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

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Blended-Wing-Body (BWB) achieve a higher L/D than conventional tube and wing aircraft due to aerodynamic shaping of the non-circular pressure vessel that is made feasible through advanced composite technologies such as Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS). Due to the relatively new nature of the BWB, sufficient historical data does not exist for conceptual aircraft designers to base their structural weight estimations on, especially for estimating weights of the pressurized cabin center body. This paper describes general parametric Mass Estimation Relationships (MERs) based on high fidelity finite element analysis using PRSEUS for estimating the weight of a BWB pressurized cabin structure that includes cabin area, center body sweep, fineness ratio, and take-off gross weight.

I. Nomenclature

BWB	=	Blended-Wing-Body
L/D	=	Lift to Drag ratio
T&W	=	Tube & Wing
PRSEUS	=	Pultruded Rod Stitched Efficient Unitized Structure
FEA	=	Finite Element Analysis
TOGW	=	Take Off Gross Weight
FEM	=	Finite Element Model
MSC	=	Multidisciplinary Structural Analysis
GASP	=	General Aircraft Synthesis Program
FLOPS	=	FLight OPtimization System
t/c	=	Thickness to Chord ratio
RHS	=	Right Hand Side
LHS	=	Left Hand Side
h	=	Height

B	=	Base
L	=	Length
E	=	Young's Modulus
G	=	Shear Modulus
rho	=	Density
1-D	=	1-Dimensional
3-D	=	3-Dimensional
v	=	Poisson's Ratio
g	=	Gravitational Force

II. Introduction

In the realm of aircraft design, innovation has always been the driving force propelling the industry forward. Among these innovations is the concept of the Blended Wing Body (BWB) aircraft. Unlike a conventional Tube and Wing (T&W) aircraft, with distinct fuselage and wing structures, the BWB integrates these two structures into a single, unified body. The unified body acts as an airfoil thus can be analyzed with airfoil theory unlike a conventional T&W. This concept has been popularized by the likes of Liebeck, who have reported on potential weight and fuel burn benefits of the BWB [1].

The center body of the BWB is unique, as it is a non-circular pressure vessel that relies on advanced composites technologies such as Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) to avoid structural failure and weight penalties imposed by both in- and out-of-plane loading [2]. Due to the relatively new nature of the BWB concept, historical data does not exist for conceptual aircraft designers to develop Mass Estimation Relationships (MERs), especially for estimating weights for the BWB pressurized center body. This results in the need to run computationally intensive high-fidelity methods, such as finite element analysis (FEA), to obtain more accurate weights of novel BWB configurations. Bradley was the first to endeavor creation of MERs for a BWB pressurized cabin center-body using conventional honeycomb structural material based on FEA for a combination of the cabin area and Take-Off Gross Weight (TOGW) [3]. An independent analysis was performed by Gern who created a program called HCDstruct, which allowed for the rapid building of BWB Finite Element Models (FEM) that could then be optimized using Multidisciplinary Structural Analysis (MSC) Nastran ®. Using HCDstruct, an optimized model was compared against Boeing reported data and showed good agreement [4]. Another independent analysis was performed by Laughlin, who created a modeling and simulation environment that could be used for multidisciplinary analysis and weight optimization of a BWB. Trade studies performed using this environment compared predicted center body weights with passenger count for a given BWB using Bradley, Gern, and Laughlin independent methods. The results of the trade studies showed non-linearity in center body weight once a passenger count of 300 was reached as well as the advantages of a 5-bay BWB for passenger counts greater than 300.

This paper describes the development of more general parametric MERs based on high fidelity finite element analysis using PRSEUS frames for estimating the weight of a BWB pressurized cabin structure that includes cabin area, center body sweep, fineness ratio, and TOGW.

III. Definition of Parameters

The definition of the center body is shown in Figure 1. The planform area of the cabin is calculated from Figure 1 by calculating the area of the triangle and rectangle comprised by the center body. Fineness ratio is defined as the ratio of center body width to length as shown in Figure 1. Center body sweep is defined by the angle created by the leading edge of the cabin. The TOGW is calculated for each area variation based on a wing loading from 80 to 250 $\frac{lb}{ft^2}$.

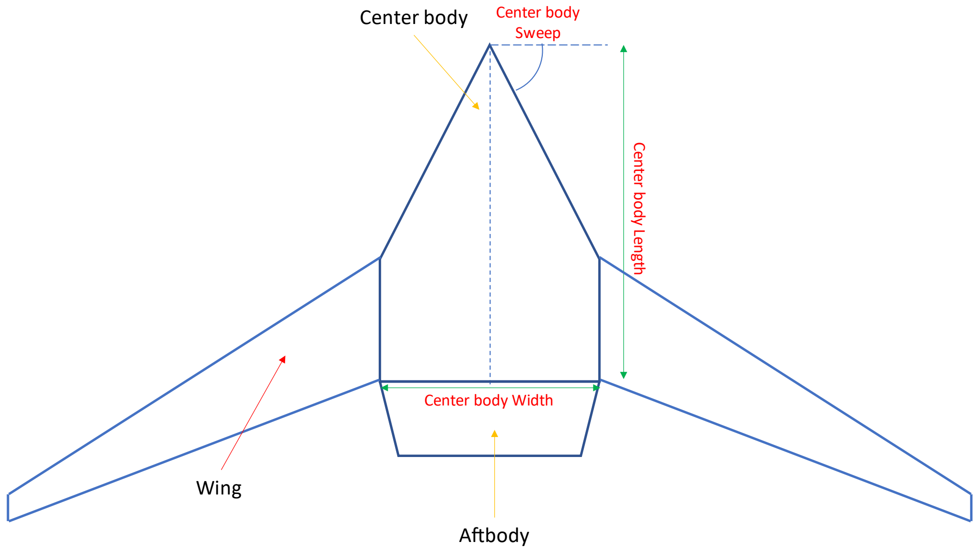


Figure 1: BWB Section Definitions

$$Fineness\ Ratio = \frac{Center\ Body\ Width}{Center\ Body\ Length} \tag{1}$$

IV. Improvements in Pressurized Cabin Weight Estimation

PRSEUS frames and stringers are modeled in the FEM allowing for an MER to be created that inherently considers the benefits of PRSEUS for all variations.

The addition of sweep and fineness ratio to the MERs allows for increased sensitivity to design changes and results in less uncertainty in the estimation of pressurized center body weights. The reduction in uncertainty in weights for the BWB is especially important, as a 10% increase in empty weight eliminates fuel burn benefits over a conventional T&W [5]. The MERs can be implemented in currently used aircraft synthesis programs, including the General Aviation Synthesis Program (GASP), Flight Optimization System (FLOPS), and Aviary, which can take advantage of the reduced uncertainty and greater accuracy to model and size a BWB for various missions.

V. Procedure

A. Parametric Variations

A total of 432 parametric variations were created using OpenVSP. Python scripts were used to prepare the input file created by OpenVSP for use in Calculix, an open-source finite element program. Parametric variations are shown in Table 1 and Table 2.

Parameter						
Cabin Area [ft^2]	1,750	2,000	2,200	3,000	4,250	5,500
Center body Sweep [°]	50	60	65	-	-	-
Fineness Ratio W/L	0.46	0.5	0.6	-	-	-

Table 1: Parametric variations of cabin area, center body sweep, and fineness ratio

	Cabin Area (ft^2)					
TOGW (lbf)	**1,750**	**2,000**	**2,200**	**3,000**	**4,250**	**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

Table 2: Variations of TOGW based on cabin area

B. Finite Element Model

Each of the parametric variations model assume centerline symmetry of the pressurized cabin of the BWB, which contains two ribs and the front, rear, and side bulkheads as shown in Figure 2. The resulting idealized cabin has a constant t/c of 17% and contains five bays. These structures were modeled using Calculix S6 elements.

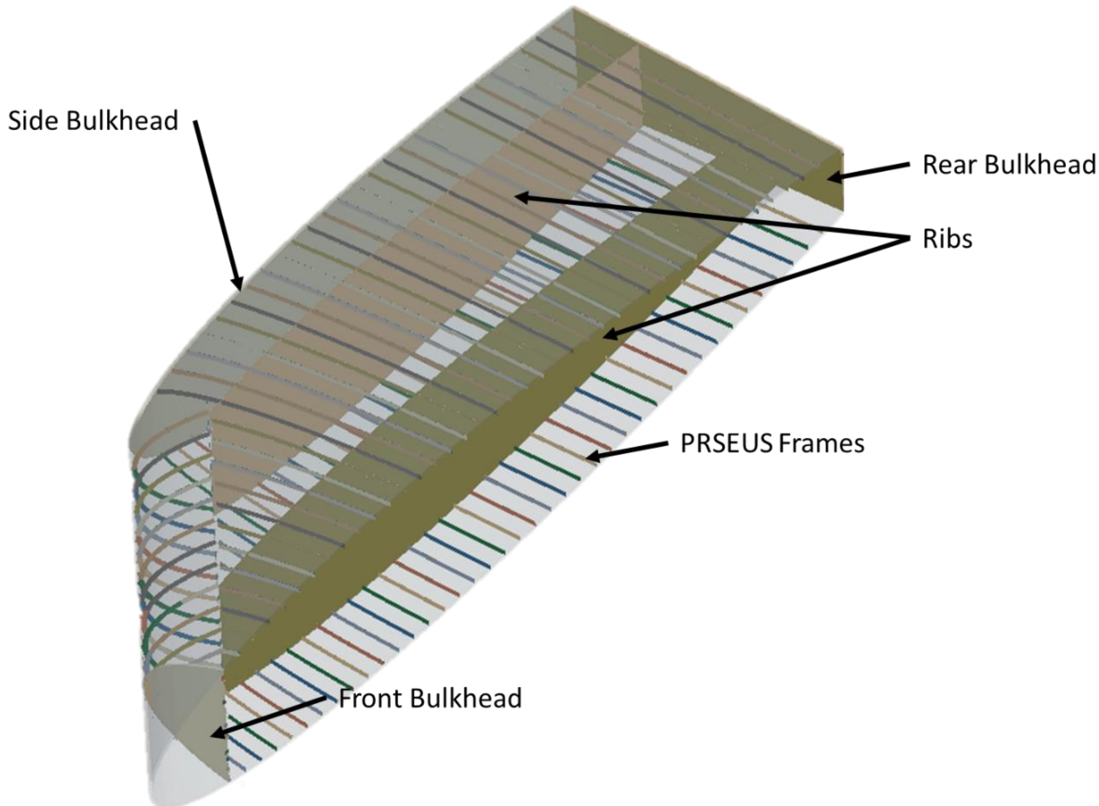


Figure 2: Structural breakdown of BWB Cabin

The parametric variations were built with explicitly modeled PRSEUS frames running spanwise and smeared PRSEUS stringers running chordwise. PRSEUS frames were modeled with Calculix B32 elements, shown in Figure 3, whereas PRSEUS stringers were modeled with S6 elements.

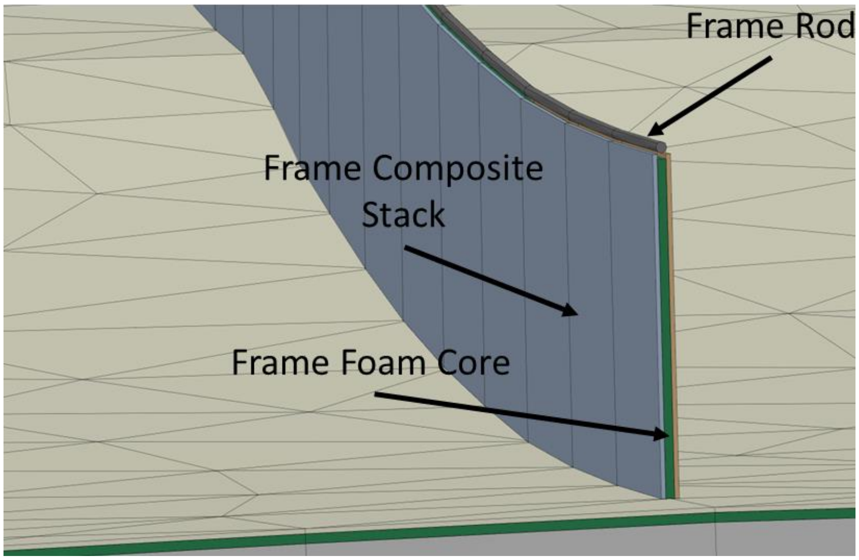
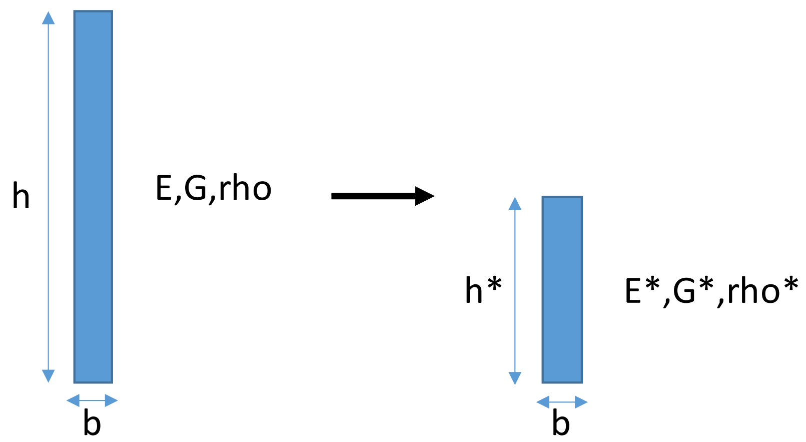


Figure 3: PRSEUS modeling in Calculix

PRSEUS frames were not modeled at full size due to curved surfaces leading to negative volumes when 1-D beam elements were expanded to 3-D elements internally in Calculix, resulting in negative Jacobians. Instead the PRSEUS frames were smeared down to a size that would allow for explicit modeling. The smeared properties were calculated by equating flexural rigidity, torsional rigidity, and density of the full size PRSEUS frames to reduced size PRSEUS frames, as shown in Figure 4. The length (L) of each PRSEUS frame varies between any given frame. As such, the smearing process is conducted for each PRSEUS frame independently and automatically with the use of Python.



$$E^* = \frac{Eh^3}{(h^*)^3}$$

$$G^* = \frac{GH(H^2 + L^2)}{H^*((H^*)^2+L^2)}$$

$$\rho^* = \frac{\rho H}{H^*}$$

Figure 4: Smearing process for PRSEUS frames

The spacing of the PRSEUS frames used are 24 inches and spacing of stringers are 6.0 inches [6]. Material properties of the IM7-8552 composite used is listed in [7], shown in Table 3. Tape is used for the skin and fabric is used for all other composite materials. Pultruded rod properties are listed in [6], shown in Table 4.

	E1 (msi)	E2 (msi)	ν	G12 (msi)	G13 (msi)	G23 (msi)
Tape	21.3	1.26	0.32	0.749	0.749	0.435
Fabric	9.58	9.55	0.052	0.738	0.492	0.492

Table 3: IM7-8552 Properties

	E1 (msi)	ν
Pultruded Rod	20.1	0.3

Table 4: Pultruded Rod Properties

C. Loads

The critical load case of the center body is considered to be the 2x internal pressure load case. The base internal pressure is chosen to be 10 psi with the 2x internal pressure being 20 psi [6]. This loading was applied to the skin and bulkheads of the center body.

In addition to the internal pressure load case, a 2.5g maneuver with a 1.5x safety factor load case was considered. Similar to [3], a triangular lift distribution was calculated for each variation and applied to the top skin of the center body. Pressures for each skin element were calculated as a function of TOGW, center body width, and chord. An example pressure distribution across the top of the center body with a 200,000 lbf TOGW, 105 ft root chord, 75 ft tip chord, and 60 ft full center body span is shown in Figure 5.

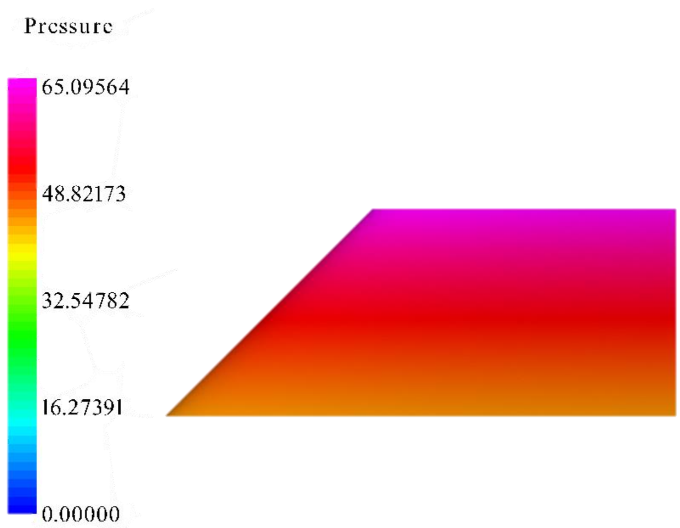


Figure 5: Top skin of center body with triangular lift distribution applied

D. Sizing of Center Body

The sizing of the center body involves modifying the heights of the PRSEUS frames to meet strain constraints of -0.0048 to $0.0059\ \mu\frac{in}{in}$ found in [6]. PRSEUS frame spacing and PRSEUS stringer dimensions and spacing were kept constant.

Although the PRSEUS frames were modeled explicitly, the frames were smeared to a shorter height. In a similar manner, modification of the height of the PRSEUS frames did not involve changing the physical height of the PRSEUS frames, rather the change of physical height was reflected in a change in material properties.

Python code was created to determine the max strain on each individual PRSEUS frame and sizes individual frames based on the maximum allowable strain to maximum observed strain ratio. After sizing, the model was rerun through the process until convergence of weight was achieved.

E. Regression using FEA Data

Three types of regression were explored to attempt to find the best fit to the data: linear, linear with table lookup, and exponential.

The linear regression method involves taking the logarithm of cabin area, sweep, fineness ratio, TOGW, and sized weight. This creates an A matrix on the LHS of size Nx5 and a B matrix on the RHS of size Nx1. Multiplying both sides by the transpose of the A matrix yields a 5x5 matrix on the LHS and a 5x1 on the RHS. These matrices can be solved to find the 5 constants. The process is outlined below from equations (2) to (5).

$$w_{centerBody} = a * Area^{b} * TOGW^{c} * Fineness^{d} * Sweep^{e} \tag{2}$$

$$ln(w_{centerBody}) = ln(a) + b * ln(Area) + c * ln(TOGW) + d * ln(Fineness) + e * ln(Sweep) \tag{3}$$

$$\begin{bmatrix} 1 & ln(Area_1) & ln(TOGW_1) & ln(Fineness_1) & ln(Sweep_1) \\ 1 & ln(Area_2) & ln(TOGW_2) & ln(Fineness_2) & ln(Sweep_2) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & ln(Area_N) & ln(TOGW_N) & ln(Fineness_N) & ln(Sweep_N) \end{bmatrix} \begin{bmatrix} ln(a) \\ b \\ c \\ d \\ e \end{bmatrix} = \begin{bmatrix} w_{centerBody_1} \\ w_{centerBody_2} \\ \vdots \\ w_{centerBody_N} \end{bmatrix} \quad (4)$$

$$A^T \vec{x} A = A^T \vec{b} \quad (5)$$

The linear regression with table lookup method follows the same method as the regular linear regression outlined above; however, the parameter of center body area is excluded from the regression. To account for center body area, a lookup table is generated that contains mean FEM weights after the sizing process for each center body area variation, shown in Table 5. The form of the center body weight estimation equation for the linear regression with table lookup method is shown in equation (6).

Area	Mean FEM Weight [lbf]
1,750	10,594
2,000	12,429
2,200	13,765
3,000	17,143
5,500	41,836

Table 5: Table lookup for center body area

$$w_{centerBody} = F[Area] * a * TOGW^b * Fineness^c * Sweep^d \quad (6)$$

The exponential regression method uses the SciPy curve fit function in order to calculate the constants using cabin area, sweep, fineness ratio, TOGW, and sized weight as parameters. The form of the center body weight estimation equation for the exponential regression is shown in equation (7). Final coefficients for each method are shown in Table 6.

$$w_{centerBody} = a * b^{Area} * c^{TOGW} * d^{Fineness} * e^{Sweep} \quad (7)$$

Coefficient	Linear	Linear (Table Lookup)	Exponential
a	26.02	16.18	27564.06
b	1.17	0.005	1.000353
c	0.003	-0.70	0.985655
d	-0.69	-0.81	0.266377
e	-0.81	-	1.000000

Table 6: Regression coefficients

F. Center Body Floor MER

The floor of the center body was not modeled in the FEM as it was not considered a structural member. Instead, a second MER was created to account for the weight contribution. The floor MER is based on the area of the center body, density of the floor, and the thickness of the floor. An aluminum honeycomb core with composite faces was assumed for the floor [3]. Material properties of the composite faces remain the same as the fabric used for the PRSEUS frames and stringers. The material properties used for the aluminum honeycomb core was found in [3].

$$w_{floor} = \mathbf{Area_{cabin}} * \boldsymbol{\rho}_{\mathbf{floor}} * \mathbf{Thickness_{floor}} \tag{8}$$

G. Anchoring of Results

The FEM created for each of the parametric variations is idealized, thus the sized FEM weight will likely be an underestimate as compared to a FEM with greater detail. As such, an anchoring factor, k_{anchor}, was required to anchor the sized FEM weights to a detailed FEM. The detailed FEM chosen was referenced from Velicki's paper, which reported a PRSEUS based center body structural weight of 32,433 lbf [8]. It was noted that this weight contained some non-optimum factors, so a 1.5x non-optimum factor, k_{no}, is used in the Joseph 2024 MERs, separate from the anchoring factor. Estimation of the geometric parameters of Velicki's model result in an area of 2000 ft^2, sweep of 60°, fineness ratio of 0.46, and TOGW of 408,700 lbf. Each of the regression methods were used to estimate the center body weight, including the 1.5x non-optimum factor. The anchoring factor can then be calculated for each regression method by comparing the center body weight estimation to the anchor weight from Velicki.

	Linear	Linear (Table Lookup)	Exponential
Joseph 2024 MER x 1.5 [lbf]	22,391	22,966	22,601
k_{anchor}	1.448	1.412	1.435

Table 7: Anchoring of various regression methods to Velicki's center body weight of 32,433 lbf

VI. Results

The three final MERs to estimate the weight of the center body were created to reflect the three regression methods used and are shown in equations (9) to (11). The MERs include a 1.5x non-optimum factor and the respective anchoring factor for the regression method from Table 7.

$$w_{centerbody} = 1.5 * 1.448 * (26.02 * Area_{cabin}^{1.17} * TOGW^{0.003} * FR^{-0.69} * Sweep^{-0.81} + w_{floor}) \tag{9}$$

$$w_{centerbody} = 1.5 * 1.412 * (F[Area] * 16.18 * TOGW^{0.0049} * FR^{-0.7} * Sweep^{-0.81} + w_{floor}) \tag{10}$$

$$w_{centerbody} = 1.5 * 1.435 * (27564 * 1.00035^{Area_{Cabin}} * 0.98565^{Sweep} * 0.26637^{FR} * 1^{TOGW} + w_{floor}) \tag{11}$$

VII. Validation of Results

To validate the MERs, comparisons were made to other sources that reported BWB center body weights with enough information to estimate parameters used. Gern used HCDstrut to optimize a BWB and reported a center body weight of 50,325 lbf with estimated area of 3250 ft^2, sweep of 70°, fineness ratio of 0.42, and TOGW of 475,800 lbf. This was compared against a Boeing reported value of 51,600 lbf for a BWB with the similar geometric parameters. FLOPS, an aircraft synthesis program that uses Bradley's cabin MER, was also used for comparison [4]. The percent differences between the Joseph 2024 MERs and various Gern sources for estimated cabin weight is shown in Table 9. The MERs comes within 4-10% of the value reported by Boeing, depending on the method of regression used. Reference values from Gern are shown in Table 9.

	Joseph 2024		
	Linear	Linear (Table Lookup)	Exponential
Gern	6.5	-3.1	-7.0
Boeing	4.1	-5.7	-9.7
FLOPS	-43.9	-58.6	-64.6

Table 8: Percent differences between Joseph 2024 MERs and various Gern sources for estimated cabin weight

Gern [lbf]		
FEM w/ PRSEUS	Boeing	FLOPS
50,325	51,600	77,412

Table 9: Reference estimated cabin weights from Gern

Laughlin's trade study contained estimated center body weights for BWBs ranging from 98 to 400 passenger count. Reported in addition was weights estimated by Gern's method and FLOPS, which uses Bradley's cabin MER [9]. The geometric parameters estimated are shown in Table 10. Estimates for Laughlin, Gern, FLOPS, and Joseph 2024 methods are plotted in Figure 6. It is important to note that Laughlin and Gern explored both 3-bay and 5-bay variations of the BWB, whereas the Joseph 2024 MERs explores only the 5-bay variation.

Below an area of 3000 ft^2 there is a good agreement for the Joseph 2024 MERs with both Laughlin and Gern, whereas above an area of 3000 ft^2 the Joseph 2024 MERs underestimates for the given parameters.

Area [ft^2]	Sweep [°]	Fineness	TOGW [lbf]
1,012.40	51.7	0.77	101,000
1,604.00	50.4	0.758	166,100
2,069.50	54.9	0.637	286,900
3,002.10	56	0.565	542,600

Table 10: Geometric parameters estimated from Laughlin's trade study

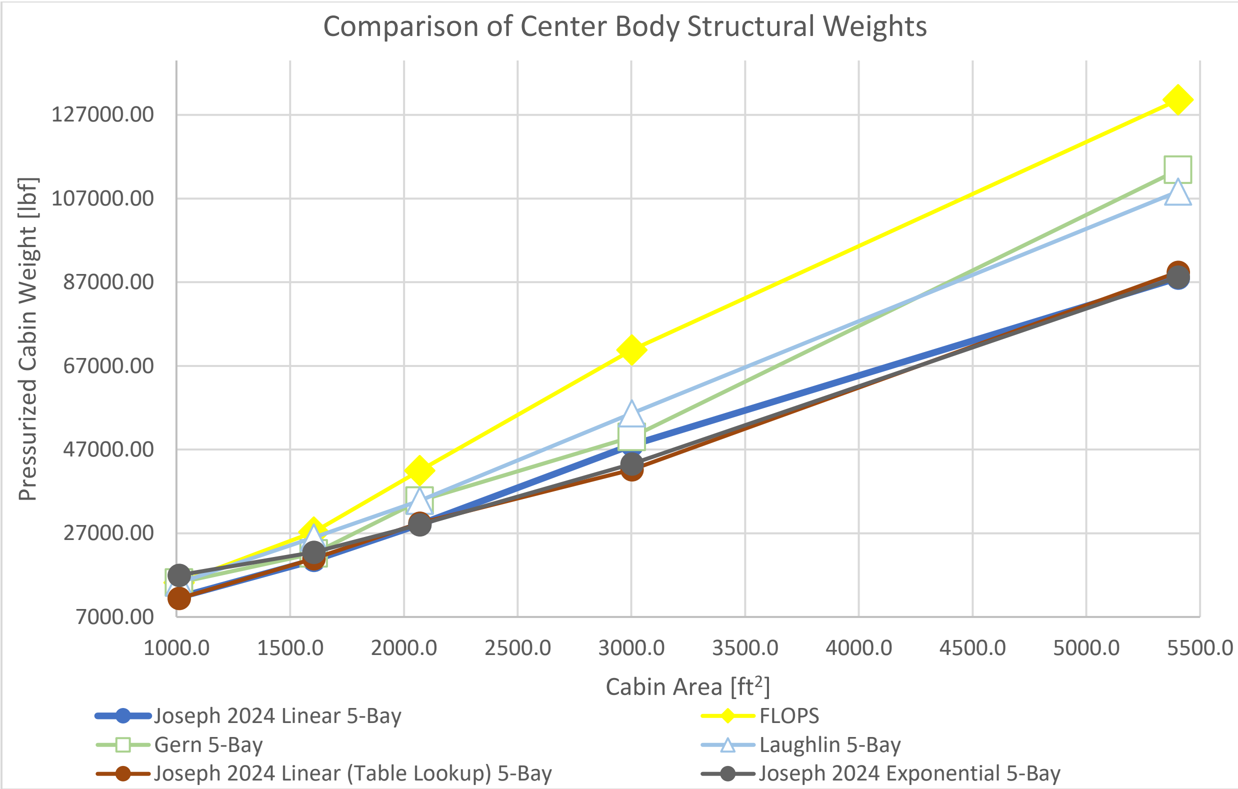


Figure 6: Comparison of center body weights for different estimation methods

VIII. Conclusions

The benefits promised by the blended-wing-body (BWB) concept have created a need for compact and accurate methods that are more time efficient and less computationally expensive to estimate pressurized cabin weights. The mass estimation relationships (MERs) presented in this paper were developed on finite element methods and anchored to a detailed advanced structural finite element analysis. Pressurized cabin weight estimates compared well below an area of 3000 ft^2 while estimating reduced cabin weight over an area of 3000 ft^2 when compared to other independent cabin weight estimates. The Joseph 2024 MERs accounts for a greater set of vehicle parameters including cabin area, take off gross weight, sweep, and fineness ratio to enable its use in vehicle synthesis programs to assess benefits over conventional tube and wing aircraft and explore optimization of BWB aircraft.

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