Structural Weight Prediction for an Urban Air Mobility Concept

Tyler Winter[1], Joe Robinson[2], Mark Sutton[3], Julius Chua[4], Armando Gamez[5], and Thomas Nascenzi[6]
M4 Engineering, Inc., Long Beach, California, 90807

Accurate structural weight prediction for novel vehicle configurations is an important and often neglected aspect of conceptual design. Many unconventional vehicle concepts are not well represented by empirical structural weight models based on historical data. Traditional finite element modeling and sizing optimization is a time-consuming man-in-the-loop process. This paper describes the process of bringing the accuracy of finite element modeling and physics-based loads modeling to the conceptual design stage in a streamlined workflow for rapid structural weight prediction. M4 Structures Studio (M4SS), a tool to parametrically define the structural configuration for aircraft and quickly estimate structural weight, has been enhanced to support the modeling of rotorcraft structures. Preliminary sizing results are presented for a NASA Urban Air Mobility concept [1].

I. Nomenclature

FEM	=	finite element model
$KEAS$	=	knots equivalent airspeed
$MTOGW$	=	max takeoff gross weight
V_x	=	forward velocity

II. Introduction

Conceptual vehicle design requires accurate estimates of weight. For many subsystems, there exist empirical estimates that are sufficient to predict weight, but structural weight is often difficult to predict accurately. Novel concepts that fall outside of historical data are poorly predicted by empirical formulations. Structural finite element models (FEM) are a common method for structural sizing and weight prediction. Traditionally, finite element models are time consuming to construct and are only created for mature designs. It would be useful to bring the accuracy of FEM earlier in the design process, especially for nonstandard vehicle configurations. M4 Engineering has developed a software tool [2][3][4], M4 Structures Studio, to simplify and parameterize structural weight prediction. This tool has been designed to integrate into conceptual design studies. This paper will detail some recent updates to M4 Structures Studio and detail an example rotorcraft structural sizing for a new urban air mobility concept.

III. M4 Structures Studio

A. Overview

M4 Engineering has developed a software toolset to rapidly estimate structural weight for the conceptual design of unconventional aerospace vehicles. The toolset, M4 Structures Studio, allows for the rapid development of structural finite element models, including internal structure, from an outer mold line (OML) geometry definition in OpenVSP [5]. The software allows engineers to build shell-based FEMs and size the structure using static, aeroelastic, flutter, and gust load cases. M4 Structures Studio supports many features important to structural weight prediction

[1] Engineering Manager, Research and Development, 4020 Long Beach Blvd, Long Beach, CA, 90807, Senior Member AIAA
[2] Senior Aerospace Engineer, 4020 Long Beach Blvd, Long Beach, CA, 90807
[3] Senior Aerospace Engineer, 4020 Long Beach Blvd, Long Beach, CA, 90807
[4] Aerospace Engineer, 4020 Long Beach Blvd, Long Beach, CA, 90807
[5] Aerospace Engineer, 4020 Long Beach Blvd, Long Beach, CA, 90807
[6] Aerospace Engineer, 4020 Long Beach Blvd, Long Beach, CA, 90807

including nonstructural mass representation, trim maneuvers, and aerodynamic control surfaces. The software has been validated against well documented research airplanes and rotorcraft as well as many unconventional configurations across all flight regimes (i.e. subsonic, supersonic, and hypersonic). Novel concepts including distributed electric propulsion (DEP) concepts and high-altitude long endurance (HALE) aircraft have been validated. M4 Structures Studio has been used to rapidly analyze concepts through high level geometry trade studies. Figure 1 depicts a variety of configurations which have been successfully modeled and analyzed within M4 Structures Studio.

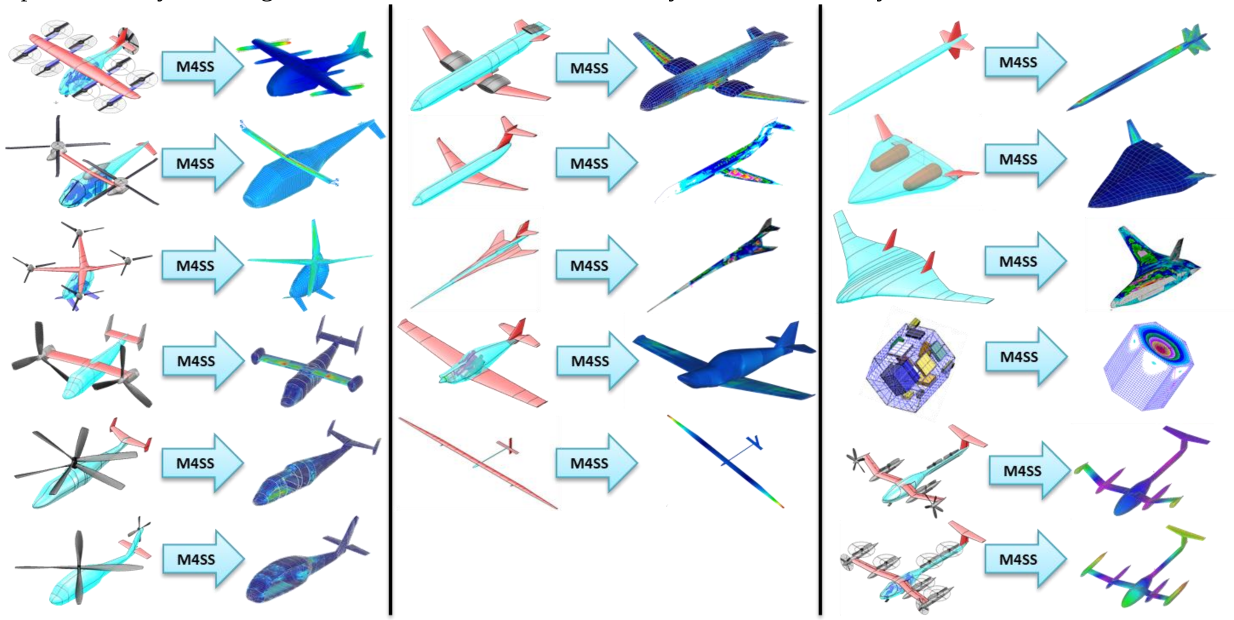

Figure 1: Example Selection of Vehicles Modeled and Sized using M4 Structures Studio.

The modelling process begins with top-level geometry. Information about the structural layout (i.e. where are the ribs and spars, what are the materials, etc.) is defined. The required geometric operations are then performed to divide the surface into numerous surface patches, each of which represents a single structural component such as a rib, a spar segment, or a skin patch. These geometric patches are then meshed automatically and written to an analysis model suitable for loads, stress, and structural optimization in NASTRAN. Figure 2 shows the workflow for creating and sizing a vehicle using M4 Structures Studio.

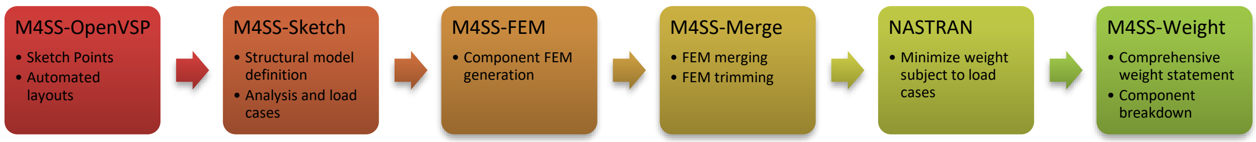

Figure 2: Workflow for M4 Structures Studio.

In generating structural models for high-fidelity analyses, more than just the shape of the structure must be defined. Assembling the detailed internal structure definition and applying that to the airframe geometry traditionally is an intensely time-consuming process that must be repeated for every change in the structural planform. M4 Structures Studio significantly improves this process by allowing the analyst to define the structural layout in parametric terms and then the software performs the remainder of the work. M4 Structures Studio is able to build a complete FEM along with the analysis definition and optimization parameters, which can be used to perform detailed structural analyses at the preliminary stages of airframe design. The types of analyses available cover most of those needed for airframe sizing: static loading, normal modes, static aeroelastic, flutter, and random gust. To improve the accuracy of the modeling, the user can add non-structural elements such as engines, nacelles, and landing gear. Also, the fuel and payload can be characterized in the FEM. These features are all added at the sketch level keeping the definition simple while bookkeeping is minimized. M4 Structures Studio includes the capability to join components together making a seamless joint between the structures. Aerodynamic models and control surfaces can also be defined. The component and vehicle sketches can be built in the M4 Structures Studio – Sketch GUI, as seen in Figure 3.

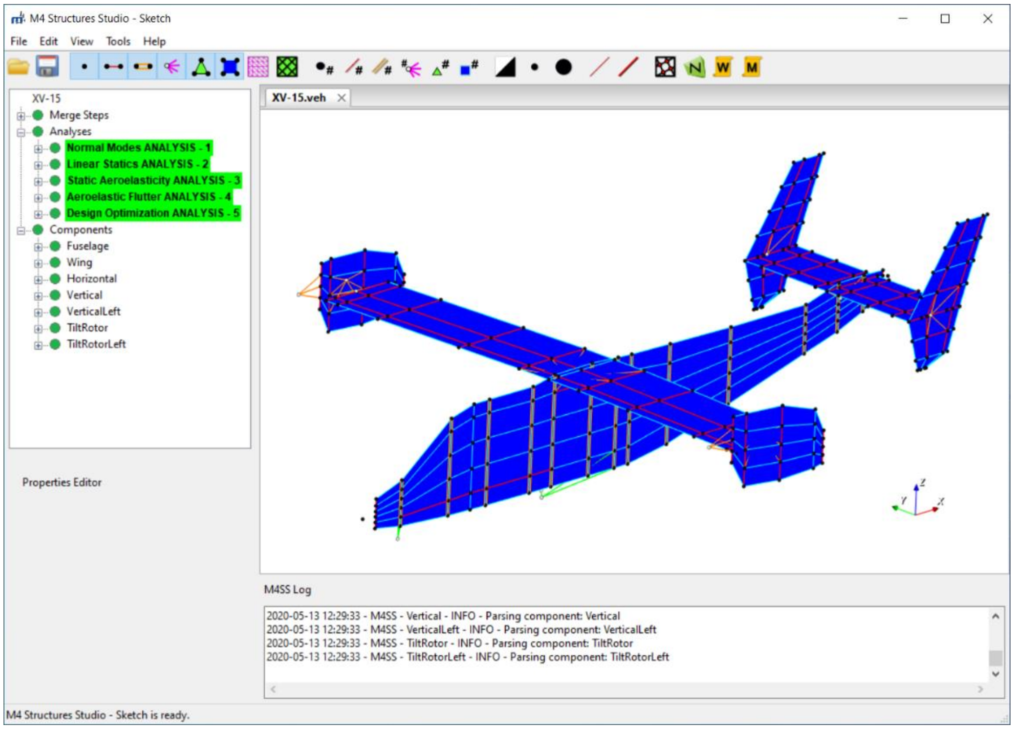

Figure 3: M4 Structures Studio – Sketch GUI with Vehicle Sketch.

B. Recent Software Updates

Several updates to M4 Structures Studio have been completed recently. The structural model building process was reorganized with a performance and ease-of-use focus. This reorganization more aligns the process and code with the real and expected uses for M4 Structures Studio in analyzing vehicles. The essential change is in the definition and organization of a model. The architecture organizes a model at a vehicle level containing several components. An example of this organizational hierarchy is illustrated in Figure 4.

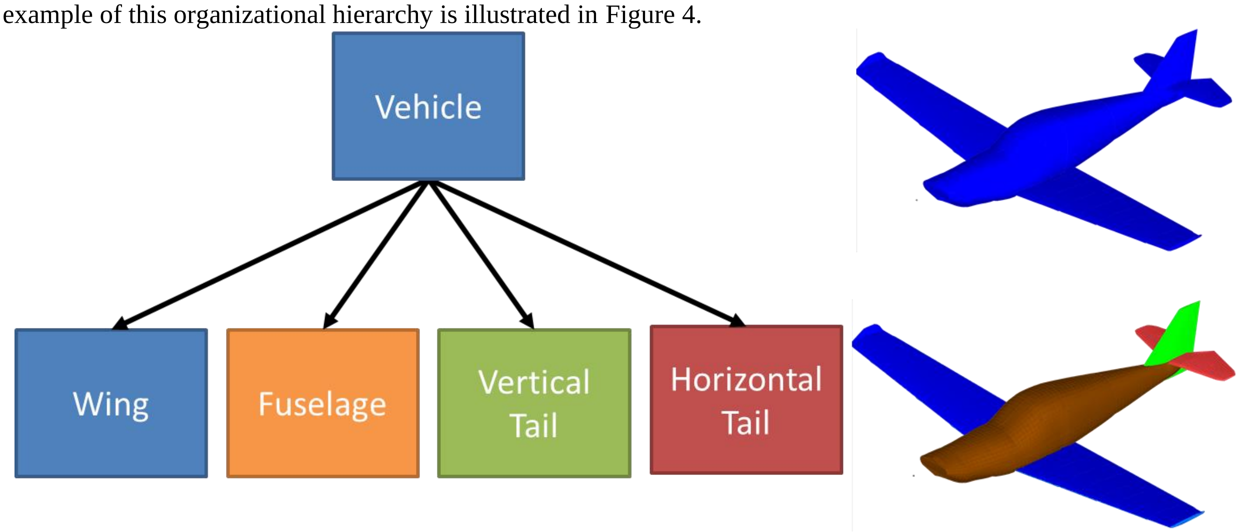

Figure 4: Example Vehicle-Component Organization.

Using the vehicle architecture approach, the software coordinates aspects of the various components. Information common between components, such as load cases, are defined in the vehicle. In addition, the merging operation is optimized by keeping track of node and element ID numbers between components and avoiding renumbering. Similarly, the user feedback in the GUI was improved to avoid potential pitfalls of conflicting properties, materials, and attachments. For the new vehicle architecture, the frontend UI had to be reworked to handle the concept of a vehicle that controls the overall parameters of an analysis. The existing UI drawable display and action widgets were removed and replaced with a single model wide screen. This new screen includes a model tree for improved visualization of the data generated during the structural layout process and allows for creation and manipulation of vehicle or component level information. Additionally, a 3-dimensional display along with additional viewing options was implemented. These enhancements are shown in Figure 5.

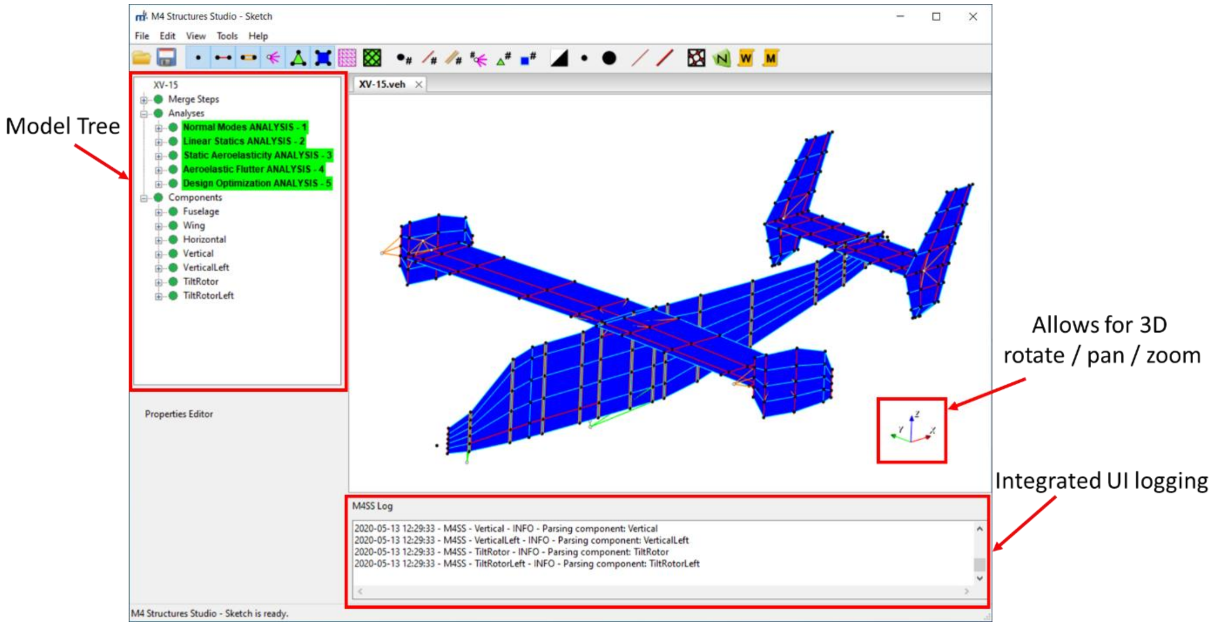

Figure 5: M4 Structure Studio – Sketch GUI Enhancements.

IV. UAM Side-by-Side Demonstration

A. Overview

In this demonstration the structural weight of the Urban Air Mobility – Side-by-Side (UAM-SBS) was sized based on a limited set of load cases. The UAM-SBS, shown in Figure 6, is a six-passenger dual side-by-side rotor helicopter with hybrid propulsion aircraft conceptualized by NASA. There is limited published data for the UAM-SBS because it is still yet to be manufactured. Some assumptions for this demonstration are listed below:

- Carbon composite structure for skins, bulkheads, and floors
- Plexiglass for the window
- Aluminum for the fuselage frames
- Fixed non-structural mass

Figure 6: NASA UAM-SBS Urban Air Transport Vehicle Concept [6].

The structure was sized with helicopter loads. A summary of the load cases can be seen in Table 1. The jump load case was defined by vertical forces at the rotors. The landing load case was defined by vertical forces on the landing gear. As a conservative simplification, no landing gear dynamics were accounted for.

Table 1: Load Cases – UAM-SBS.

Load Case	Altitude [ft]	V_x [KEAS]	Mass
Jump - 2.0g	0	0	MTOGW
Landing - 1.33g	0	0	MTOGW

B. OpenVSP Model

The UAM-SBS OpenVSP model defined the geometry of the vehicle. It contained the fuselage, wing strut, tail, engine nacelles, rotor hubs, rotors and other miscellaneous items, i.e. landing wheels, strakes. Only the fuselage, wing strut, and the tail were used for the OML components to generate finite element model meshes. Internal structures, ribs, spars, bulkheads, and floors, were laid out on these structural components. Other components were represented as fixed nonstructural masses. The OpenVSP model and the structural components can be seen in Figure 7 and Figure 8.

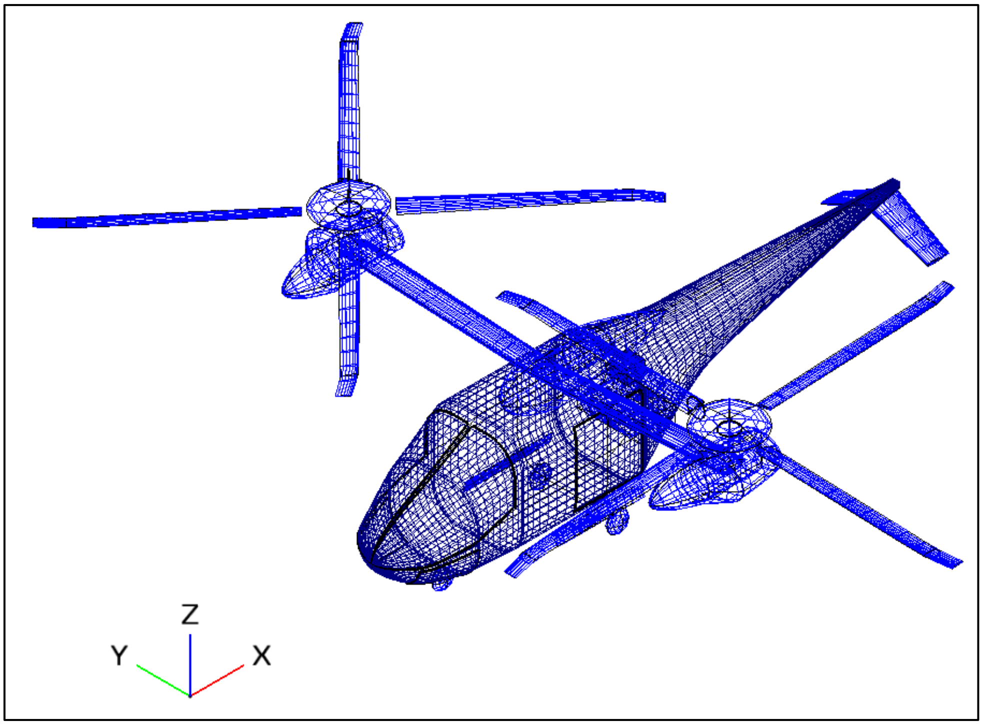

Figure 7: UAM-SBS OpenVSP Model.

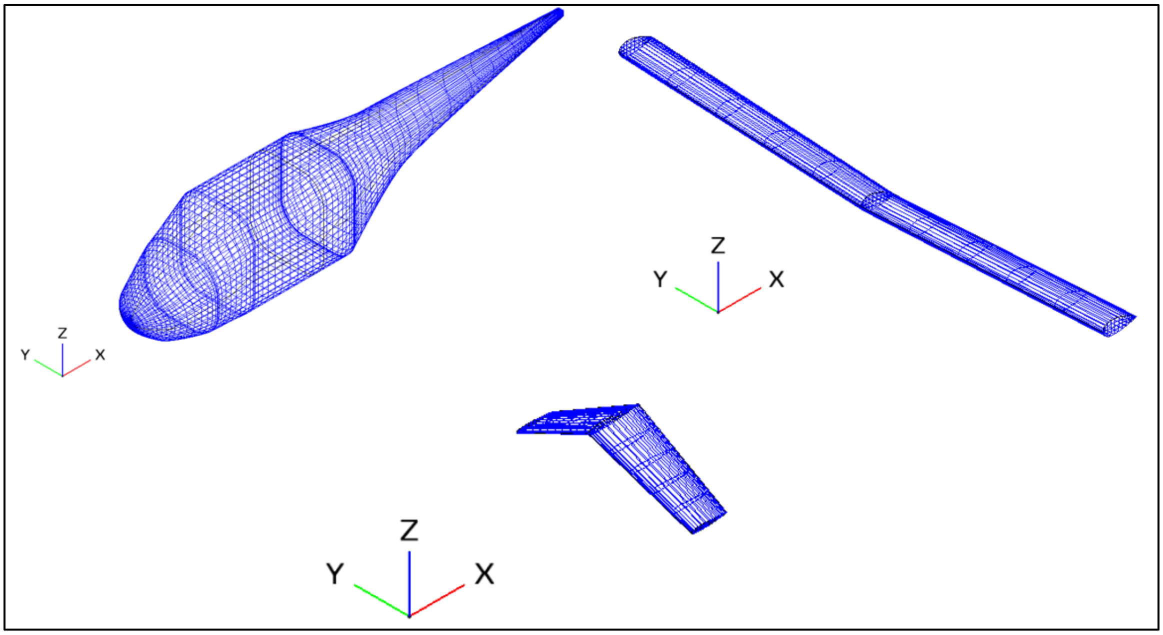

Figure 8: UAM-SBS OpenVSP Components.

C. Nonstructural Mass

Nonstructural components were represented with point mass items. Component weights were taken from published reference [6].

Table 2: Nonstructural Mass Summary – UAM-SBS.

Concept Paper	Aircraft Component	Weight [lbs.]	Location
Passengers	Passengers	1200	Fuselage
Rotor Group (Structure)	Rotor Group R	124	Wing Strut
	Rotor Group L	124	Wing Strut
Alighting Gear Group (Structure)	LDGR_F	53	Fuselage
	LDGR_B	161	Fuselage
Fuel	Fuel	409	Fuselage
Propulsion	Propulsion Misc.	283.5	Fuselage
	Engine L	93.5	Wing Strut
	Engine R	93.5	Wing Strut
	Engine M	93.5	Wing Strut
	Battery	101	Fuselage
Systems	Systems	508	Fuselage
Flight Controls	Flight Controls	98	Fuselage
Not Described in Paper	Miscellaneous	20	Fuselage
	Total	**3362**	

D. Preliminary Load Cases

1. Jump - 2.0g

A 2g jump takeoff load case was simulated. Forces were applied at each wing strut end, as seen in Figure 9. No aerodynamic forces from the wing or tail were considered. This load case was expected to size the wing strut primary structure.

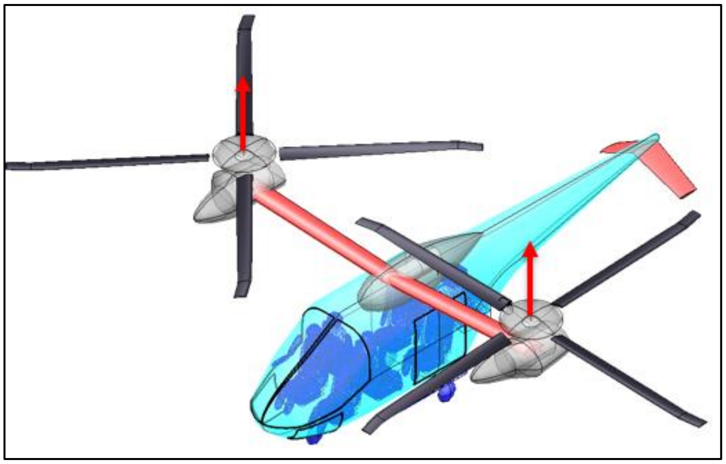

Figure 9: UAM-SBS 2.0g - Jump Load Case.

2. Landing – 1.33g

A 1.33g landing load case was simulated. Forces were applied at the bottom of the fuselage at the locations of landing gear, as seen in Figure 10. This load case was expected to size frames and skins of the fuselage at landing gear locations.

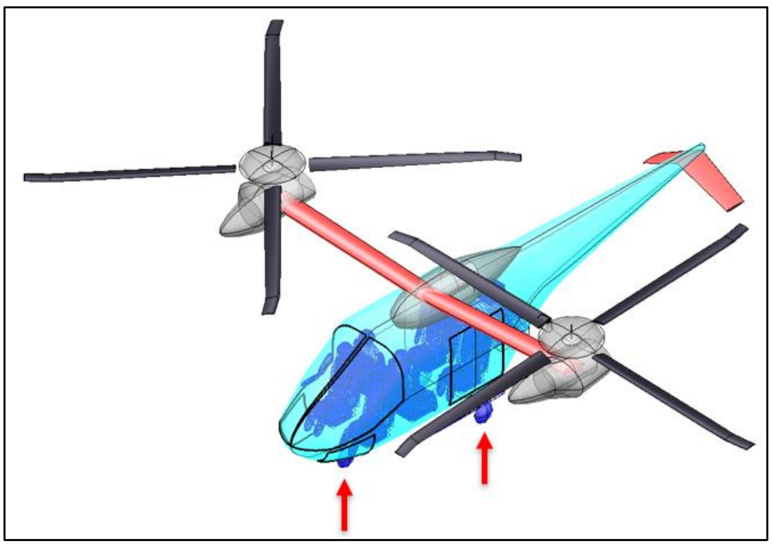

Figure 10: UAM-SBS 1.33g - Landing Load Case.

E. Component Sketches

Sketch files were generated for each component. Skins for the entire OML were made with SKIN4 cards. Internal structures were represented with BEAM and FRAME cards. Materials and property regions were defined. The aerodynamic model was defined for the tail only. Control surfaces were defined for elevators. The nonstructural masses listed in Table 2. were represented with an ATTACHMENT cards. The load cases defined in Table 1 were included. The component sketches can be seen in Figure 11 though Figure 13.

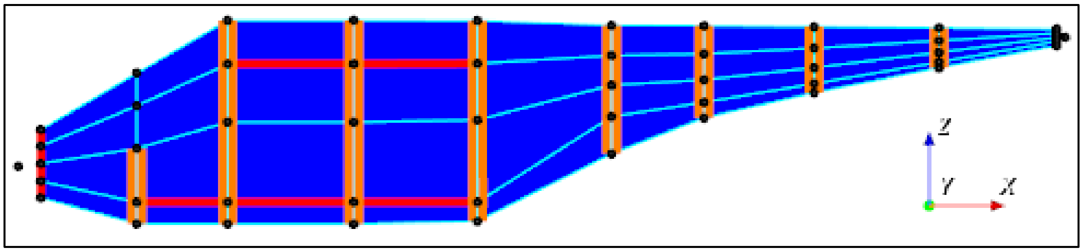

Figure 11: UAM-SBS Fuselage Sketch.

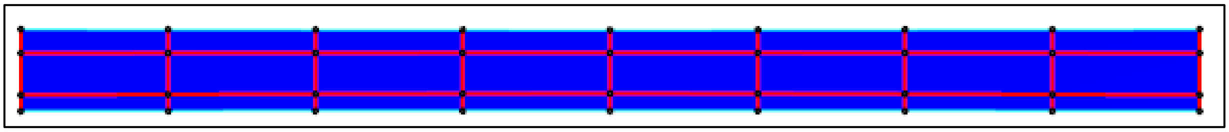

Figure 12: UAM-SBS Wing Sketch.

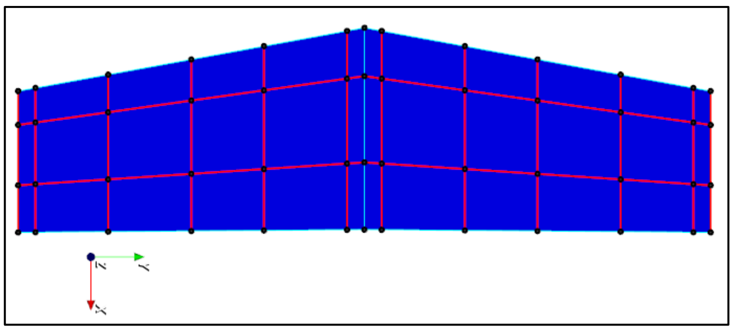

Figure 13: UAM-SBS Tail Sketch.

F. Material System

The following assumptions were made regarding the vehicle material system: 1) a carbon composite structure (skins and beams), 2) plexiglass for the windshield, and 3) uniform metallic structure (aluminium) for the frames. In addition, there is fixed nonstructural mass (NSM), two separate load cases, and defined strain/stress allowables: carbon composite 4000 $\mu\epsilon$, Aluminium 24 ksi. Table 3 details the baseline composite material layup.

Table 3: Baseline Composite Material Layup.

Layer	Plies	Thickness per Ply [in]	Thickness [in]	Ply Angle [deg]
UD carbon	1	0.0055	0.0055	0
PW carbon	3	0.0079	0.0237	+-45
PW carbon	3	0.0079	0.0237	0/90
Core	1	0.375	0.375	0
PW carbon	3	0.0079	0.0237	0/90
PW carbon	3	0.0079	0.0237	+-45
UD carbon	1	0.0055	0.0055	0

G. Finite Element Model

The finite element half model of the UAM-SBS vehicle was assembled component by component and merged into a single vehicle model. The model consisted of approximately 8000 nodes and 8500 elements. Majority quadrilateral shell elements made up the structure. Internal structures were represented with shell and beam elements The components were attached to each other using quasi-rigid attachments. The attachments utilized very stiff spring elements between rigid elements connected to spar/rib or bulkhead/skin intersections. Nonstructural mass items were represented with point masses rigidly attached to structural hardpoints. An overall view of the mesh can be seen in Figure 14. The internal structures can be seen in Figure 15.

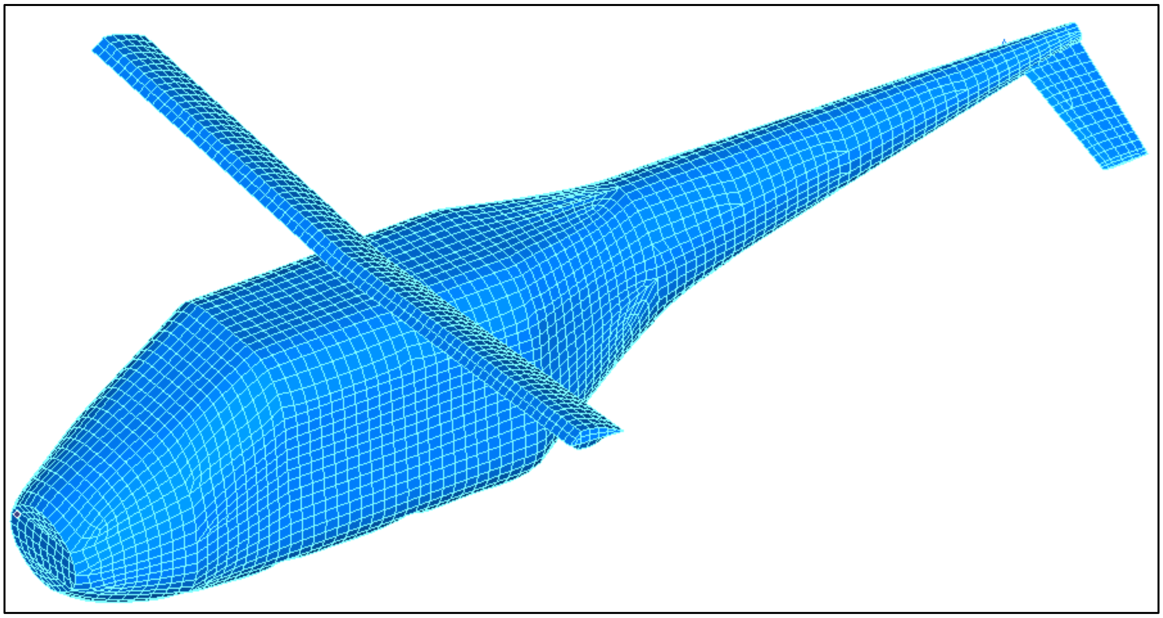

Figure 14: UAM-SBS Finite Element Model.

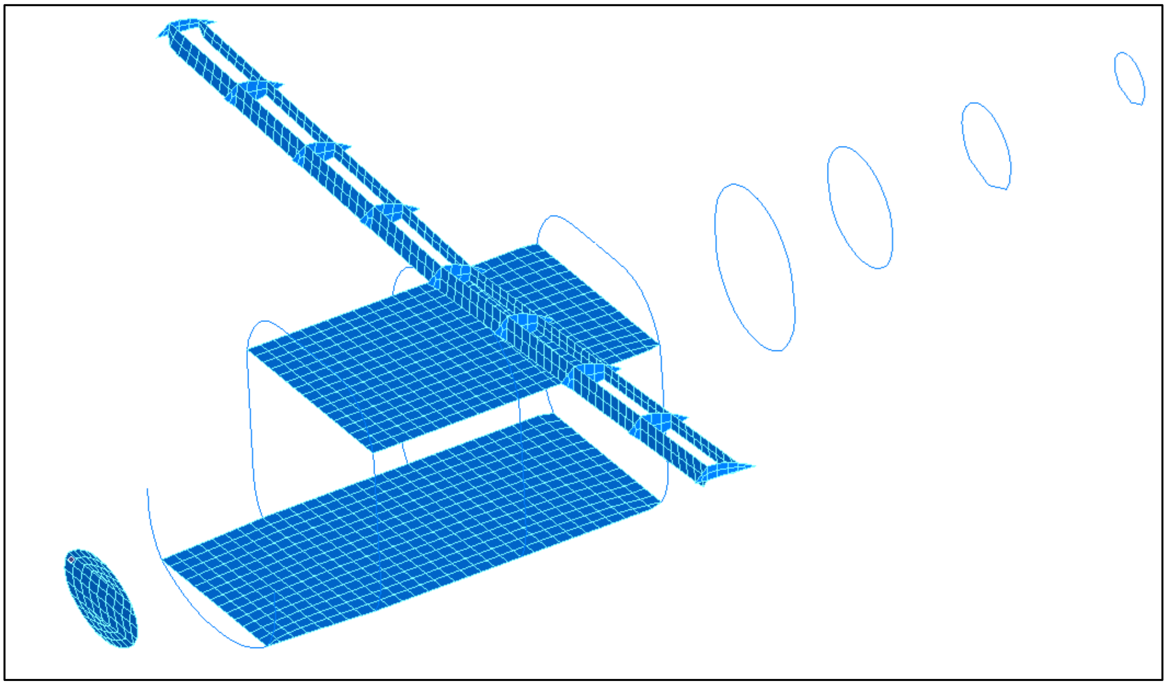

Figure 15: UAM-SBS Finite Element Model Internal Structure.

H. Sizing Results

A preliminary structural sizing has been performed with the 2.0g jump and 1.33g landing cases. A weight statement comparison to published data [6] can be found in Table 4. M4SS shows reasonably good agreement with published data. Some important assumptions affecting these results include:

1) the windshield was not sized,
2) a conservative composite layup minimum gauge was assumed (i.e. a layup with fewer plies could be used),

3) and for the wing strut, a basic structure was assumed (i.e. some items not modeled)

The plot shows a maximum or minimum strain depending on which was critical for the pictured side of the wing strut. The peak strains occur at the center of the wing strut as seen in Figure 16 and Figure 17. Note, the 1.33g Landing Load does not size the wing strut since the maximum strains come from the 2.0g Jump. The frames in the aircraft support the stresses that occur from the landing loads at minimum gauge without exceeding the allowable of 24 ksi.

Table 4: UAM-SBS Weight Statement Comparison [6].

	Published Data [lbs.]	M4SS [lbs.]	Error (%)
Fuselage Structure	374	400	7.0
Fuselage NSM	2834	2834	0.0
Wing Strut Structure	131	108	17.6
Wing Strut NSM	529	529	0.0
*Horizontal Tail Structure	83	23	72.3
Horizontal Tail NSM	-	-	-
****Total Structure**	**588**	**531**	**9.7**
Design Gross Weight	**3950**	**3893**	**1.4**

*Horizontal Tail Structure = Total Structure –Rotor Group (Published) -Landing Gear (Empirical) –Fuselage (Published) –Wing Strut (Published)
**Total Structure = Total Structure –Rotor Group (Published) –Landing Gear (Empirical)

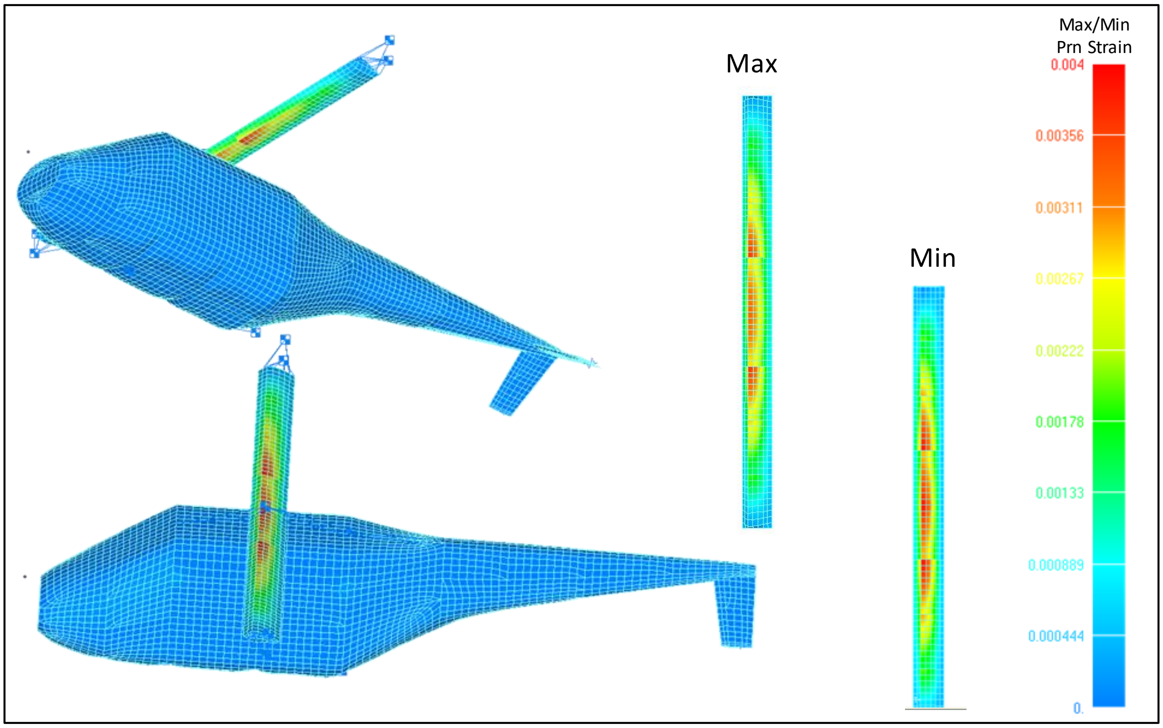

Figure 16: UAM-SBS Wing Strut Max/Min Principal Strain – Jump – 2.0g.

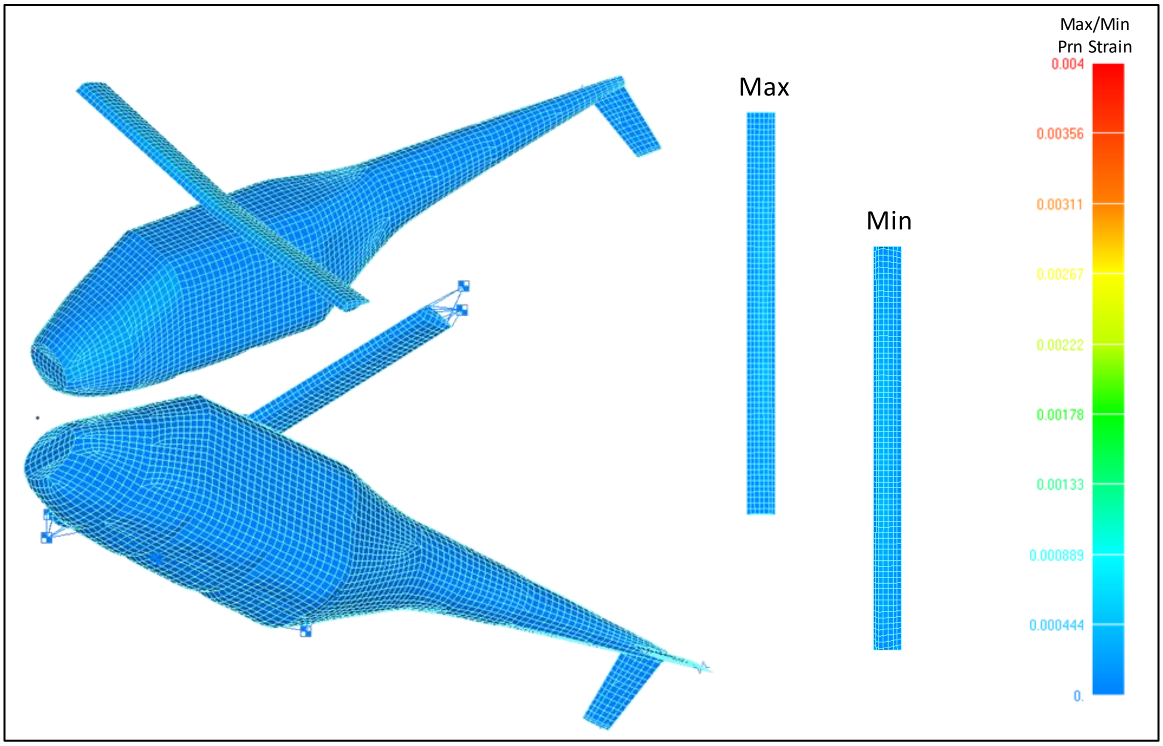

Figure 17: UAM-SBS Wing Strut Max/Min Principle Strain - Landing – 1.33g.

V. Conclusion

A variety of enhancements and refinements to M4 Structures Studio have been described. These included a simplification of the user-defined inputs and features particular to rotorcraft configurations. A sample rotorcraft configuration has been modeled, preliminarily sized, and compared with published structural weight predictions. Predictions from M4 Structures Studio correlated well with other published predictions. Work is ongoing to expand the capabilities for rotorcraft structural sizing. Future features will include crashworthiness loads and integration with industry standard rotorcraft tools such as RCAS and CAMRAD II. Once these features are incorporated, this example will be revisited with extended capabilities and fidelity.

Acknowledgments

The work presented was funded by NASA SBIR from NASA Ames and Army Ames under contract number 80NSSC18C0190 and by NASA CCRPP under contract number 80NSSC19C0077.

References

[1]Silva, C. "VTOL Urban Air Mobility Concept Vehicles for Technology Development," *AIAA Aviation 2018*, Altanta, GA, June 25-29 2018.

[2]Winter, T., Marquez, J., Scheneman, B. "Development of a Physics-Based Weight (PBWeight) Prediction Tool for Conceptual Design," *AIAA Modeling and Simulation Technologies Conference (AVIATION 2016)*, AIAA, Washington D.C., 2016.

[3]Winter, T., Scheneman, B., Marquez, J., and Sidhu, J. "Continuing the Development of a Physics-Based Weight (PBWeight) Prediction Tool for Conceptual Design: Build 1," *AIAA SciTech Conference*, AIAA, Grapevine, TX, 2017.

[4]Winter, T., Scheneman, B., Fung, D., and Chung, P. "Continuing the Development of a Physics-Based Weight (PBWeight) Prediction Tool for Conceptual Design: Build 2," *AIAA AVIATION Conference*, AIAA, Denver, CO, 2017.

[5]Hahn, A. "Vehicle Sketch Pad: Parametric Geometry for Conceptual Aircraft Design," *48th AIAA Aerospace Sciences Meeting*, AIAA-2010-657, AIAA, Orlando, FL, January 4-7 2010.

[6]Johnson, W., Silva, C., and Solis, E. "Concept Vehicle for VTOL Air Taxi Operations," *AHS Specialists Conference on Aeromechanics Design for Transformative Vertical Flight*, San Francisco, CA, 2018.