Aircraft Conceptual Structural Design Using the AMMIT Structural Analysis Tool

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Aircraft conceptual structural design is the process of developing and refining an idea for an aircraft into a feasible structural design. The process typically involves multiple evaluations of a single configuration and can require designers to examine thousands of concepts. Standard approaches to conducting structural analyses in this phase are either based on the use of historical or empirical data or often require significant expertise in structural analysis to perform these rapid assessments. The AMMIT structural analysis tool includes structural line models and handbook methods wrapped in a simple to use interface that can enable rapid, physics-based structural designs without requiring extensive structural expertise. The objectives of the present paper are to introduce AMMIT, describe the methods used in AMMIT, and present the results of the validation effort. Validation of the AMMIT methodology was performed on nine aircraft to determine the accuracy of the methods, highlight features of AMMIT, and guide future development of the methodology. Results of the validation effort indicated that AMMIT provides a prediction of primary structural weight for each aircraft with an acceptable level of error during the preliminary design phase with a minimal expenditure of computational resources.

Nomenclature

AMMIT	=	Aircraft structural analysis Method for iMmediate weIght esTimation
CFD	=	Computational Fluid Dynamics
CSV	=	Comma-Separated Values
FEM	=	Finite Element Modeling
HWB	=	Hybrid Wing Body
I/O	=	Input and Output
MDAO	=	Multidisciplinary Design Analysis and Optimization
MER	=	Mass Estimating Relationship
NASA	=	National Aeronautics and Space Administration
OpenVSP	=	Open Vehicle Sketch Pad
TACP	=	Transformative Aeronautics Concepts Program
TTT	=	Transformational Tools & Technologies

I. Introduction

Aircraft conceptual structural design is the process of developing and refining an idea for an aircraft into a feasible structural design. This early phase of aircraft design is highlighted by rapid changes as information is learned about the concept and the concept is slowly refined. In this phase, trade studies are used to explore the design space and optimize the design. Ideally, the design space gradually narrows as more information is learned about the aircraft. For example, early on several different vehicle configurations may be examined, such as hybrid wing body (HWB) or standard tube and wing designs like the Boeing 737-200. Later in the conceptual design phase, once the major details of the concept have been determined, the trades become more selective and focused on the refinement of the design and possible enhancements.

In the course of a conceptual design process, thousands of individual concepts may be examined. Due to the rapid pace of design iterations, higher-order tools that require significant computational resources and designer effort are typically not preferred because by the time the analysis is complete the design has changed significantly and initial

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results are no longer applicable. Generally, as the order or fidelity of the tool increases the requirements for discipline expertise, designer effort, computational resources, and information about the concept increases. Therefore, despite the increased insight provided by higher-order tools, lower-order tools are often used exclusively in the early phase of conceptual design and higher-order tools are gradually incorporated as the design matures. An example of different fidelity levels in the aerodynamics discipline in conceptual design would be a vortex lattice method as lower-order, inviscid Euler computational fluid dynamics (CFD) as medium-order, and Navier-Stokes CFD as higher-order. Where depending on the complexity of the model and computational resources, the vortex lattice method can execute in minutes, Euler CFD in hours, and Navier-Stokes CFD in days.

Similar to the aerodynamics discipline, there are tools and methods available at several different analysis levels for the structures discipline. Early in the development process, the structures discipline is often represented by low-order tools such as mass estimating relationships (MERs). MERs are typically regression equations based on historical data and many are publicly available [1-3]. These methods are well suited to early conceptual design because they typically require little information about the concept, require little designer effort, and require little to no structures discipline expertise to use. However, as these methods are not physics based, they are only applicable to concepts both similar in design and flight envelope to the aircraft in their calibration dataset. Furthermore, the selection of aircraft used to in the calibration dataset is typically not publically available, which often leaves the designer with uncertainty as to whether or not each MER is applicable to their design. Additionally, certain design options, such as whether or not to include winglets, may not be reflected in these methods.

As a design matures, medium-fidelity tools are gradually implemented. These typically are handbook methods based on beam or shell theory. Handbook methods can be used to determine structural weight and the airframe response to external loading with limited computational effort. However, these require expertise in the structures discipline to develop and frame the problem in such a way that handbook methods can be applied.

Above handbook methods, at what could be considered high-fidelity for the conceptual design process is finite element modeling (FEM). FEM can be used to estimate structural weight and provide a full structural response to load conditions at a high level of detail. However, FEM requires significant expertise and designer effort. Additionally, depending on the complexity of the model and type of analysis FEM can require significant computational resources. Due to the significant effort required for FEM several tools have been developed to simplify the process of applying FEM for certain aircraft types [4, 5].

The AMMIT structural analysis tool was developed to break the trend between fidelity and required expertise by providing a medium-order tool that requires little structural expertise and designer effort to apply. AMMIT uses medium-order handbook methods to rapidly design an optimum aircraft primary structure. Sizing methods have been selected and coded efficiently such that a typical design requires only a few seconds to complete. These qualities make AMMIT ideal for primary structural weight predictions, broad trade space exploration, and the refinement of structural design variables in preparation for FEM.

The objective of the present paper is to introduce AMMIT, briefly describe the methods that have been implemented and present validation results for several aircraft. In the remainder of the paper, a description of the AMMIT software and methods, an analysis of nine aircraft using AMMIT, and a discussion of the analysis results will be provided.

II. AMMIT Software and Methodology

AMMIT has been developed in the C++ coding language. Releases are tested on Windows and Linux operating systems; however, AMMIT should be theoretically compatible with any compiler and system that supports C++17. The AMMIT execution process is shown in Fig. 1. The remainder of this section will include a discussion of each step in the execution process.

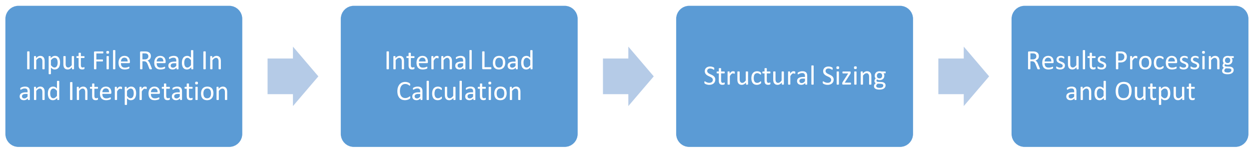

Fig. 1 AMMIT Software Execution Process.

A. Input File Read In and Interpretation

The Input File Read In and Interpretation phase of execution includes reading input files, the creation of the internal geometry based on the input, and the creation of load distributions. As the input files are the primary means that users will interact with AMMIT the CSV (Comma Separated Value) format is used for easy visualization and scripting. To make AMMIT simple to use, the number of variables that require structural expertise has been limited to reduce the expertise necessary to use the tool. To accommodate multiple levels of detail, the input files have been developed to accept either detailed information about the aircraft or very sparse information. For example, if only the total lift is known, it can be applied to a wing using a built in elliptical distribution or if detailed CFD results are available the lift can be specified with hundreds or thousands of individual point loads.

AMMIT has been developed to be unit agnostic and only requires that inputs be provided using consistent units of length and force. Units of feet and pounds were used to define the input in the subsequent analysis, but AMMIT has also been demonstrated with inches and pounds, and meters and newtons.

Aircraft in AMMIT are composed of a single fuselage and as many semi-span trapezoidal wing sections as desired. Geometry is either defined using parameters in the CSV input files or imported from the OpenVSP (Open Vehicle Sketch Pad) Hermite file format [7]. The fuselage shape is defined as a series of cross sections. Cross sections can be defined using the following shapes: circle, super ellipse, rectangle, horizontal symmetric double bubble, custom shapes defined by a series of points, and points (which can be used to begin and end the fuselage). Geometry between the user-defined cross sections is linearly interpolated between surrounding cross sections.

Semi-span trapezoidal wing sections can be placed anywhere on the geometry, provided that they are attached at the root to the fuselage or to another trapezoidal wing section. This approach enables the same trapezoidal component to be used to represent wings, tails, canards, winglets, and other components. This generalized approach allows the same physics based sizing methods to be applied to all of these components. Additionally, complex geometries can be formed by chaining multiple AMMIT trapezoidal wing sections together. One example of the potential of this approach is shown in Fig. 2, which contains a plot of a generalized ‘C’ wing aircraft that has been created from chaining multiple trapezoidal wing sections. A consequence of defining wings in semi-span sections is that a more traditional tube-and-wing aircraft will require definitions for at least five trapezoidal sections: two for the wing, two for the horizontal tail, and one for the vertical tail. However, AMMIT includes options to mirror wing sections to reduce the input burden on users.

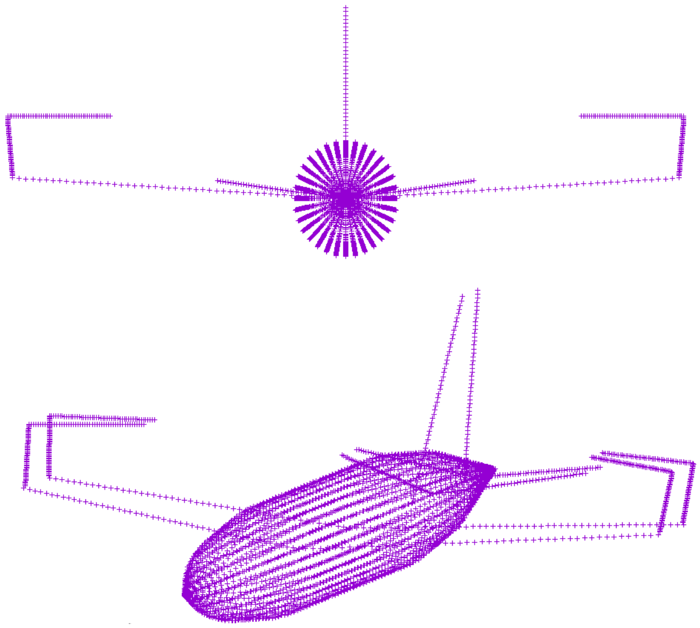

Fig. 2 Example geometry showing a possible ‘C’ wing configuration.

All materials in AMMIT are assumed to be homogenous. Material properties include density, elastic modulus, poisons ratio, yield stress, and minimum gauge. The fuselage definition allows for unique material properties to be provided for the skin, stringers, and spars. Material properties can vary between wing sections and different materials may be specified for the skin and spars.

AMMIT load cases are designed to be extremely flexible without placing too much of a burden on users. Internally a load case is essentially a list of point weights that define the aircraft weight properties, a list of external point loads, wing tip deflection limits, fuselage internal pressure, and a safety factor. Point loads and weights can either be defined one at a time or through several built in distributions. The flexible approach allows load cases to be quickly created for typical aircraft, but provides flexibly for unique cases, such as distributed propulsion or a vertical take-off concept.

B. Internal Load Calculation

The next phase of an AMMIT execution is the internal load calculation. The internal loads developed in this phase are referenced during the structural sizing phase to determine the minimum size of each structural element. This phase includes resolving each load case to determine its resulting internal loads and the creation of a combined set of internal loads that is used for stress sizing.

Each load case is resolved using the process described in Fig. 3. The first four steps of are necessary to develop line models for the trapezoidal wing sections and the fuselage. The final step is to use line models to calculate the internal loads for each component.

Fig. 3 Process to calculate internal loads for each load case.

AMMIT uses line models to calculate all six components of force and moment about the center of the structure of the fuselage and each trapezoidal wing section. Line models have been successfully used to determine the loads on vehicles in past design programs [6]. An example line model showing only the calculation of one shear component and one moment component is shown in Fig. 4. In this example, internal loads are calculated on the structure due by summing the loads from the wing tip to the wing root. Line models resolve the internal loads on a structure very quickly; however some load information is lost in the process of determining the internal loads about a single line. For example, the equal and opposite forces applied to the wing (in blue) in Fig. 4 cancel out and have no net effect on the shear or moment diagrams. Because equal and opposite loads will cancel in a line model, pressure loads on the fuselage must be handled separately and are not part of the line model process.

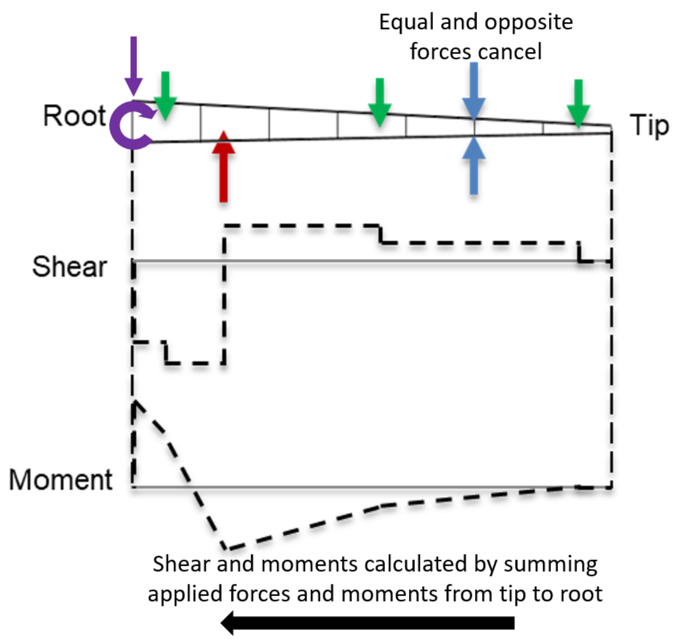

Fig. 4 Example line model applied to a wing to calculate the shear and moment along its length.

After the user provided load cases have been processed, a combined set of internal loads is created to allow the stress sizing to be completed with only one set of internal loads. This set of internal loads effectively represents the largest internal loads generated by the load cases. The benefit of this approach is that it significantly reduces the computational resources required for the stress sizing; however, it has the effect of making the overall sizing method more conservative.

C. Structural Sizing

The next phases of the software execution process include sizing the structure of each trapezoidal wing section for stress loading, sizing the fuselage structure for stress and stability, and finally sizing each trapezoidal wing section to meet deflection requirements. AMMIT includes methods to size only the primary structure of aircraft. For trapezoidal wing sections this includes the wing box, which is formed by the forward and aft spars and connecting skin. For the fuselage, the sized structure includes the frames, skin, and stringers. Stress and stability sizing is performed with only the combined set of internal loads and the deflection sizing is performed once for each load case. This subsection will include a discussion of the structural geometry and sizing methods for the wing sections and the fuselage.

To allow the wings to be sized quickly the process shown in Fig. 5 is used to simplify the geometry into elements that can be rapidly sized using beam methods. First, the wing geometry is divided into many small sections that will be sized independently. Then each section is then simplified into a rectangular wing box by averaging the dimensions at the start and end of each section. Subsequently it is then relatively simple to extract flat plates for the skin and 'I' beams for the spars from the simplified geometry. The number of section cuts used depends on the size of the component, with larger components generally having more sections than smaller ones. With this approach, smaller section cuts introduce less error; however, this comes at the cost of increased computation time.

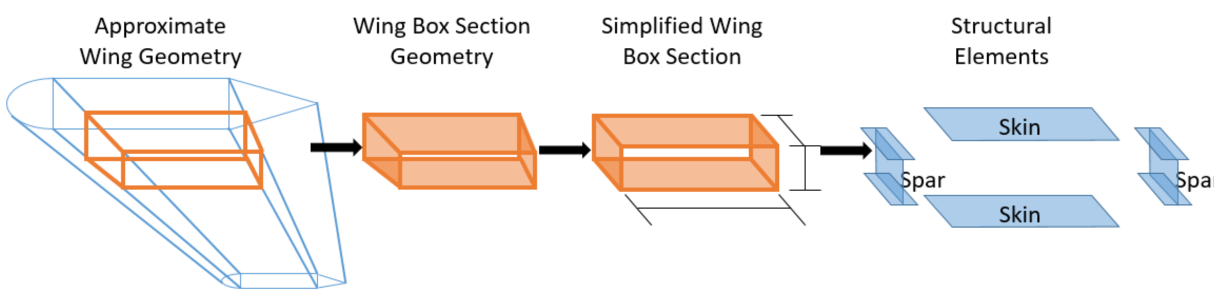

Fig. 5 The process used to extract structural geometry from the wing geometry.

Each wing section is sized based on the maximum internal load applied to it using the Von Mises failure criterion. Internal loads are applied to the structure according to the assumptions shown in Fig. 6 with each component of force and moment assigned to a structural element. The skin and spars of each section are sized to the minimum thickness (above minimum gauge) required to resist the applied loads using beam methods. Additionally after the wing stress sizing is the complete the deflection of each trapezoidal wing section due to each load case is calculated using a work-energy approach [8]. If the resulting vertical tip deflection exceeds a user provided limit then the spar caps in the wing box sections that contribute most to the tip deflection are thickened in an iterative process until the deflection requirement is met.

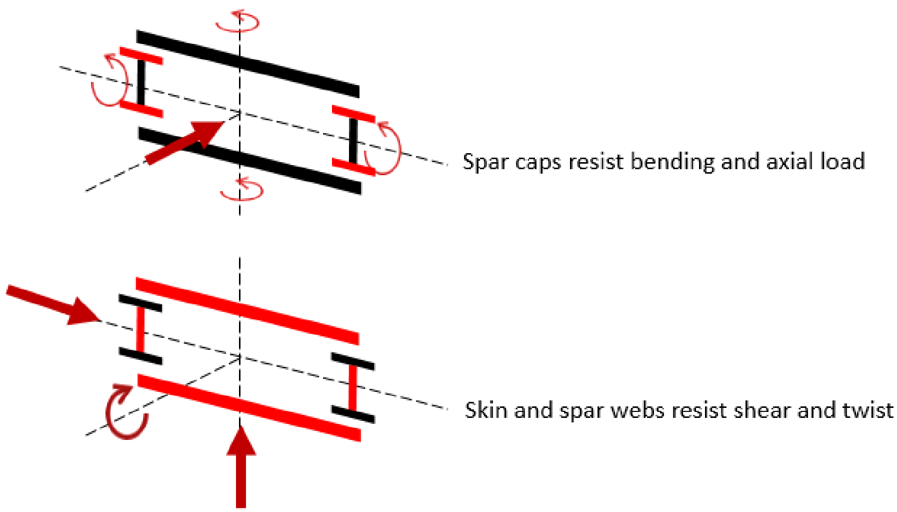

Fig. 6 Loading assumptions for trapezoidal wing section sizing.

The process for transforming the fuselage geometry into individually sizable structural elements follows a similar process as the wing sections. First, the fuselage is divided into sections by the frame locations. Frames are placed at locations where spars from wing components transfer load into the fuselage and filled in between these locations based on the user provided maximum frame spacing. Frames are formed by the outer mold line of the fuselage geometry and have an 'I' cross section shape. Stringers are placed around the cross section either according to a user defined minimum distance between stringers or to meet a user defined number of stringers. Either 'Z' or 'I' shaped stringers can be used. Skin sections are formed by flat plates connecting the stringers as in shown in Fig. 7. If the cross section geometry features sharp changes, such as the corners of a rectangle, the stringer closest to each sharp change is moved to that location.

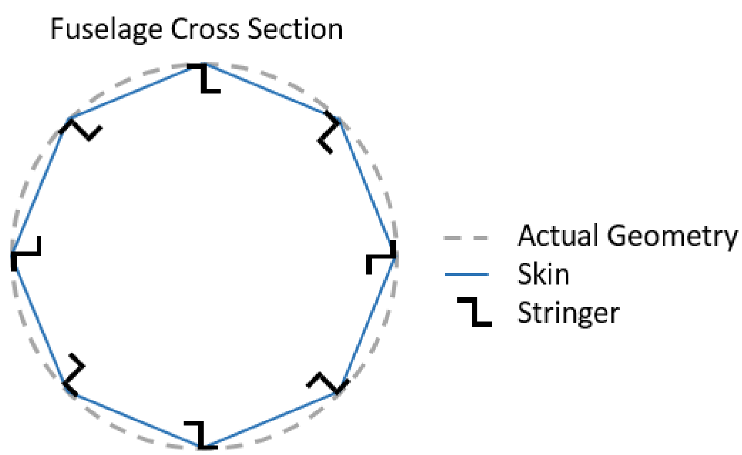

Fig. 7 Simplification of fuselage cross sections into skin and stringers.

Each fuselage section is sized independently based on the maximum internal load in that section and the fuselage internal pressure. Each skin, stringers, and frame is sized using beam handbook methods with the Von Mises failure criterion. Similar to the approach taken for the wing sections, each component of the internal loads are assigned to a structural element with the following loading assumptions: Stringers are sized to resist bending, axial loads, and a portion of the loads due to pressure. The skin is sized to resist shear loads due to shear forces and the twisting moment, and a portion of the hoop loads caused by the pressure. The frames are sized to resist a portion of the pressure loading. In addition, the dimensions of each fuselage frame are checked against a historical method to ensure the stability of the fuselage [9].

D. Results Processing and Output

The execution process ends with the creation of the output files. This process includes processing of the results of the subsequent sizing section to generate the output. For ease of use and compatibility with Microsoft Excel, the CSV format is used wherever it is practical. Output includes primary structural weight, the properties of the sized structure including dimensions, details on each load case, a table of the internal loads that can be plotted to highlight trends, and a representation of the vehicle geometry that can be plotted visualization and debugging (Fig. 2). Additionally, to increase execution speed, an option is available to reduce the amount of data presented in the output to the minimum necessary for a typical execution.

III. Aircraft Structural Sizing Validation

In order to demonstrate AMMIT's rapid sizing approach, AMMIT was used to size nine commercial transport aircraft: Boeing 707-320C, Boeing 727-200, Boeing 737-200, Boeing 747-200F, Douglas DC-8-62, Douglas DC-10-30, Fairchild F-27A, Lockheed L-1011-1, and the North American T-39A. These aircraft were selected based on the availability of structural data and because they are of a similar class of aircraft, but vary greatly in size.

This section includes a description of the load cases and geometry used for each of the aircraft and a discussion of the results from the analysis. Presented results include the differences between the predicted structural weight and actual structural weight, a wing deformation for the Boeing 737-200, and an examination of software execution time.

A. Load Cases and Geometry

The structure of these aircraft were sized using the following load cases. The load cases are primarily adapted from [5, 10], with substitutions for the rudder reversal and dynamic overswing load cases.

- +2.5G maneuver with full fuel
- +2.5G maneuver with empty fuel
- -1G maneuver with full fuel
- -1G maneuver with empty fuel
- +2G runway bump full fuel
- Engine out full fuel
- Engine out empty fuel
- Maximum Pressurization

While AMMIT has the capability to receive higher fidelity aerodynamic loads, propulsion loads, and weight properties, simple distributions were used to define the load cases to approximate the typical use case for AMMIT. For maneuver load cases, a distributed load was applied to the wings to generate the required rigid body acceleration using an elliptical distribution. For the runway bump load case point loads were applied at the main landing gear locations to generate the required accelerations. For the engine out cases, the aircraft was set in level flight (1G elliptical load applied to the wings) with all engines at maximum thrust except for the outboard most engine on one side of the aircraft. The Maximum pressurization load case included only pressurization loads applied to the fuselage. A yield factor of safety of 1.5 and a 10% semi-span wingtip deflection limit was used for all load cases. Weight properties for all load cases were approximated by applying the total weight using a volume based distribution. Full fuel refers to the aircraft in its ramp weight configuration and empty fuel refers to the aircraft in its operating empty weight configuration.

A similar low-fidelity approach was taken for the vehicle geometry. Therefore, fuselage geometries were defined using no more than ten cross sections. Instead of defining wings using multiple trapezoidal sections, each wing was approximated as a single trapezoidal section with no breaks in geometry. The geometries for the selected aircraft were estimated from publically available information and drawings [13-19]. Information on the structural configuration of each aircraft was estimated using [11]. Information that could not be found, such as tail spar locations, were estimated using reasonable approximations. As reliable information on the material choices for each aircraft could not be found, all structural elements were assumed to be constructed of aluminum 2024-T4 with material properties from the Aerospace Specification Materials, Inc. (ASM) website [12].

B. Results and Discussion

With any preliminary design tool some error is expected between the predicted value and the actual value. The amount of error that is acceptable depends on the analysis. However, trends or consistency between results is desired as studies comparing several different designs can influence the overall direction of a project. Therefore, while the differences between the AMMIT predictions and actual values are discussed in this section, this comparison is focused on the overall trends in the AMMIT weight predictions.

Table 1 includes the percent error between the AMMIT predicted structural weight and the actual structural weight for each of the aircraft. This includes errors for the fuselage, wing, horizontal tail, vertical tail, and total primary structure. The average and standard deviation of the errors are included on the right most columns to highlight trends in the results. Negative and positive values indicate under and over predictions by AMMIT respectively.

Table 1 Percent error between the AMMIT predicted and actual primary structural weight.

Aircraft	707-320C	727-200	737-200	747-200F	DC-8-62	DC-10-30	F-27A	L1011-1	T-39A	Average	Std Dev
Fuselage	-25%	-21%	-11%	16%	-30%	-27%	-10%	-32%	-7%	-16%	14%
Wing	14%	-15%	-15%	1%	-25%	28%	14%	1%	No Data	0%	17%
Horizontal Tail	-6%	15%	15%	-2%	8%	12%	55%	-14%	71%	17%	27%
Vertical Tail	-14%	0%	21%	17%	-16%	-56%	91%	98%	74%	24%	50%
Total Primary	-4%	-16%	-10%	7%	-25%	1%	8%	-15%	No Data	-7%	11%

With the exception of the Boeing 747-200F, the AMMIT predicted fuselage weight was lower than the actual value for each of the aircraft. As there are elements of the structure that are not considered in AMMIT such as joints, structural cutouts, and wing/fuselage connections an under prediction is largely expected. A potential cause of the over prediction of the Boeing 747-200F structure is the unique shape of the aircraft's fuselage geometry. On average AMMIT under predicted the fuselage weight by 16% with a standard deviation of 14%. This indicates that updates to address the discrepancy with the Boeing 747-200F and a calibration factor (determined based on additional analysis) could significantly improve the accuracy of the fuselage weight prediction.

The variation in error of the wing weight prediction was greater than the fuselage variation, with values ranging from a 28% over prediction for the Douglas DC-10-30 to a 25% under prediction for the Douglas DC-8-62. The mixture of over and under predictions averaged to 0%, indicating that a flat calibration factor would not improve the accuracy. The analysis indicates that additional work is required to refine the wing weight predictions to improve the precision of the results.

One unexpected outcome was that during the analysis the method showed larger than expected sensitivity to the forward and aft spar locations. As AMMIT users are assumed to have minimal structural expertise and a poor selection of spar location can have a detrimental effect on the weight prediction, methods need to be investigated to have AMMIT automate the selection of spar locations.

The horizontal and vertical tail weight predictions display significant errors. However, these errors have little effect on the overall structural weight prediction since the tails represent a low fraction of the overall structural weight. The error largely is a result of the use of a volume-based distribution used to approximate each aircraft's weight properties and that none of the selected load cases are well suited to appropriately size the tails and control surfaces.

The resulting error in the total primary structural weight prediction show that for most aircraft the errors in the fuselage, wing, and tail predictions cancel out to give a lower overall error. For the examined aircraft, the average was a 7% under prediction and the maximum was a 25% under prediction for the Douglas DC-8-62. As the canceling of errors cannot be relied upon, the error seen in the fuselage and wing should be assumed to apply to the primary structure in future analysis.

Table 2 contains the percent error between the AMMIT predicted primary structural weight and the total aircraft structural weight (including secondary structure). As AMMIT only includes routines to calculate the primary structural weight large errors are expected in this comparison. Despite this as the total structural weight is needed to complete an aircraft weight buildup it is useful to examine. The percent error in the results are fairly consistent, with an average 44% under prediction and a low standard deviation of 6%. While this is partially due to the canceling of errors described in the primary structural weight comparison, it does indicate that a calibration factor could potentially be applied to allow AMMIT to make a prediction of total structural weight.

Table 2 Percent error between the AMMIT predicted primary structural weight and the total structural weight of each aircraft.

Aircraft	707-320C	727-200	737-200	747-200F	DC-8-62	DC-10-30	F-27A	L1011-1	T-39A	Average	Std Dev
Primary + Secondary	-44%	-52%	-50%	-34%	-51%	-38%	-36%	-47%	-40%	-44%	6%

Deformation of each semi-span wing section was calculated for each aircraft due to the loads of each load case. As the results for each aircraft are largely similar except for the magnitudes, only results for the Boeing 737-200 wing are presented. Fig. 8 is a plot of vertical out of plane deflection of the Boeing 737-200 wing as it varies with percent span location for each load case. Percent semi-spans of zero and one correspond to the wing root and tip respectively. The results show that the 2.5 G full pull up case (light blue) causes the largest upward deflection and the negative 1 G case (gray) causes the largest downward deflection. The 2G taxi bump case (dark blue) is also of interest as it highlights the interaction between the landing gear load pushing the wing up and inertial forces pulling the wing down.

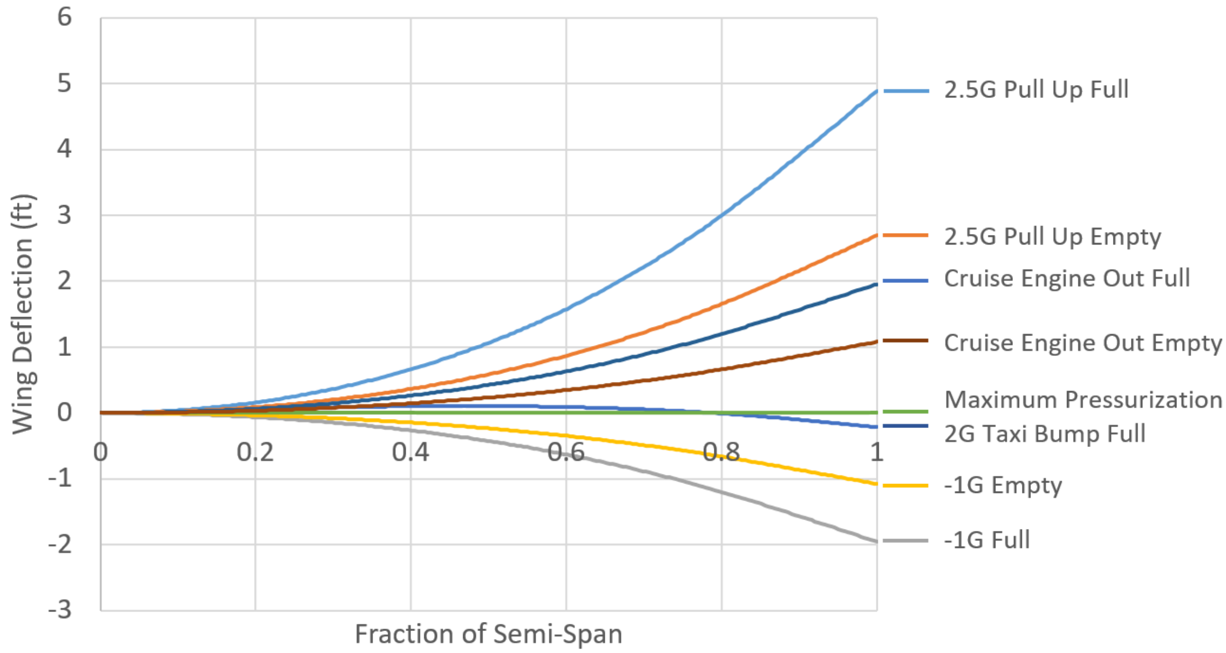

Fig. 8 Vertical deflection of Boeing 737-200 wing for each load case.

A short execution time is critical to enabling AMMIT to be incorporated into automated design optimization loops without unacceptably long computation times. Table 3 contains the execution time for each aircraft along with the approximate split between input and output (I/O) and sizing calculations. These times were computed as the average of four AMMIT executions on a Windows laptop. As described in the proceeding sections, input includes reading from input files and processing each entry and output includes processing the results of the sizing processes and printing them to the appropriate output files.

The large percentage of execution time devoted to input and output indicates that there are significant opportunities to reduce execution time without impacting the sizing methodology by streamlining the I/O process. Additionally, the results show a trend between aircraft size and execution time, with the Boeing 747-200F taking 37 seconds to complete while the much smaller North American T-39A required only 5.5 seconds. This time difference is due to how AMMIT sizes the structure in small sections with larger aircraft being divided into more sizing sections than the smaller aircraft.

Table 3 AMMIT execution time for each aircraft based on an average of four executions.

Aircraft	707-320C	727-200	737-200	747-200F	DC-8-62	DC-10-30	F-27A	L1011-1	T-39A
Load Calculation & Sizing (s)	1.7	1.0	0.8	2.1	1.1	2.4	0.7	1.4	0.4
I/O (s)	17.9	24.3	18.0	34.9	18.2	28.3	14.9	19.3	5.2
Total (s)	18.2	25.2	18.8	37.0	19.4	30.7	15.6	20.7	5.5

IV. Concluding Remarks

The AMMIT structural analysis tool fits between MER-based approaches to estimating structural weight and more complex FEM to provide a physics based estimate that can be easily used without the expertise required for finite element analysis. AMMIT can be used to predict structural weight and to refine a structural concept before expending significant effort on FEM. In the analyses that have been presented, AMMIT has been shown to predict fuselage weights across the nine aircraft configurations at an average error of 16% with a minimum error of 7% and a maximum error of 32%. Similarly, wing weight was predicted with an average error of near zero with a minimum error of 1% and a maximum error of 28%. The near zero average wing error is due to the averaging of over and under predictions.

The overall primary structural weight was generally under predicted by an average of 7% with a minimum error of 1% and a maximum error of 25%. In conclusion, AMMIT was determined to be an effective tool for performing conceptual designs of aircraft structures based on the following important features: lower-fidelity approach used for parameter input, minimal effort required to setup and execute an aircraft analysis, and the inherent rapid execution time for obtaining solutions.

Future work identified through this initial investigation may be divided into two categories: accuracy and user interface improvements. Future improvements to the accuracy of the methodology should include an examination of the causes for the discrepancy in the fuselage weight prediction for certain aircraft, e.g. the Boeing 747-200F, an examination of the wing sizing routines, and the examination of possible calibration factors to approximate total structural weight from the AMMIT predicted primary structural weight. Future improvements to the user interface should include an examination of methods to enable AMMIT to calculate wing spar locations instead of requiring them as a user input and code improvements with I/O revisions to reduce the execution time.

V. Acknowledgments

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