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TRUSS-BRACED WING USING THE HIGHER-FIDELITY CONCEPTUAL DESIGN
AND STRUCTURAL OPTIMIZATION TOOL

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Aerostructural Weight Estimation for a Transonic Truss-Braced Wing using the Higher-fidelity Conceptual Design and Structural Optimization Tool

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Continued development and enhancements of the Higher-fidelity Conceptual Design and structural optimization (HCDstruct) tool have been driven largely by advanced aircraft concepts of interest to NASA. While previous versions of HCDstruct were limited to hybrid wing body (HWB) and generalized tube and wing (TW) aircraft concepts, the latest version of HCDstruct supports the analysis of Truss-Braced Wing (TBW) aircraft concepts, enabling users to model both high and low wing configurations as well as strut and jury geometries parametrically. Additionally, new methods for modeling advanced composite materials within HCDstruct have been implemented. These recent tool enhancements were demonstrated for an independent assessment of the NASA/Boeing SUGAR Phase VI Mach 0.8 Transonic Truss-Braced Wing (TTBW) concept.

Nomenclature

BWB	= Blended Wing Body
CLPT	= Classical Laminate Plate Theory
CBEAM	= NASTRAN Beam Structural Element
FEM	= Finite Element Model
FLOPS	= Flight Optimization System
GRID	= NASTRAN Structural Node
HCDstruct	= Higher-fidelity Conceptual Design and structural optimization
HWB	= Hybrid Wing Body
LaRC	= Langley Research Center
MPC	= Multi-Point Constraint
OML	= Outer Mold Line
OpenVSP	= Open Vehicle Sketch Pad
PBEAML	= NASTRAN Beam Properties
SUGAR	= Subsonic Ultra Green Aircraft Research
TTBW	= Transonic Truss-Braced Wing
TW	= Tube and Wing
TS	= Tensile Strength
ν	= Poisson's Ratio

I. Introduction

Sizing of conventional aircraft concepts is commonly performed using low-order regression methods with databases of relevant configuration data, such as those used in the Flight Optimization System (FLOPS) tool.¹ However, these methods are ill-suited for application to unconventional aircraft concepts such as the hybrid wing body (HWB) or blended wing body (BWB) concepts due to their highly integrated structures and streamlined outer mold line (OML). Similarly, past efforts to structurally size double-bubble fuselage configurations^{2,3} using conventional sizing methods have suggested a need for more advanced

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approaches. In order to meet this demand, the Higher-fidelity Conceptual Design and structural optimization (HCDstruct) tool⁴ was significantly enhanced to include a generalized tube and wing (TW) airframe sizing capability, as described in Ref. 5, and most recently to include a truss-braced wing configuration.

NASA and its industry partners have devoted great effort in recent years to the advancement of a Transonic Truss-Braced Wing (TTBW) airframe, as depicted in Fig. 1. With the demand for rapid airframe sizing analyses, this paper highlights the most recent HCDstruct development of a truss-braced wing airframe sizing capability, as well as further consideration of application of advanced materials models. These tool enhancements are described in the current paper in sections II.A and II.B, respectively. Weight prediction comparisons with independent Boeing models and FLOPS models are detailed in III.B. Finally, a summary of the work and a discussion of future work is provided in section IV.



Figure 1. High aspect ratio Transonic Truss-Braced Wing configuration (NASA Photo).

II. HCDstruct Development

HCDstruct was developed at NASA Langley Research Center to fill a critical analysis gap between lower order approaches commonly used for conceptual design and higher order approaches based on finite element optimization, which are commonly used in preliminary design. Specifically, HCDstruct was developed to complement FLOPS, a sizing and synthesis code for conceptual and preliminary design and analysis of advanced aircraft concepts. However, the design sensitivities associated with off-design conditions are generally inaccessible by simplified approaches such as the regression-based sizing algorithms^{1,6} used by FLOPS. While the detailed finite-element-based sizing analyses often performed later in the design cycle may theoretically offer such insights, the computational resources required for these efforts often limit them to single-point design analysis. Thus, HCDstruct was developed to bridge the gap between the FLOPS empirical-based sizing techniques (based on historical and experimental data) and current physics-based finite-element approaches. In fact, the tool has evolved to provide a means of optimizing the primary structure for the fuselage and wing for a given aircraft configuration using finite element methods while only requiring FLOPS-level user input.

As new advanced concepts and configurations are formulated, the modeling capabilities available in HCDstruct must keep pace in order to provide the critical physics-based aerostructural sizing needs for concept designers and analysts. Most recently, these tool advancements have focused on development of a modeling capability for TTBW configurations.

A. TTBW Geometry Capability

The TTBW geometry utilizes a strut and jury to achieve a high aspect ratio wing that is structurally sound. The guiding objective of this work was to independently assess the airframe weight for a TTBW concept. Previously, HCDstruct only supported a low wing position on tube and wing bodied aircraft. With the recent additions to the code, the user can now define the location of the wing to be fixed with MSC NASTRAN multipoint constraints (MPC)⁷ either to the belly or top of the fuselage. The user can specify the location and dimensions of the strut and jury, as well as the types of joints used to connect these components to the wing or fuselage.

1. Strut and Jury

Referencing a geometry model, such as OpenVSP,⁸ one can determine the location on the wing where the strut and jury are fastened. HCDstruct allows the user to define the percent of span and chord where the

upper end of the strut and jury will be secured on the wing. HCDstruct will calculate the coordinate location on the wing and select the nearest NASTRAN structural node (GRID) on the wing. Similarly, a GRID point on the fuselage is also determined for the strut connection. Once HCDstruct calculates these two points (one on the wing and the other on the fuselage), it will generate an equation of a line between those two points used to generate GRID coordinates and element lengths. The user defines the number of NASTRAN structural beam elements (CBEAM⁷) desired across the strut and the code will generate the appropriate number of GRID points along that line. The same process is used for the jury, only it uses one grid point on the wing and one on the strut.

The main strut and jury are created in the Finite Element Model (FEM) using CBEAM elements and defined by the NASTRAN beam properties (PBEAML). PBEAMLs are used to define element cross sections and material types.⁷ The reason for this approach is that the strut for the TTBW is a tapered component and the CBEAM allows for the user to define different cross sections at the wing and fuselage. Just as the user defined the locations for contact at the wing and fuselage, it is also necessary to define the cross-sectional area at both ends of the component. The cross-sectional type for the CBEAM is square channeling, referred to in NASTRAN as “type= BOX”. With the two areas for each component defined, HCDstruct will uniformly create each element connecting the nodes previously generated, resulting in a tapered beam of the desired cross sections, which is also useful in the optimization. NASTRAN SOL 200⁷ will optimize the weight for the wing and fuselage, which use SHELL elements, by optimizing individual shell thicknesses.⁹ For the strut and jury, however, the optimized parameter is cross sectional area. Figure 2 shows the generated HCDstruct FEM.

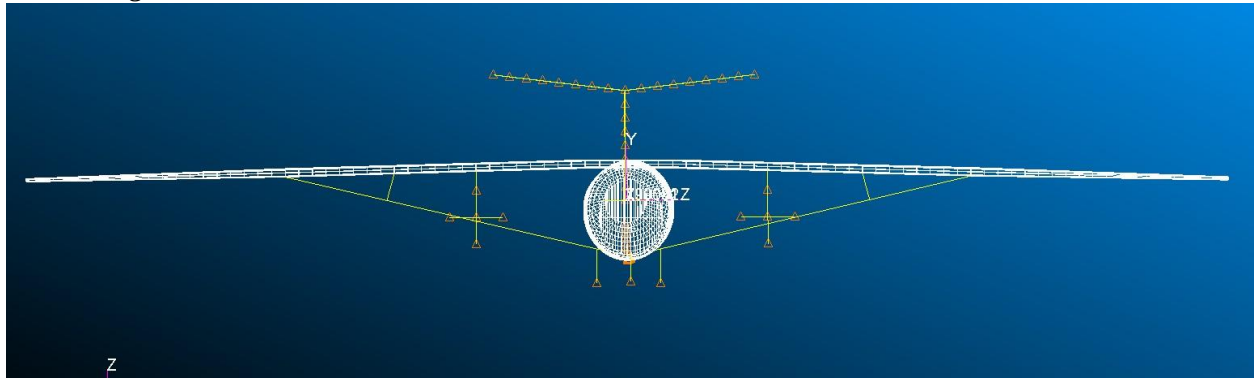


Figure 2. HCDstruct FEM of the TTBW geometry.

2. Joint Connections

Once the strut and jury are created with nodes and elements, it is necessary to create the boundary conditions at the end points. Having just generated the nodes and elements, the strut and jury are free from constraints, not having been attached to the rest of the airframe. For the specific application of the TTBW, there are two joint structures under consideration, including a conventional fixed joint, where there are no degrees of freedom, and a pinned connection, where there is one degree of freedom allowing rotation about the x-axis. There are a number of ways one can incorporate these boundary conditions; for this work the boundary conditions were implemented via NASTRAN RJOINTs.⁷ RJOINTs allow the user to select the two nodes being constrained together. For this case, the four locations are the upper strut node to wing node, upper jury node to wing node, jury lower node to strut node, and strut lower node to fuselage node, as shown in Fig. 3. An RJOINT allows for six degrees of freedom: translation along the x, y, z axes and also rotation about these axes. These are denoted in the RJOINT using integers 1 through 6. The integer is present for no degree of freedom and omitted if a degree of freedom is allowed. For example, the RJOINT for a fixed connection where there are no degrees of freedom allowed at the joint would be defined as:

RJOINT, strut node number, wing node number, 123456

For the pinned connection the RJOINT would be defined as:

RJOINT, strut node number, wing node number, 12356

With the “4” being omitted, it allows rotation about the x-axis. The six digits correspond to $T_x T_y T_z R_x R_y R_z$ (T_x = translation on the x-axis, R_x = rotation about the x-axis, and so on). If desired, other joint connections could be considered as well by allowing for more degrees of freedom.

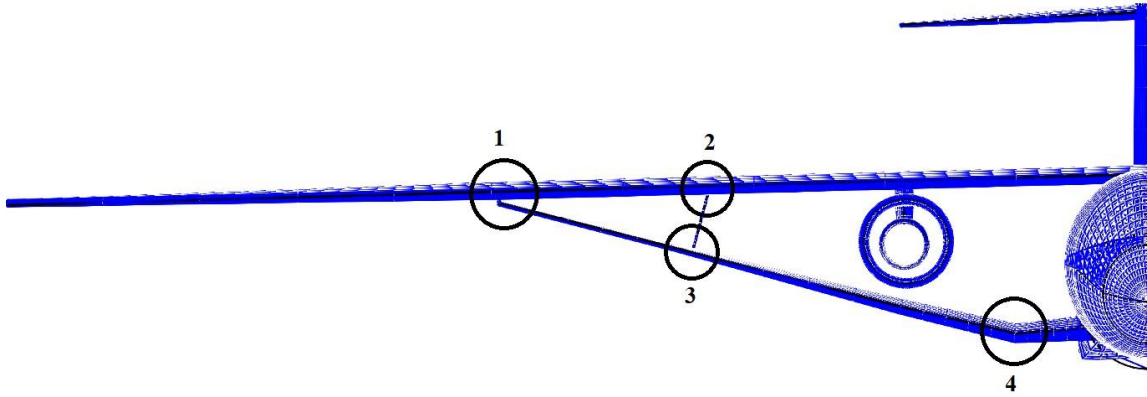


Figure 3. Half geometry model depicting the joint connections of interest.

B. Advanced Composites

Currently, HCDstruct only supports isotropic material inputs. Most of the unconventional concepts under consideration utilize non-isotropic, advanced composite materials, which introduce various modeling complexities. However, the aim of HCDstruct is to remain a mid-fidelity, rapid analysis tool. Rather than updating the code base to model and optimize each lamina layer of the composite material, the material properties were calculated by assuming a consistent laminate throughout each component that is isotropic, or at least quasi-isotropic. The material considered in this study was the IM+/3960.¹⁰

Using Classical Laminate Plate Theory (CLPT) and a standard $[\pm 45, 90, 0]$ symmetrical layup, the material characteristics longitudinal to the span of the wing were calculated and are presented in Table 1. These CLPT values of the IM+/3690 material were used to characterize the wing. The fuselage, strut, and jury were defined with a comparable material used by an industry partner.¹¹

Table 1. CLPT values calculated from IM+/3960.

E_1	6.95 Ksi
G_{12}	3.80 Ksi
ν	0.32
TS	55.4 Ksi

III. Transonic Truss-Braced Wing (TTBW) HCDstruct Analysis

A. Minimum Gauge and Nonstructural Factor Estimation

In order to ensure the model was not artificially constrained, sensitivity studies were conducted on the minimum gauge of shell elements and a nonstructural factor. Increasing these two values would yield an expected increase in airframe weight. The minimum gauge is designed to capture the manufacturability limitations of the structural elements and is implemented within the HCDstruct model as a thickness constraint on the shell elements. The sensitivity study consisted of developing several HCDstruct TTBW FEM models, each with unique minimum gauge values ranging from 0.01 to 1.0 inches. Referencing Fig. 4 and Fig. 5, it can be seen that the minimum gauge for shell elements on the fuselage and wing have a positive correlation with their respective weights. An estimated skin thickness for the wing was determined by the given layup sequence and the individual ply thickness. From Fig. 6, a minimum gauge estimate was made by taking the total thickness from the skin to the end of the stringer; however, since that is not the uniform thickness across all areas of the wing, the minimum gauge was assumed to be approximately 25% of that total thickness, resulting in a minimum gauge of 0.25 inches. For the fuselage, the minimum gauge of 0.15 inches is based on a similar fuselage used and calculated in a previous study.⁵

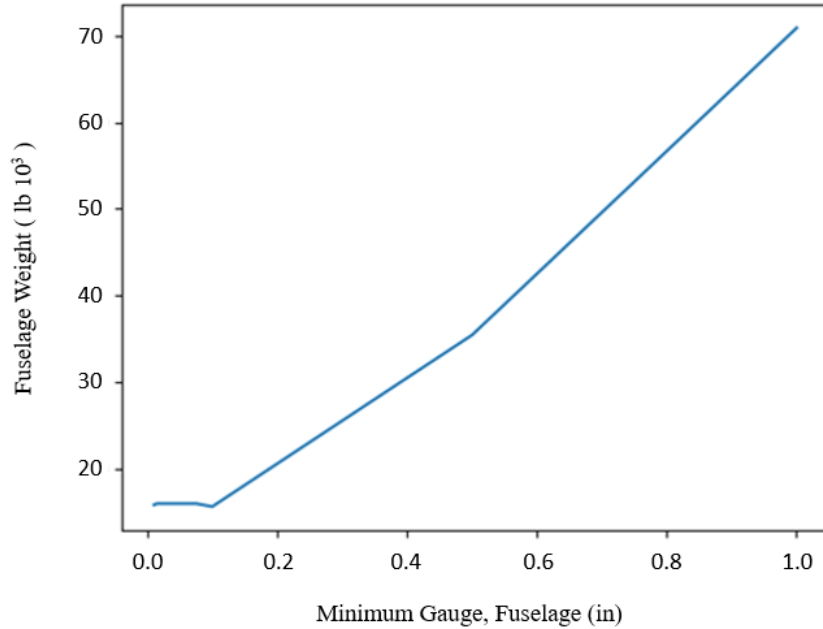


Figure 4. Fuselage weight as a function of varying minimum gauge values.

The nonstructural factor is designed to capture the structural weight growth of the fuselage and wing components associated with secondary and tertiary structural elements and design features not captured through the sizing of the primary structure. Like the minimum gauge, as this value increases (given the model is not artificially constrained) one would expect to see the component weights increase. Figures 7 and 8 show the plots of the fuselage and wing weights as functions of the nonstructural factor. The strong correlation between structural weight estimates and the nonstructural factor are apparent, thereby demonstrating the need to calibrate the factor.

The SUGAR Phase IV final reports¹¹ contained a weight breakdown for the wing structure that permitted estimates for the nonstructural factor. Unfortunately, the data was not detailed enough to estimate a single value. Instead, using two interpretations of the available data, estimates for the minimum and maximum

bounds of the nonstructural factor were computed as 1.75 and 2.15, respectively. A parametric weight estimation across this range was conducted to help understand the trade space, and the final nonstructural factor value was set to 1.95 for the wing by averaging the minimum and maximum estimates. The resulting weight predictions were comparable to those presented in the SUGAR Phase IV Report and those obtained from an analysis framework combining FLOPS with a joint Georgia Tech and Virginia Tech wing weight methodology.¹² For the fuselage, a nonstructural factor of 1.74 was used based on the factor calculated from data on the Boeing 737-200 and assuming a similar fuselage structural design and weight breakdown.

B. Weight Prediction and Comparison

The final FEM of the TTBW was created in HCDstruct with the custom integration of the strut and jury, as shown previously in Fig. 2. The structural weight was optimized using NASTRAN SOL 200 while subject to stress and strain constraints and a suite of sizing maneuver static aeroelastic solutions using SOL 144. Figure 9 depicts the comparison of the predicted NASTRAN values with those values obtained from the Boeing SUGAR Phase IV report and FLOPS. The FEM model results in a weight prediction well within 5% of the other two methods. The component weights also match relatively well to the other methods, noting that FLOPS does not distinguish between the wing, strut, and jury weights individually.

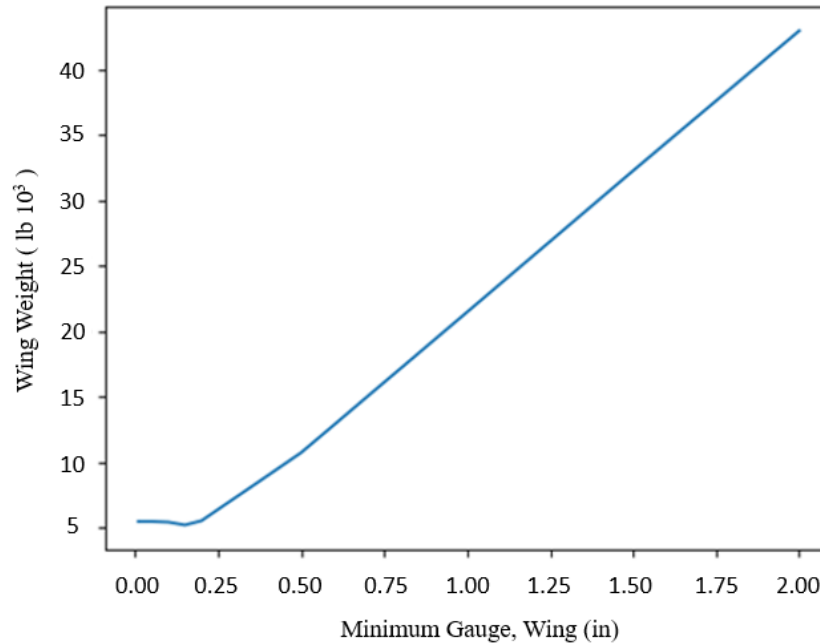


Figure 5. Wing weight as a function of varying minimum gauge values.

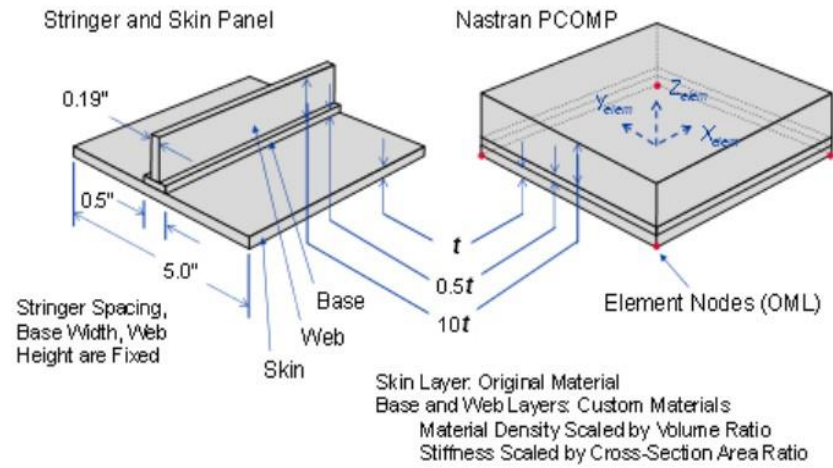


Figure 6. Composite laminate representation of the stiffened panels.¹¹

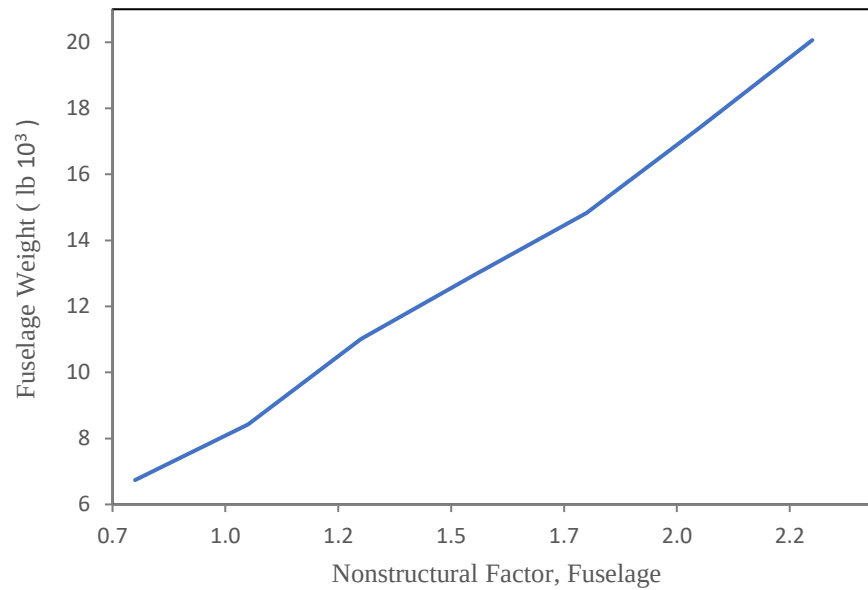


Figure 7. Fuselage weight as a function of varying nonstructural factor.

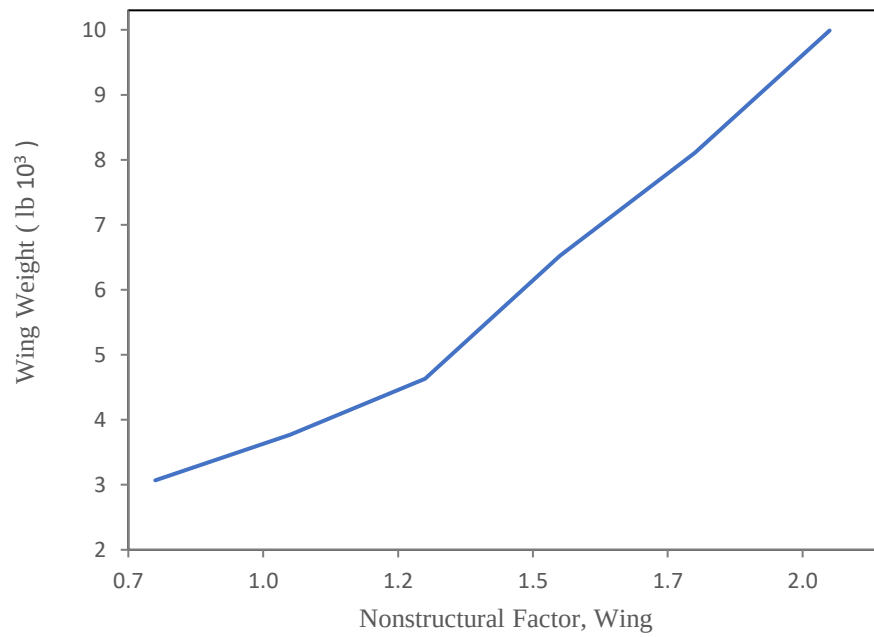


Figure 8. Wing weight as a function of varying nonstructural factor.

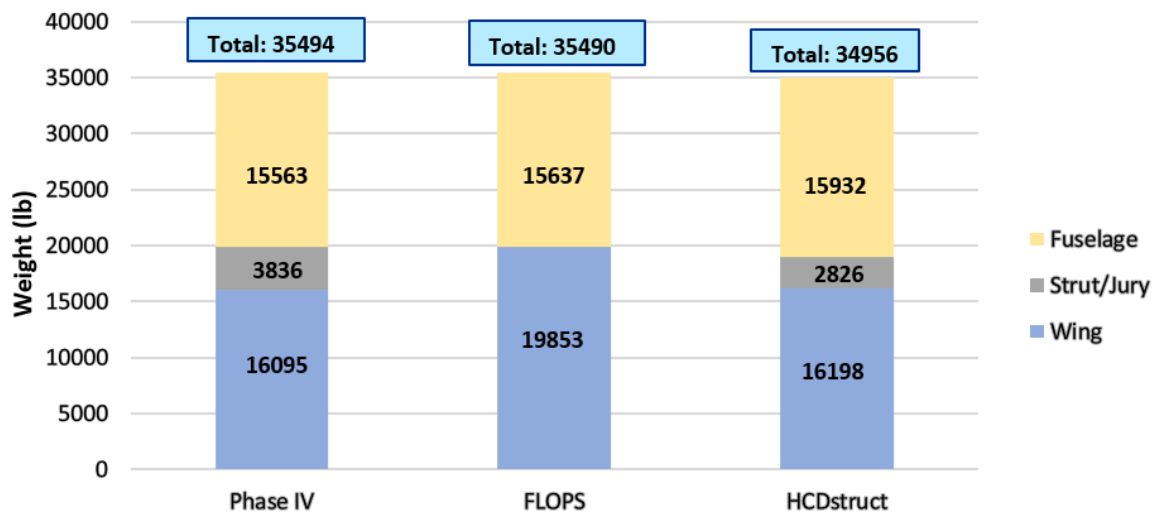


Figure 9. Comparison of the predicted total as well as component weights from the Boeing SUGAR Phase IV report, FLOPS, and HCDstruct.

IV. Summary and Future Work

In this paper, recent modifications to HCDstruct required to support a TTBW configuration were presented. These modifications included the capability for a user to attach the wing either to the top or belly of the fuselage using NASTRAN MPC constraints. For high wing configurations, further developments made it possible to define and generate a strut and jury as supports to a high aspect ratio wing. The user can now define cross sectional areas as well as contact points on the wing and fuselage. HCDstruct populates the distance between end points of the strut and jury with NASTRAN GRID points, and connects them with CBEAM elements completing the structural component. Stress and strain constraints are applied to the SOL 200 optimization analyses to output predicted weights.

Prior to this study, HCDstruct did not offer advanced composites materials modeling capabilities. In this work, Classical Laminate Plate Theory was used to calculate the assumed isotropic properties for composite materials used in the wing. Sensitivity studies were conducted on two input parameters, the minimum gauge of the shell elements and the nonstructural factor. A nonstructural factor is used to capture secondary and tertiary structures not explicitly modeled in the FEM. These both showed strong correlation in the predicted weight outputs. The appropriate minimum gauge was estimated using knowledge of the lamina thickness and layup sequence, as well as information on stiffened panels from the Boeing SUGAR Phase IV report. The nonstructural factor was calculated using data found in the Boeing report as a basis. The outcome of the work presented was an aircraft weight prediction within an acceptable percent difference of the Boeing SUGAR model and the independent assessment from FLOPS.

Ongoing work includes HCDstruct integration into a larger, multidisciplinary framework being constructed using OpenMDAO.¹³ Many of the steps and inputs required to generate an HCDstruct model can and will be automated when connected to the appropriate disciplines that present the required data and inputs (for example, mission analysis and subsystem weight data derived in FLOPS). Additional ongoing development focuses on design capabilities for joint structures and wing design, which will allow users to define boundary conditions for the strut and jury and certain wing design parameters for purposes of design space exploration and uncertainty quantification.

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Author Biography

Zachary Windous obtained a Bachelor of Science degree in Mechanical Engineering at Brigham Young University - Idaho in 2017. He went on to earn a Master of Science degree in Aeronautical and Astronautical Engineering at Purdue University with a research focus in composite manufacturing and simulation at the Indiana Manufacturing Institute. While at Purdue, he also worked toward and was granted a Master of Business Administration degree. Zach has been working at NASA Langley since 2019, where he began as a Pathways intern in the Aeronautics Systems Analysis Branch. His work has included supersonic aeroelastic uncertainty quantification and subsonic transport finite element and weight prediction modeling.

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