Mass Estimation Relationship for Conceptual Design of Blended-Wing-Body Cabin with Advanced Structures

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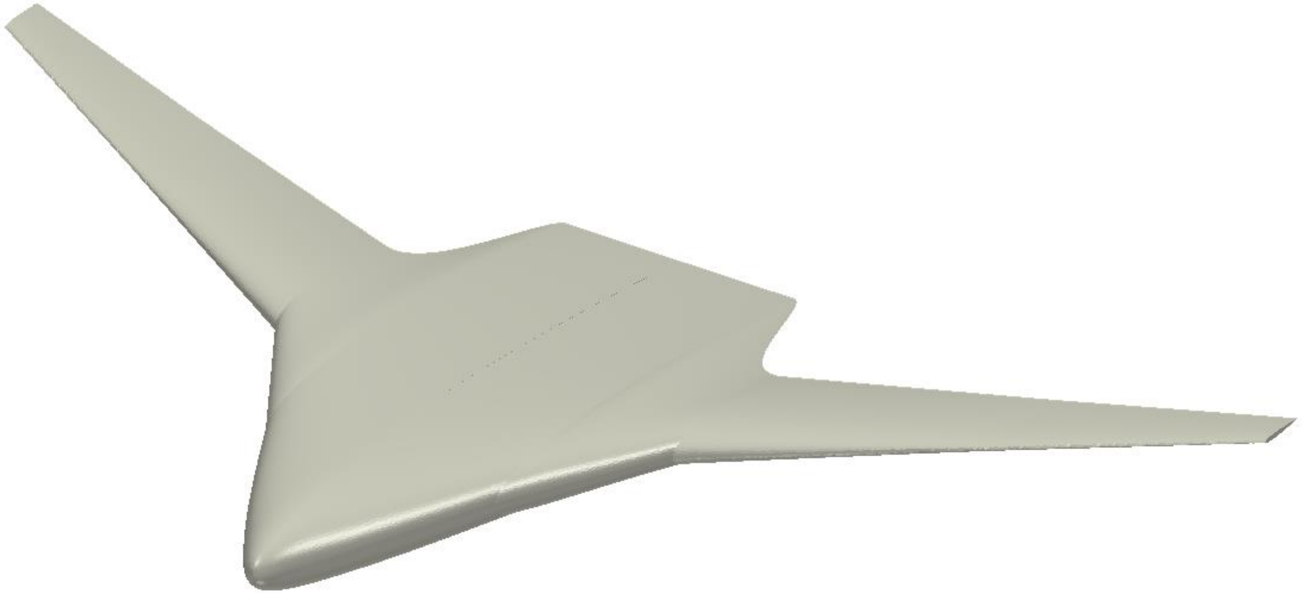
Objectives

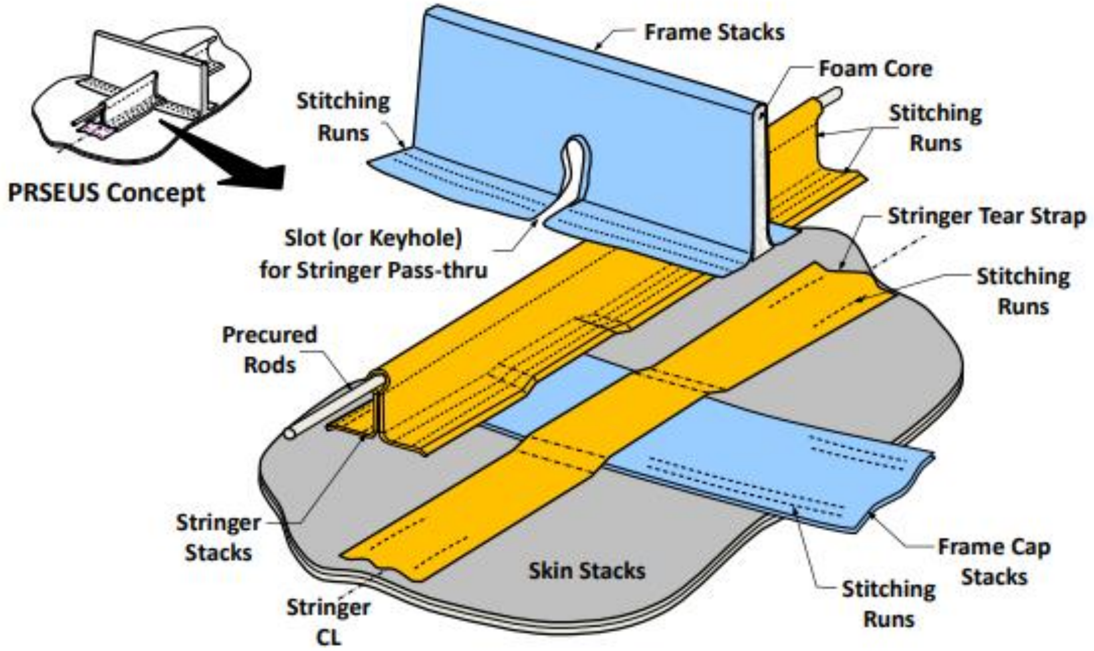
- Develop Blended-Wing-Body (BWB) Cabin Mass Estimation Relationship (MER) accounting for:
  - Advanced Pultruded Rod Stitched Efficient Unitized Structures (PRSEUS)
  - Range of passenger counts and additional geometric parameters
- Based on numerous Finite Element Analyses (FEA)
- For use in aircraft synthesis analysis tools

Background

- The Blended Wing Body (BWB) aircraft concept integrates the fuselage and wing structures of a Tube & Wing (T&W) into a unified structure
- Parametric Mass Estimation Relationships (MERs) are mathematical formulas which capture general trends in data based on set parameters
- Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) is a type of stitched composite panel which employs pre-cured rods for increased stiffness
  - Breakthrough for the BWB center body due to a combination of in- and out-of-plane loading



Generic BWB Design



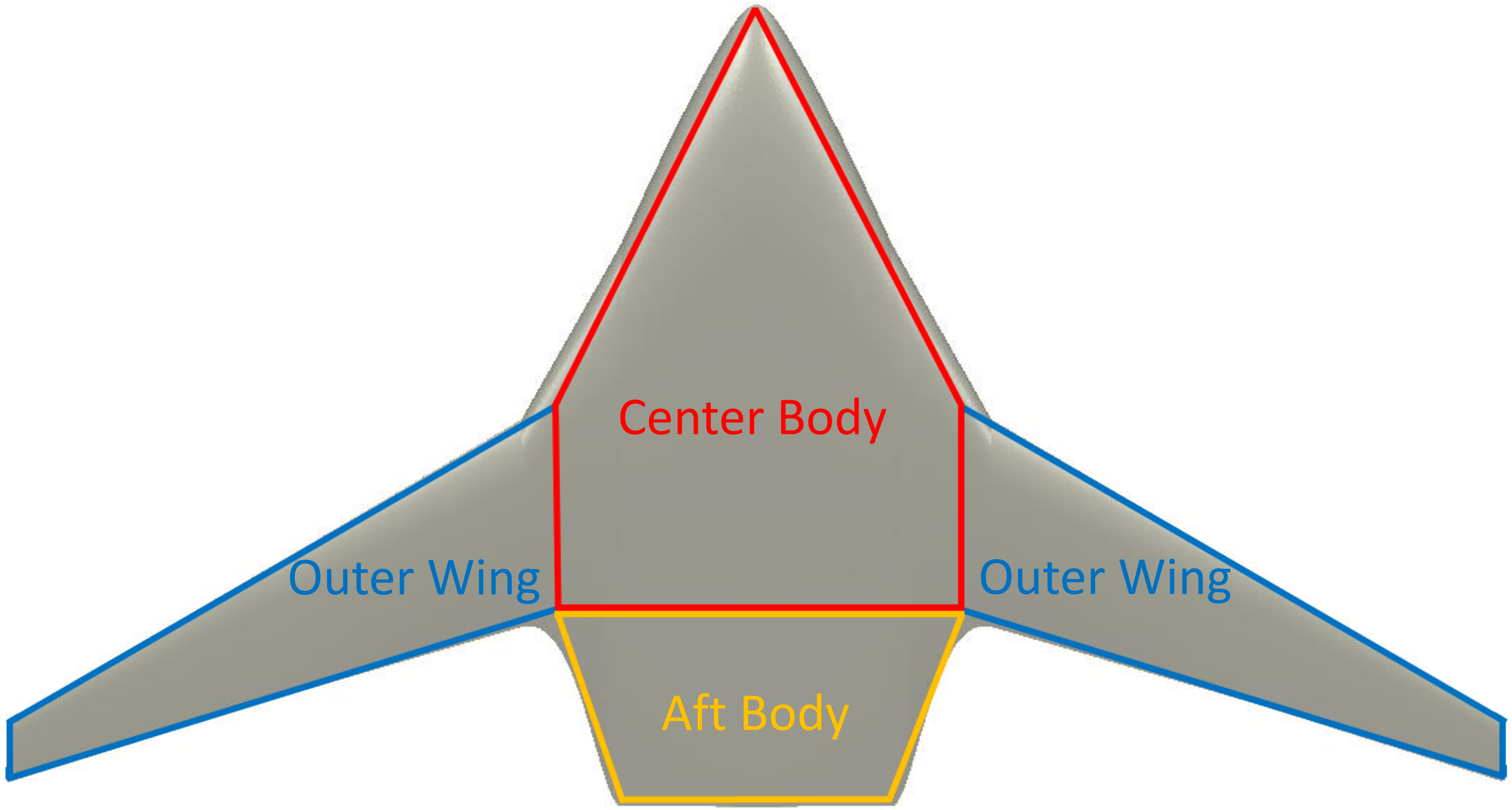
PRSEUS Components [1]

Background

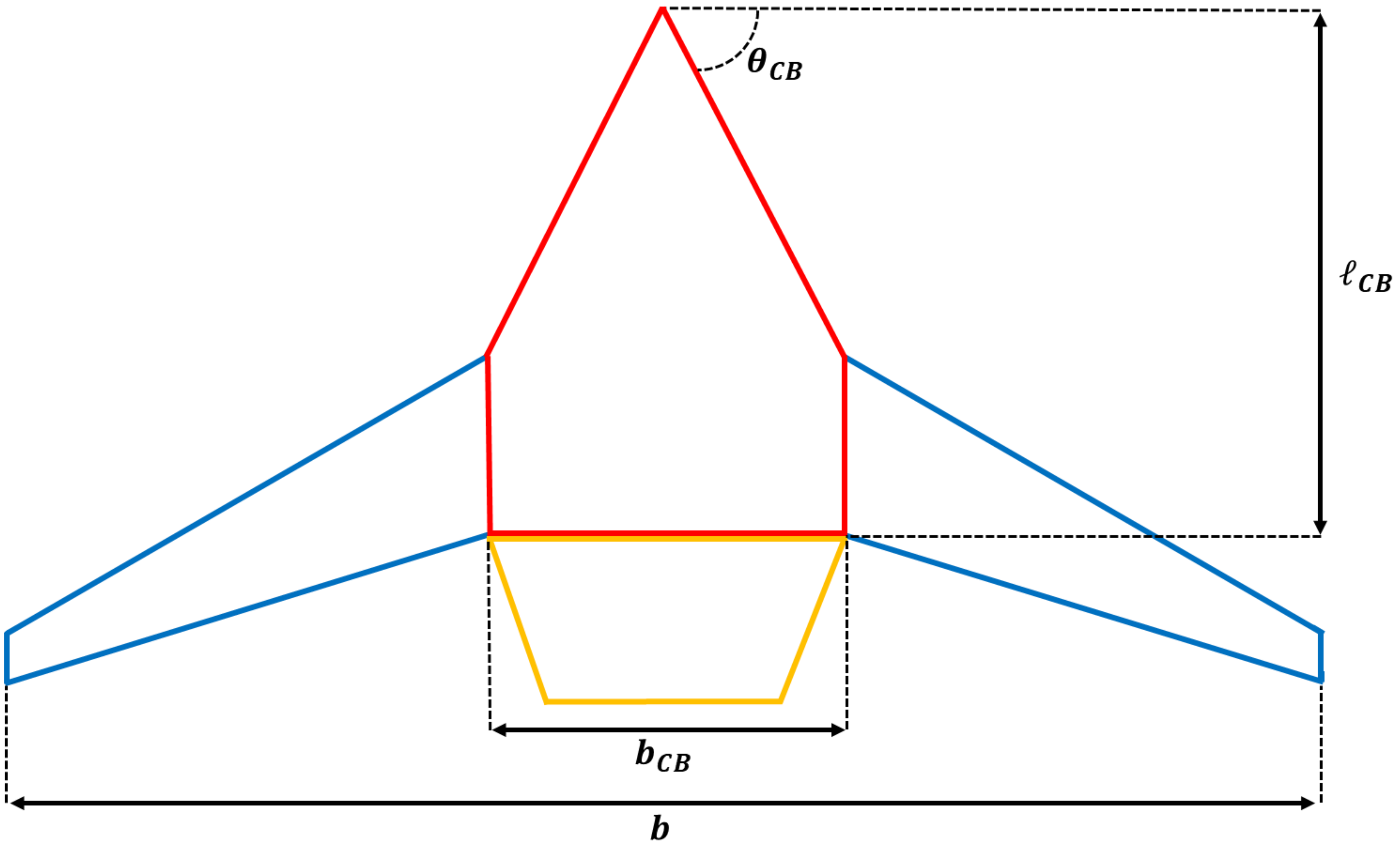
- The BWB configuration has shown promise to reduce Operating Empty Weight (OEW) by 19% and fuel burn per seat by 32% compared to similar class advanced T&W [2]
- Empirical and historical data for PRSEUS based BWBs do not exist
- Others have created methods to estimate center body weights for a BWB:
  - Bradley created a MER [2] which was amended with a “PRSEUS factor” to account for PRSEUS weight savings [3]
  - Gern created a program called HCDstruct to build and optimize PRSEUS based BWBs [5]
  - Laughlin created a MER using a custom modeling and simulation environment to optimize a partially PRSEUS based BWB [6]

There is a need for a fully PRSEUS parametric BWB center body MER based on high-fidelity methods

Section Definitions



Section Definitions



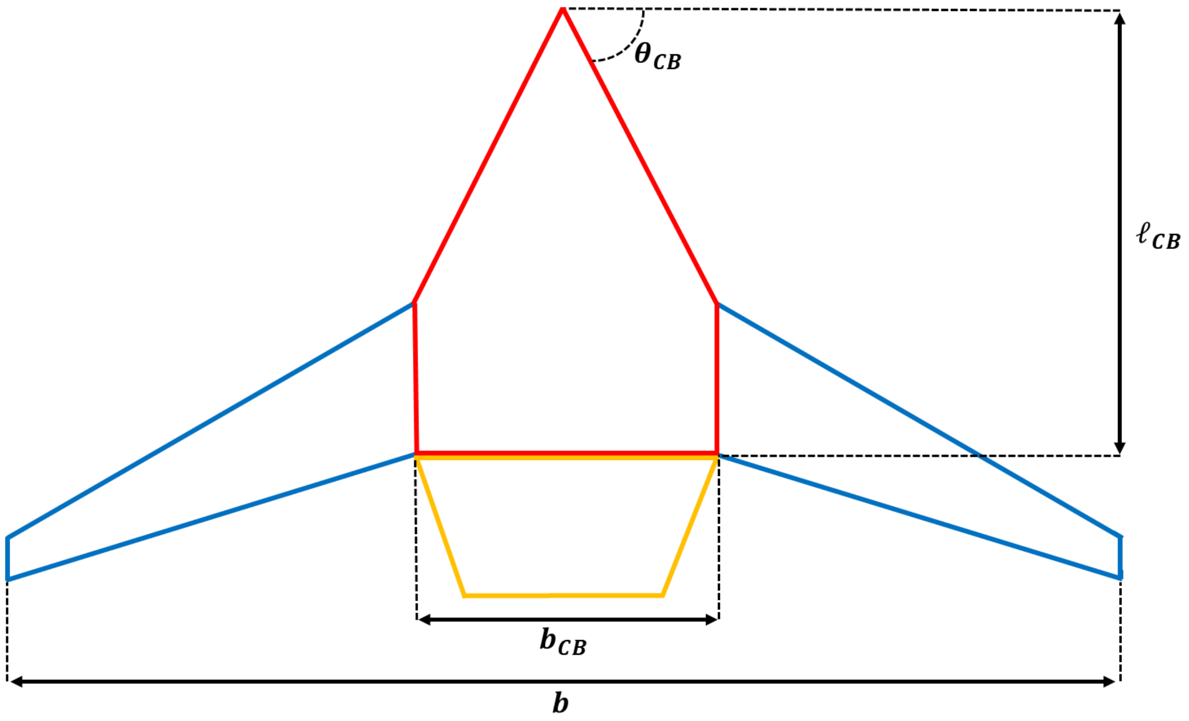
Parametric Definitions for Proposed MER

Proposed MER form $$w_{CB} = k_{no} \cdot k_{anchor} \cdot (w_{struct} + w_{f_{pass}} + w_{f_{cargo}})$$

$$w_{struct} = a \cdot A_{CB}^{b} \cdot TOGW^{c} \cdot FR^{d} \cdot \theta_{CB}^{e} \cdot SR^{f}$$

$$w_{f_{pass}} = A_{CB} \cdot \rho_{f_{pass}} \cdot t_{f_{pass}}$$

$$w_{f_{cargo}} = f_{con} \cdot A_{CB} \cdot \rho_{f_{cargo}} \cdot t_{f_{cargo}}$$

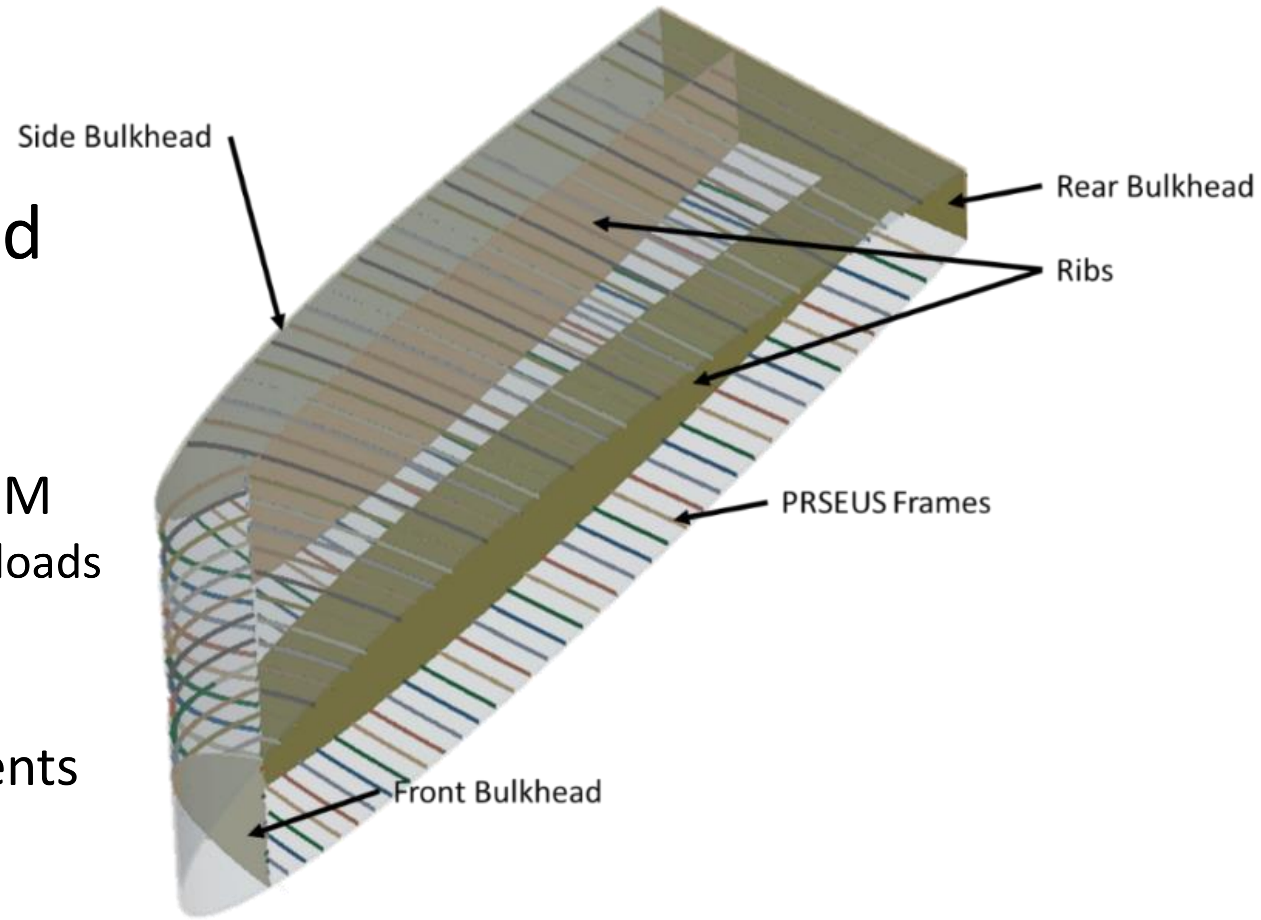


A_{CB}	Center Body Area [ft]
TOGW	Take-off Gross Weight [lbs]
FR	Fineness Ratio
θ_{CB}	Center Body Sweep [°]
SR	Span Ratio
$\rho_{f_{pass}}, \rho_{f_{cargo}}$	Passenger/cargo floor material density [lbs/ft³]
$t_{f_{pass}}, t_{f_{cargo}}$	Passenger/cargo floor thickness [ft]
f_{con}	Contour factor to account for contoured shape of the cargo floor
a-f	Parameter Coefficients
k_{no}	Non-optimum factor
k_{anchor}	Anchoring factor

$$FR = \frac{b_{CB}}{\ell_{CB}} \qquad SR = \frac{b_{CB}}{b}$$

Finite Element Model: Setup

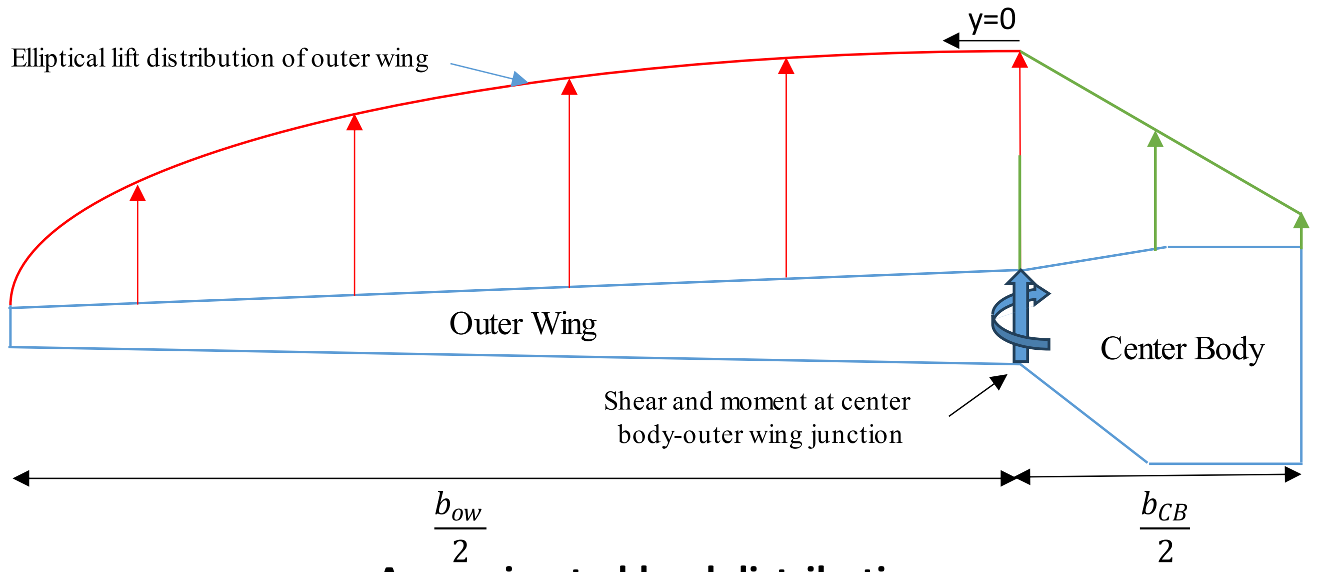
- OpenVSP and Python were used to create 1,296 Finite Element Models (FEM)
- Parameters ranges were chosen based on existing BWB concepts
- Assumptions and idealizations:
  - Outer wing and aft body are not included in FEM
    - Outer wing aerodynamic influence is included in loads
  - Constant thickness/chord of 17%
  - Five bays across all models
  - Cabin and cargo floor are non-structural elements and are not modeled



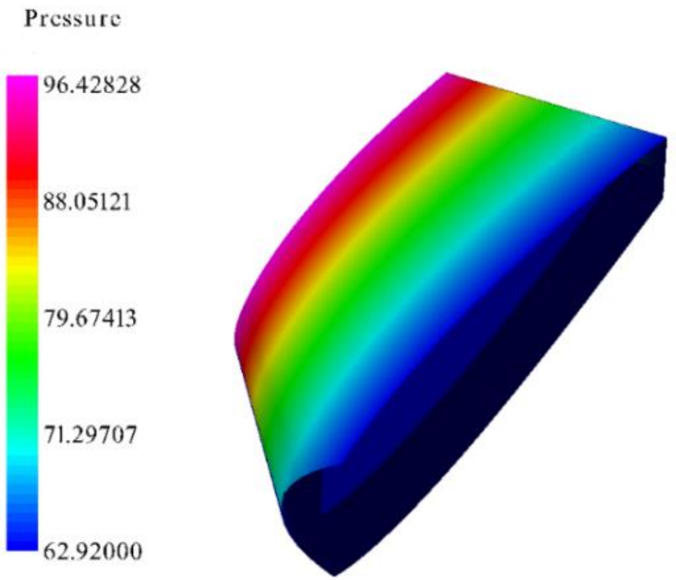
Example FEM and components

Finite Element Model: Loads

- Critical load cases:
  - 2P internal pressurization load
    - 20 psi applied to skin and bulkheads
  - 2.5g maneuver
    - Triangular loading applied to top surface of center body
    - Magnitude of loading dependent on TOGW, b_{cb}, and local chord
    - Aerodynamic load influence of outer wing is applied to center body using rigid body constraint, assuming elliptical lift distribution on outer wing
- Assumptions:
  - Center body contributes one third of lift
  - Lift = TOGW



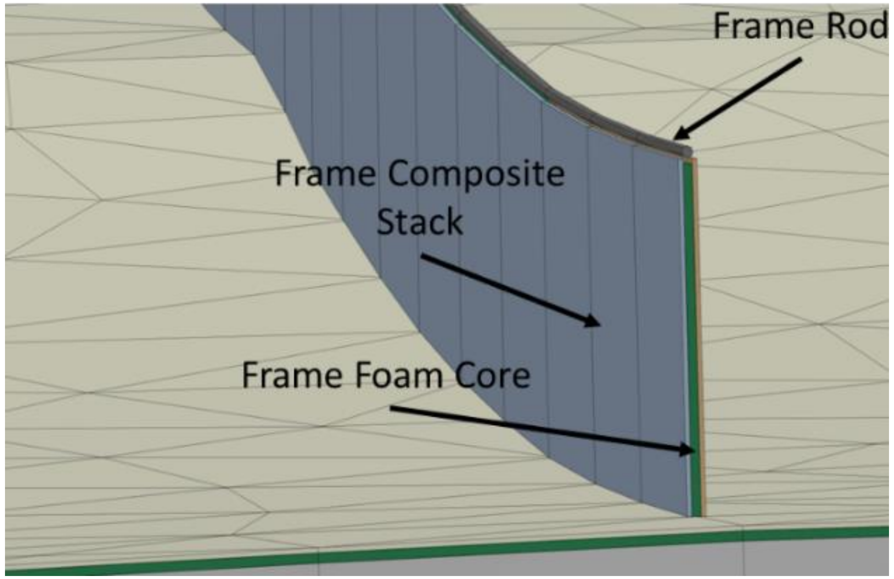
Approximated load distribution



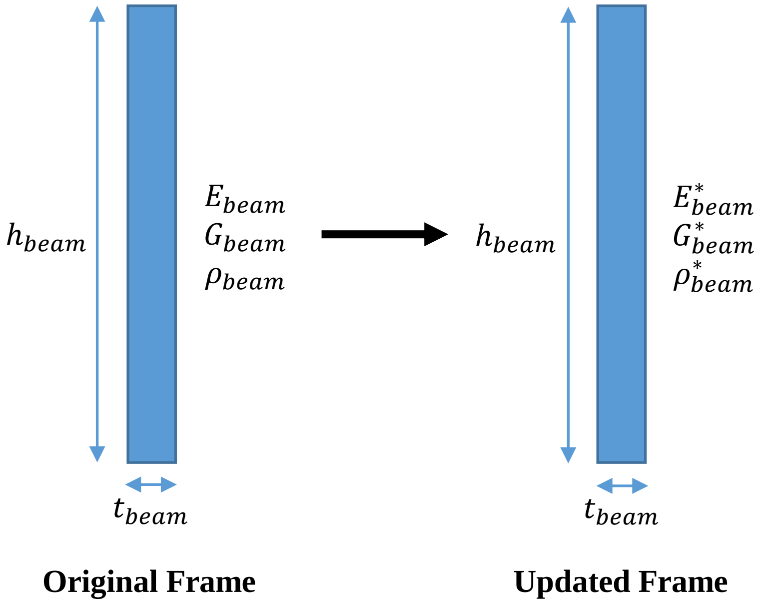
Triangular pressure distribution on top surface

Finite Element Model: Sizing Methodology

- PRSEUS panels (skin, stringer, and frames) are dimensioned to be consistent with Wu [1]
- Single design variable, PRSEUS frame height, was chosen to lower computational time
  - Sized to meet strain constraint
- Frame heights updated indirectly by varying material properties
- Calculix used as finite element program



PRSEUS frame modeling in Calculix



Indirect frame sizing

Results: Regression

- After running all 1,296 FEA cases, linear regression was used to calculate constants

Related Parameter	Coefficient	Value
-	a	105.95
A_{CB}	b	0.9700
TOGW	c	0.0020
FR	d	-0.7500
θ_{CB}	e	-0.6200
SR	f	-0.0008

- Structural MER:

$$w_{struct} = 105.95 \cdot A_{CB}^{0.97} \cdot TOGW^{0.002} \cdot FR^{-0.75} \cdot \theta_{CB}^{-0.62} \cdot SR^{-0.0008}$$

- A MER was developed to account for the weight of the passenger bay floor:

$$w_{f_{pass}} = A_{CB} \cdot \rho_{f_{pass}} \cdot t_{f_{pass}}$$

- An additional MER was developed to account for the weight of the cargo bay floor:
  - Cargo floor contour factor (f_{con}) is added to account for contoured shape of the cargo floor

$$w_{f_{cargo}} = f_{con} \cdot A_{CB} \cdot \rho_{f_{cargo}} \cdot t_{f_{cargo}}$$

- Joseph MER:

$$w_{CB} = k_{no} \cdot k_{anchor} \cdot (w_{struct} + w_{f_{pass}} + w_{f_{cargo}})$$

Results: Non-Optimum and Anchoring

- Joseph MER results anchored to results in paper by Velicki [7]
  - Finite Element Analysis (FEA) based comparison between a traditional composite and PRSEUS pressurized cabin
  - Velicki's model is very detailed with inclusion of structures which were not modeled in the Joseph MER
- Comparison to Velicki's FEM weight shows ~6% difference between the Joseph MER and Velicki's weight

A_{CB} [ft²]	θ_{CB} [°]	FR	TOGW [lbs]	SR	Joseph MER [lbs]	Velicki [lbs]	k_{anchor}
2,200	65	0.46	408,700	0.28	30,481	32,433	1.06

- Non-optimum factor of 1.20 applied, similar to Velicki [7]

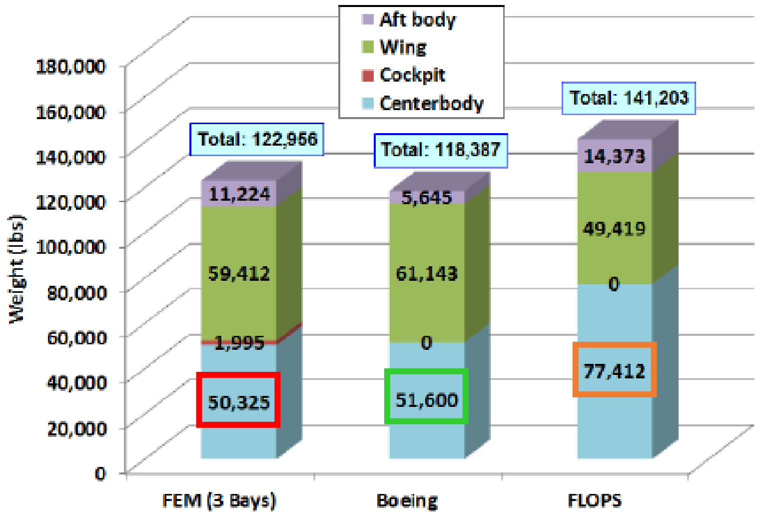
$$w_{CB} = 1.20 \cdot 1.06 \cdot 105.95 \cdot (A_{CB}^{0.97} \cdot TOGW^{0.002} \cdot FR^{-0.75} \cdot \theta_{CB}^{-0.62} \cdot SR^{-0.0008} + w_{f_{pass}} + w_{f_{cargo}})$$

Anchoring factor and non-optimum factor were applied to Joseph MER based on Velicki's high fidelity PRSEUS center body FEA [7]

Results: Validation

- Independent analysis by Gern compared [5] BWB cabin weights from FEM to a weight from Boeing and FLOPS (vehicle synthesis code which uses Bradley's MER)

Weight comparison between Gern's sources [5]



Cabin Weight Estimation Comparison between Gern, Boeing, FLOPS and Joseph MER

						Frank Gern Publication [5]		
A_{CB} [ft²]	θ_{CB} [°]	FR	TOGW [lbs]	SR	Joseph MER [lbs]	FEM [lbs]	Boeing [lbs]	FLOPS [lbs]
3,000	56	0.57	542,600	0.33	50,035	50,325	51,600	77,412

Results: Validation

- Independent analysis by Laughlin also found relationships between PAX and pressurized cabin weight [6]
  - Equivalent center body areas were calculated and were used to compare Gern, FLOPS (Bradley MER), Laughlin and Joseph MER results
- Lower weight prediction above 3,000 ft^2 could be due to sizing methodology used
  - Higher cabin areas might require greater stiffness in ribs and bulkheads, which are not sized
  - Internal NASA systems analysis studies have shown that A_{CB} and TOGW are generally under 3500 ft^2 and 500,000 lbs, respectively, for a 450 PAX configuration

Conclusions

- Newly developed MER (*Joseph MER*) was created to account for:
  - Advanced Pultruded Rod Stitched Efficient Unitized Structures (PRSEUS)
  - Additional vehicle parameters including:
    - Center body area
    - TOGW
    - Sweep
    - Fineness ratio
    - Span ratio
  - Anchored to Velicki's FEM pressurized cabin weight
  - Joseph MER shows good agreement with Laughlin and Gern's PRSEUS based FEM weight predictions of a Blended-Wing-Body (BWB) pressurized cabin
  - Comparison to Bradley MER used in FLOPS generally predicts higher pressurized cabin weights than the Joseph MER

BACKUP

References

[1] H.-Y. T. Wu, P. Shaw and A. Przekop, "Analysis of a Hybrid Wing Body Center Section Test Article," *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference,* 2013.

[2] R. H. Liebeck, "Design of the Blended Wing Body Subsonic Transport," *JOURNAL OF AIRCRAFT,* Vols. Vol. 41, No. 1, 2004.

[3] K. . R. Bradley, "A Sizing Methodology for the Conceptual Design of Blended-Wing-Body Transports," *NASA/CR-2004-213016,* 2004.

[4] Bowles J, Jegley D., "Personal Conversation regarding applicable factor to Bradley MER to account for PRSEUS" 4/27/2021.

[5] F. H. Gern, "Update on HCDstruct - A Tool for Hybrid Wing Body Conceptual Design and Structural Optimization," *15th AIAA Aviation Technology, Integration, and Operations Conference,* 2015.

[6] T. W. Laughlin, J. A. Corman and D. N. Mavris, "A Parametric and Physics-Based Approach to Structural Weight Estimation of the Hybrid Wing Body Aircraft," *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition,* 2013.

[7] A. Velicki, "Damage Arresting Composites for Shaped Phase 1 Final Report," *NASA/CR-2009-215932,* 2009

FEA (Calculix) Proposed Parameter Sweeps

- A combination of Area, Forebody Sweep, Take Off Gross Weight (TOGW) and Fineness Ratio was used for each case **totaling 1296 FEA cases** run out with Calculix.
- Minimum and maximum TOGW was determined using an estimated minimum and maximum cabin loading (gross weight/cabin area) of 80 lbf/ft2 and 120 lbf/ft2, respectively

Parameter						
Area Cabin [ft2]	1,750	2,000	2,200	3,000	4250	5,500
Forebody Sweep [°]	50	60	65	-	-	-
Fineness Ratio	0.46	0.5	0.6	-	-	-
Span Ratio	0.2	0.25	0.3	-	-	-

	Area (ft2)					
TOGW (lbs)	**1,750**	**2,000**	**2,200**	**3,000**	**4250**	**5,500**
1	140,000	160,000	176,000	240,000	340,000	440,000
2	163,333	186,666	205,333	280,000	484,500	513,333
3	186,666	213,333	234,666	320,000	556,750	586,666
4	210,000	240,000	264,000	360,000	629,000	660,000
5	262,500	300,000	330,000	450,000	701,250	825,000
6	320,833	366,666	403,333	550,000	773,500	1,008,333
7	379,166	433,333	476,666	650,000	918,000	1,191,666
8	437,500	500,000	550,000	775,000	1,062,500	1,375,000