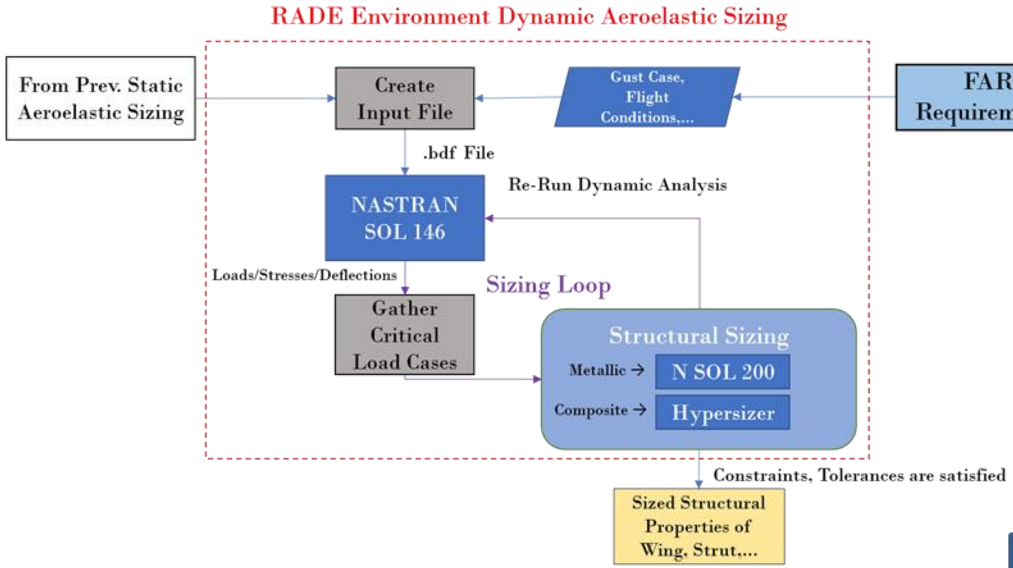
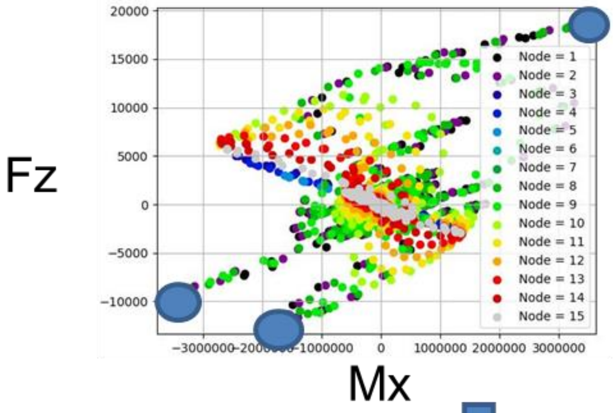

RADE Environment Static Aeroelastic Sizing
From Aerodynamic pre-processing
From Structural pre-processing
Create Input File
Fixed Pitch Maneuvers, Other Flight Conditions
FAR Requirements
.bdf File
NASTRAN SOL 144
Re-Run Static Analysis
.op2 file →
Loads/Stresses/Deflections
Sizing Loop
Prepare Aeroelastic Loads
Structural Sizing
Metallic →
N SOL 200
Composite →
Hypersizer
Sized Structural Properties of Wing, Strut,...


+2.5g
-1.0g

Modeling in RADE: Mass & Loads

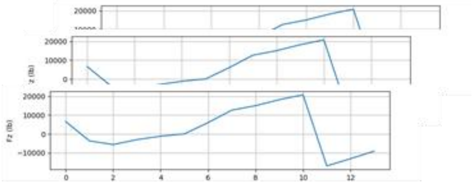


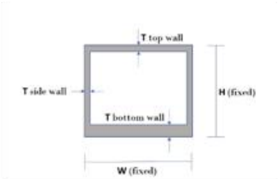


Load Case 1

Load Case 2

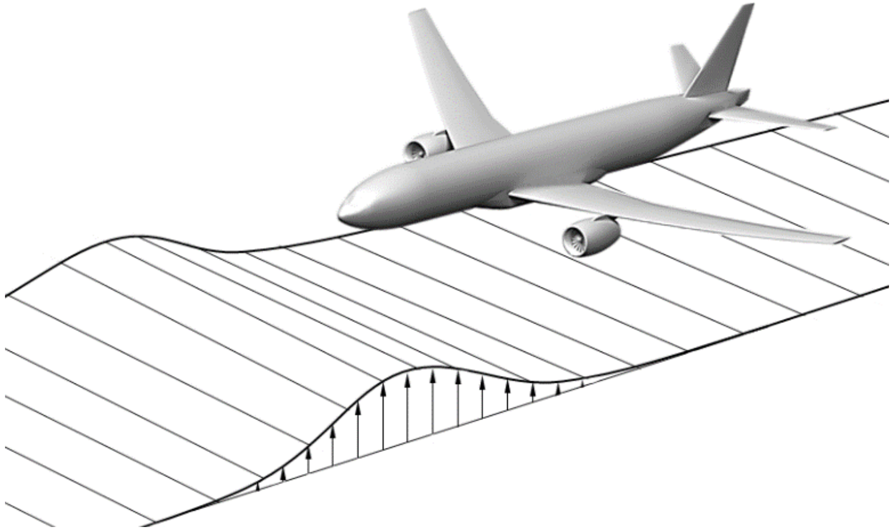
Load Case 3

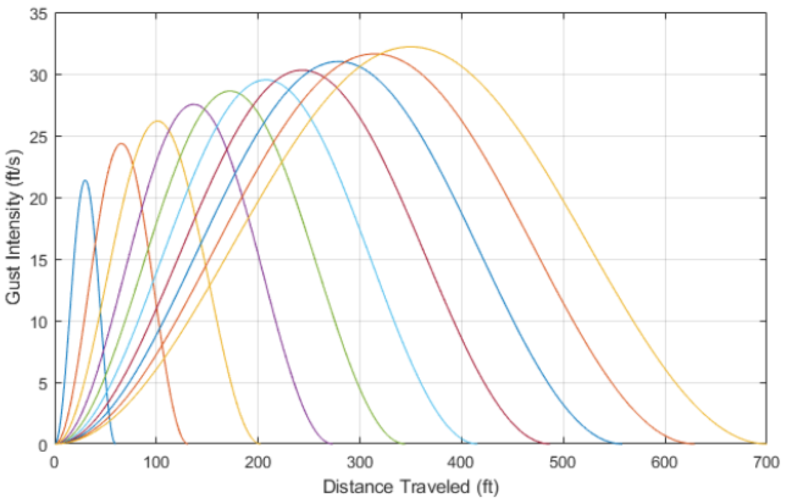




Optimize Structure for Loads

Modeling in RADE: Mass & Loads





$$U_{ds} = U_{ref} \cdot Fg \cdot (\frac{H}{350})^{\frac{1}{6}}$$

$$w_G = \frac{\bar{w_G}}{2} \cdot (1 - cos(2\pi \cdot ft))$$

- Total Simulation Time: 5s
- Method for Modal Analysis: Modified Givens
- Gust delay: 1s
- Modes: 10

Characteristic	Name
Total Sim Time	5s
Method Modal Analysis	Modified Givens
Gust Delay	1s
Modes	10

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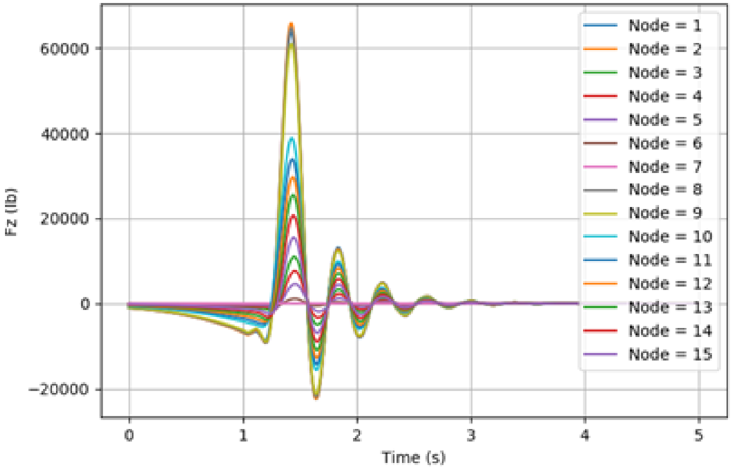
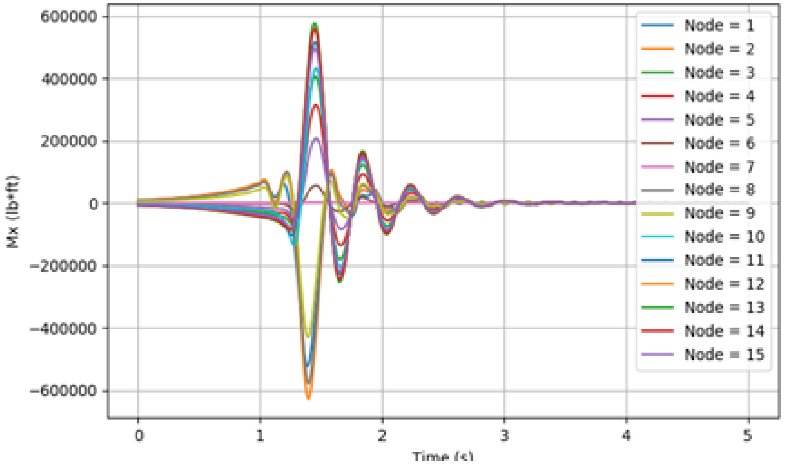
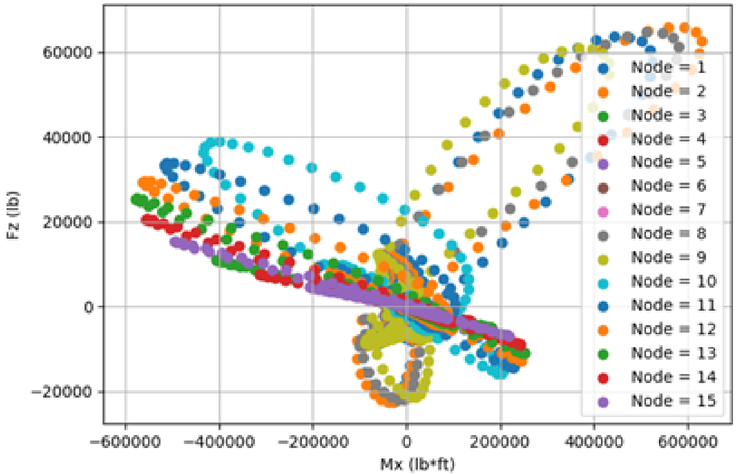
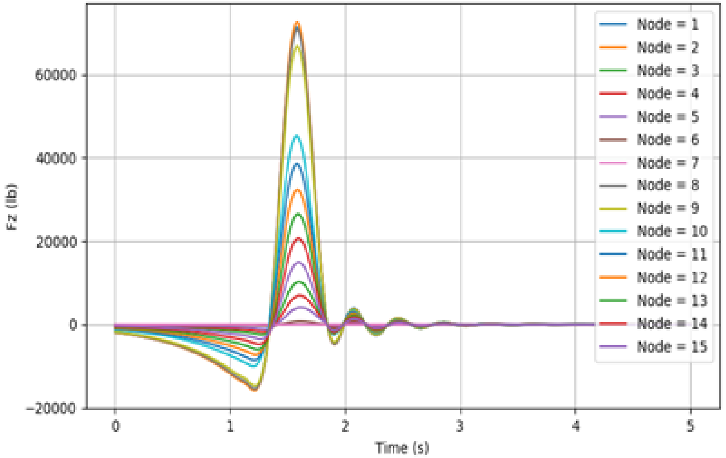
Modeling in RADE: Mass & Loads

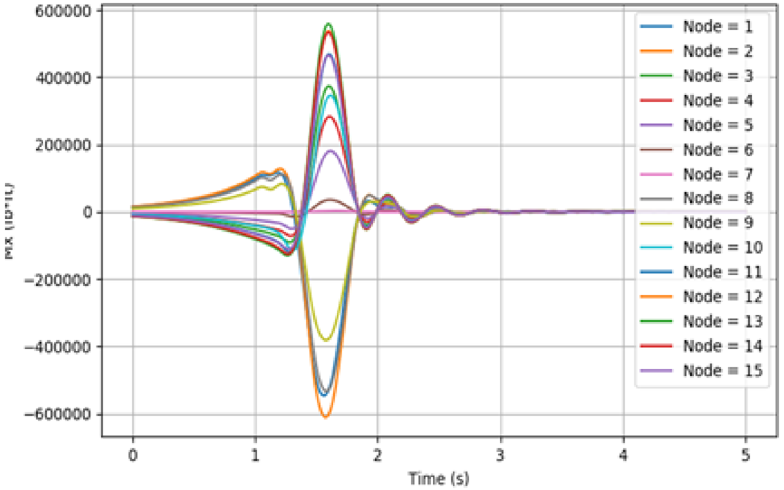
136 ft peak distance, peak speed 27.7 ft/s

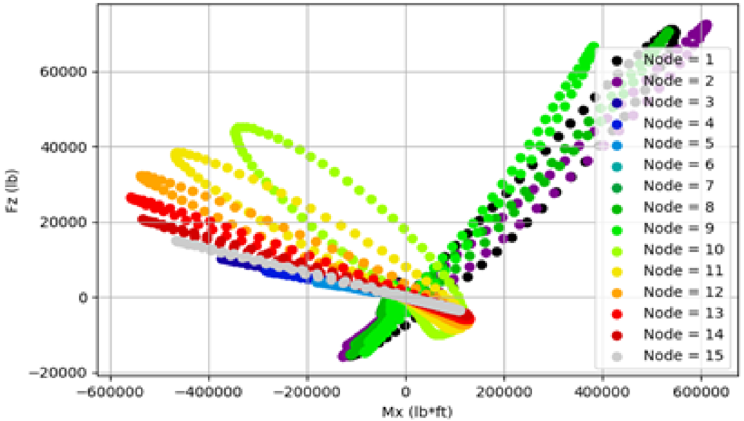












278 ft peak distance, peak speed 31.2 ft/s

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Modeling in RADE: Properties & Structural Sizing

- Materials: Isotropic, Orthotropic, Anisotropic, Composite

- Properties: Beam, Shell, Smeared Stiffness, Guyan Reduction

- Structural Sizing:
  - Nastran
    - Gradient-based optimization of isotropic materials
    - “Fully stressed” sizing
    - Limited number of built-in failure modes
    - *Offline gradient-based optimization currently under development*

  - HyperSizer
    - Grid search approach with custom bounding convergence
    - Optimization for all material types and granularity for skin & stiffener dimensions/materials
    - 30+ failure modes can be used for every type of beam and panel concept

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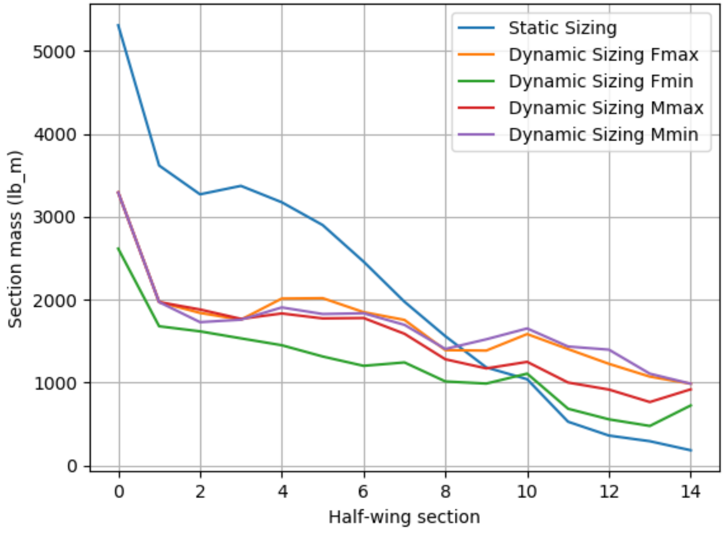
Modeling in RADE: Structural Sizing with Dynamic Loads

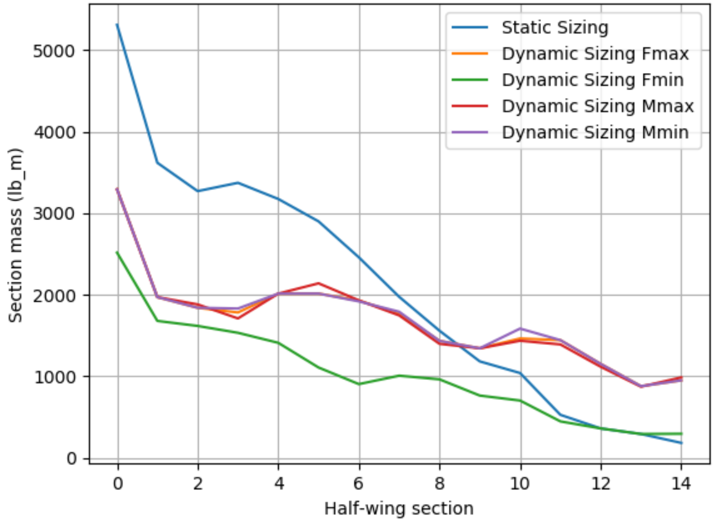
Structural Sizing Responses

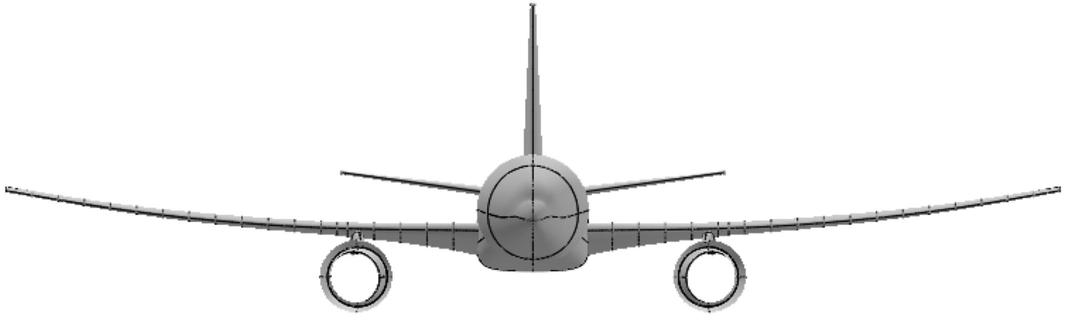
Optimizing the structure independently for each load case & time step selection criteria

136 ft peak distance
27.7 ft/s peak speed

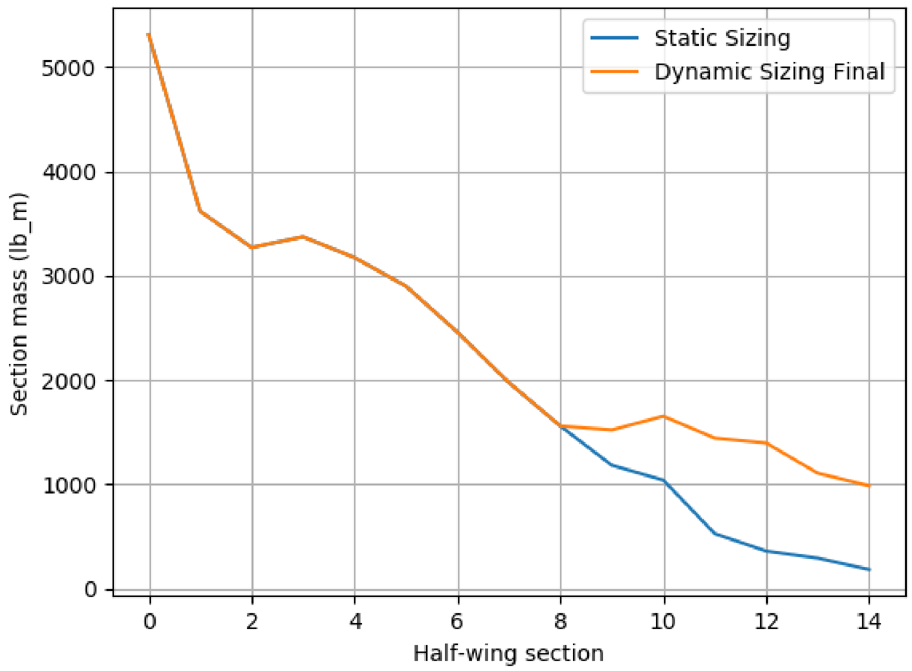


278 ft peak distance
31.2 ft/s peak speed

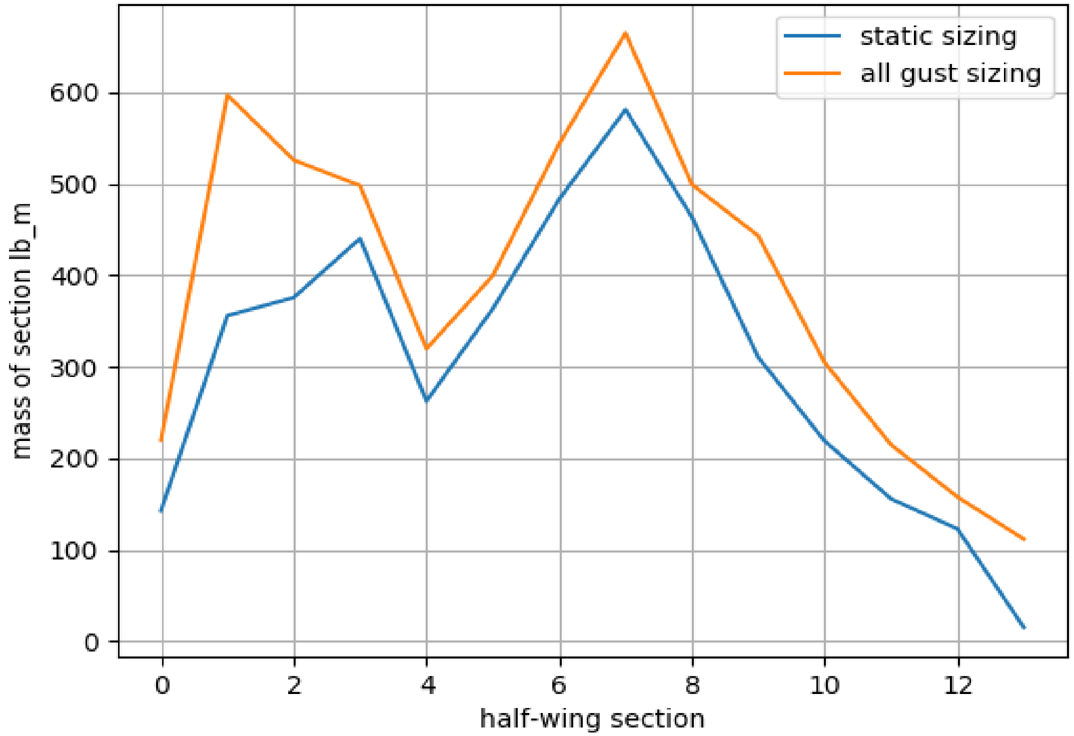




Considering All Load Cases in Constraints



Modeling in RADE: Structural Sizing with Dynamic Loads



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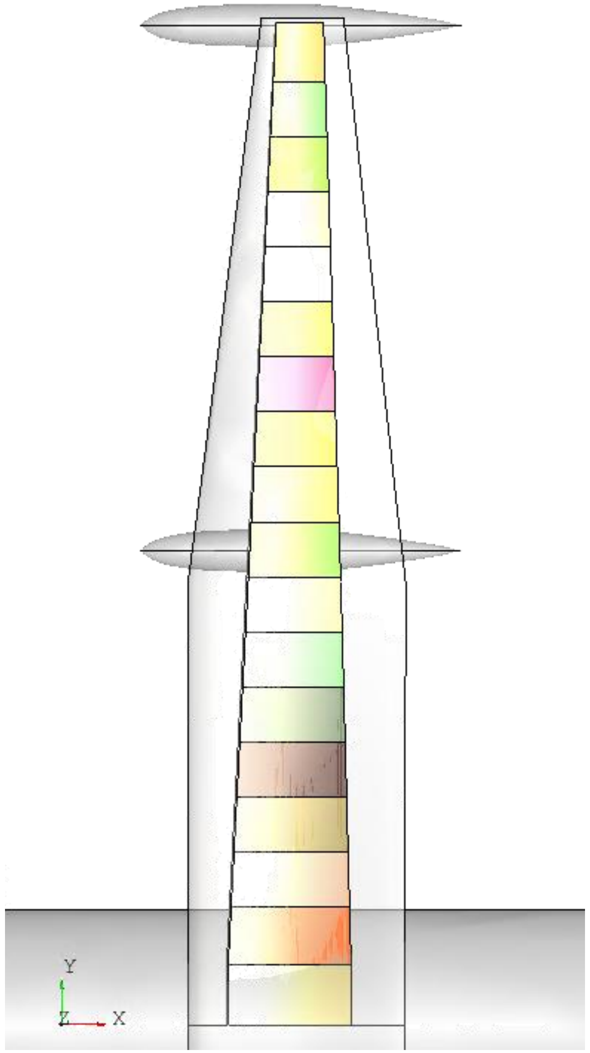
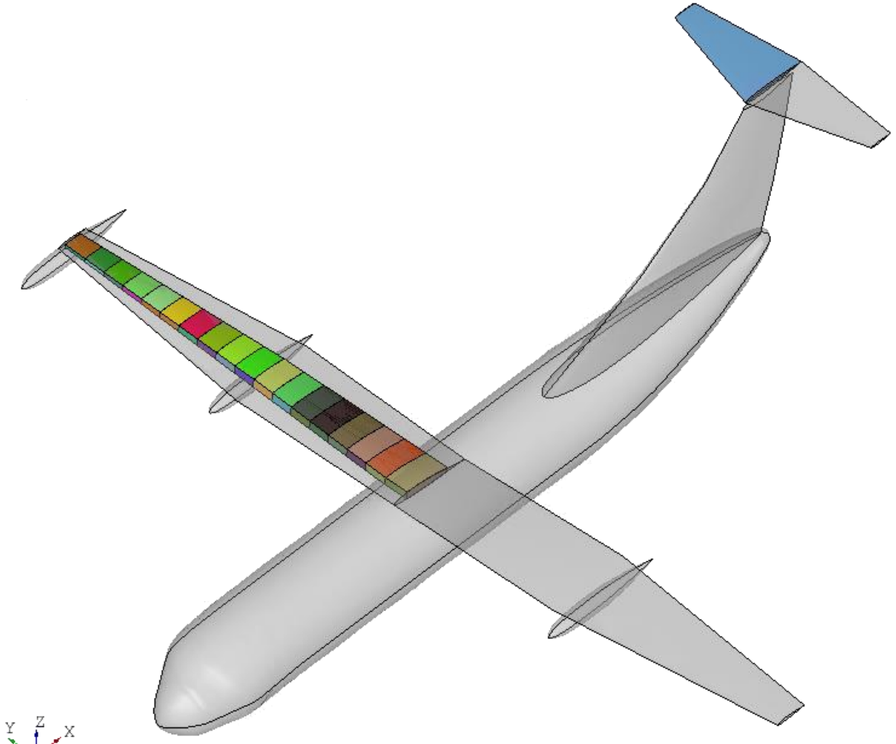
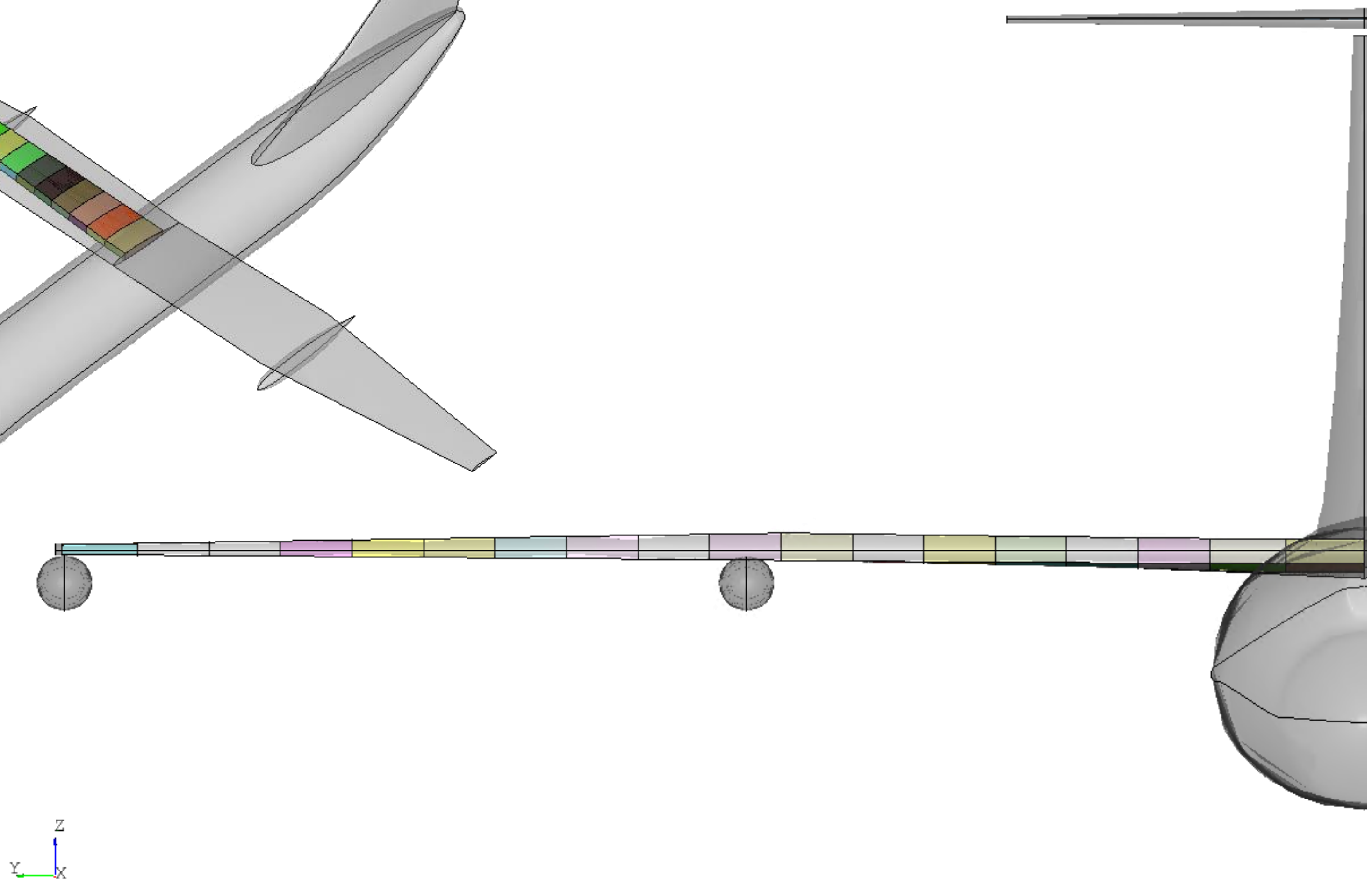
GT-ASDL PEGASUS Model in RADE: Structural Geometry

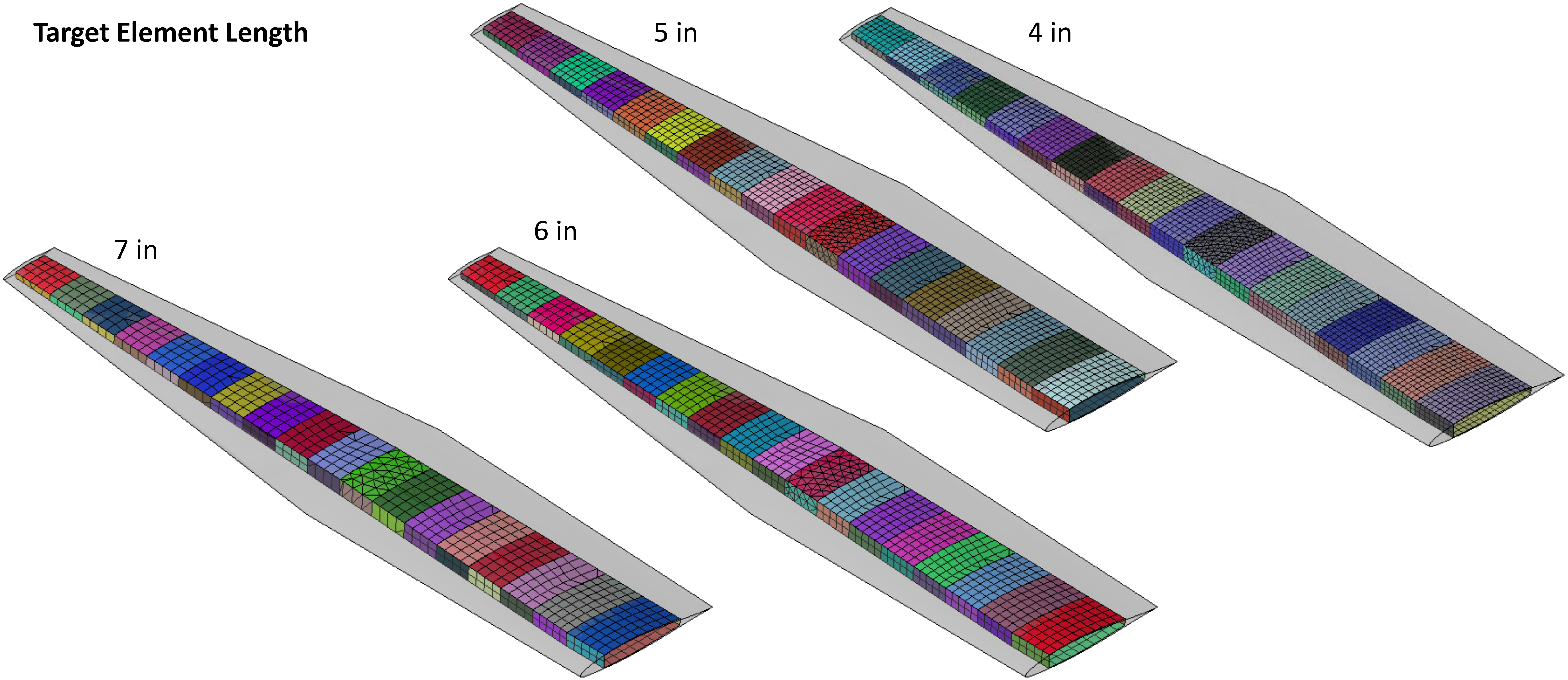




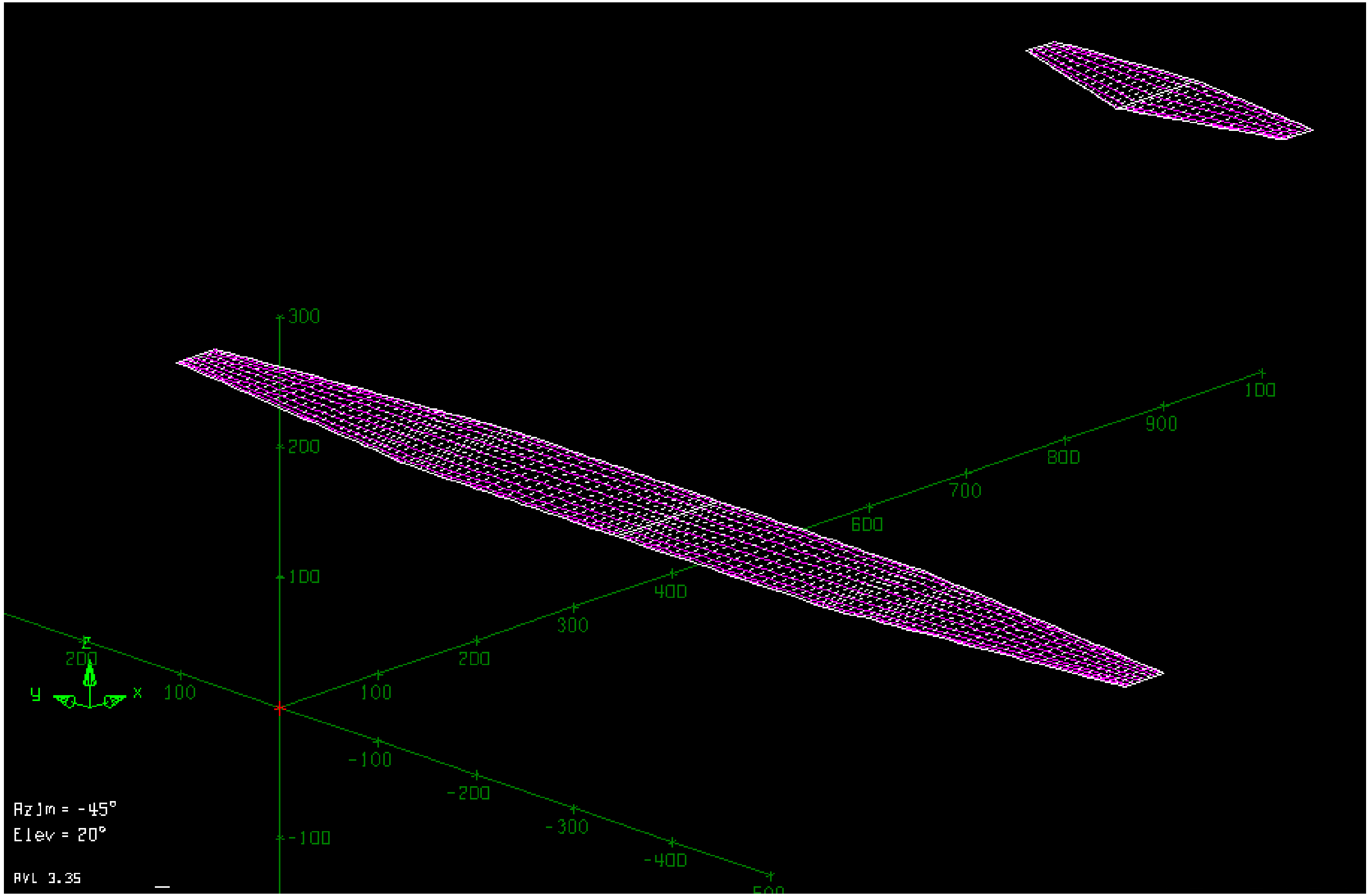


GT-ASDL PEGASUS Model in RADE: Structural Mesh

Target Element Length



GT-ASDL PEGASUS Model in RADE: AVL



Wing Elements:

Main Wing
Horizontal Tail

Control Surfaces:

Elevator

η= [0: 1]

c = [0.6: 1]

Load Cases (Default):

Mach = 0.5

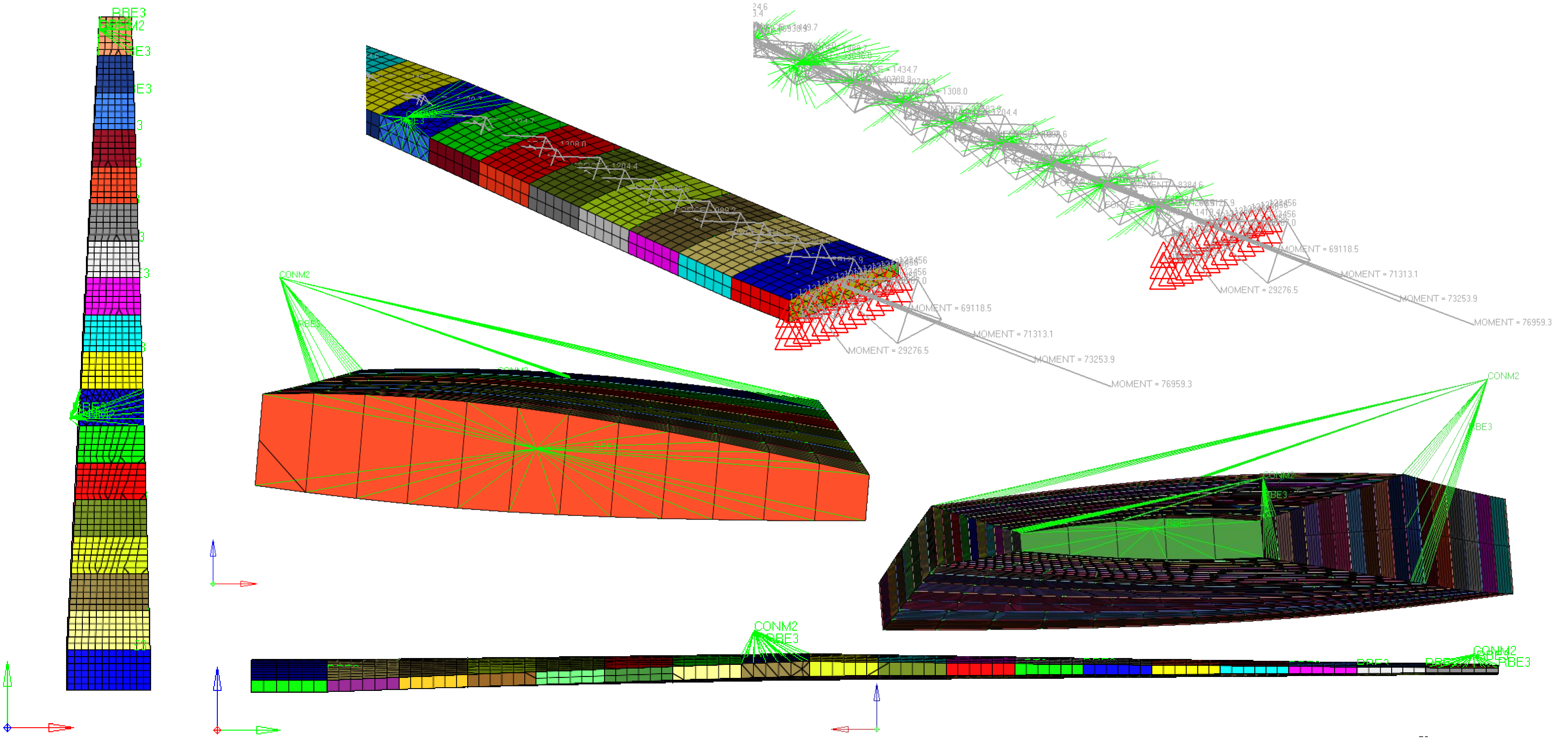
Altitude = 20,000 ft

Constraints:

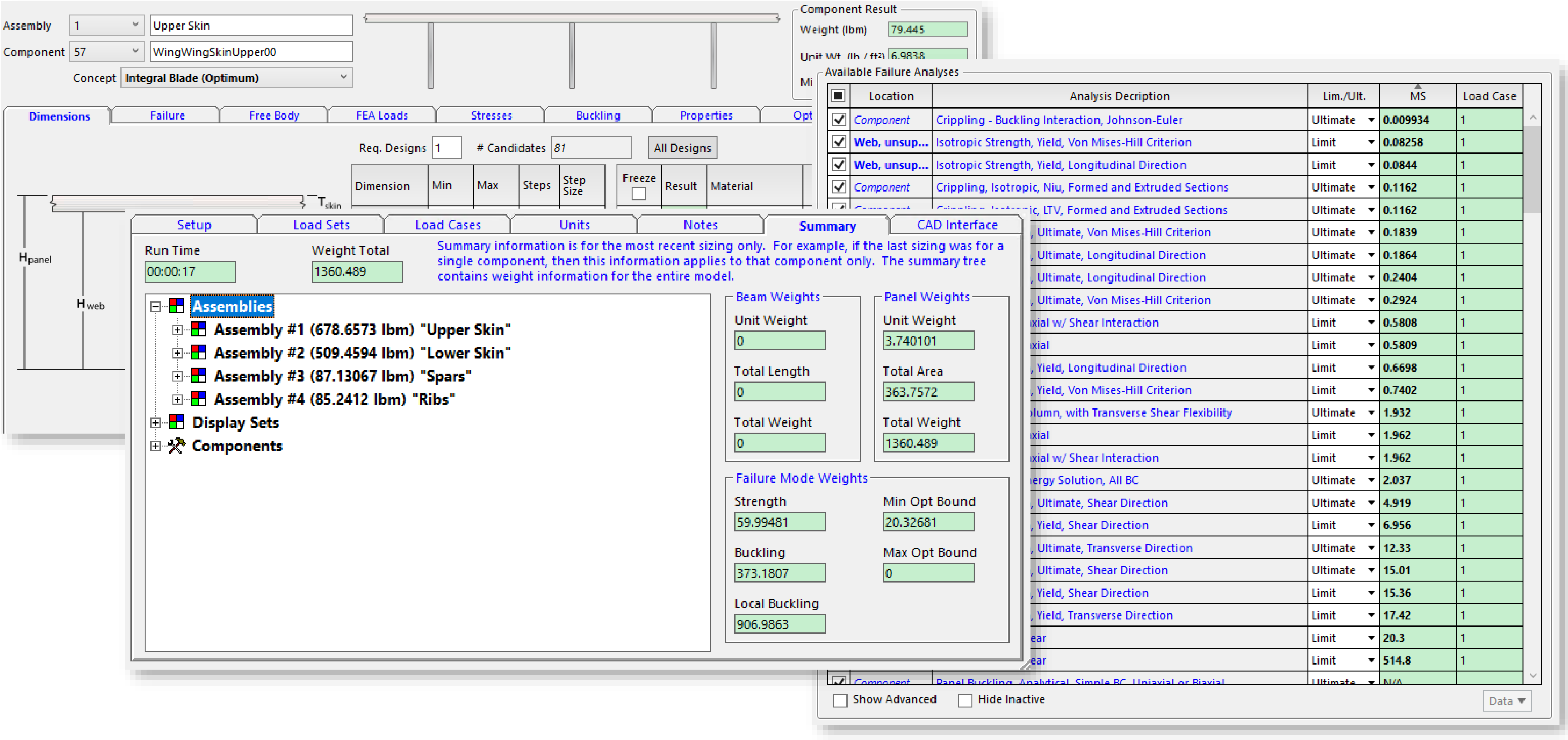
Load Factors = [-1.0, 2.5]

Pitch Moment = 0

GT-ASDL PEGASUS Model in RADE: Nastran

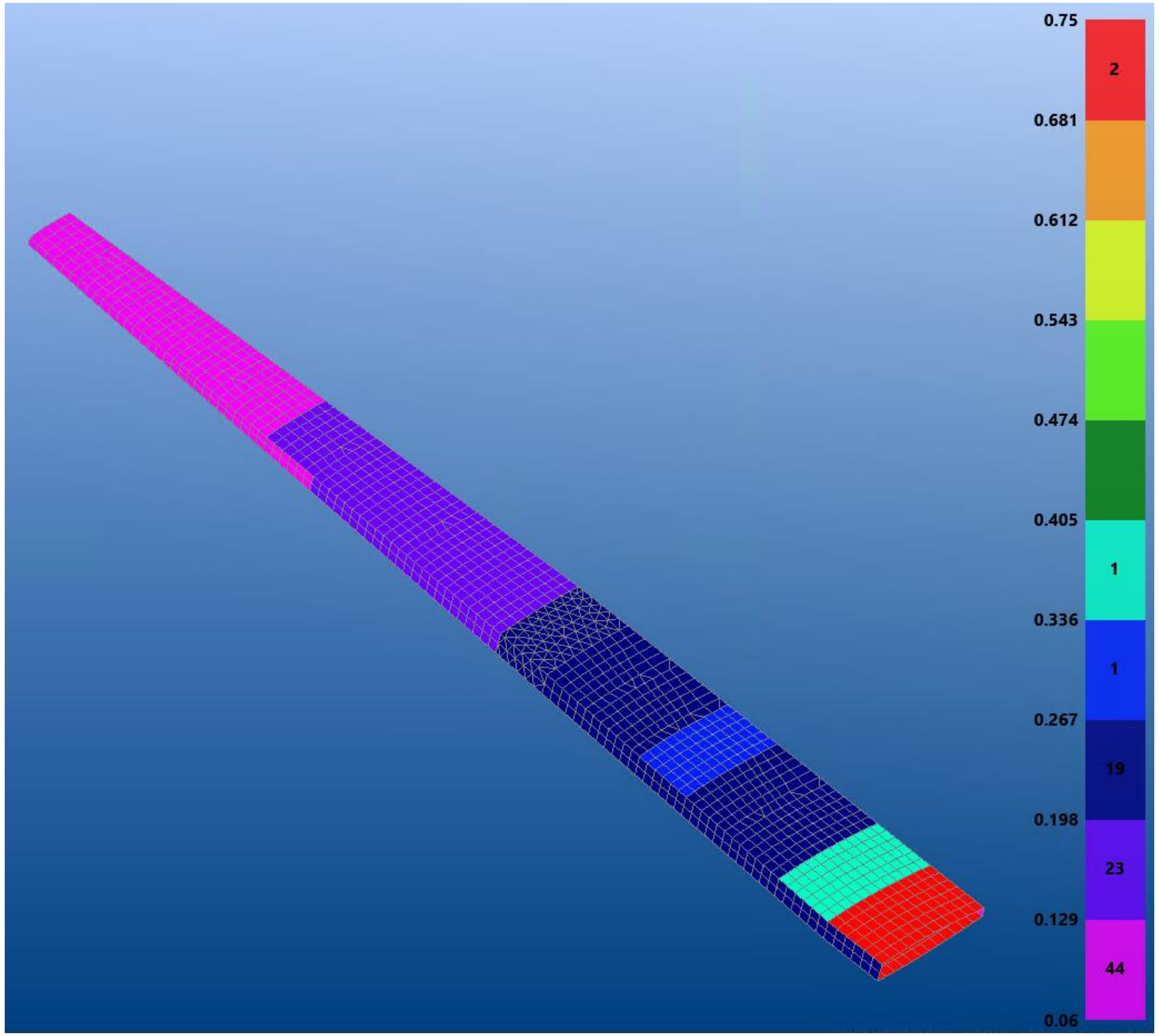


GT-ASDL PEGASUS Model in RADE: HyperSizer Setup

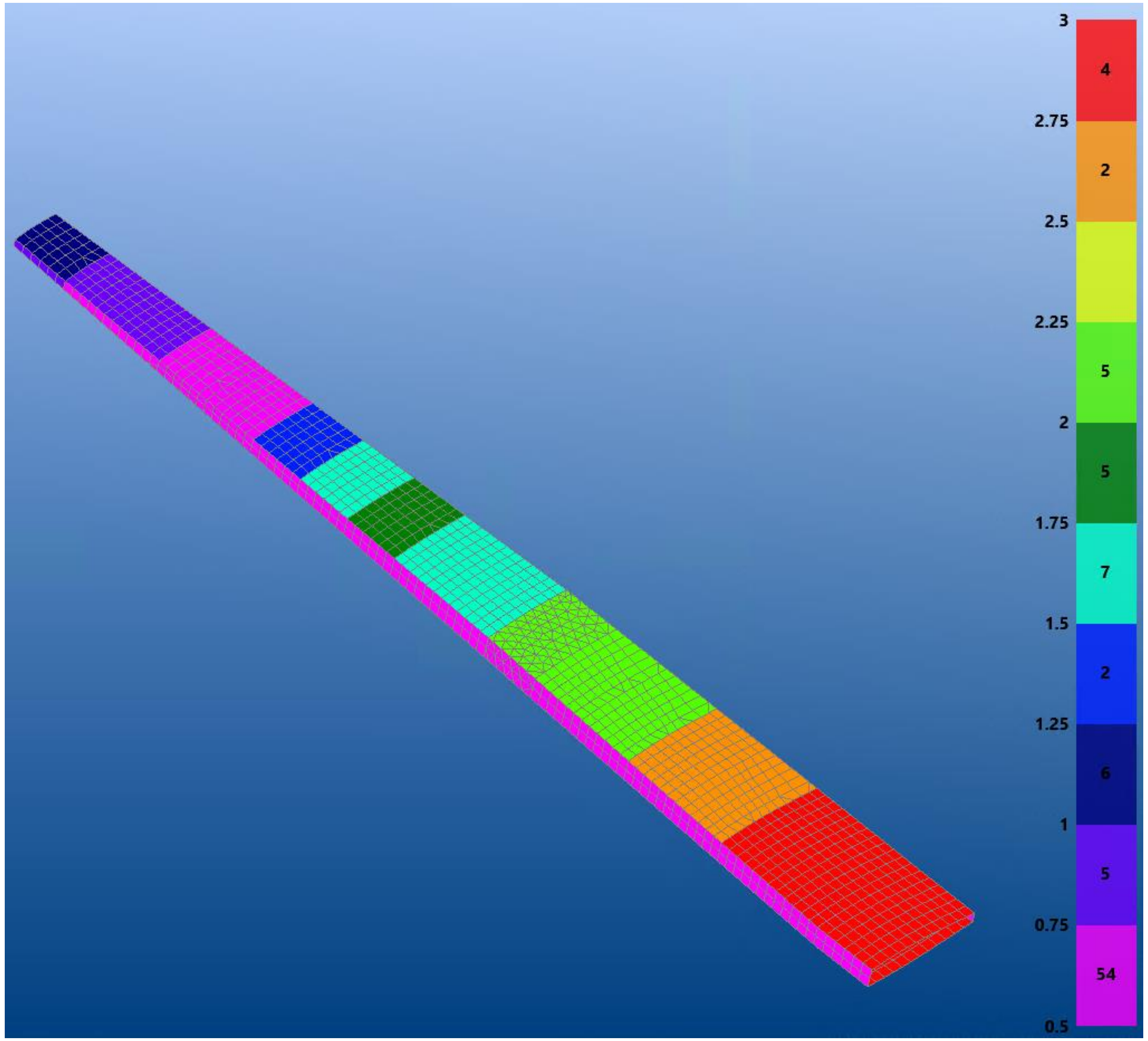


GT-ASDL PEGASUS Model in RADE: HyperSizer Results

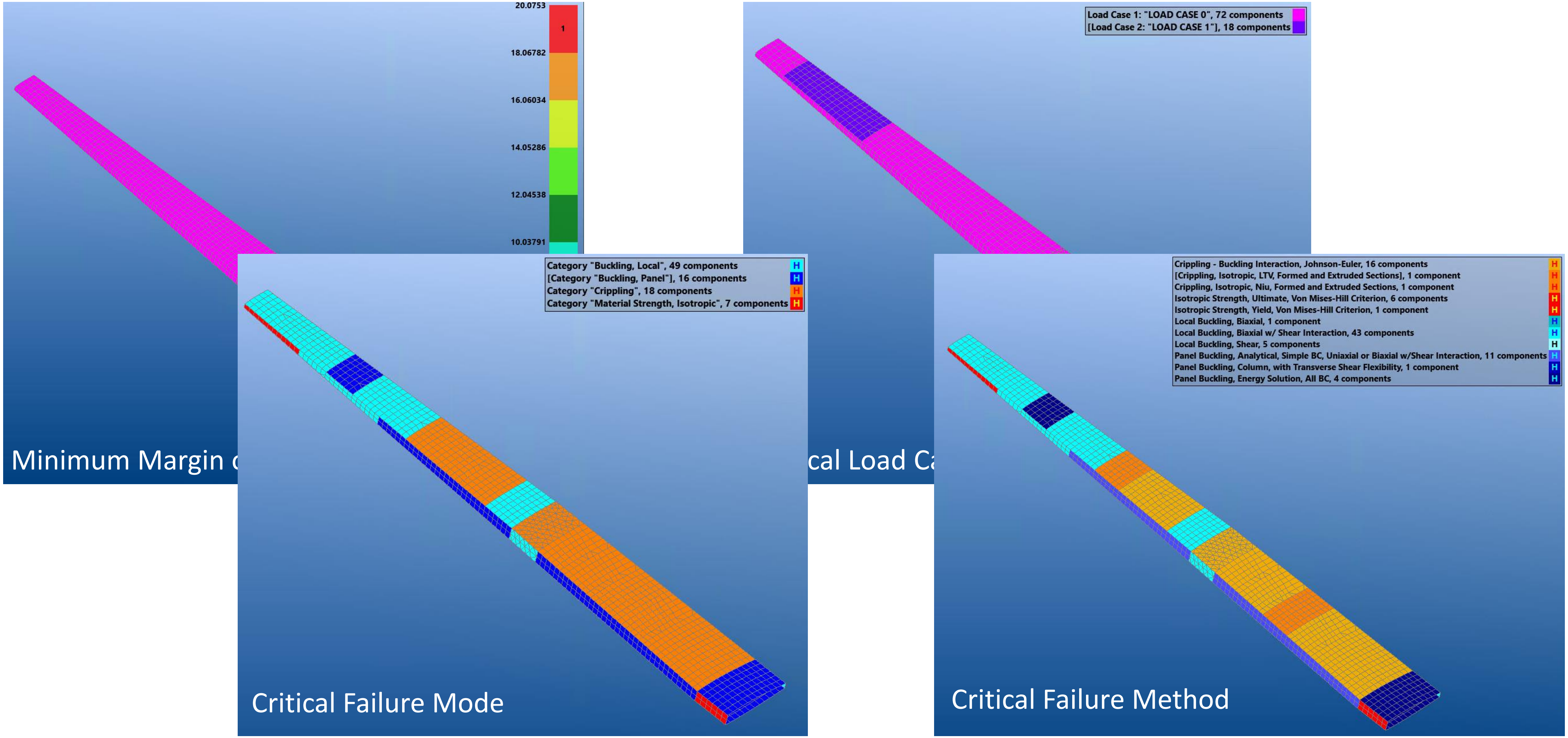
Skin Thickness



Stringer Web Height



GT-ASDL PEGASUS Model in RADE: HyperSizer Results



Tow-Steered Composites

Overview

Structural Weight Estimation

TSC Performance Estimation

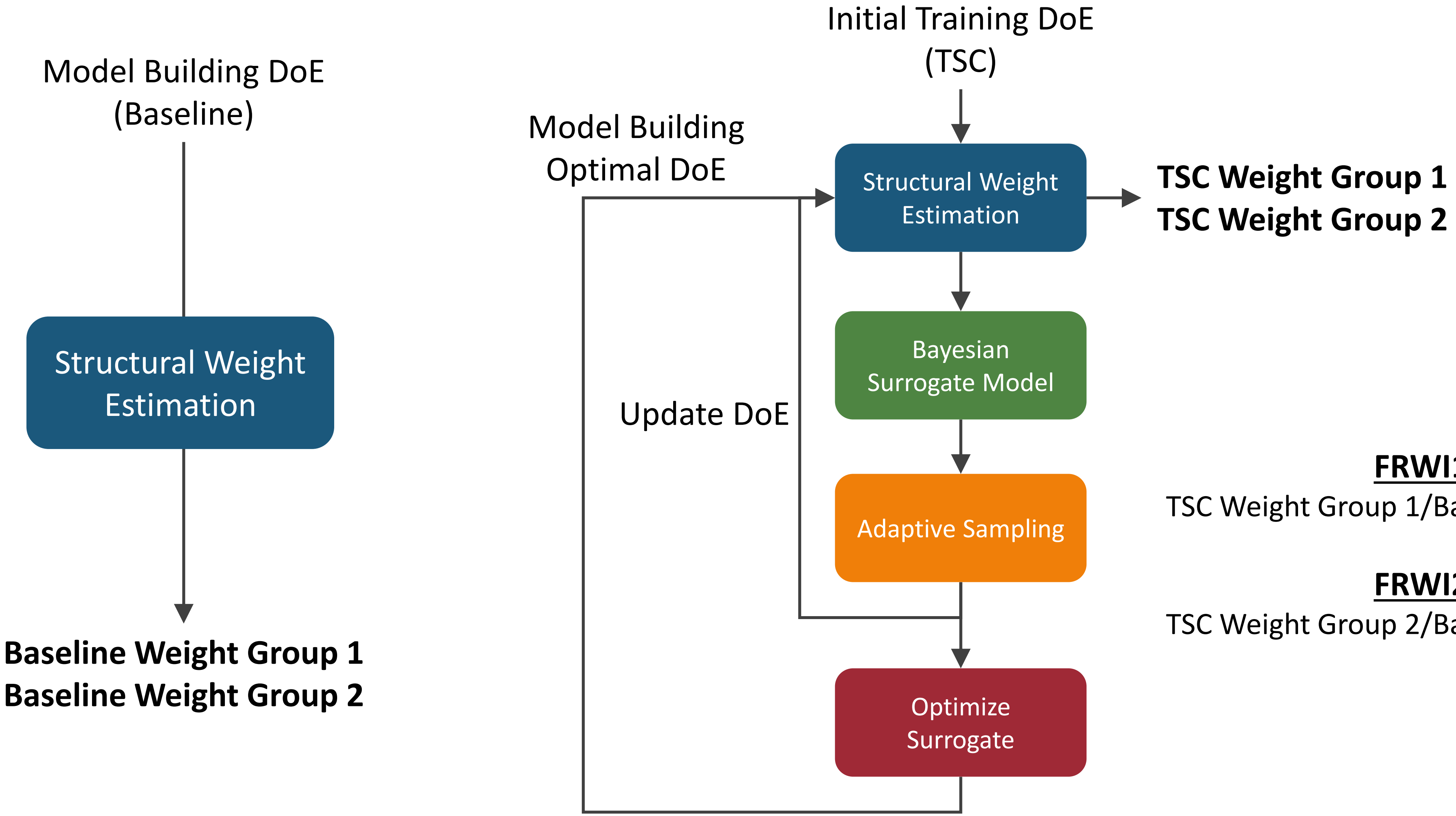
Value Assessment

Objectives for TSC Technology Performance Estimation

- Obtain TSC weight reduction performance as a function of Area (Wing Loading), Aspect Ratio design space to perform systems level trades: 150PAX TBW & 300PAX T&W
  - Structural Weight Estimation
  - Baseline & Technology Vehicles
  - Optimization of Tow-Steering w/in Area/AR Design Space

- Formulate breakdown of sources of uncertainty associated with implementation of TSC on production-phase aircraft
  - Enumeration of Sources of Uncertainty
  - Mapping to Technology Performance Estimation Process

Approach for Performance Estimation in Planform Design Space



FRWI1_TSC

TSC Weight Group 1/Baseline Weight Group 1

FRWI2_TSC

TSC Weight Group 2/Baseline Weight Group 1

Tow-Steered Composites

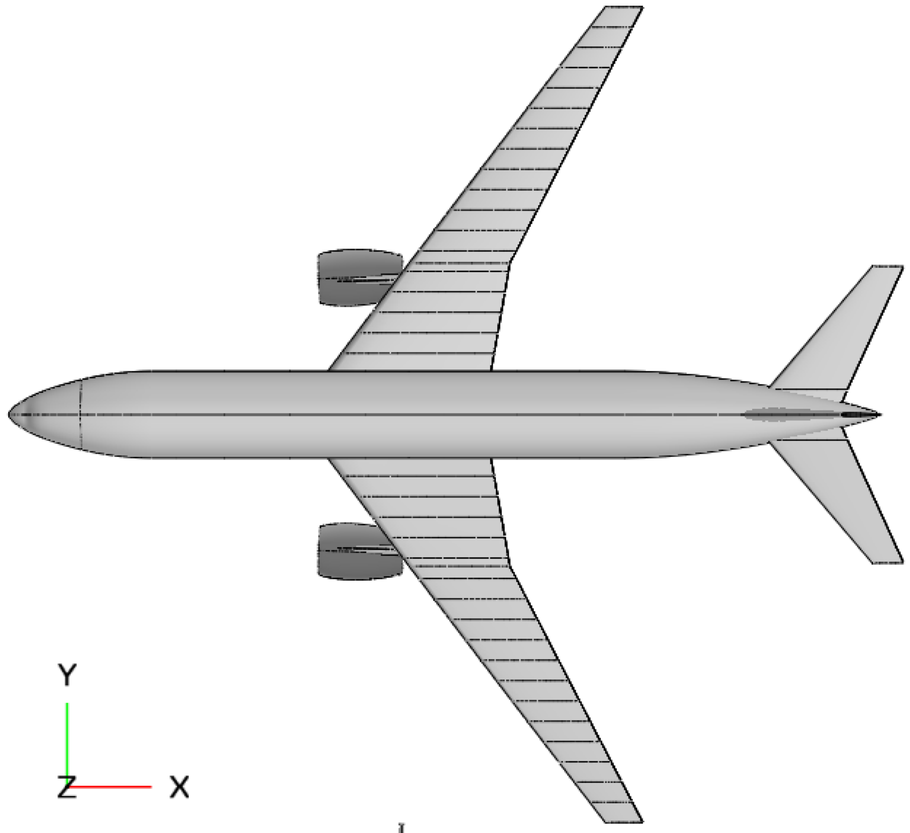
Overview

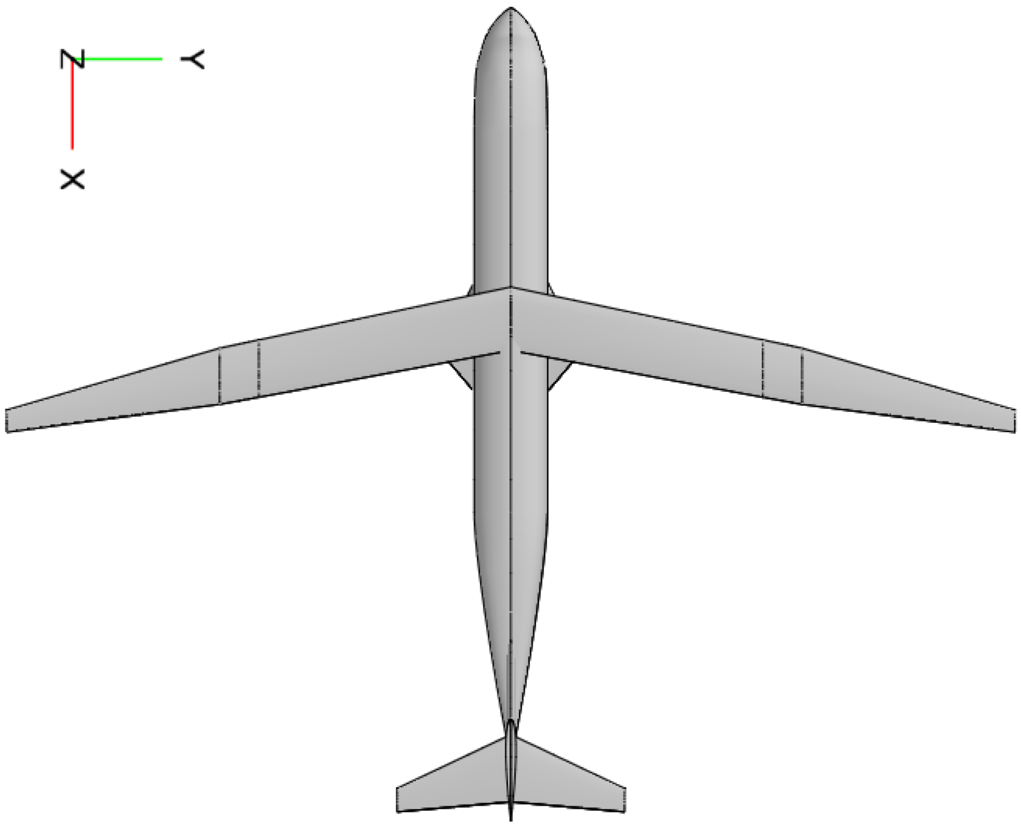
Structural Weight Estimation

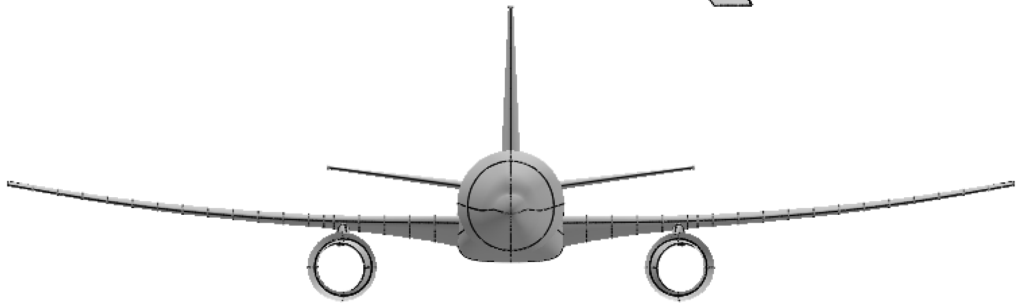
TSC Performance Estimation

Value Assessment

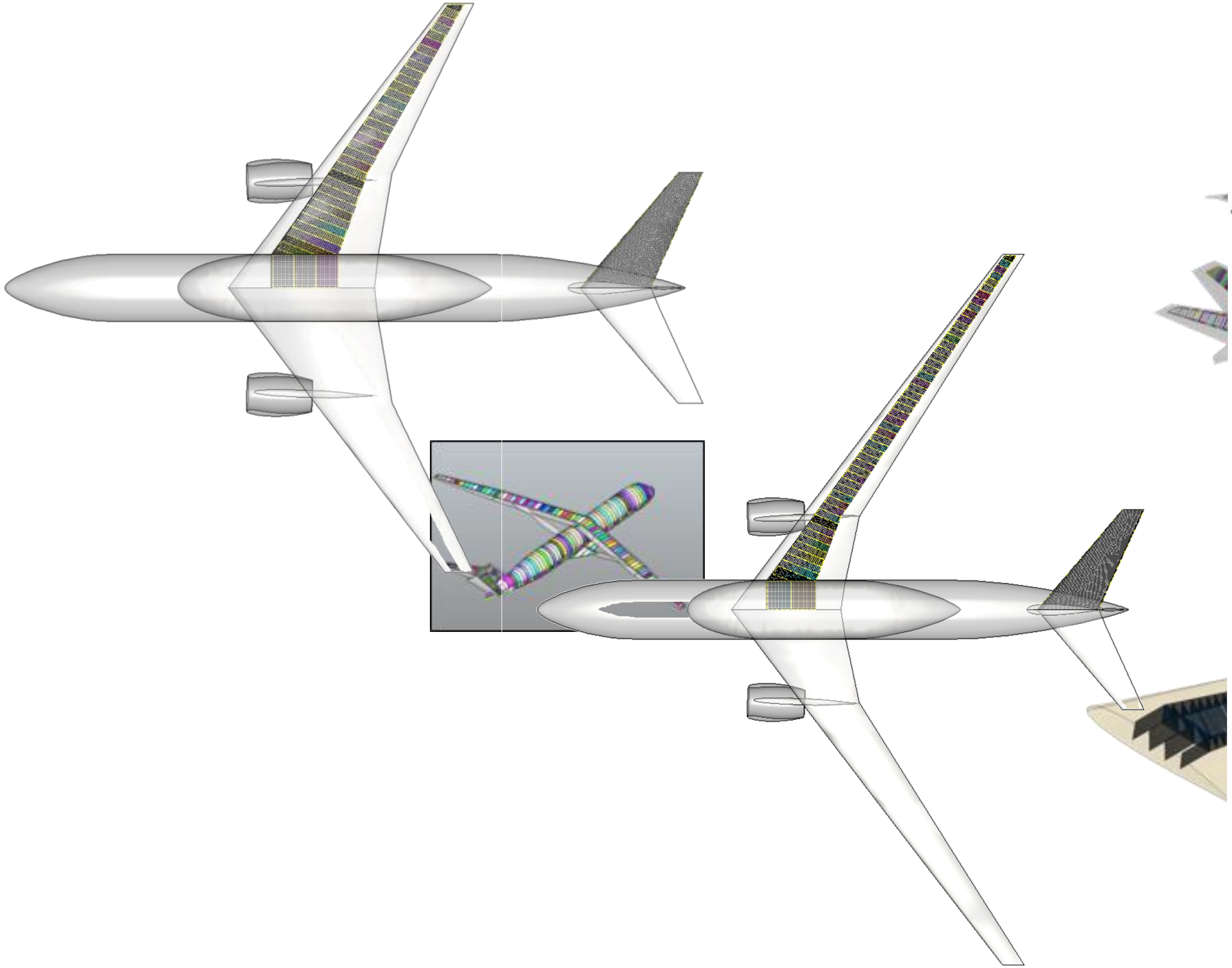
Structural Weight Estimation: OML Parameterization

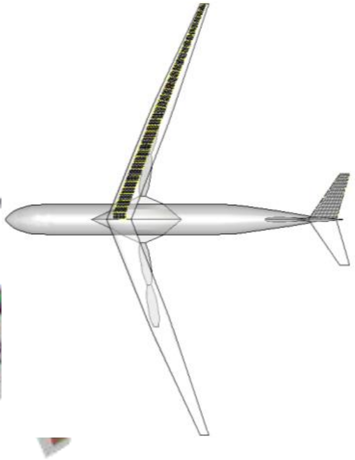




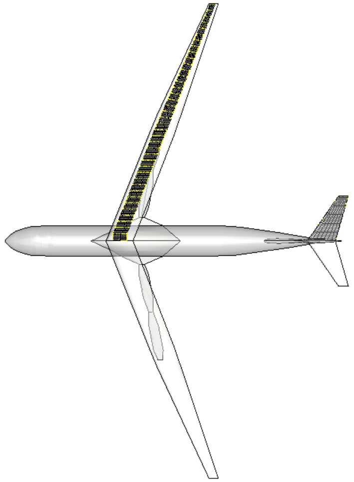


Structural Weight Estimation: Structural Configuration

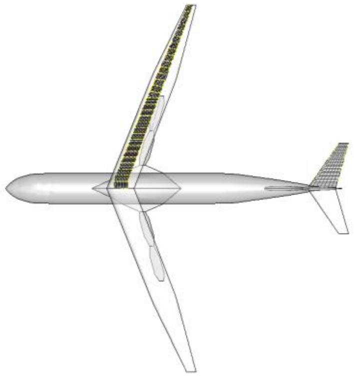




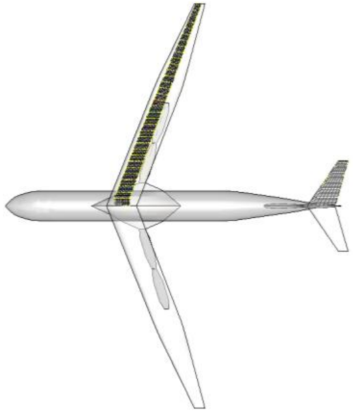
S=1400 ft^2 AR=22



S=1700 ft^2 AR=22



S=1400 ft^2 AR=16



S=1700 ft^2 AR=16

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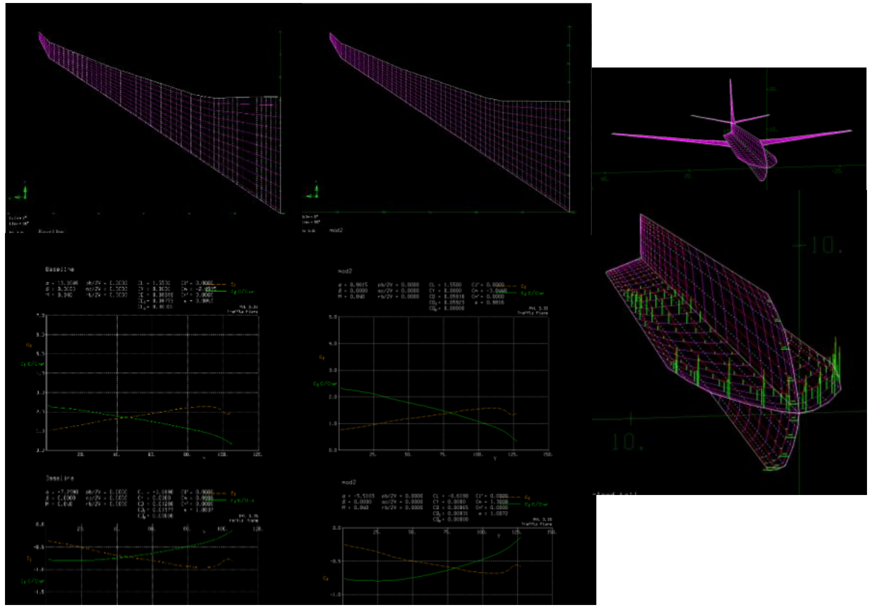
Structural Weight Estimation: Aeroelastic Loads

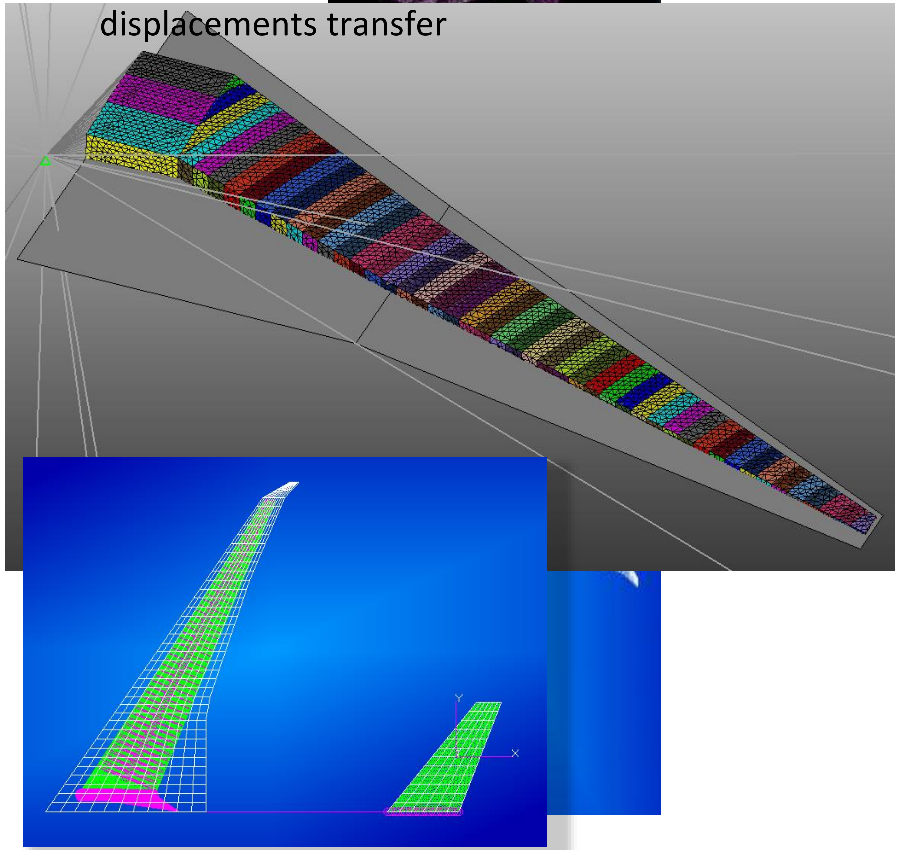
Static Loads (Vortex Lattice)

- Standalone aerodynamics analysis for low order C_L, C_M distributions and loads generation
- Used as a camber correction for Nastran doublet lattice model



Nastran Doublet Lattice Aeroelastic

- Integrated mo… o connect DL with structu… mesh for loa… d displacements transfer



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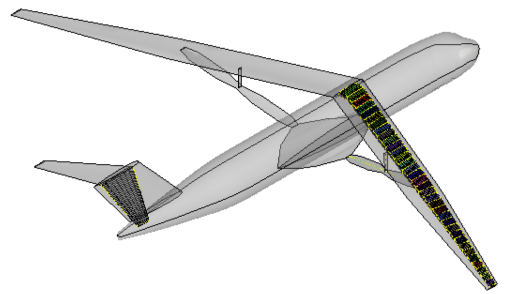
Structural Sizing in HyperSizer

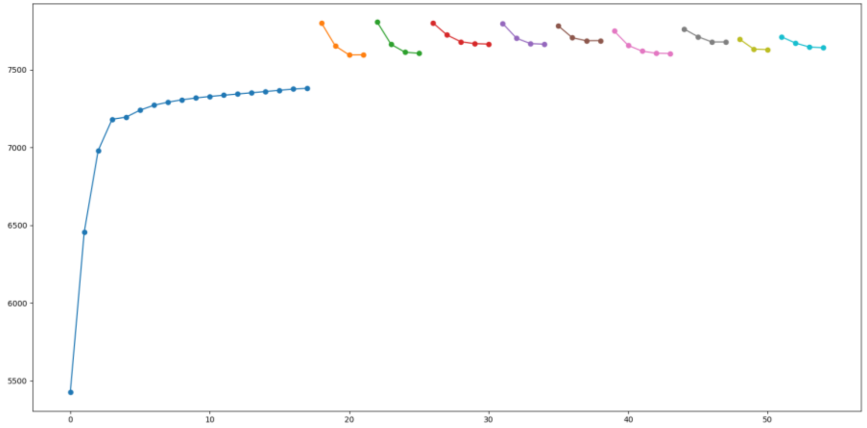
- Currently updating a transonic truss-braced wing (TTBW) wingbox structural sizing program to have parametric laminate orientations
  - Aeroelastic load analysis with Athena Vortex Lattice and Nastran
  - Solid mechanic analysis with Nastran
  - Structural property and failure analysis with HyperSizer



TTBW OML and structure

- Original program used effective laminates, but in HyperSizer these laminates are restricted to only use the ply angles 0°, ±45°, and 90°
  - Skin panels now use discrete laminates that add an offset to these ply angles

- Original program had weight convergence issues due to bad iteration logic between material properties and aeroelastic loads
  - Alternate iteration strategy has been implemented and resolves problem



HyperFEA iteration weights

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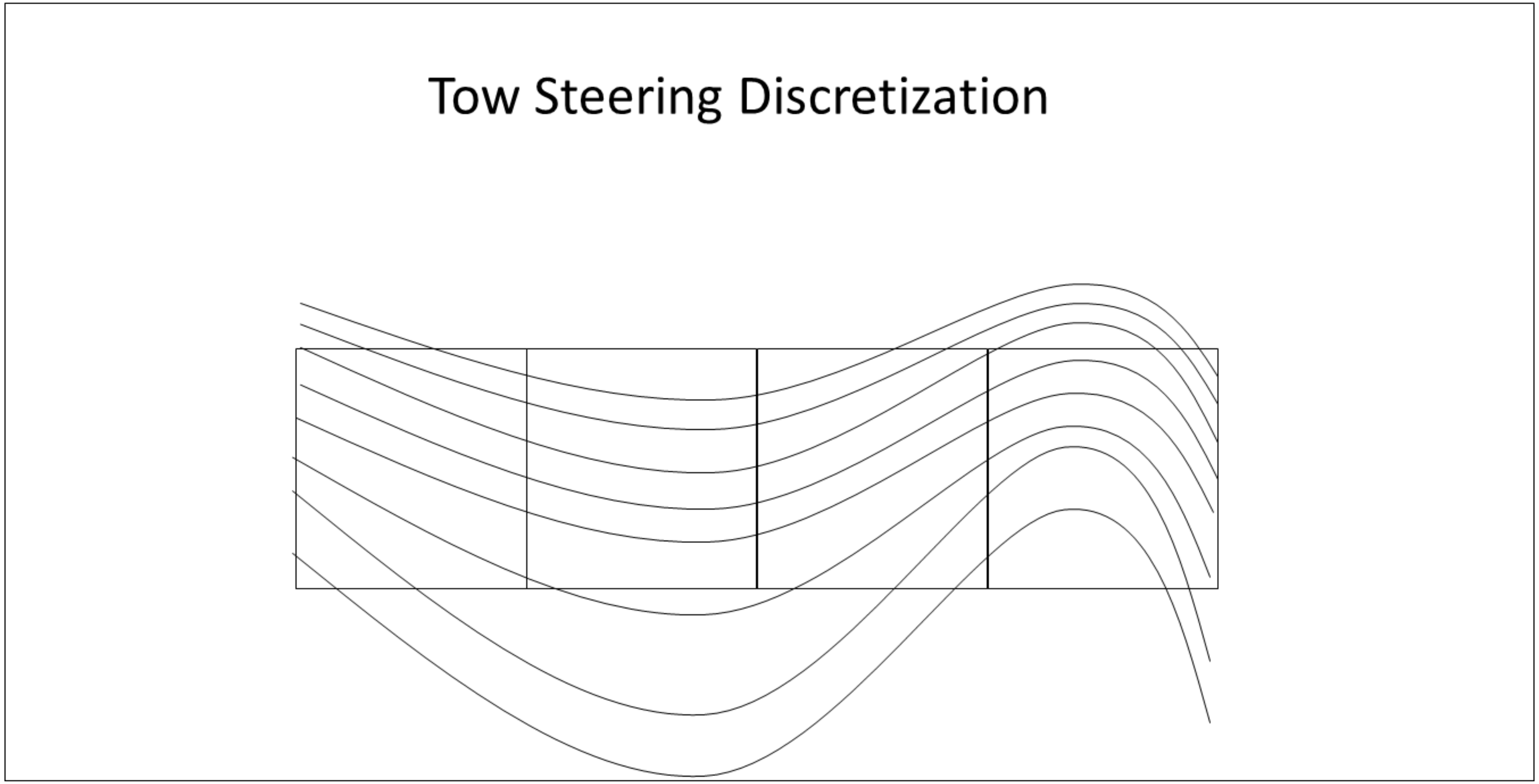

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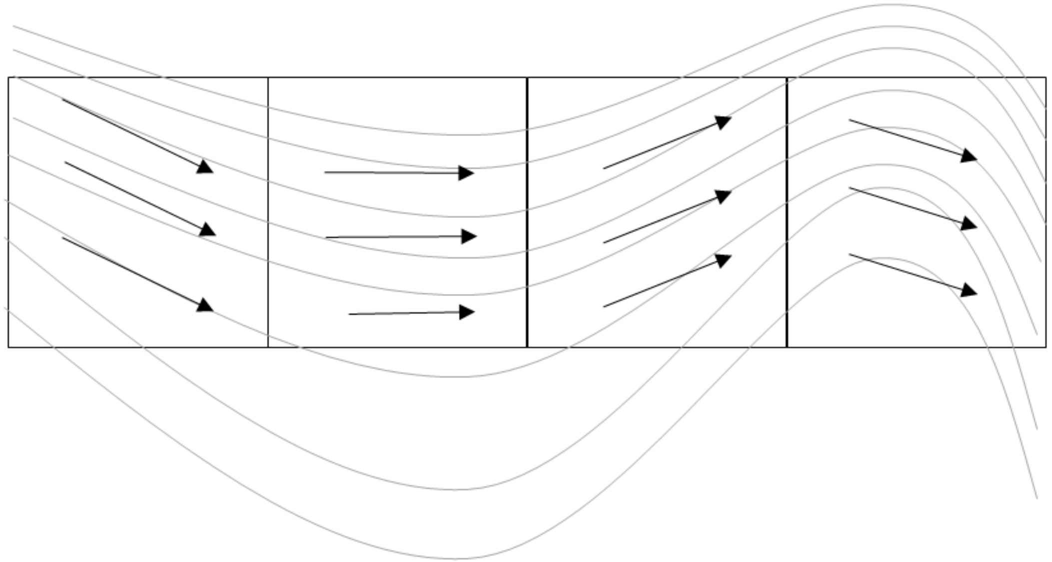
Tow Steering Discretization



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Tow-Steered Composites

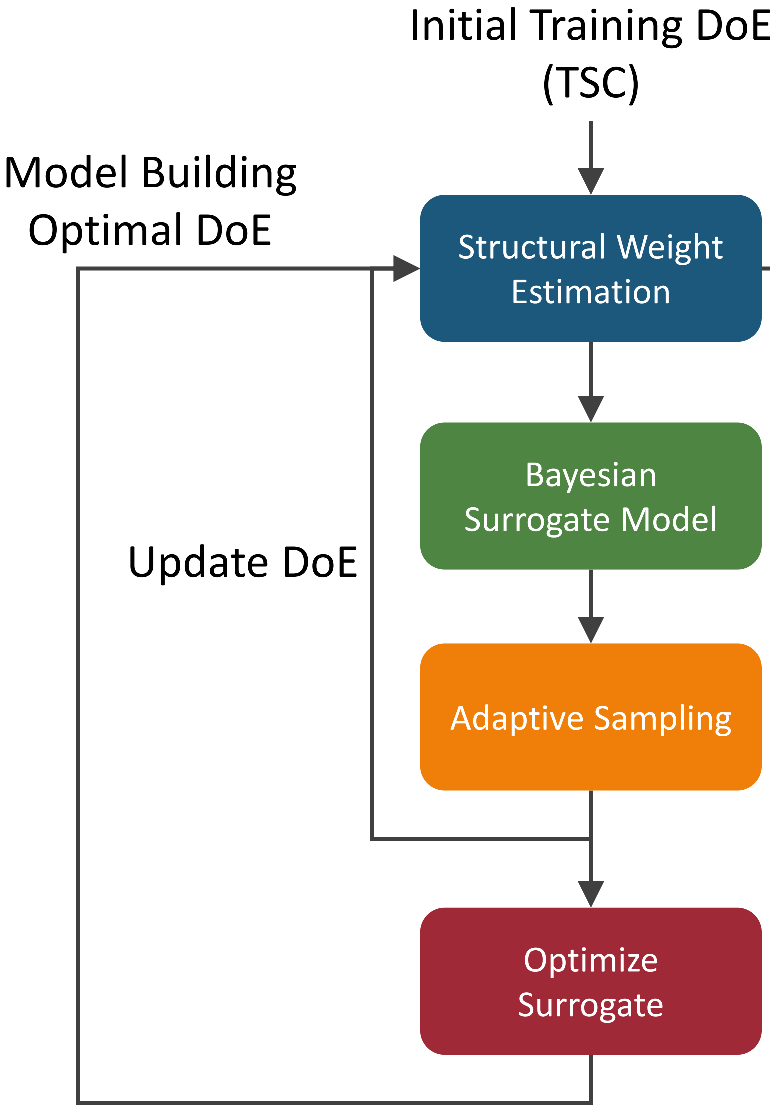
Overview

Structural Weight Estimation

TSC Performance Estimation

Value Assessment

TSC Performance Estimation: Tow-Steering Optimization



TSC Weight Group 1
TSC Weight Group 2

FRWI1_TSC

TSC Weight Group 1/Baseline Weight Group 1

FRWI2_TSC

TSC Weight Group 2/Baseline Weight Group 1

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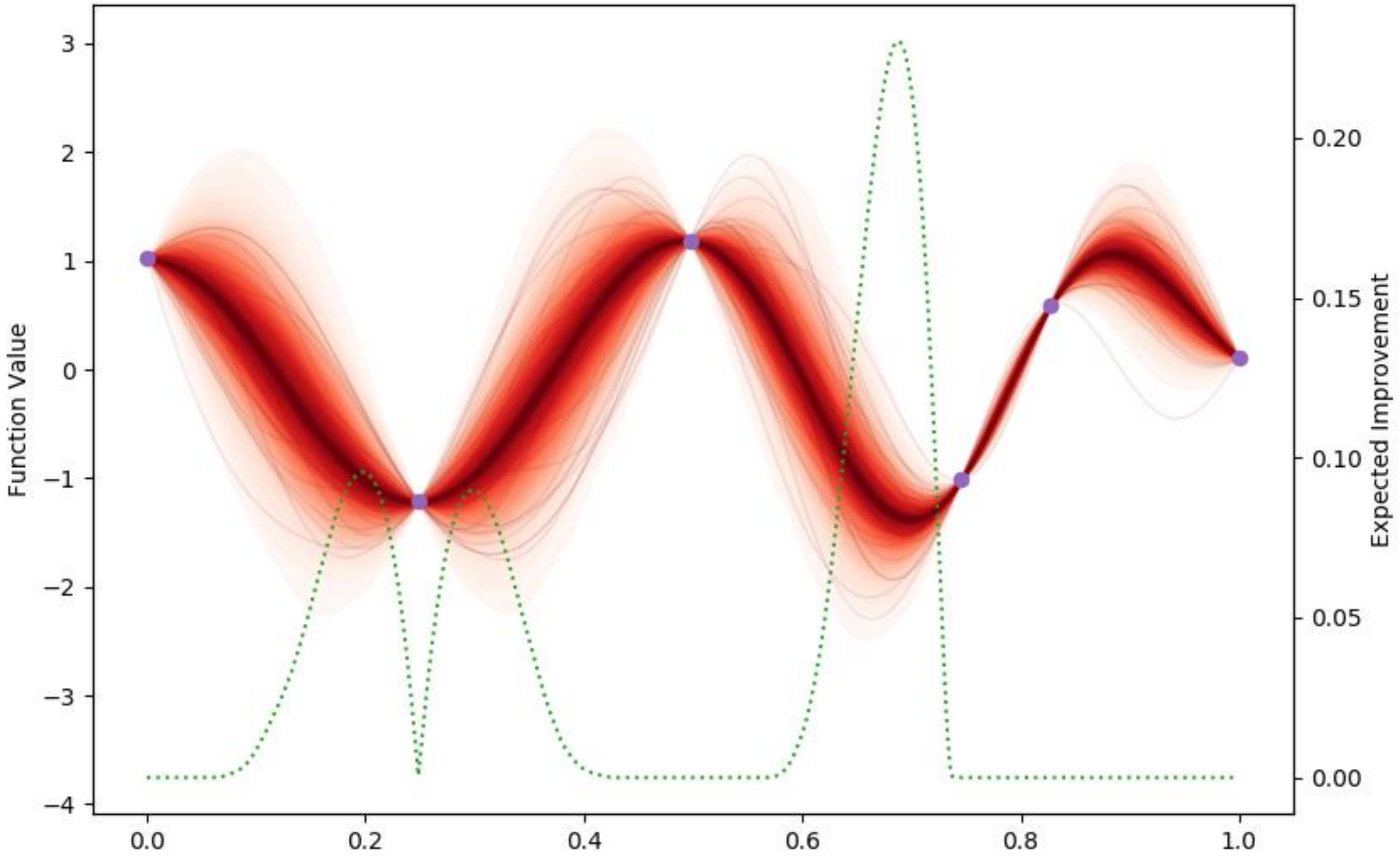
TSC Performance Estimation: Tow-Steering Optimization



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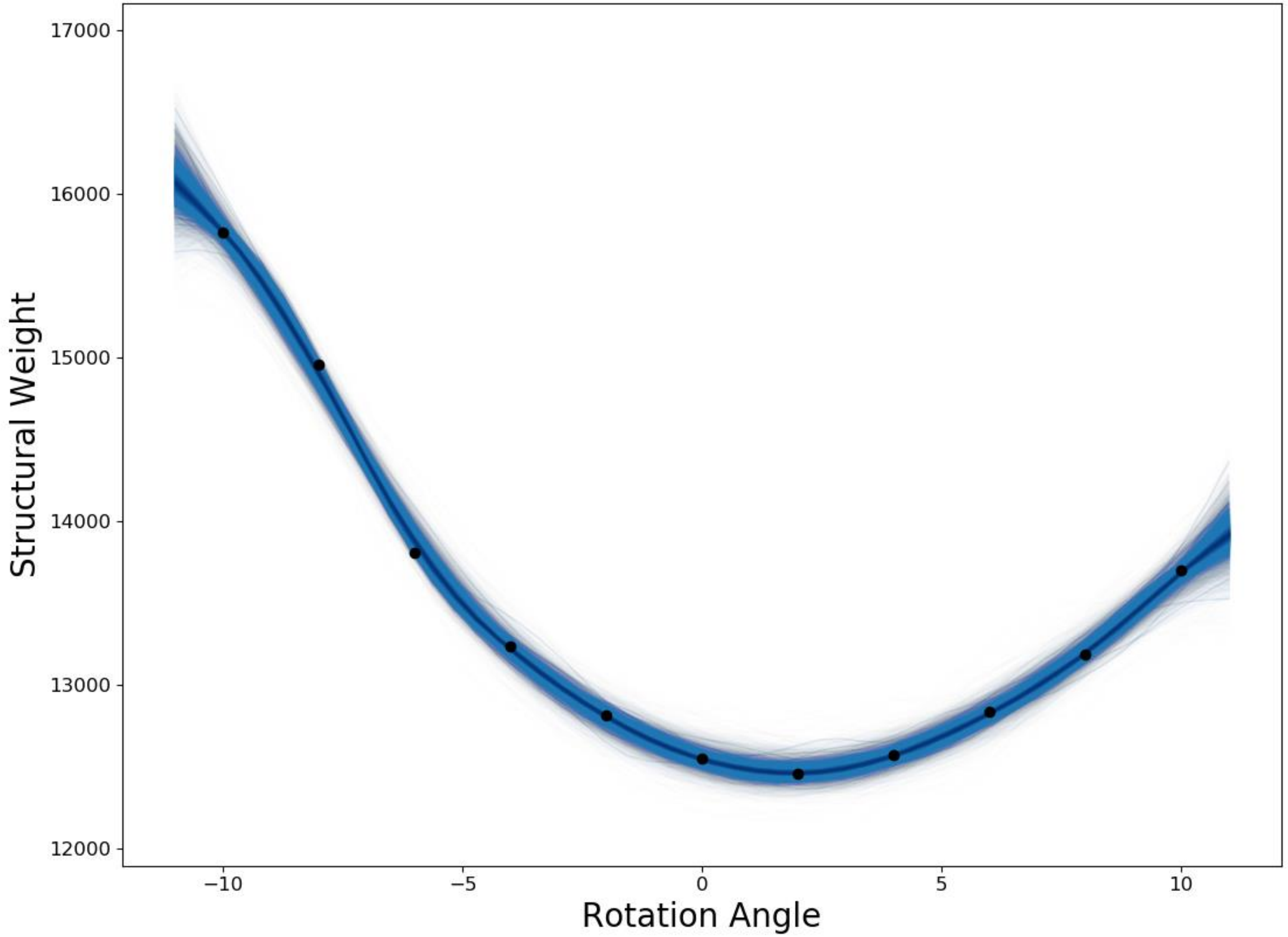
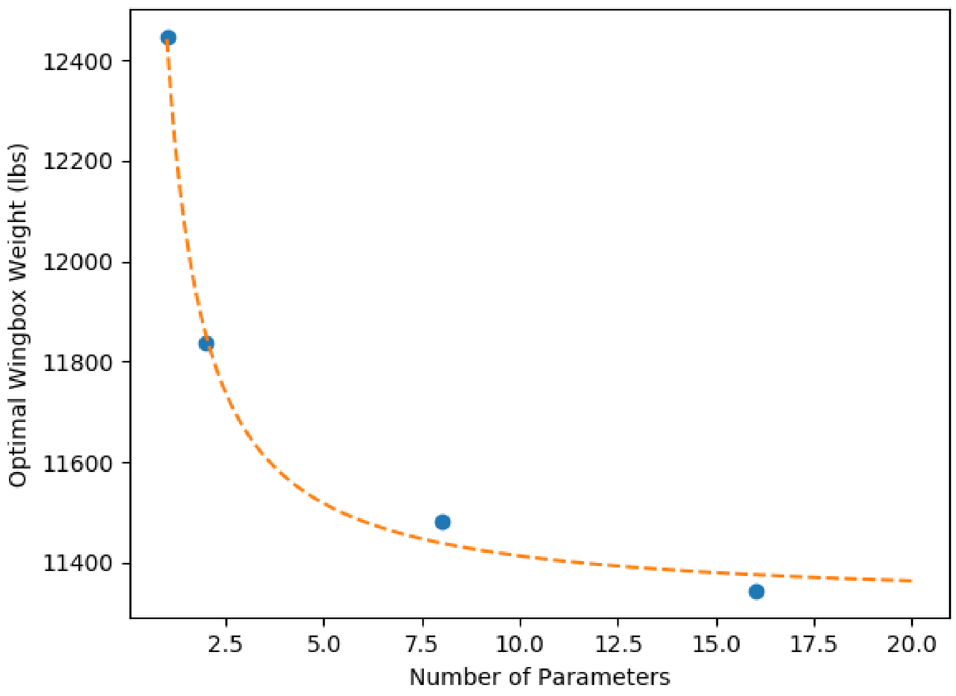
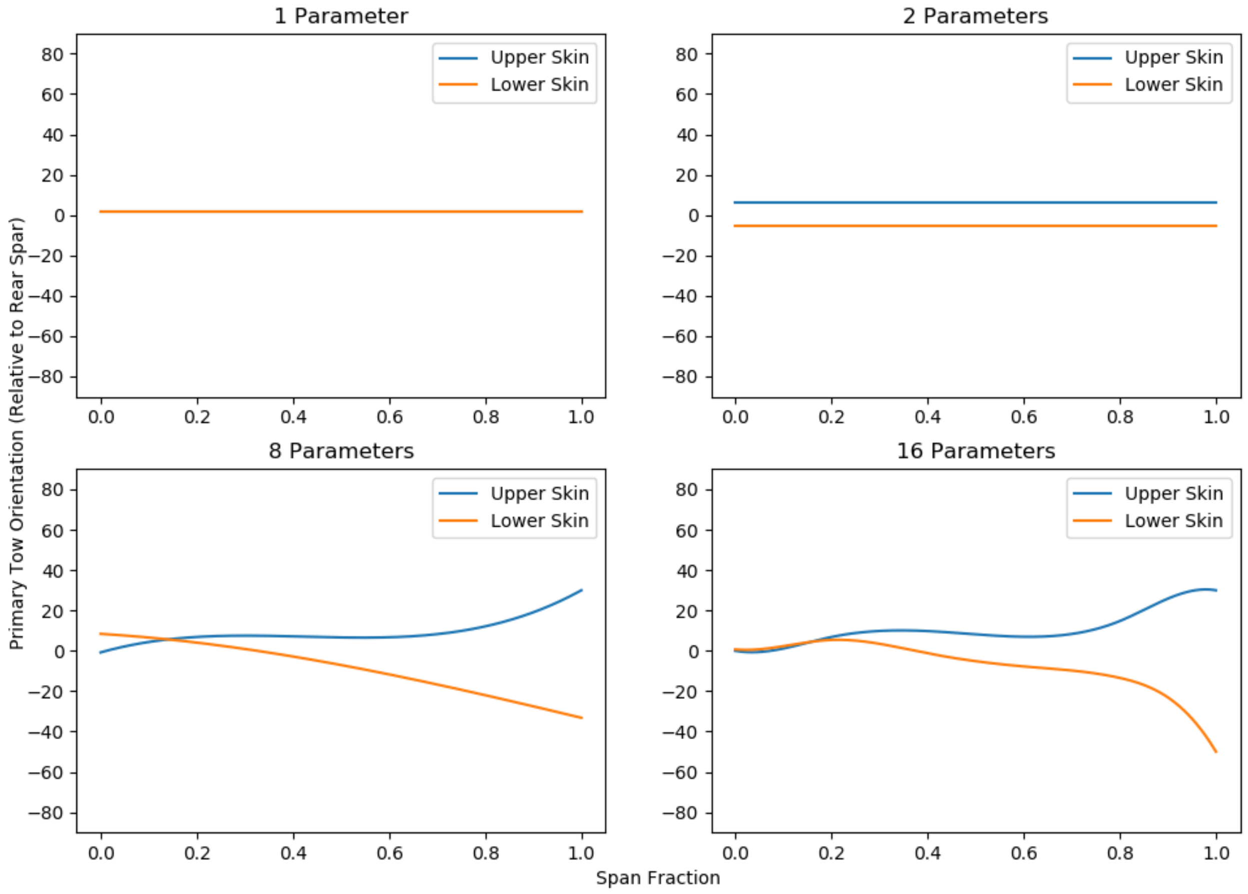
Preliminary Testing for Shape Function Implementation

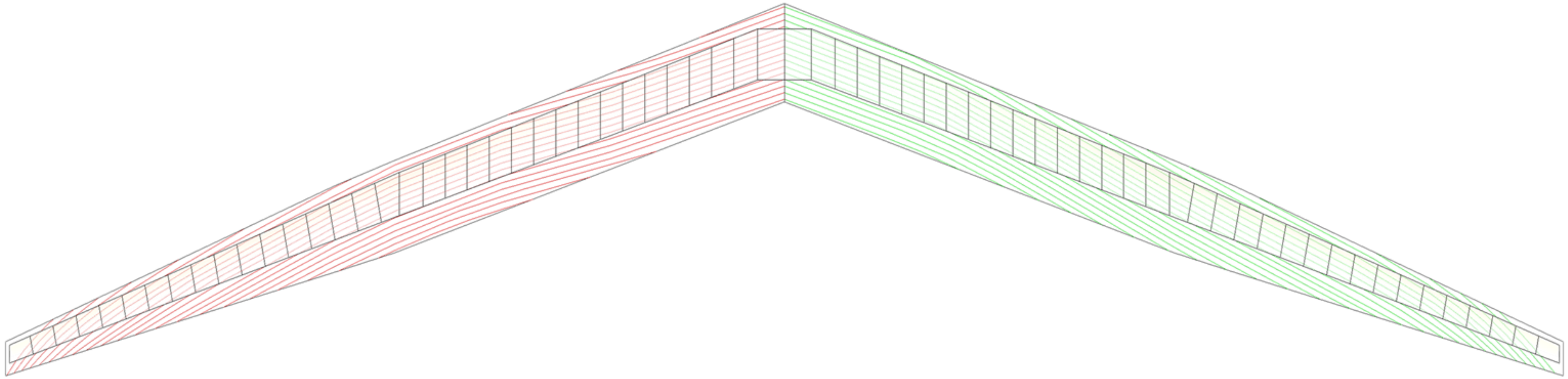


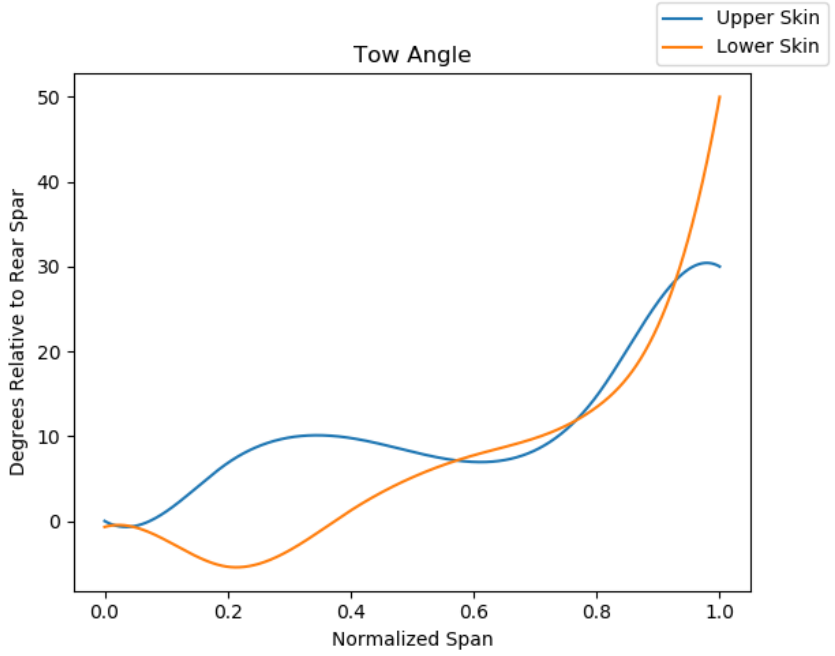
Preliminary Testing for Shape Function Implementation

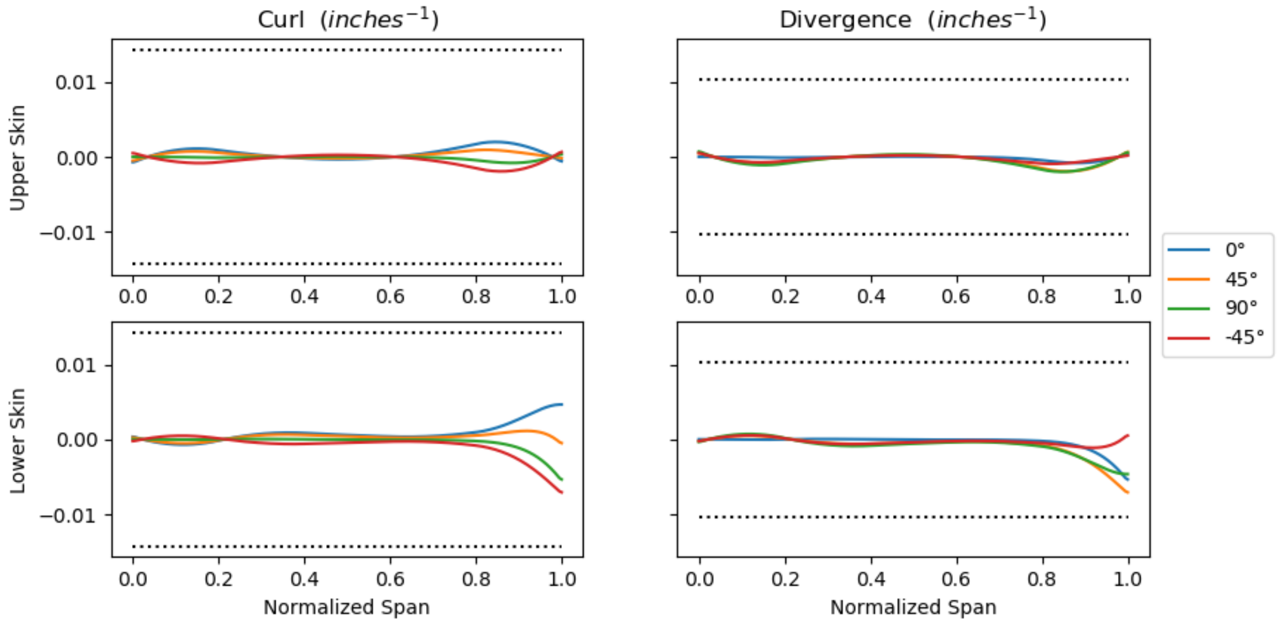




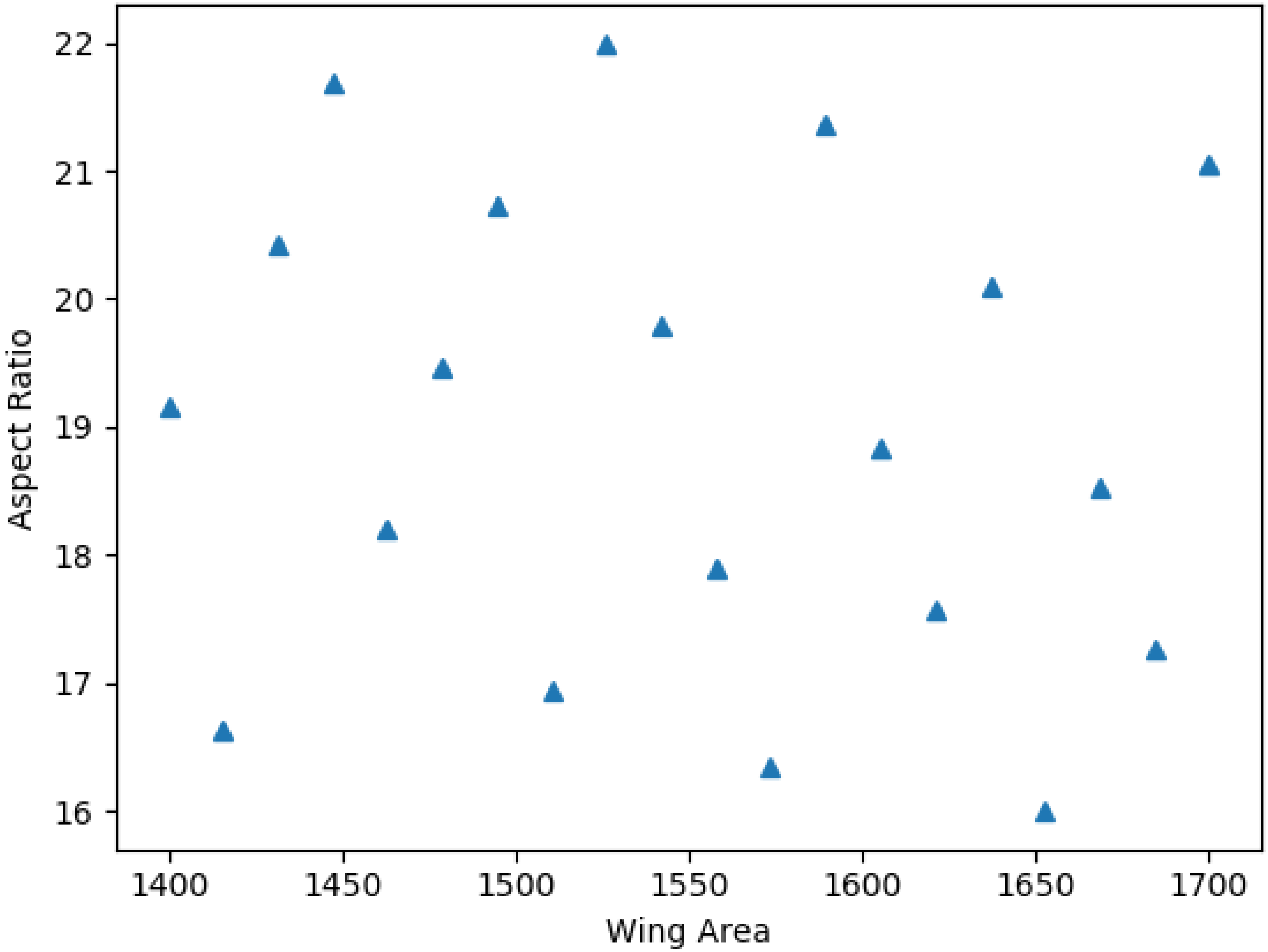
Optimized TSC for Truss Braced Wing







TBW Model Building DoE for FLOPS Implementation



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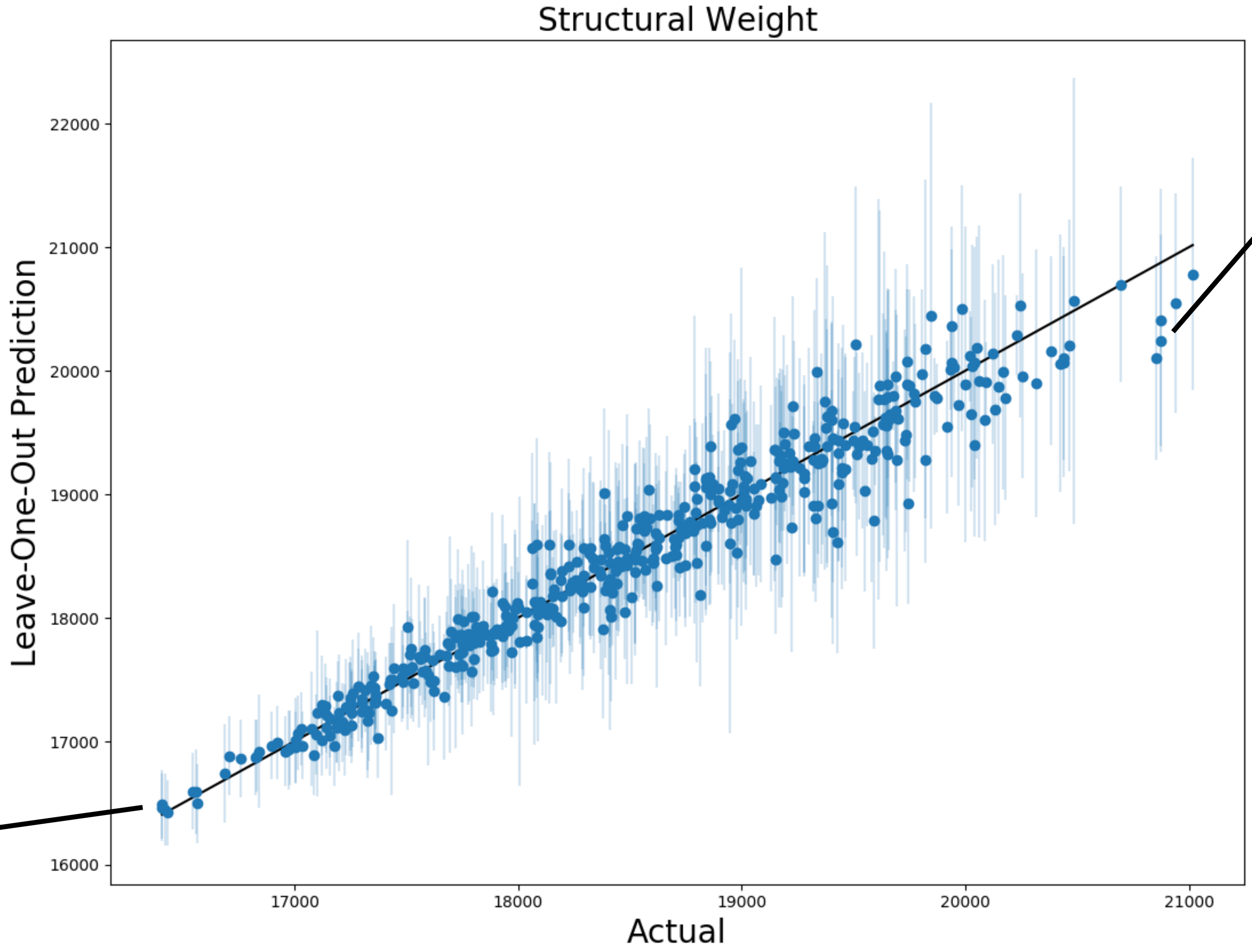
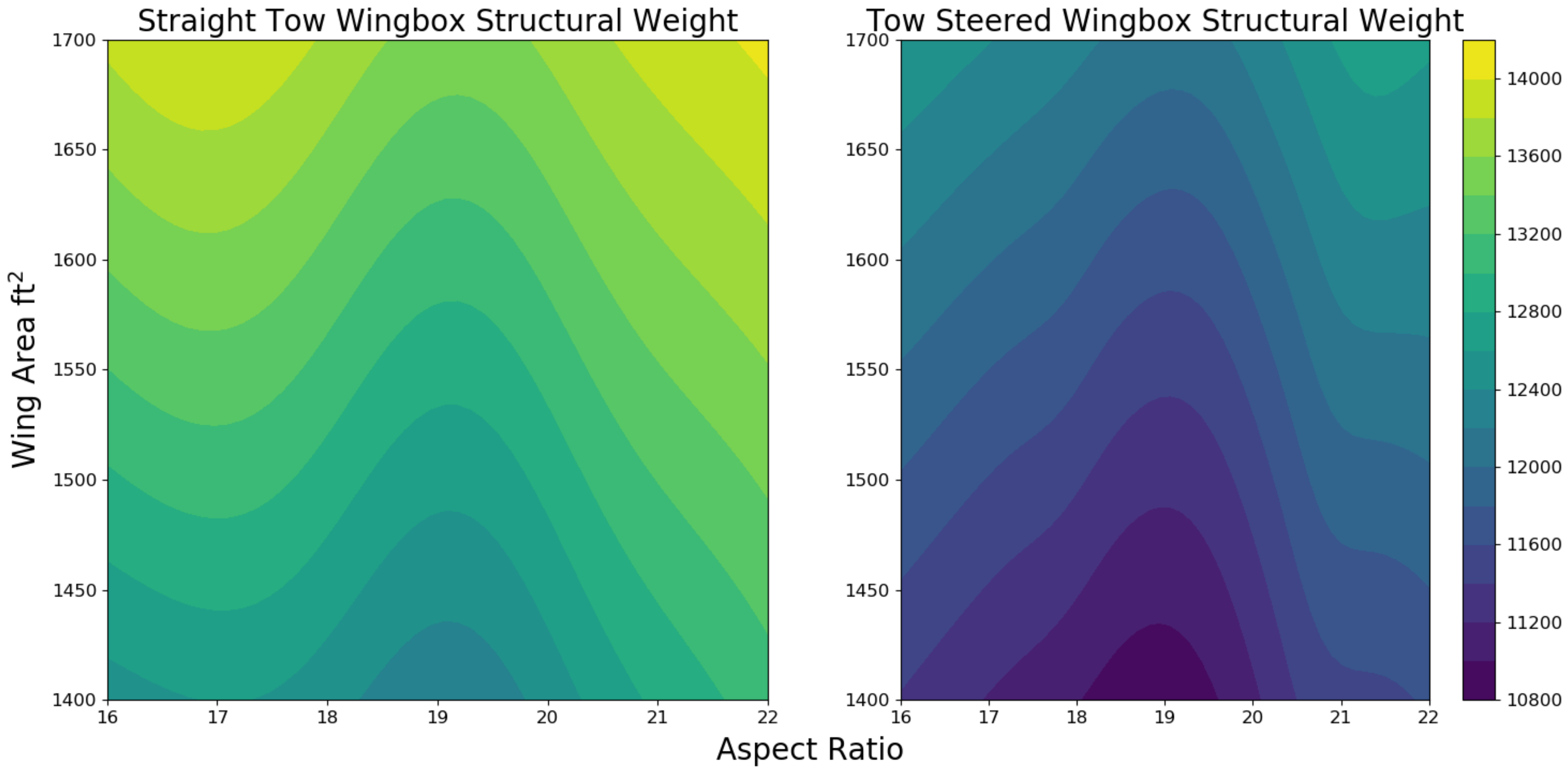
Visualization of Surrogate Model Fit: TBW



Worse performing points have more uncertainty due to sparse sampling from poor regions

Better performing points have less uncertainty due to increased density of samples in favorable regions

TTBW Structural Weight



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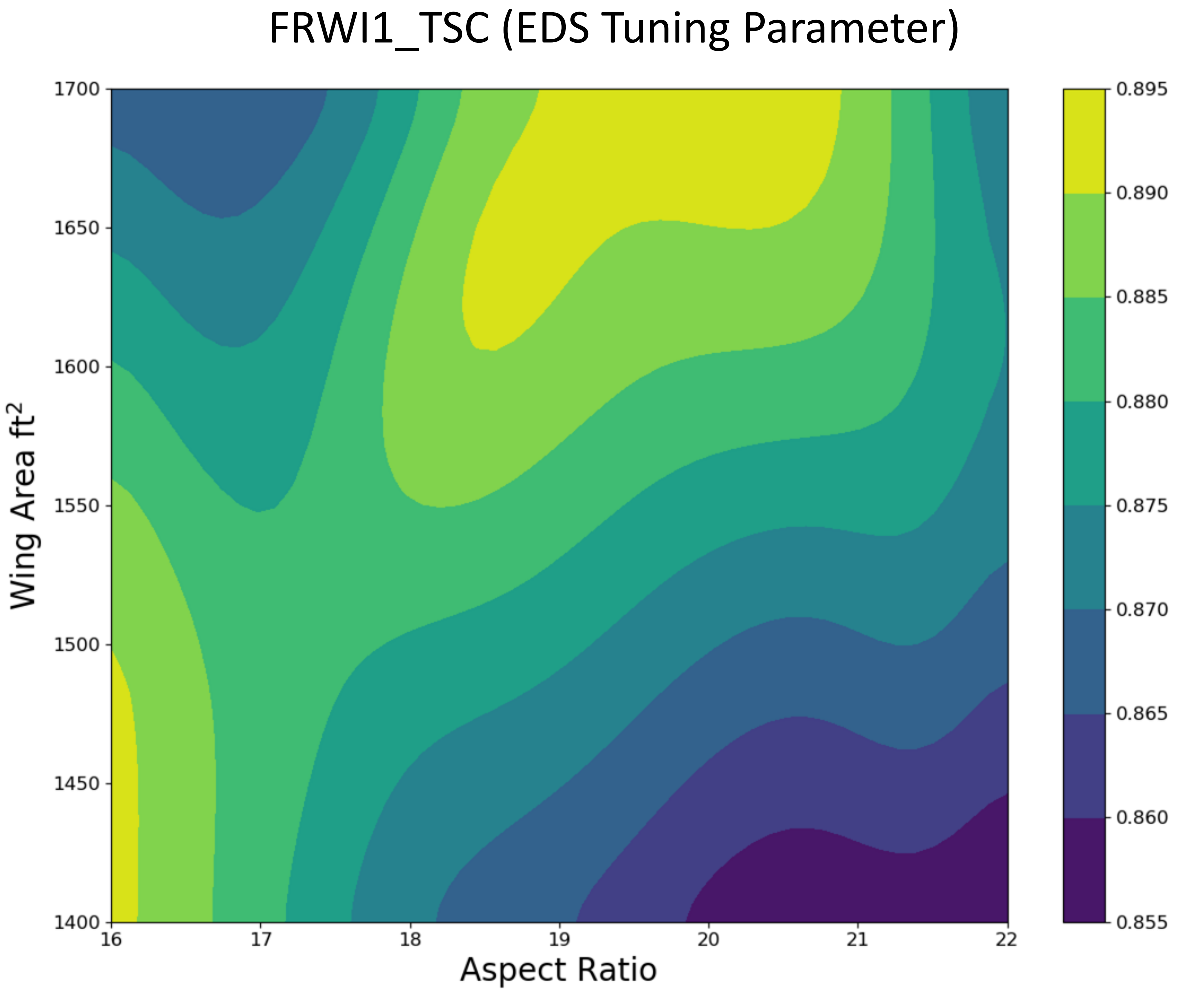
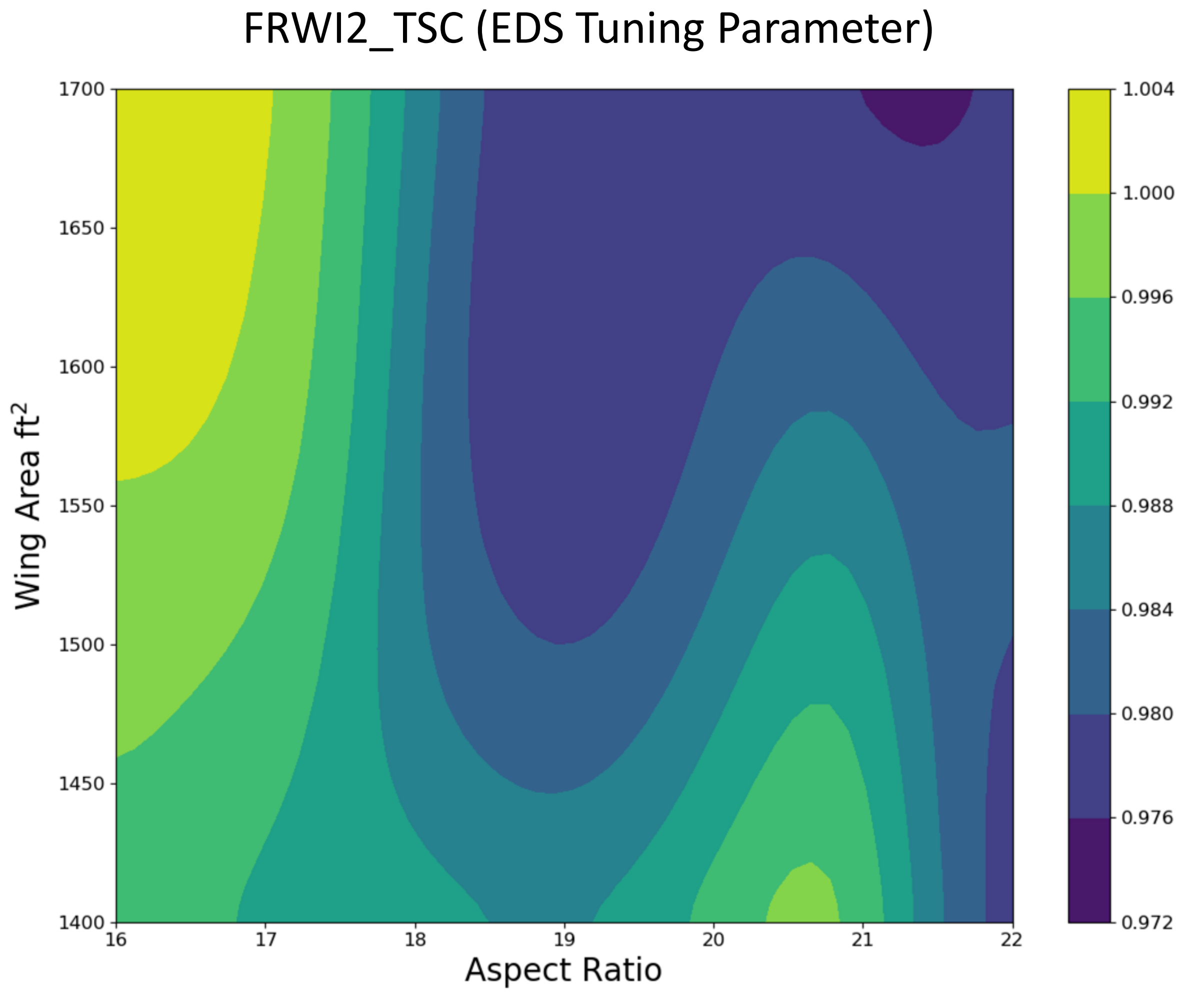
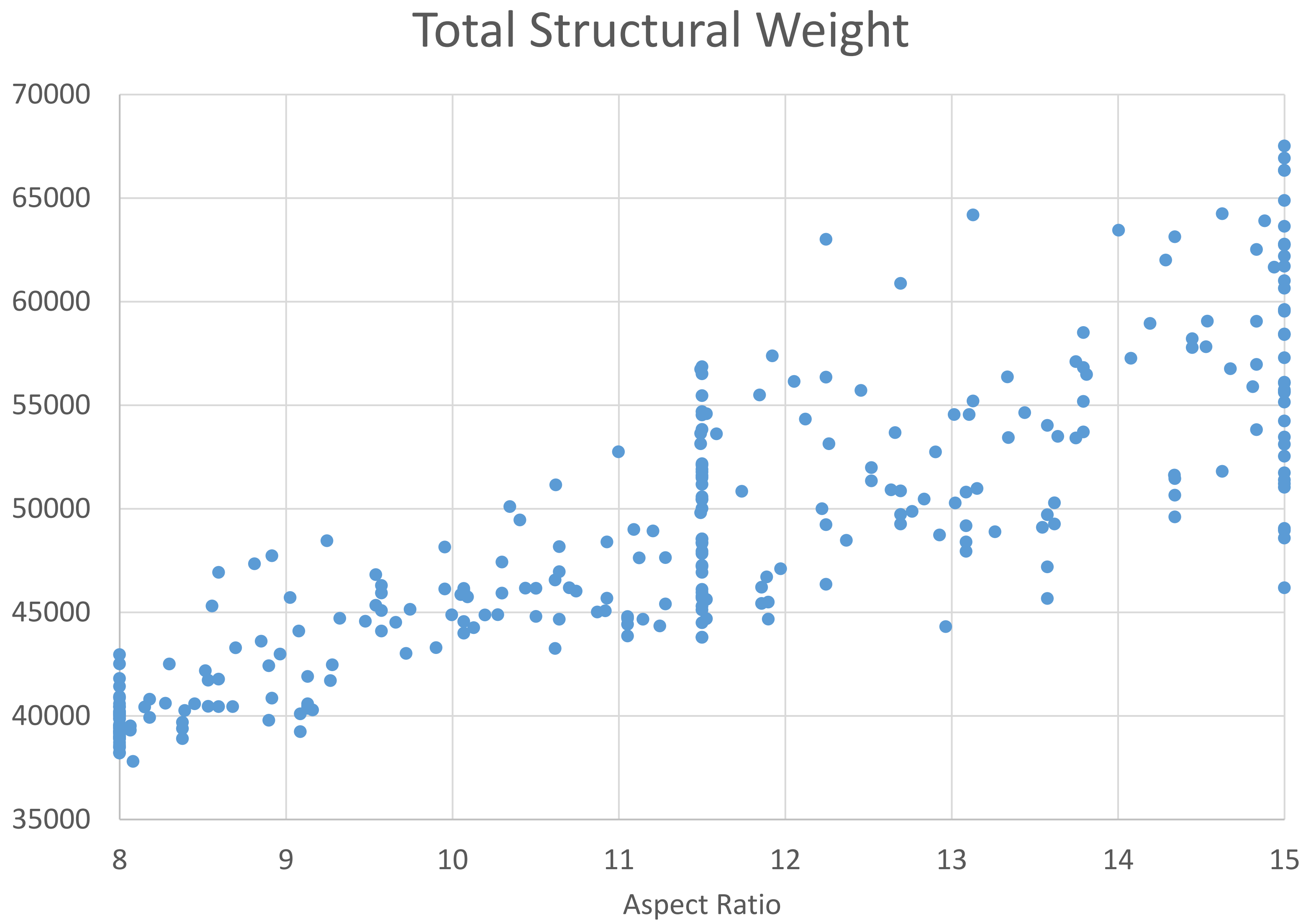
TTBW TSC-to-Baseline Ratio

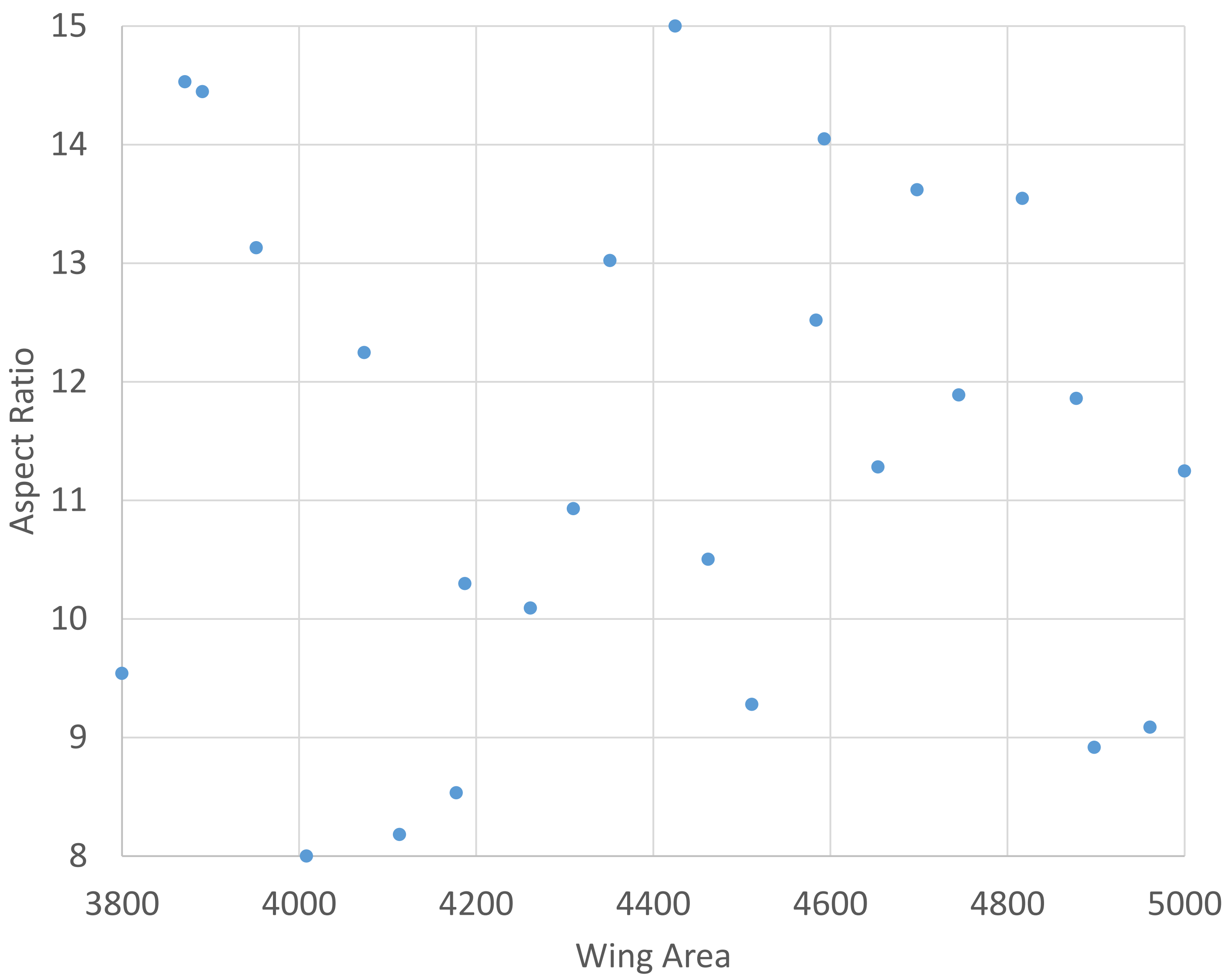




CRM Model Building DoE for FLOPS Implementation



CRM Model Building DoE for FLOPS Implementation



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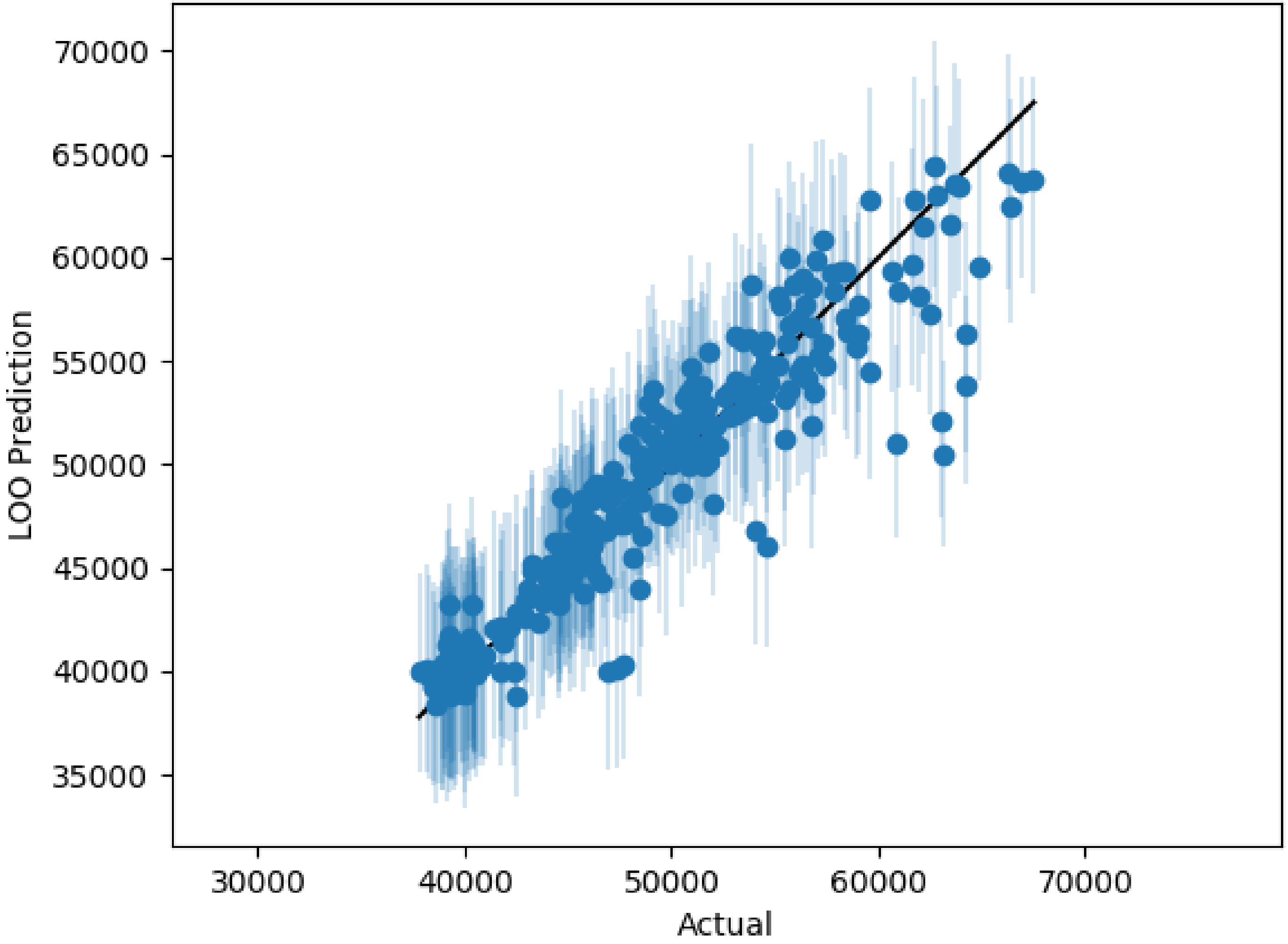
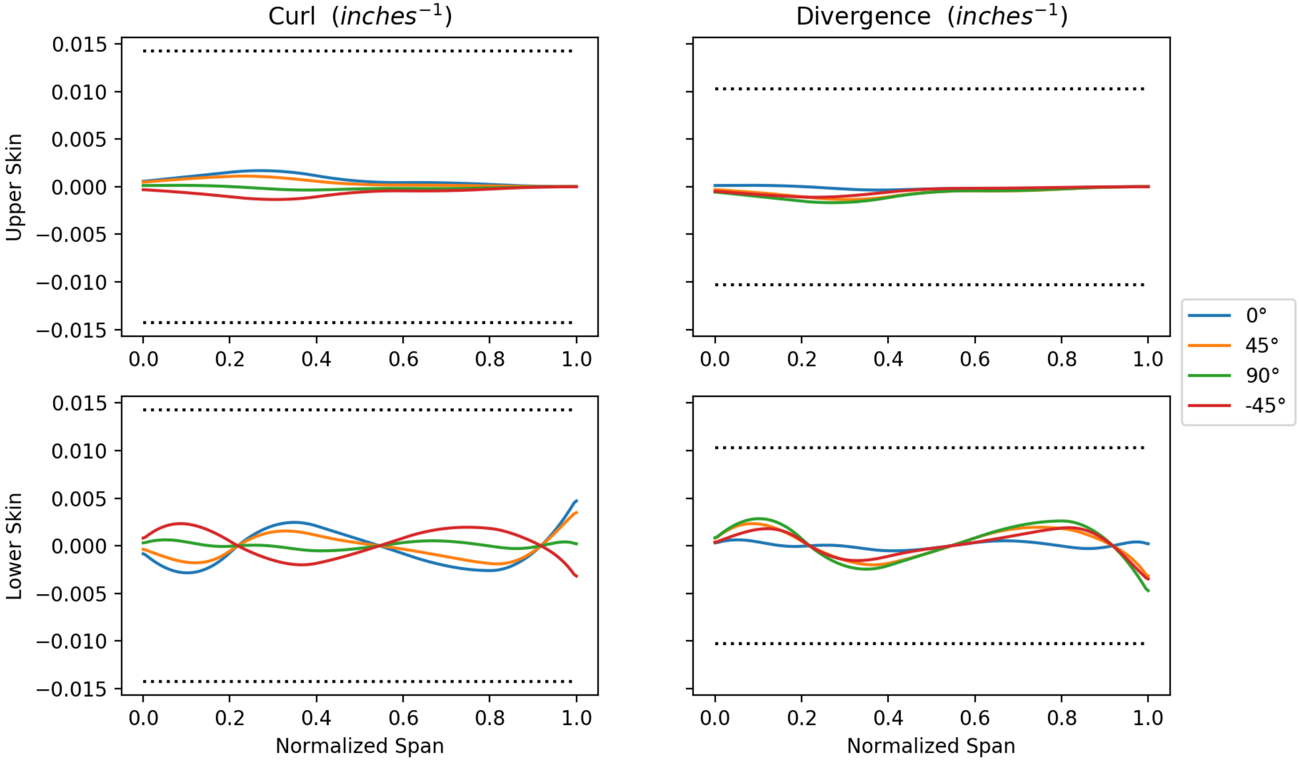
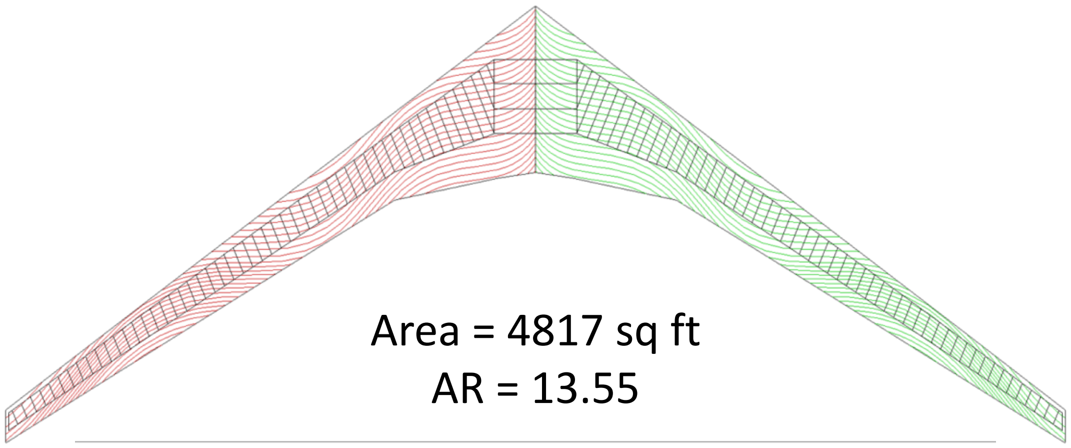
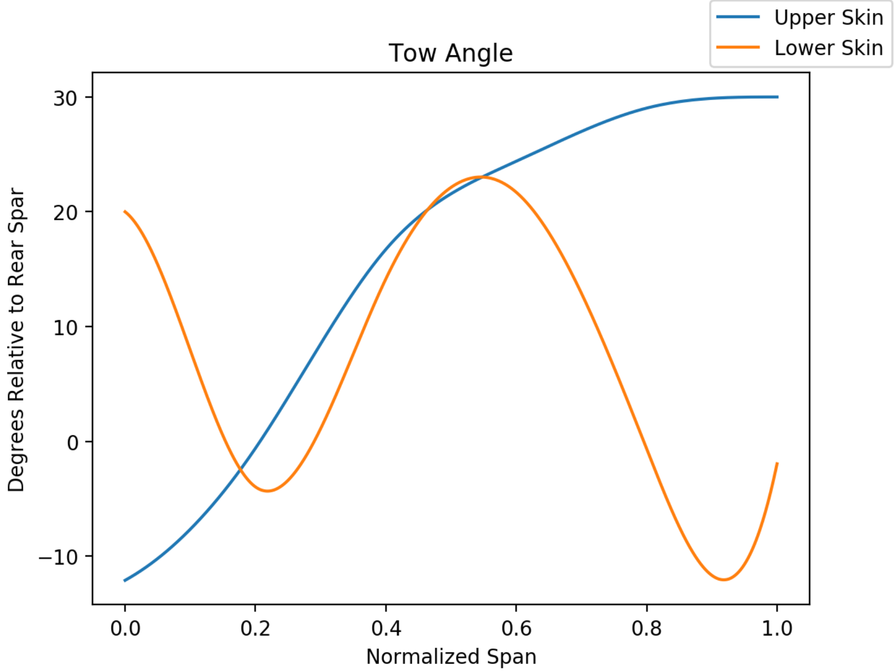
Visualization of Surrogate Model Fit: CRM



CRM Optimal Tow-Steering







Weight Reduction Compared to Baseline: CRM